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POWER CONVERTERS AND CONTROL FOR GRID CONNECTED MICROGRIDS UNDER UNBALANCED OPERATING CONDITIONS

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DEDICATION

I dedicate this work to the memory of Professor Alfio Consoli for his generous help and immense support during my first steps towards my PhD.

I also dedicate this work to my family, especially to my wife (Eng. Amal Omar) and my children's (Maram, Leen & Aseel) for their love, patience and sacrifice; to my parents and grandparents for their prayers and encouragement; to my sisters and brothers for their support.

Challenges make you stronger

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ABSTRACT

"Power Converters and Control for Grid Connected Microgrids under Unbalanced Operating Conditions".
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Nowadays, Renewable Energy Sources (RESs) have become more attractive and affordable due to recent advances in power electronic devices and control systems. Micro-Grids (MGs) represent a new paradigm of electrical grids with Distributed Generation (DG) units: they are generally composed of power converters, RESs, Energy Storage Systems (ESSs), local loads with measurement and control systems.

MGs have the potential to operate in both, grid connected and islanded mode. During islanded mode, ESSs are essential for MGs to enable grid forming control. On the other hand, during grid connected mode, the ESSs allow the MGs to provide different services to the main grid. For example, grid power supporting during peak periods; however, in case of unbalanced operational conditions for MGs, due to single phase loads and single phase generation units, the power exchange between MGs and the main grid will add negative effects to the main grid.

Since the MG is supposed to be grid friendly when connected to the external grid, the unbalanced currents should preferably be handled within the MG. Therefore, the power converters of MGs have to provide the zero sequence and negative sequence currents.

The main objective of this thesis is to obtain grid friendly MGs, in order to improve the functionality of MGs during the grid connected mode, under unbalanced operating conditions.

Power converters with ESSs can be adopted to mitigate the negative effects of unbalanced grid connected MGs. However, suitable control strategies are required. In this thesis, a control strategy based on vector control and symmetrical components is proposed for three-phase four-legs power converter interfaces Energy Storage Batteries (ESBs) to obtain a Multi-Functional Power converter (MFPC), in order to resolve the problems of the unbalanced three phase currents, and to the reactive power compensation.

Several working conditions have been analyzed, and solutions for some common and frequent critical conditions, such as the imbalance of the power system due to single-phase loads and single phase DGs have been presented. Discussions of technical issues like output filter design and four legs VSIs modulation techniques, synchronization, power converters topologies and control have also been discussed.

The proposed control strategy of MFPC is able to mitigate the negative effects of grid connected MGs such as, unbalanced and reactive power compensation. This allows the MGs to become "grid friendly", even it is working under highly unbalanced and poor power factor conditions, and also performs power management to optimize the MGs supporting services with smart grid functionality.

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LIST OF ABBREVIATIONS

3D-SVM	Three Dimensional Space Vector Modulation
3P4L	Three-Phase four-Legs
AC	Alternating Current
CAES	Compressed Air Energy Storage
CE	Clean Energy
CPWM	Carrier-based Pulse Width Modulation
CS	Crystalline Silicon
DC	Direct Current
DFIG	Duple Fed Induction Generator
DG	Distributed Generation
DRs	Distributed Resources
DSM	Demand Side Management
EEI	Energy Efficiency Improvements
EMI	Electromagnetic Interference
EMSs	Energy Management Systems
EPS	Electrical Power System
ES	Energy Saving
ESBs	Energy Storage Batteries
ESSs	Energy Storage Systems
FACTS	Flexible AC Transmission Systems
GaN	Gallium Nitride
Grid-SM	Grid Supporting Mode

GTO	Gate Turn Off Thyristor
HVDC	High-Voltage Direct Current
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
L V	Low Voltage
MFPC	Multi-Functional Power Converter
MGs	Micro-Grids
MG-SM	Microgrid Supporting Mode
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NOCT	Normal Operating Cell Temperature
PCC	Point of Coming Coupling
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
RESs	Renewable Energy Sources
SCADA	Supervisory Control And Data Acquisition
SCR	Silicon Controlled Rectifier
SCT	Symmetrical Component Theory
SG	Smart Grid
SH	Self-Healing
SiC	Silicon Carbide
SMES	Superconducting Magnetic Energy Storage
SOA	Safe Operating Area

SOC	State of Charge
SOGI	Adaptive Second Order Generalized Integrator
SPWM	Sine Pulse Width Modulation
SRF	synchronous rotating frame
STC	Standard Test Condition
SVM	Space Vector PWM Modulation
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VAR	Volt Ampere Reactive
VRLA	Valve Regulated Lead Acid batteries
VSI.	Voltage Source Inverter
% VUF	Percentage of Voltage Unbalance Factor

Chapter 1 Introduction

This chapter summaries the motivations and objectives of this work. It gives a general background of electrical energy systems, MGs and smart grid concept. The roles and challenges for developing this field is briefly presented. A review of system configurations and schemes in the electric power system is provided, an explanation of the effects of imbalance in power systems with symmetrical components are explained. Other related concepts are presented and a literature review is also provided, followed by the thesis outline and the scope of research.

1.1 Background

1.1.1 Electrical Energy

Energy plays its continuous role in all spheres of human life, since the industrial revolution started, the world started looking towards productivity and modernity. The main sources of power generation are fossil fuels and nuclear power plants. These sources maybe are sufficient for our generations, however for future generations there is necessity to look for sustainability and finding new solutions to resolve the problem of increasing energy demand and exhaustible fossil fuels resources.

Further, generation of electric power via conventional means is unsustainable, it is considered the main source of greenhouse gases mainly CO_2 which harms the environment drastically and causes global warming, ozone depletion and climate change. Thus one of the major priorities for the worldwide is focusing on the sustainability terms; Renewable Energy (RE), Energy Efficiency Improvements (EEI) and Energy Saving (ES), which are representing an interesting areas for researchers and engineers to overcome these problems by introducing solutions for keeping the environment and looking for sustainability.

Clean Energy (CE) is generated by RESs like solar energy, wind energy, geothermal and other forms like biomass. These kinds of sources have been used in the past just for special purposes; for supplying rural areas with electricity, wherein supplying these areas from utility grids requires more infrastructures; transmission lines and transformers with more losses and huge investment costs. Nowadays renewable energy is commonly used in different applications mainly in grid connected systems.

1.1.2 Electrical Power System (EPS)

The main challenge of an electrical power system is to supply electricity to the end-users with reliable and efficient way. In traditional power systems, bulky power generation plants supply most of the power in unidirectional power flow and passive electrical distribution network: this makes the energy efficiency improvements a complicated task. Nowadays the world is looking to find new solutions and adds more improvements to this huge market by utilizing small units for power generation in distributed side. As a result passive unidirectional networks become bidirectional active networks as illustrated in Figure 1.1. The energy consumer becomes "prosumer"; who can produce/consume energy with his own DG units and support the main grid with excess energy [1, 2].

As a consequence RESs become more attractive to penetrate and support the main grid to improve the reliability and efficiency of all system by using DG units instead of centralized large generation units.

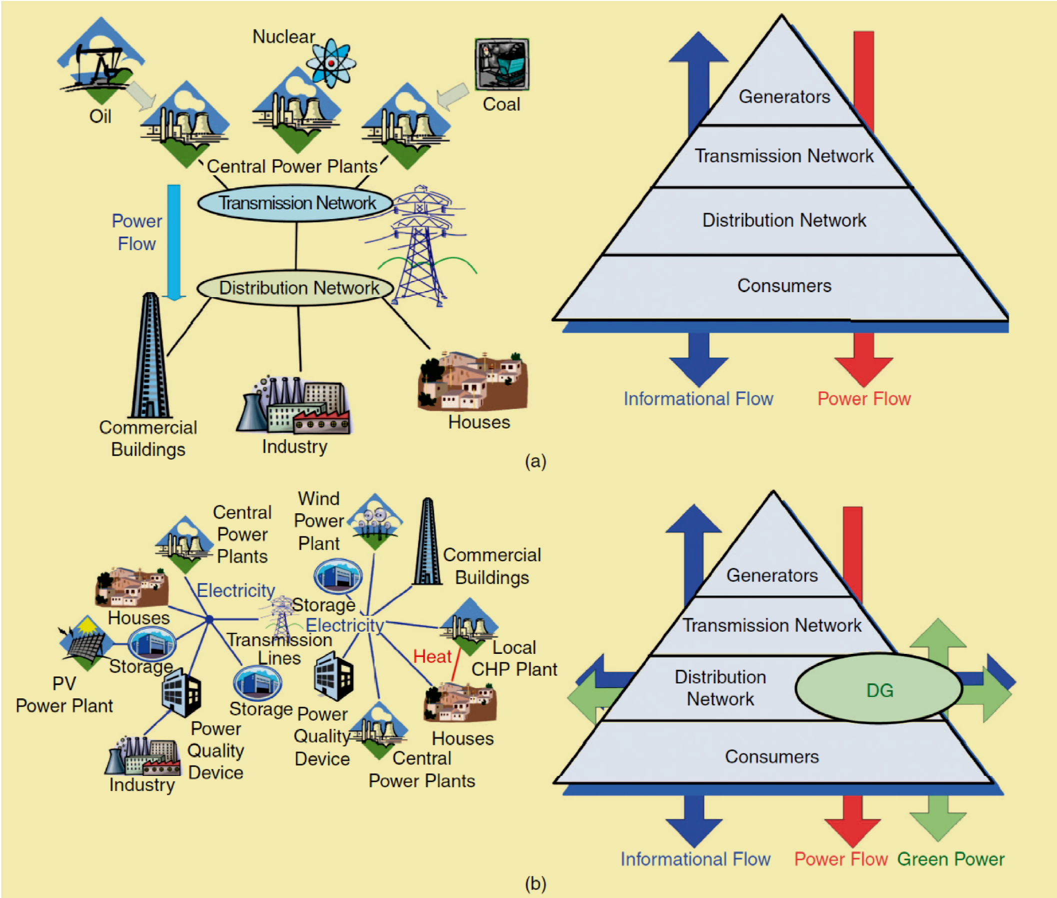

Figure 1.1 Power plants toward distributed power generation:

(a) Traditional power systems; (b) Decentralized future power systems.[1]

1.1.3 Distributed Generation

As mentioned before due to energy crisis and environmental pollution carbon free RESs are urgently needed, as they are environmentally clean and economically viable, integrating DG units with the main grid as shown in Figure 1.2. As these DG units are close to the loads, the losses will decrease at transmission and distribution level, moreover the reliability will increase for the overall system as different sources are combined and working together. DGs are play a significant role to improve the overall efficiency, sustainability and reliability of power system [3, 4].

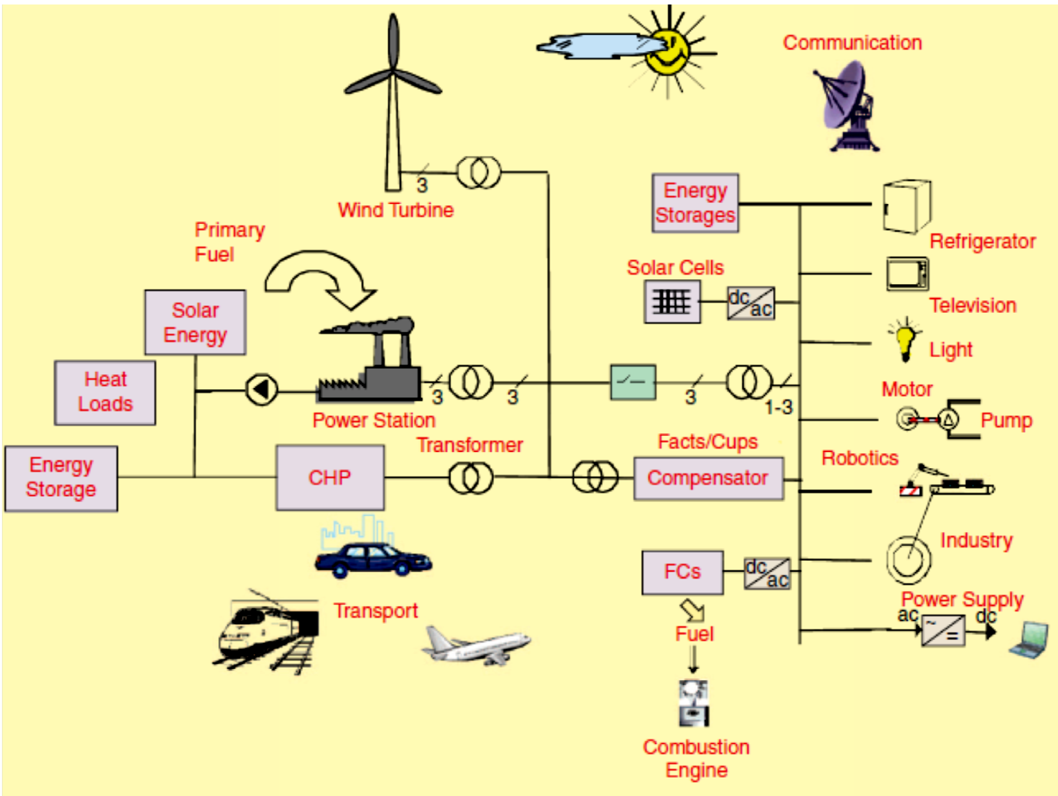

Figure 1.2 The distributed electrical generation systems [1].

Electrical power generation sectors are looking for increasing the penetration level of RESs in their electrical energy systems, since they are sustainable and a flexible nor polluting, besides numerous technical and economic benefits which can be achieved from installation of DG units such as [5, 6, 7]:

- Efficiency improvements by losses reduction in the system components.
- Reduction of environmental pollution.
- Voltage profile improvement.
- Reliability and security enhancement.
- Improved power quality.
- Energy security enhancement.
- Reserve requirements reduction.
- Saving investments cost of transmission and distribution infrastructure.

1.1.3.1 Challenges of DGs

Even though aforementioned advantages and benefits of DGs are clear, there are so many challenges poses increasing penetration of RESs integration which needs to be overcome. Main challenges can be summarized in the following:

- Power conversion efficiency.
- Power quality improvement, harmonics, unbalanced.
- Energy storage integration.
- Energy management.

There are so many other challenges related to nontechnical issues and standardization, however in this thesis only the technical issues have been considered.

1.1.4 Microgrids

Aforementioned advantages of interconnecting DG units with the main grid encourage interconnecting more units to the main grid. However increasing the penetration level of DGs in electrical networks adds more complexity and poses challenges like disconnection or islanding from the main grid. This requires a new paradigm of active electrical networks which can cover a part of distribution system in low and medium voltage networks: such system is known as "Microgrids" (MGs) [8, 9]. Based on IEEE Std. 1547.4-2011 [10], MGs are defined "a Distributed Resources (DRs) used for intentional islands. Island systems are EPSs that have DRs and load, and the ability to disconnect from and parallel with the EPS area. As well to achieve the emerging potential and development of DG systems, a MG approach which composites RESs and associated loads with

ESSs in a subsystem must be taken into account as it is shown in Figure 1.3, depicted from [11].

In normal conditions, MGs operate with grid connected mode. During disturbances islanded mode takes place: the generation and corresponding loads can be separated from the distribution system, to isolate the MGs loads from the disturbance without harming the transmission grid's integrity [12].

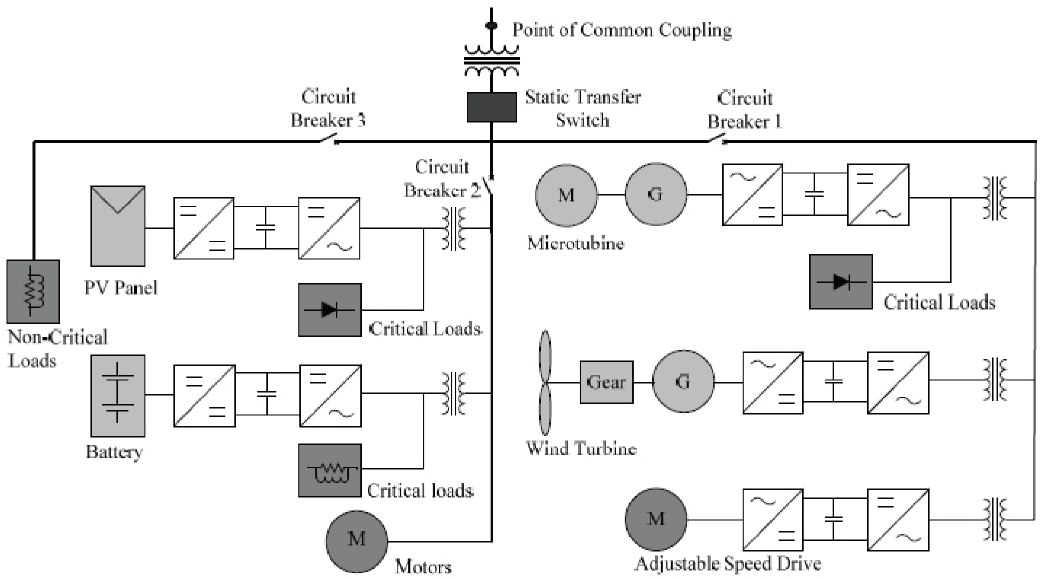

Figure 1.3 The configuration of a grid interactive ac MG system.

The cooperation between different MGs or power system clusters leads to manage the generation and the consumption with energy management systems by utilizing information technology and smart meters for matching between RESs, ESSs and load demands. Wherein Smart Grid (SG) concept is arising, it represents a vision for continuous development of electricity market towards more sustainability of EPS.

1.1.5 Smart Grid Concept

In the literature SG is defined by people have different perspectives. For example, the authors in [13] gave a general definition of a SG: it is defined with an intelligent, auto-balancing, self-monitoring power grid, that accepts any power source and transforms its generated power into the end-users, to be used efficiently in different purposes.

SG may also can be defined as a vision for future electric power market to keep going towards more developments and improvements of electrical power sector by utilizing more REs and maintain DG units interconnection to the main grid even under grid abnormalities or blackouts [14]. Energy Management Systems (EMSs) is an attractive solution to manage and distribute the generated power to the customers efficiently with reliability improvements.

EMSs in SGs require interaction between power electronic converters controllers and information technology to resolve the complexity of this technology. This aspect requires introducing new technologies, for example the requirements of technical issues have been changed from using local supervisory control and data acquisition (SCADA) into other recent central data loggers [15, 16]. New solutions instead the limited-capacity communications in SCADA systems like, for example, technology of agents, which is used to send an appropriate alarms to the central computers [14].

Aforementioned technologies provide the SG with data logging, monitoring, prediction, forecasting, SG status, state estimation, protection and energy management. Which allows the SG to be with more controllability, reliability and sustainability. Such power grid responds smartly to the all changes and interacts with weather conditions, end users behaviors, smart houses, smart meters, Demand Side Management (DSM) and optimal power flow. Indeed smartly means system management intelligently for efficient supply, feasible, sustainable electric power services with more reliability and flexibility [14].

1.1.5.1 Smart Grid Functions

A SG typically performs the following functions [17]:

- Power generation balancing by meeting local loads demand as well as the excess energy that is feeding to the main grid.
- Local loads management: have different categories as critical loads, normal loads and programmable loads.
- Energy storage capability to smooth the intermittent output of RESs and store excess energy and sell this energy in beneficial time.
- integration of technologies smart houses, smart meters and sensors capable of measuring electrical system parameters which are used for control of power converters with a certain accuracy.
- Interacting technical issues with communications and information technology for improving the overall system performance and EMSs.
- Offering and providing solutions for customers requirements and needs in all seasons and times.
- Making the electrical grid a Self-Healing (SH); speedy responding and reacting to real or potential abnormalities.
- Enabling market of electricity by different functions for different users and companies.

1.2 Asymmetry and Symmetrical Components

The unbalanced conditions are very common for Low Voltage (L V) MGs, because of single phase loads and single phase inverters usage. The unbalanced conditions create unbalanced currents circulating between MGs and the main grid, which adds negative affects into grid and the MGs.

1.2.1 Impacts of Asymmetry in Power Systems

Asymmetry in current and voltage add negative effects throughout the process of power delivery. The negative sequence voltage increases heat and losses of induction motors. The negative sequence currents reduce the system efficiency. Asymmetry also affects the power system components with the following [18, 19]:

- Protection relays and measuring instruments malfunction.
- Motors and generators : losses, vibration, temperature.
- Transmission lines : the capacity of the lines is reduced.
- Transformer: the zero sequence currents circulating in the delta side, causing heat and losses.

According to [20], the International Electrotechnical Commission (IEC) gives a definition of the degrees of the unbalance: the unbalance factor is described in terms of the negative-sequence unbalanced factor and zero-sequence unbalance factor expressed in the following equations.

$$Unbalance\ (N)\% = \frac{X_n}{X_P} \times 100 \tag{1-1}$$

$$Unbalance\ (z)\% = \frac{X_0}{X_P} \times 100 \tag{1-2}$$

Where $X_{p,n,0}$ are positive, negative and zero sequence components.

1.2.2 Symmetrical Components

The Symmetrical Component Theory (SCT) is widely used in power system fault analysis [21]. According to SCT, a asymmetrical three-phase signal (either current or voltage) can be represented as a sum of positive, negative and zero-sequence components [22] as shown in Figure 1.4. The transformation is given by

$$\begin{bmatrix} X_p \\ X_n \\ X_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} \tag{1-3}$$

Where X could be V (voltage) or I (current) and α is an operator and has the value of

$$a = e^{j2\pi/3}, a^2 = e^{j4\pi/3} \tag{1-4}$$

$$\begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} = \begin{bmatrix} X_{A\_p} \\ X_{B\_p} \\ X_{C\_p} \end{bmatrix} + \begin{bmatrix} X_{A\_n} \\ X_{B\_n} \\ X_{C\_n} \end{bmatrix} + \begin{bmatrix} X_{A\_0} \\ X_{B\_0} \\ X_{C\_0} \end{bmatrix} \tag{1-5}$$

Where:

$$\begin{bmatrix} X_{A\_p} \\ X_{B\_p} \\ X_{C\_p} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} \tag{1-6}$$

$$\begin{bmatrix} X_{A\_n} \\ X_{B\_n} \\ X_{C\_n} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix} \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} \tag{1-7}$$

$$\begin{bmatrix} X_{A\_0} \\ X_{B\_0} \\ X_{C\_0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} X_A \\ X_B \\ X_C \end{bmatrix} \tag{1-8}$$

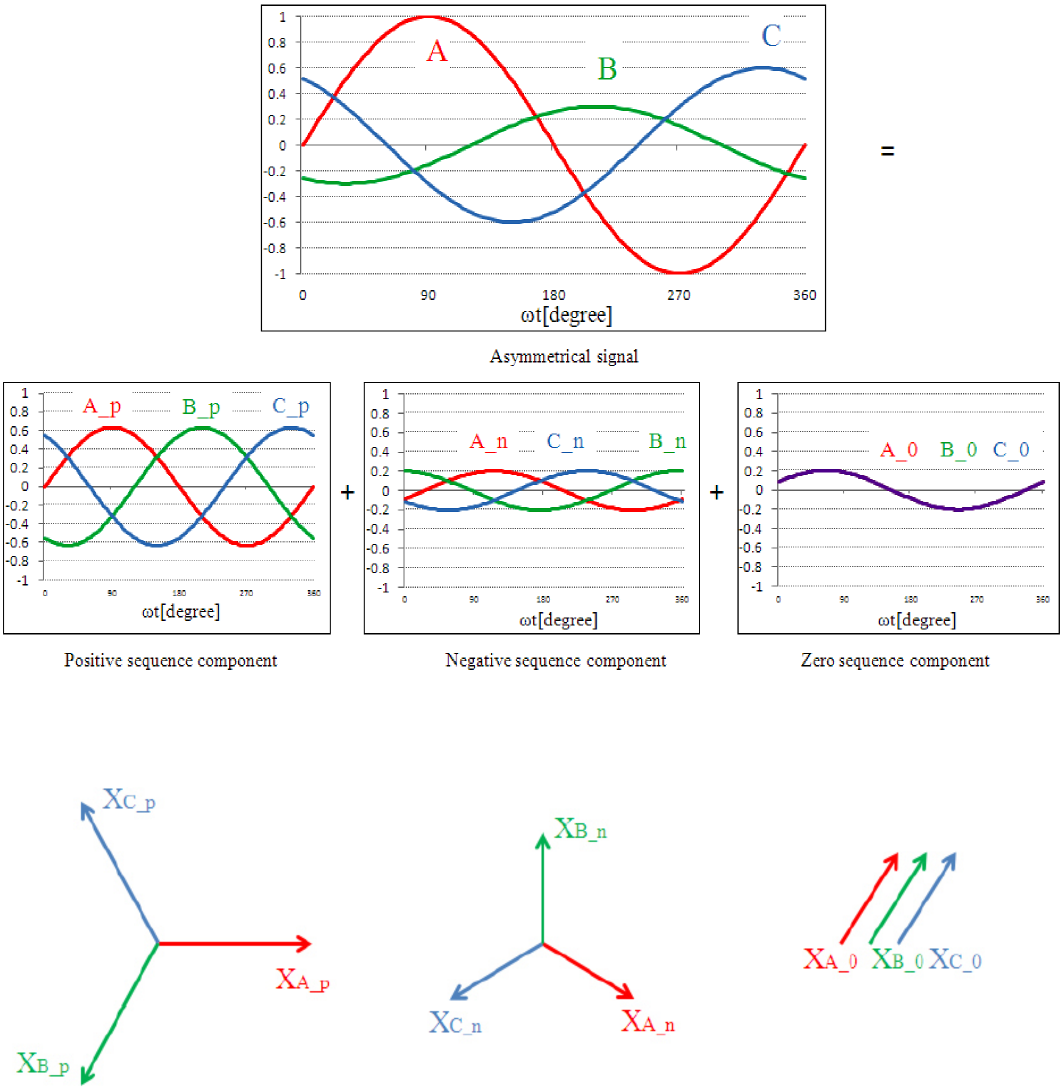

Figure 1.4 Symmetrical components representations.

1.3 Literature Review

Many research studies have been conducted to investigate and analyze MGs issues with different perspectives; configurations, operation, management and control improvements. Analysis of several MGs configurations AC MGs and DC MGs has been discussed in [23]. The control of islanded MGs, primary, secondary and tertiary control has been analyzed in [24]. The primary control of power converter or droop control has been illustrated in [25]. The control of power converters in stationary reference frame for MGs has been discussed in [26].

In most of these research studies, the analysis has been carried out with the assumption of symmetrical operation or balanced three phase loads in MGs, however, in practice, single phase generation, like rooftop photovoltaic inverters, and single phase residential loads are commonly used in LV MGs. The output power of single phase DGs in LV MGs and residential loads are various and highly dependent on the surrounding conditions and the end-users behaviors. Therefore the unbalanced operations are more common to take place, especially in low voltage MGs with majority of single phase inverters and loads. which will increase the negative sequence currents to flow in MGs and causes serious problems and abnormal operation of sensitive equipment in the MGs [27]. Voltage asymmetry compensation in islanded MGs is proposed in [28]. The authors proposed a control strategy for three wires MGs to resolve the problem of unbalanced voltage in MG by compensating the negative sequence components. The authors didn't discuss the zero sequence components as they considered three wires MG, however the neutral line is important in case of using single phase inverters and residential single phase loads in MGs.

In case of using delta-wye transformer to provide the neutral bath, the transformer will block the zero sequence currents as these currents will circulate in delta side, however the negative sequence currents will pass with a phase shift of 30 degrees as discussed in [29]. Therefore the transformer will not resolve the problem completely.

Since the MG is supposed to be grid friendly when connected to the external grid, the unbalanced currents should preferably be handled within the MG. Therefore the power converters of MGs have to provide the zero sequence and negative sequence currents [29]. A control strategy for unbalance compensation in MG has been previously described in [30]. The latter control strategy was based on stationary reference frame, and was proposed to mitigate the negative effects of grid connected MGs by using unbalance compensator without discussing PQ control as they didn't consider ESSs. MGs during islanding mode (not discussed in this work) should be disconnected from the main grid for safety and standard requirements of [1]anti-islanding. During islanded mode, grid forming units provide the MG sources and loads with voltage and frequency. The latter units must have ESSs to enable grid forming control. As a result ESSs are essential for any MG, and therefore it can be used with more functions during grid connected mode.

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[1]Islanding refers to the condition in which a DG continues to power a location even though electrical grid power from the electric utility is no longer present. Islanding can be dangerous to utility workers, for that reason, distributed generators must detect islanding and immediately stop producing power; this is referred to as anti-islanding [31].

In this thesis four-legs power-converter is proposed to be a MFPC: during grid connected mode, mitigates the negative effects and performs other functions based on the grid operator and MG conditions, like supporting the grid with active and reactive power or supporting the MG during power generation shortage, mitigation of voltage drop and voltage rise, increasing DG penetration level and performing power quality improvements. Also it can be used as a grid forming unit during islanded mode.

1.4 Problem Description

In recent years, RESs interconnection with the main grid has become more common due to increased importance of environmental issues and economical benefits for electricity market. as a consequence more distributed power sources based on photovoltaic and wind power generation, in addition to other resources, are installed. Increasing the penetration level of these sources requires more integration of DG units. As a result, problem of system complexity leads to introduce new configurations and schemes of power system networks. MGs are a new paradigm of power system networks and have been extensively studied by researchers to investigate different issues in MGs.

MGs can be used for supporting the main grid during peak period time. On the contrary during off-peak time the main grid is utilized for charging the ESBs of the MGs or supplying it’s local loads in case of power generation shortage or with batteries minimum state of charge. In MGs single-phase generation like PV rooftop can be utilized and different loads can be used by the end-users which can cause the grid currents to be unbalanced with poor power factor as shown in Figure 1.5.

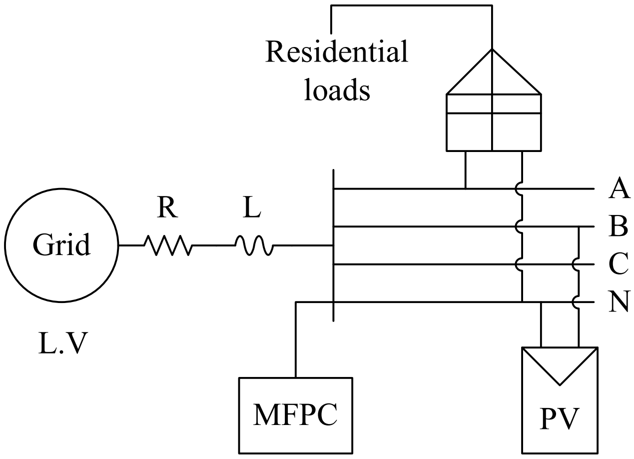


Figure 1.5 MG with unbalanced operation.

Unbalanced operation of MGs may lead to serious problems such as unbalanced faults, asymmetrical voltage drops, more losses, loads failure [27, 32]. Thus it is essential, to make MGs friendly with the main grid, improving the quality of power exchange in both power flow directions which allows to improve the overall efficiency and increase the penetration level of DG.

1.5 Thesis Objectives

- Review of power converters in MGs, operation principles and control strategies.
- Perform analysis and simulation of MFPC control strategy for grid connected MGs for unbalanced and reactive power compensation.
- Examine the responses of control strategy with different power management modes for "grid friendly" MGs with unbalanced operation.
- Simulation of different cases, showing the advantages of proposed control strategy, voltage drop mitigation and other related advantages.

1.6 Thesis Outline

This thesis is organized in 6 chapters:

Chapter 1 introduces an overview of electrical energy systems, DGs, MGs and smart grid concepts. Literature review about asymmetrical operation of grid-connected systems, followed by problem description and research objectives is also presented.

Chapter 2 presents a background about power electronic converters including power devices, applications, power converters topologies, issues of power converters interfacing PLLs, and filter interfacing and pulse width modulation for three-legs and four-legs power converters.

Chapter 3 discusses a general overview about RESs and energy storage in MG, photovoltaic dynamic characteristics, PV-inverters and ESS description.

Chapter 4 focuses on control of power converters in MGs, mainly during grid connected mode, Proposes a control strategy for MFPC for grid supporting functions, unbalanced and reactive power compensation and examines the proposed control strategy with different operating modes by time domain simulation.

Chapter 5 employs the proposed MFPC to obtain grid friendly MGs, simulates and investigates different cases and conditions, including reactive power compensation, unbalanced loads, and voltage quality improvements for grid connected MG under unbalanced operating conditions.

Chapter 6, finally, reports the thesis conclusions and future work.

Chapter 2 Power Conversion and Interfacing in MGs

In this chapter power conversion technology, power electronic systems, power devices and power converters applications are discussed to fulfill deep understanding of the idea. Power converters topologies and PWM modulation strategies for VSIs are illustrated. AC filters topologies with focusing in LCL filter design and its dynamic behavior analysis. Synchronization with PLLs are described and discussed.

2.1 Power Electronics Converters

The development of power electronic devices contributes substantially in developing of the technology of DG, whereas each DG unit needs to be interconnected with the main grid through power electronic converters to control and improve the output power [33, 34]. In MGs power electronic converters represent the key elements for operation and functionality improvements, the main purposes of using power converters in MGs, are power control, power sharing, RESs interfacing, power quality improvement and energy management.

2.1.1 Power Electronics Devices

Semiconductor switches represent the main part, "the heart" of power electronic converters. These power devices have distinct characteristics, like switching frequency, Safe Operating Area (SOA), thermal performance and other characteristics. Figure 2.1 shows different power levels and switching frequencies of power devices [35]. Silicon Controlled Rectifier (SCR) and Gate Turn Off Thyristor (GTO) operate up to near 1 kHz. It can be employed in high power converters where the switching frequency is not important. As a result such power converters are bulky with low power density.

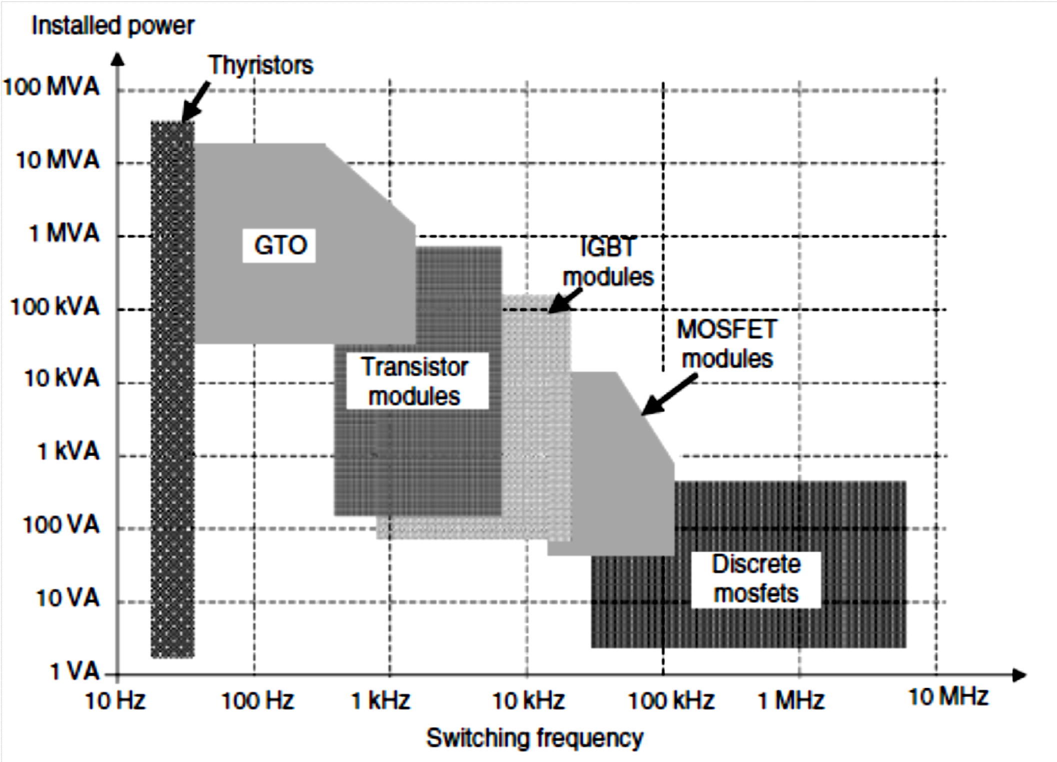


Figure 2.1 Power switches availability [35].

Insulated Gate Bipolar Transistor (IGBT) and power Metal Oxide Semiconductor Field-Effect Transistor (MOSFET), has higher switching frequency ratings. They are used in the lower power applications hence high speed power devices are preferable with high switching frequency to reduce the size of passive components. IGBT has lower switching frequency in comparison with MOSFET. It has very low on-state losses “conduction losses” [36]. However IGBT suffers from a phenomena that called “tailing” which causes extra high turn-off losses and leads to relatively high switching losses [37].

Power MOSFETs on the other hand switch very fast, have very low switching losses and require very little power for their control. However they have a very high on-state resistance and thus dissipate a large amount of power during the on-state [36, 37] as a result they are not used for high power applications.

With the increasing power rating of the power converters used in different industrial applications, the high voltage and current require series and parallel configurations of power converters. This needs costly active or passive snubbers and other expenses for cooling. Therefore the need of high-power, high voltage rating devices, operating with high switching frequencies and high limits of junction temperatures are growing, especially for advanced power converters. These new requirements need to look for new materials to overcome silicon based material limitations with wide band gap semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC) devices [38].

2.1.2 Power Modules

A power semiconductor module may be defined as a device which contains more than one semiconductor chip and provides electric and a heat flux paths [39]. Power electronic systems have become much more compact, cost efficient and reliable, which require advanced device packaging and integration technology.

2.1.3 Power Conversion Efficiency and Power Density

The main concerns in modern power electronic systems are delivering the power with maximum efficiency, minimum cost and high power density (weight reduction).

Power conversion efficiency is a crucial challenge for DG technology. Thus using high efficient power converters for interfacing renewable power sources like (photovoltaic, wind, fuel cells) with the utility grid is strongly recommended to enhance the utilization of these sources.

Passive elements (inductors and capacitors) are used in power converters for filtering out harmonics thereby the Total Harmonic Distortion (THD) of current and voltage is reduced within the standard limits. The size of passive elements is proportional to the switching frequency. Therefore, using high switching frequency devices leads to decrease the size of these elements, reduce the losses, increase the efficiency; as a result the power density of these converters will also increase [40].

2.1.4 Electromagnetic Interference (EMI)

EMI in power electronics is an issue that comes from fast switching, *di/dt* and *dv/dt* increasing at switching periods while time of switching *dt* is decreasing. EMI noises is a major issue in most power electronic systems due to significant over voltage and leakage current generated by fast switching and stray components of the system. Electromagnetic compatibility for power converters operating at switching frequencies higher than 9 kHz is recommended. This is primarily a cost problem for filtering such noises caused by high switching [41]. In addition over voltages might be created due to high *di/dt.* They may be created in presence of parasitic inductance in current paths; high *dv/dt* may creates significant leakage current in magnetic elements and electric motors due to stray capacitive. As mentioned before the switching losses can be reduced by increasing the switching frequency, however fast switching increases EMI noise as *dv/dt* and *di/dt* increases. Thus, it is a trade-off between losses reduction and EMI to determine the optimal switching frequency. The other alternative is to reduce stray inductance and capacitance of power electronics systems by using a better layout or bus-bars, interconnection and configuration to suppress the EMI at high switching frequency.

2.2 Applications of Power Electronic Converters

Power electronic converters have a significant role in different industrial applications include regulated power supplies (DC and AC), Uninterruptible Power Supply (UPS) systems, electronic welding, Volt Ampere Reactive (VAR) compensators, Flexible AC Transmission Systems (FACTS), High-Voltage Direct Current (HVDC) systems, RESs power converters (PV, wind Fuel cell), high-frequency heating, ESSs, electric vehicles, electrical transportation and motor drives.

Different applications for power electronic converters are illustrated in Figure 2.2. It is clear that the applications of drives and renewable energy represent large percent with respect to other applications.

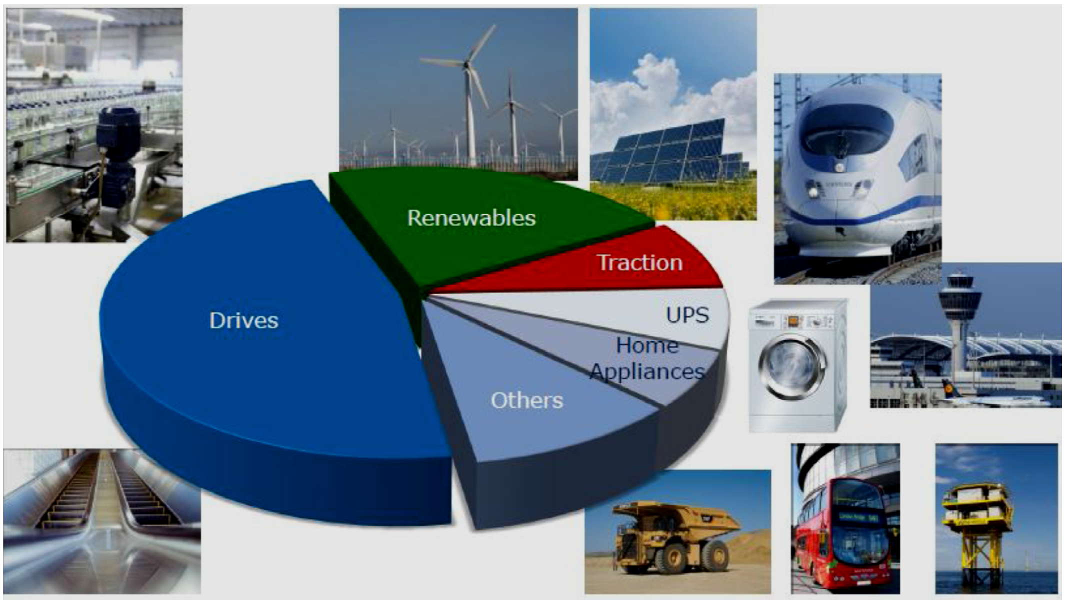


Figure 2.2 Sectors of power converters applications [42].

The ratings of power electronic converters vary depending on the applications as shown in Figure 2.3. Different rating levels of power converters for different applications, low power applications employ discrete components, power modules and stack are employed for medium and high power applications.

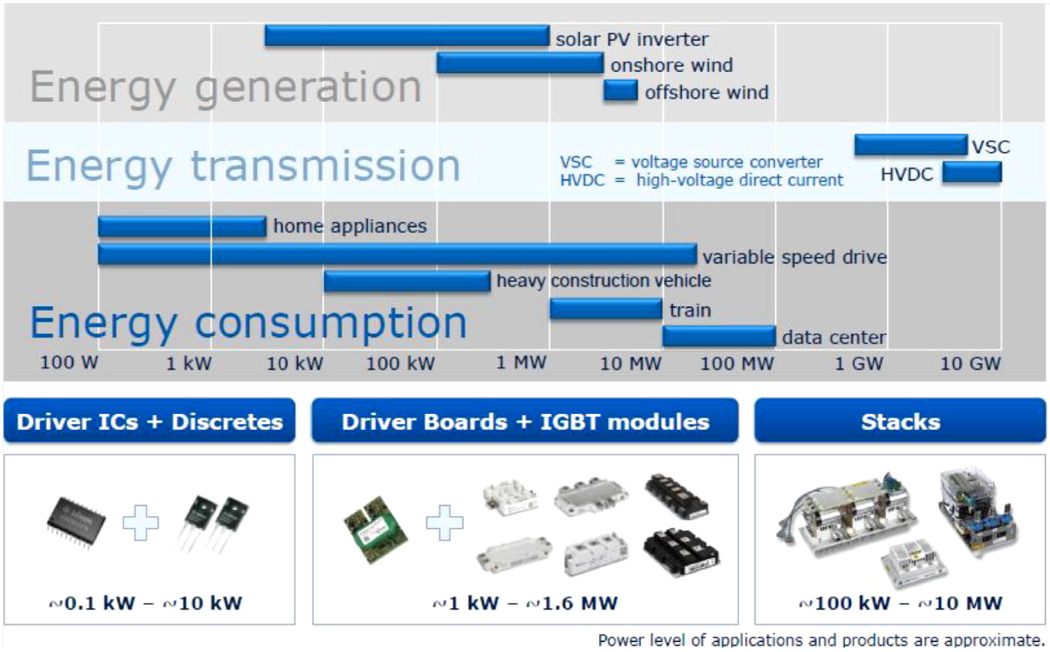


Figure 2.3 Power converters applications with different ratings [42].

2.3 Power Conversion Technology

Power conversion process consists of two stages, power and control stages. As shown in Figure 2.4, the power stage is to convert the input power (AC or DC) and deliver it to the output side (AC or DC). The control stage is used for controlling the power converter to synthesis reference output power, by measuring input and output currents and voltages.

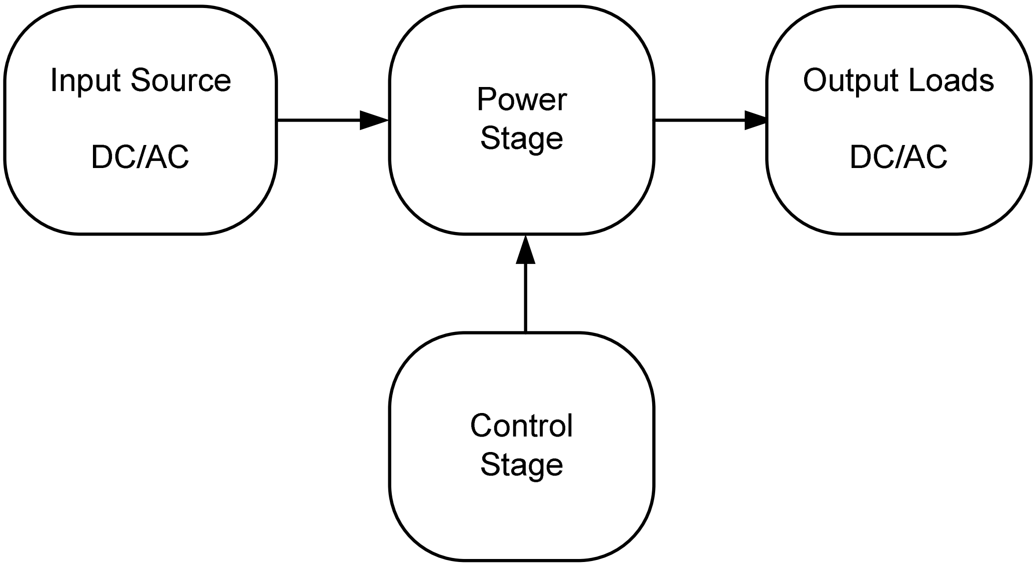


Figure 2.4 Power electronic conversion.

Power conversion can be divided into four different categories according to the input and output power forms [38, 43]. In Figure 2.5, four different combinations of power converters can be used for power conversion of renewable energy sources.

- DC-DC converter.
- AC-DC converter (rectifier).
- DC-AC converter (inverter).
- AC-AC converter.

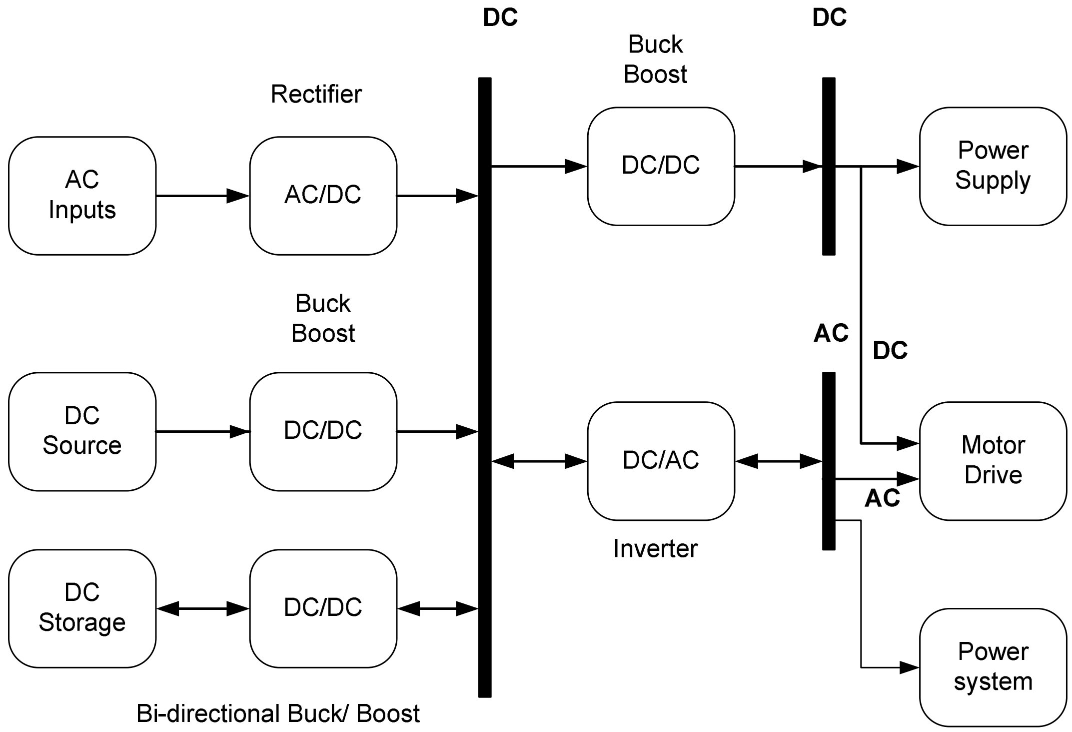


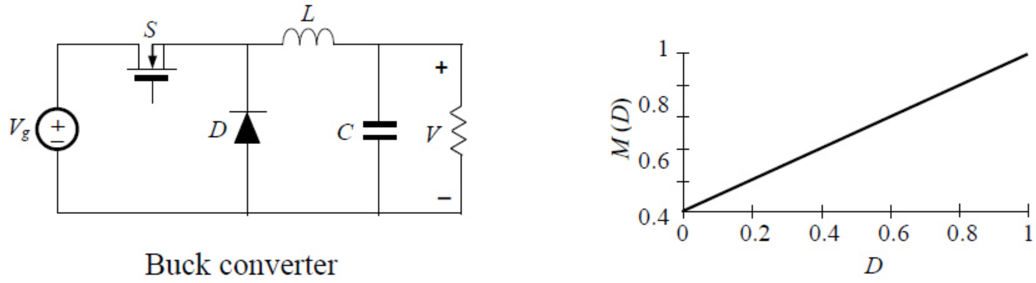
Figure 2.5 Energy conversion technologies based power converters.

2.3.1 DC-DC Power Conversion

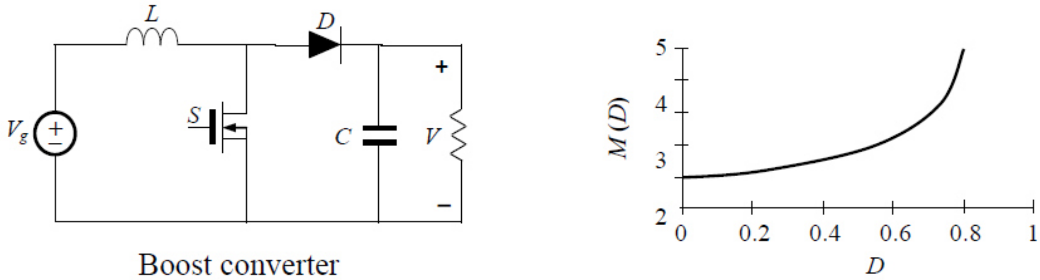
DC/DC power converters are used in renewable energy systems to increase or decrease the DC voltages. Commonly used converters, the buck is used to decrease the voltage, the boost for increasing the voltage and buck-boost for both functions (bidirectional) conversion.

The DC-DC power converters are available with different topologies or circuits [43]; isolated and non-isolated circuits. In Figure 2.6 DC-DC converters with non isolated circuits are shown along function of duty cycle D, with voltage gain. Power MOSFETs represent the ON/OFF switching to achieve desired duty ratio based Volt-Second balance and diode is used for freewheeling the inductor current.

Buck converter is used to decrease the input DC, as shown in Figure 2.6.a, the duty ratio is varied from zero to 1, that means the output voltage less than the input voltage.



a)



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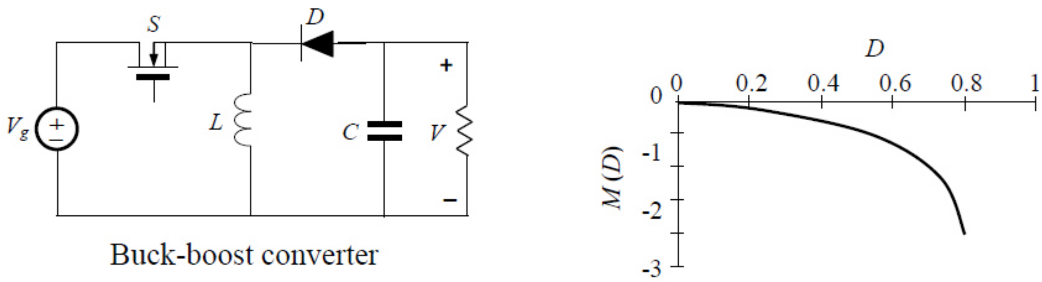


c)

Figure 2.6 DC-DC Power converters with voltage gain.
(a) buck; (b) boost; (c) buck-boost.

Boost converter on the other hand is used to boost or increase the voltage up to certain limit as shown in Figure 2.6.b. This limitation is due to non ideality of the inductor as can be seen the $V_{out}/V_{in}=1/(1-D)$. theoretically as the duty ratio is equal to 1, the gain will increase to infinity, this is true for ideal converter. In practice the non-ideality of the converter should be considered, so the tradeoff is between the voltage gain and the efficiency of the converter.

Buck-Boost converter also is shown in Figure 2.6.c, MOSFET switches alternately connects the inductor across the power input and output voltages. This converter output with inverse polarity of the input voltage. It can either increase or decrease the voltage magnitude. The conversion ratio is [-*D*/ (*1*-*D*)].

Other topology of buck-boost converter is shown in Figure 2.7 is used for increasing the conversion efficiency [44]. It provides bidirectional power transfer with two operation modes buck and boost.

• **Buck mode:** In buck operation the power is transferred from V_{dc} to V_B.

• **Boost mode:** In boost operation, the power is transferred from V_B to V_{dc}.

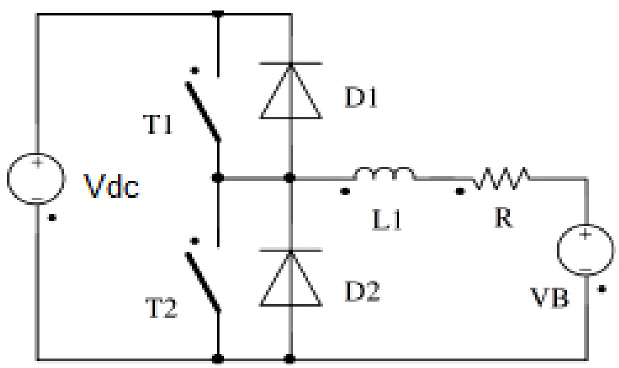


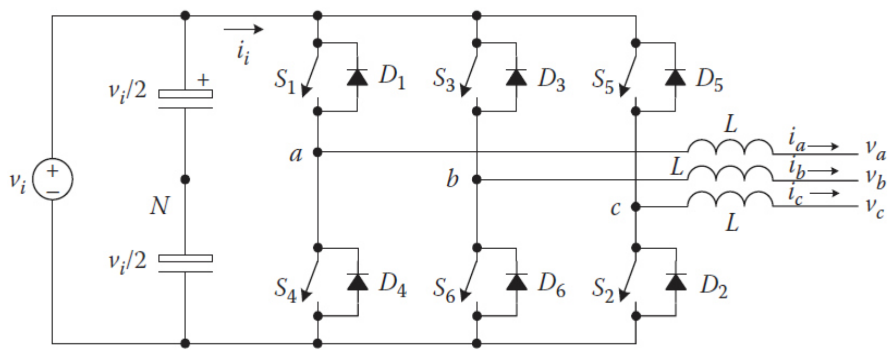
Figure 2.7 Bidirectional DC-DC converter.

In the bidirectional boost converter control, since T_1 and T_2 cannot be switched on simultaneously, a practical control strategy is to turn on one of the two switches per operation mode, i.e. T_2 off at the same time T_1 is controlled and the vice versa is true.

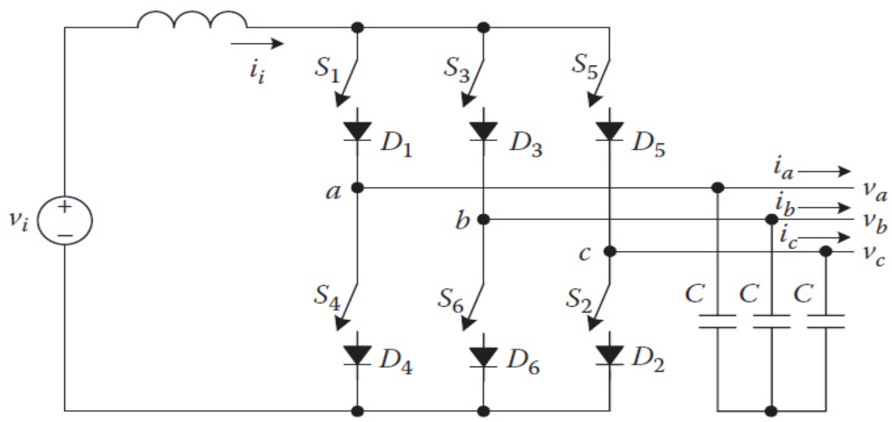
2.3.2 DC-AC Conversion for Three Phase, Three Wires Systems

DC/AC power converters is used in different applications like UPS, motor drive, power system applications. Some of these applications need to control the voltage magnitude and the frequency, which is achievable by using Voltage Source Inverter (VSI). For grid connected RESs the voltage and frequency are synchronized with the grid and working as current sources, however sometimes mainly during isolated or islanded mode the power converter is used to modify and control the output voltage and frequency.

The input of VSI is DC as shown in Figure 2.8.a, it must be greater than the output voltage as it is working as buck converter. VSIs create voltage waveforms at the output and the current waveforms follow the loads requirements or it could be controlled to be leading or lagging currents for reactive power supplying or consuming. CSI (Current Source Inverter) is another topology as shown in Figure 2.8.b. The input is DC current source as a large inductor is connected in series with the DC bus. CSI has disadvantages like bulky and heavy [45, 46, 47]. Figure 2.8.c, shows another Inverter topology with combination of CSI and VSI, it is called impedance-source (z-source inverter). it is used in some applications, it can work in buck and boost operation, but it has more passive components. The economical issue is arising with high power ratings [47]. In this thesis VSI is considered as it is commonly used for renewable energy applications.



(a)



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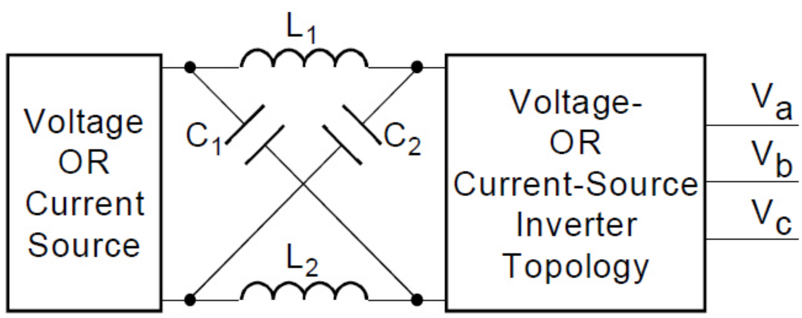


(C)

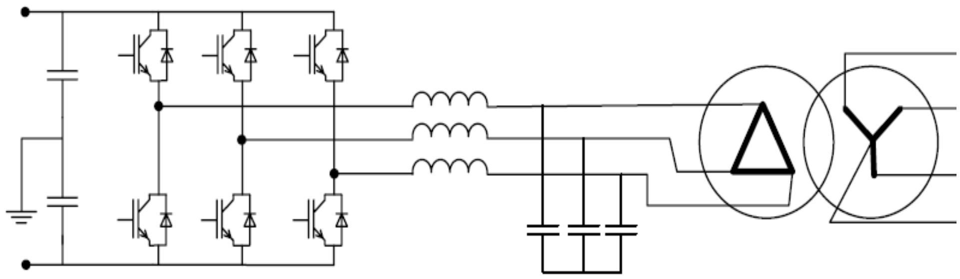
Figure 2.8 Basic DC/AC converter topologies:

(a) Voltage source inverter; (b) Current source inverter; (C) Z-source inverter.

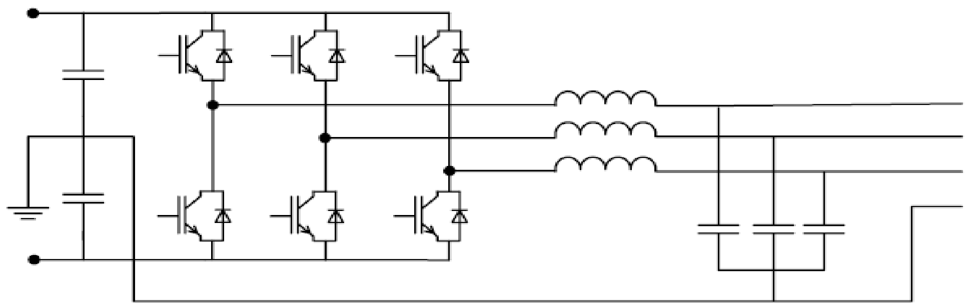
2.3.3 DC-AC Converters for Three Phase, Four Wires Systems

Single phase loads or DG in MGs require 4 wires systems. Therefore unbalanced operation arises. Thus it is required to have power converters that can handle the unbalanced negative and zero sequence currents. In Figure 2.9 different topologies of DC/AC converters are shown for four wires systems [29]. The topology of using three-legs with delta-wye transformer is shown in Figure 2.9.a. Without using transformer usually the neutral wire is connected to the conventional three-phase inverter by splitting the DC-link into two adjacent capacitors as shown in Figure 2.9.b. The problem faced to the split DC-link, is the unequal voltage sharing between the capacitors. This requires large DC link capacitors or an extra voltage balancing control scheme. Another drawback for this configuration, is that the unbalanced and non-linear loads cause neutral currents and can distort the output voltage, while zero sequence current will affect the DC bus or the input. To overcome these drawbacks, the four-legs topology shown in Figure 2.9.c can be used instead of the split DC-link. The fourth leg allows the full control of neutral connection, resulting in better output voltage. The addition of the forth leg also makes a voltage balancing control scheme unnecessary. Such an inverter is called Three-Phase four-Legs (3P4L) [48].

Applications of four-legs power converter is growing and will have a larger market share [49]. Four legs inverter is used for interfacing DG units, as shown in [50, 51]. DGs can work either in islanded or grid connected mode, and such inverter with four-legs provides a three-phase output with a neutral connection. In [52] a four-legs inverter is proposed to resolve power quality problems (active power filter) for harmonic compensation. It is also employed in (UPS) systems [53], other applications like active rectifier [54] and electrical drive systems [55].



(a)



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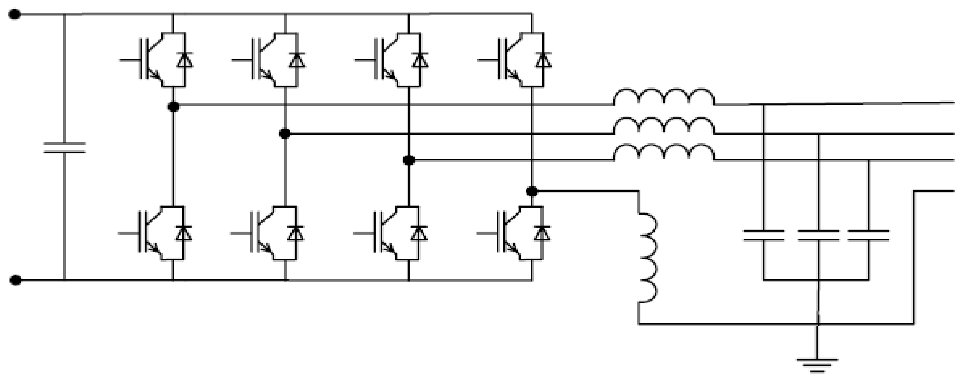


(c)

Figure 2.9 VSIs topologies for three phase, four-wires systems:
(a) Three legs with transformer; (b) Three-legs with split capacitor;
(c) Four-legs VSI.

2.3.4 Pulse Width Modulation (PWM)

PWM is widely used in different power electronic converters. High switching frequency for DC-DC converters can be achieved by PWM to reduce the ripple in output voltage and current. In DC-AC conversion, PWM is used in a different way to control the amplitude and frequency of the output. PWM strategy plays an important role for harmonics and switching losses minimization in power converters. The main goal of any modulation strategy is to obtain a variable output with a maximum fundamental component and minimum harmonics [56].

The Sine Pulse Width Modulation (SPWM) technique is easy implemented therefore is widely used in industrial applications and converters, however the DC bus voltage utilization for SPWM is low. Space Vector Modulation (SVM) is the most popular PWM technique [56, 57, 58]. It is used in three-phase power converters and in comparison with SPWM, SVM gets more DC-bus voltage utilization and generates less harmonics in output. In SVM the reference signals are modified according to the operating conditions of the VSI in every sampling period, which improves the quality of the AC outputs and leads to lower THD [59].

2.3.4.1 Sine Pulse Width Modulation (SPWM)

The SPWM principle is based on the comparison of a carrier signal and pure sinusoidal control signals, as shown in Figure 2.10. For three phase VSI, the three modulating sinusoidal signals, with 120 degrees phase shift, are compared with a triangular waveform or carrier signal which is with higher frequency. The ratio between the amplitude of the control voltages V_c, and the triangular signal peak V_t is defined as the modulation index $m= V_c/V_t$ where V_c and V_t are respectively the amplitude of the modulating wave and amplitude of the carrier wave [46].

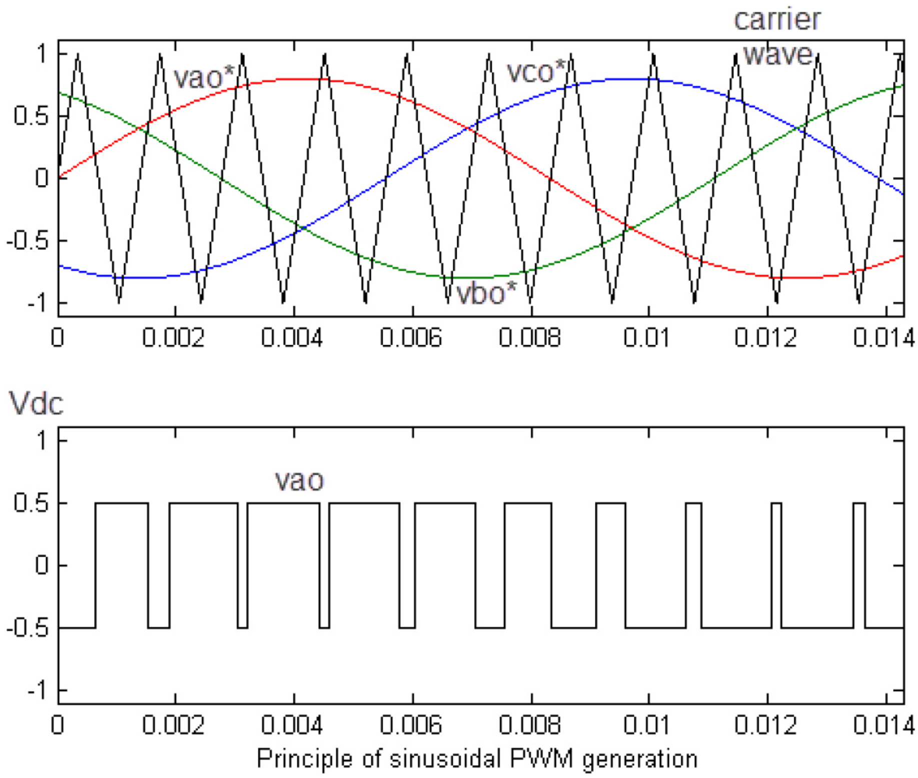


Figure 2.10 VSI Three phase SPWM principle

By changing the modulation index m, between 0 and 1 which is called the linear region, the widths of pulses vary, which results in variations in the amplitude of the output voltage. The maximum output voltage when (m=1) is given in equation:

$$VLL = \frac{\sqrt{3}}{2\sqrt{2}}\, m\, Vdc = 0.61\, Vdc$$

The inverter switching frequency is constant and equals the carrier signal frequency f_c, and the frequency of the control signals $f_{m,}$ determines the frequency of the output voltage.

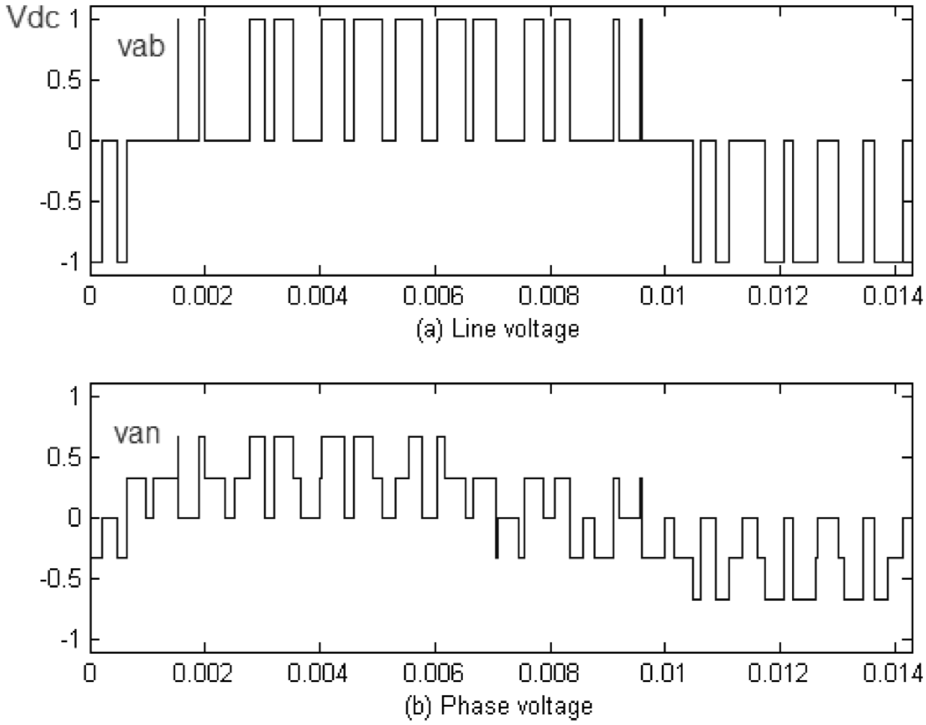


Figure 2.11 VSI line and phase voltage waves of PWM

Frequency modulation ratio (M_f) is the ratio between switching frequency and the modulating signal frequency, $M_f = f_c/f_m$. The frequency spectrum of the output voltage of a SWPM inverter contains harmonics orders around M_f, $2M_f$,$3M_f$.

M_f is recommended always to be chosen an odd integer number (to ensure quarter cycle symmetry), therefore avoiding even-order harmonics, and in particular a small dc component, at the output voltage. If M_f is an integer number, the PWM is so-called synchronous PWM. On the other hand, there is asynchronous PWM, in which Mf is not an integer number, and it can be employed when the modulation frequency ratio is high [37], however with a high value that trades off between switching losses increasing and harmonic decreasing.

2.3.4.2 Space Vector PWM Modulation (SVM)

Basically SVPWM looks to VSI as one unit and not separate legs like SPWM, VSI has six switches as shown in Figure 2.12. Each leg has two switches and they always switching in complementary fashion, so VSI has eight different switching states, six for active vectors and two for zero vector as shown in Table 2.1.

The active vectors divide the vector plane into 6 sectors as shown in Figure 2.13. The rotating reference vector can be obtained in each switching cycle by switching between the two adjacent active vectors and the null vectors. In general to obtain any vector, the phase angle of the vector should be known to define in which sector the vector exist. In order to maintain the effective switching frequency at a minimal value, the sequence of the toggling between these vectors is organized in such way that only one leg is affected in every step [60].

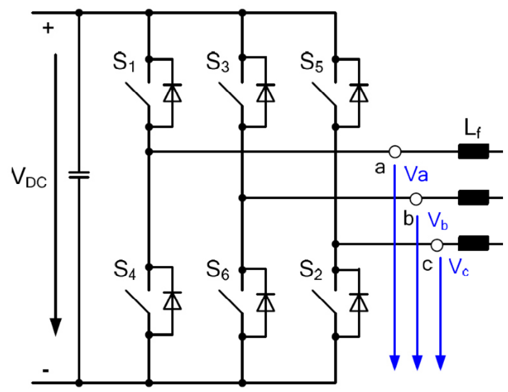


Figure 2.12 Three phase, three legs VSI

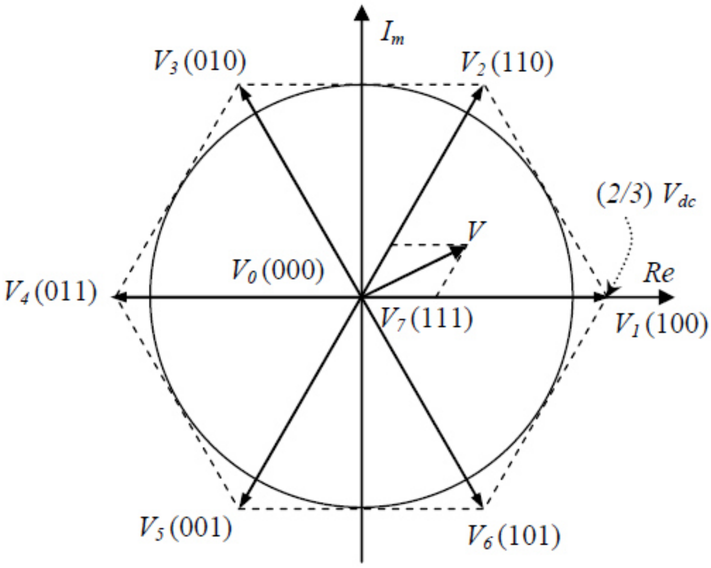


Figure 2.13 Three-phase converter space vector.

Table 2.1 Output voltages for three phase converter switching states

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_0
s_1	1	1	0	0	0	1	1	0
s_2	1	1	1	0	0	0	0	1
s_3	0	1	1	1	0	0	1	0
s_4	0	0	1	1	1	0	0	1
s_5	0	0	0	1	1	1	1	0
s_6	1	0	0	0	1	1	0	1
V_a	$\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	0	0
V_b	$-\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	0	0
V_c	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	0	0

2.3.3.2 Four Legs VSIs Modulation Techniques

Various modulation techniques have been proposed for switching the 3P4L converter. The Three Dimensional Space Vector Modulation (3D-SVM) technique was proposed in [61, 62]. It requires complex calculations for the selection of the switching vectors by employing an $\alpha\beta0$ transformation.

Carrier-based Pulse Width Modulation (CPWM) is another option [63]. It has been shown that CPWM is equivalent to a 3D-SVM but with an easier implementation. Because of that, it was chosen to be used in this work for converting the reference three signals, from the control loops, into four gating signals for the four-legs inverter. Its diagram is shown in Figure 2.14, the three inputs (U_a, U_b and U_c) and the four outputs are the gating signals of 3P4L converter.

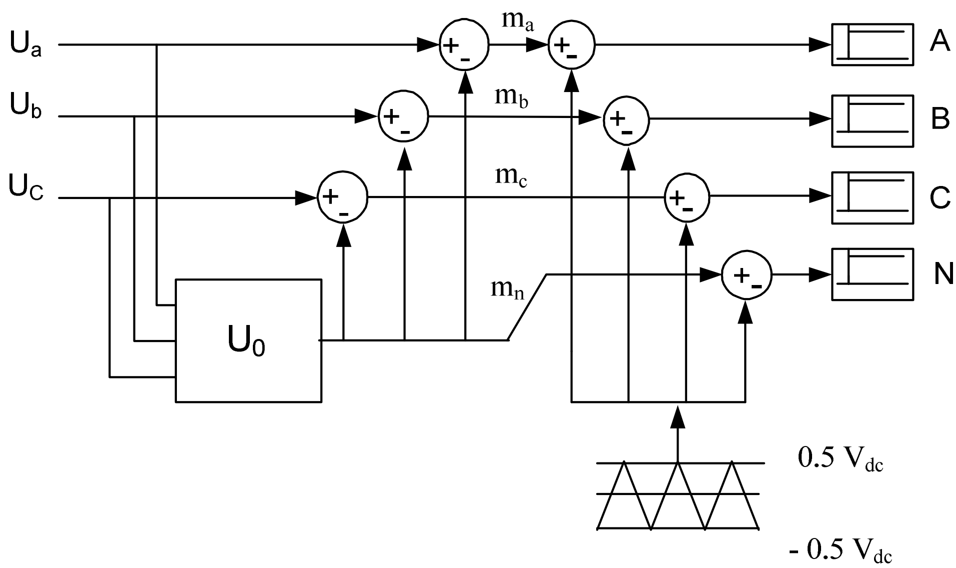


Figure 2.14 Carrier-based pulse width modulation scheme.

The zero sequence signal can be given with the following :

$$U_0 = \frac{1}{2}\left(max\{U_a, U_b, U_c\} + min\{U_a, U_b, U_c\}\right)$$

$$[m_a, m_b, m_c] = U_x - U_0, x = (a, b, c)$$

$$m_n = U_0$$

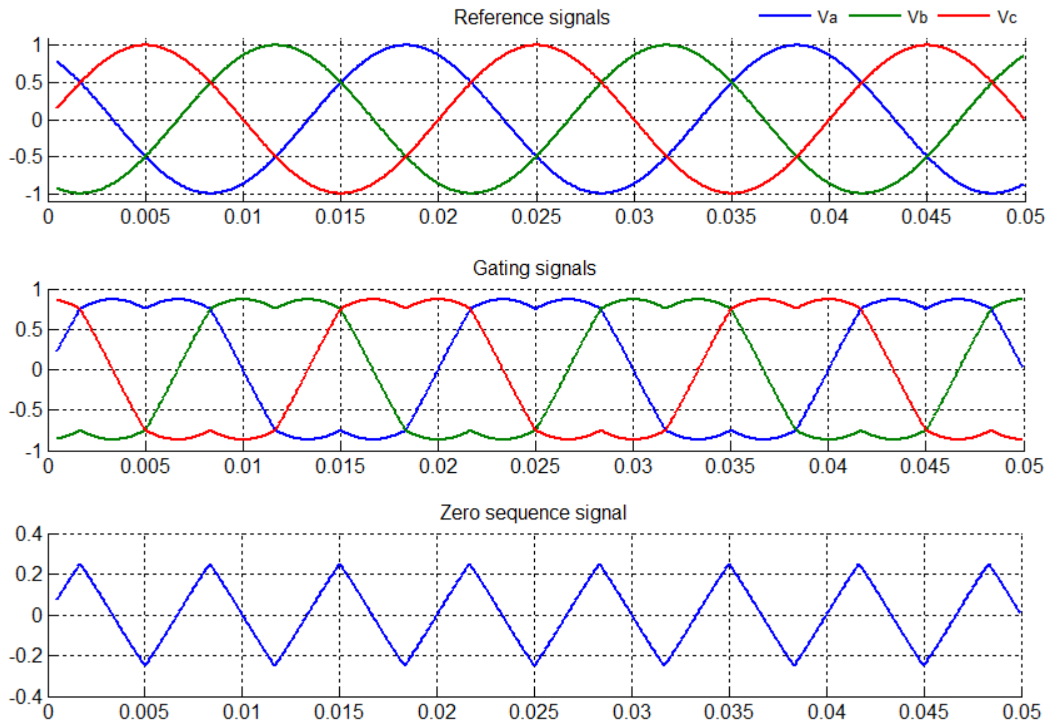


Figure 2.15 Gating signals of CPWM for four-legs VSI.

2.3.4 AC Filters for Power Converters

2.3.4.1 Filter Topologies

The output power of converters, synthesized by using PWM which has high frequency harmonics, needs to connect AC filter across the converter. AC filters types as shown in Figure 2.16 come with three configurations [64].

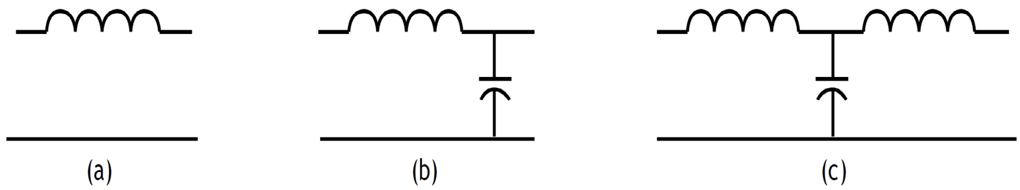


Figure 2.16 Filter topologies: a) L-filter ;b) LC-Filter and c) LCL-filter.

L-filter is the simplest filter it needs high switching frequency to attenuate the high harmonics sufficiently. LC-filer can be made by shunt capacitor with the inductor so it is a second order filter, it is employed where the load impedance across shunt element is relatively high at and above the switching frequency [64]. Inductor-capacitor-inductor (LCL) filter, as compared with the L filter, the LCL filter, is more attractive because it has ability for higher harmonics attenuation and also it is allow the inverters to work in both islanded and grid connected modes. It is non sensitive regarding the grid impedance, thus it is commonly used with MGs inverters, MGs can operate in both modes: islanded and grid connected. The power converter which will work as universal one suitably uses LCL filter [65,66]. For mentioned advantages it has been employed for our case study.

Due to resonance, LCL filter may lead to unstable operation therefore passive or active damping is required to resolve this issue. Passive damping is obtained by adding a resistor element in series or in parallel and active damping by changing the controller design [66].

2.3.4.2 LCL Filter Design

Figure 2.17 shows an one line diagram of LCL filter. The elements can be defined as inverter inductor, grid side inductor and capacitor, taking into account the damping resistance and inductors resistances.

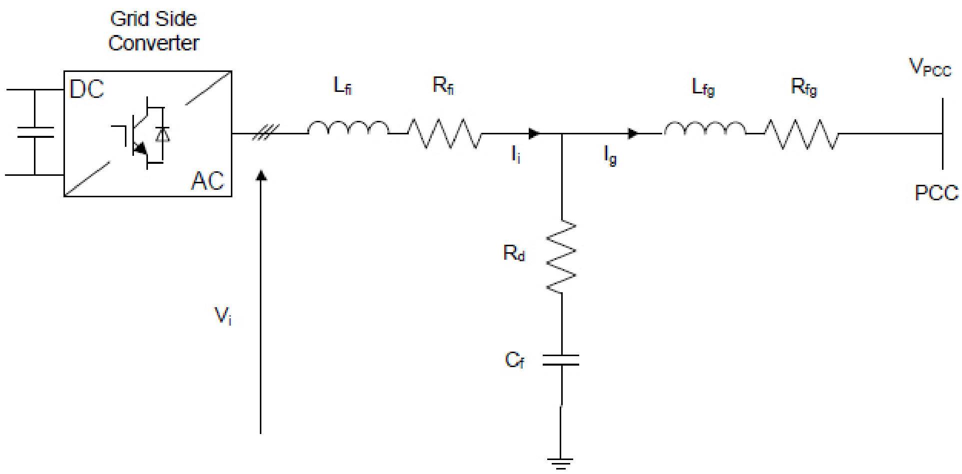


Figure 2.17 LCL per phase equivalent circuit.

Aforementioned elements can be sized with different approaches mentioned in literature. In all approaches the rating capacity of VSI, switching frequency and output voltage represent main factors for sizing [67]. Step by step approach as illustrated in Figure 2.18 has been used for sizing the LCL filter [68, 69].

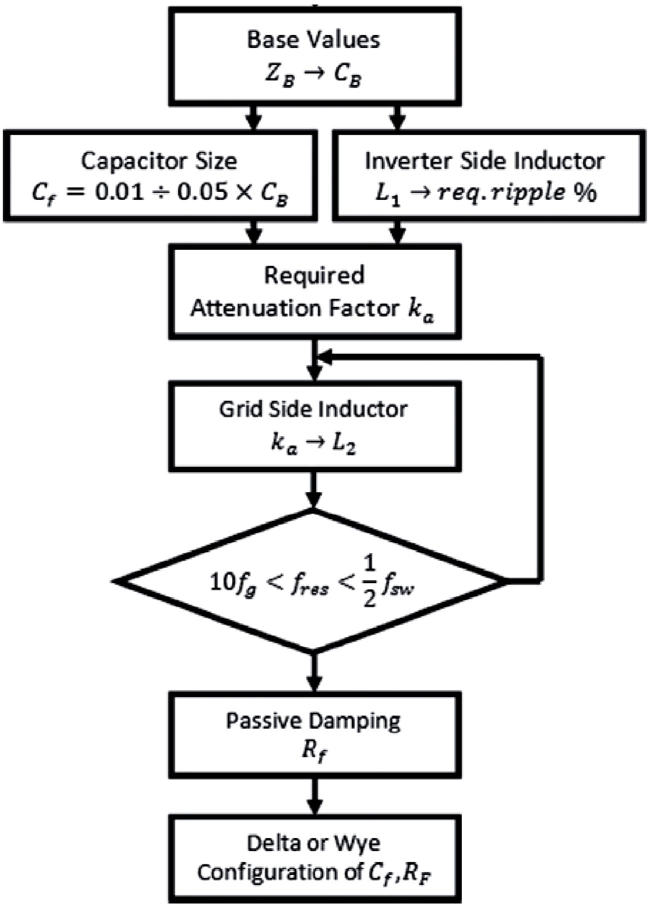


Figure 2.18 Procedure of LCL filter design.

An LCL filter is utilized for attenuating the harmonics and meeting IEEE 519 harmonic standard. The instability issue associated with an LCL filter is dampened by using a passive damping element [67].

2.3.4.3 LCL Filter Components

LCL filter components have been chosen for MFPC by using step by step procedure as shown in Figure 2.18. The design parameters are: VSI with 30 kVA rating, grid frequency 50 Hz, switching frequency 12150 Hz, output voltage 230 V_{RMS}. The parameters of LCL filter are given in Table 2.2.

Table 2.2 LCL filter components.

Element	Value
L_f	3e-3 H
C_f	30e-6 F
L_g	0.1e-3 H
R_f	0.1 Ω
R_g	0.1 Ω
R_d	2 Ω

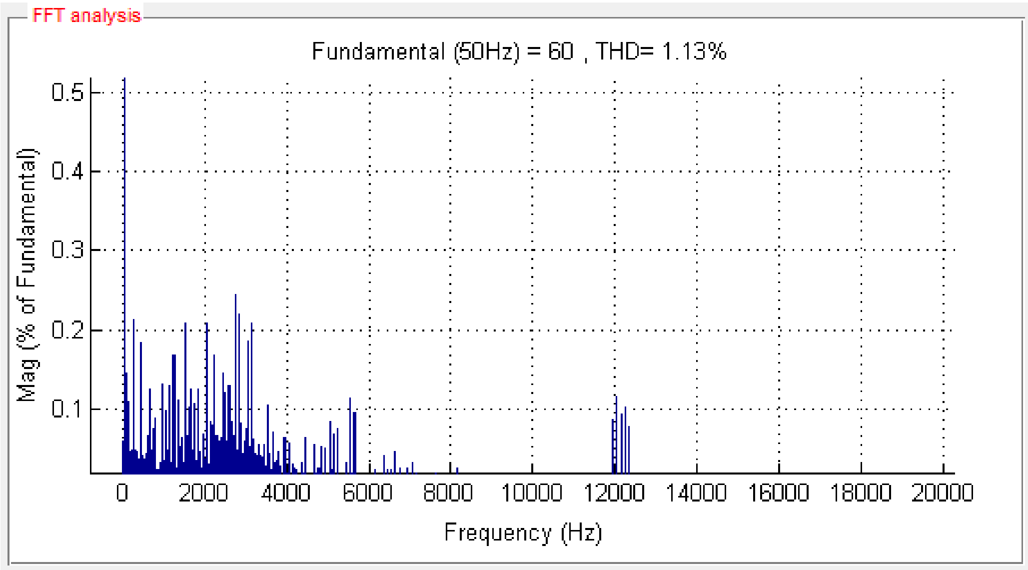


Figure 2.19 THD of MFPC currents.

As shown in Figure 2.19, the THD of MFPC output currents (60 A peak) is 1.12 %, which is below the 5% limit imposed by IEEE-519 Std.

2.3.4.4 LCL filter transfer Function and frequency response

In this section, the transfer function of LCL filter with damped $G_{LCLD}\,(s)$ and without damped $G_{LCL}\,(s)$ will be described. Based on [69], the transfer function of LCL filters in both cases is written with the following equations with inductors resistances neglecting:

$$G_{LCL}\,(s) = \frac{1}{(L_f * C_f * L_g) * s^3 + (L_f + L_g) * s}$$

$$G_{LCLD}\,(s) = \frac{C_f * R_d * s + 1}{(L_f * C_f * L_g) * s^3 + C_f(L_f + L_g) * R_d * s^2 + +(L_f + L_g) * s}$$

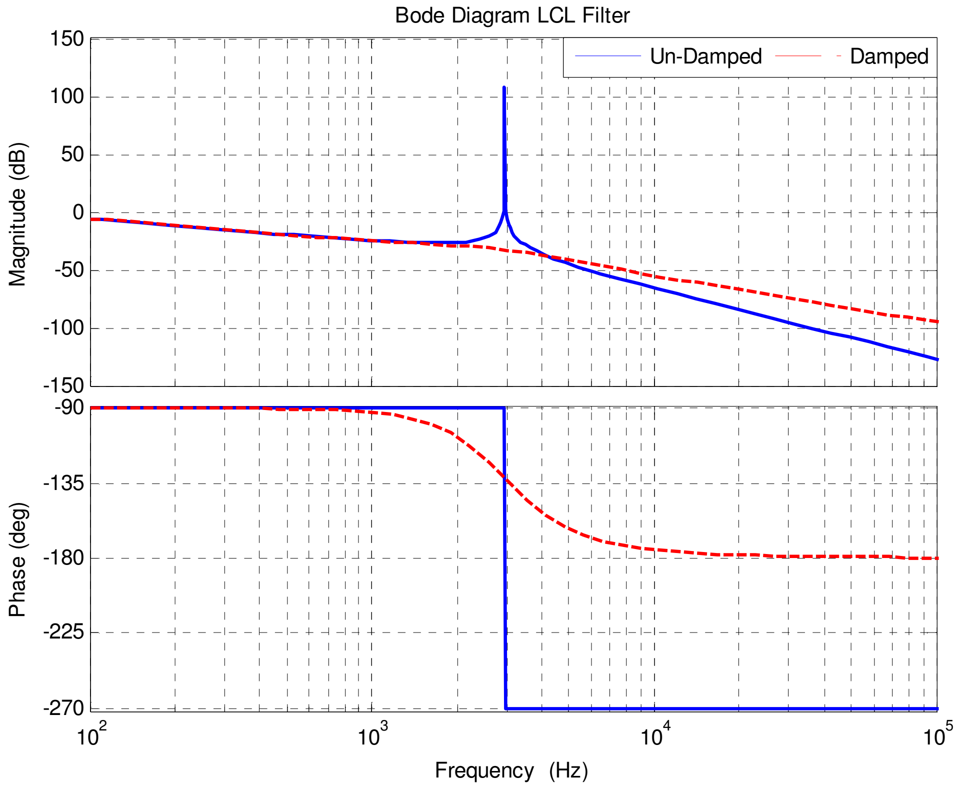


Figure 2.20 LCL filter frequency response with/without damping.

As we can see in the Figure 2.20 in the range higher than resonance frequency, the attenuation rate of LCL filter is −60dB/Decay. Also it can be observed how the damping resistance suppress the gain spike, smoothing the response at high frequency -270° and to -180°.

2.3.5 Phase Locked Loop

Phase Locked Loop (PLL), is essential for inverter synchronization with the utility grid. It is a feedback circuit which takes the grid three phase voltages as input signals and the output is the phase angle of one of these phases as shown in Figure 2.21. The phase angle for the other two phases is obtained by assuming that main voltages are symmetrical and the phase shift between the various phases is 120 deg. The output signals are synchronized with the input ones both in frequency and in phase.

PLLs are available mainly with three types for phase tracking: synchronous rotating reference frame (SRF), stationary reference frame and zero crossing. The first one; SRF PLL gives the best performance under non-ideal grid conditions therefore it is commonly used with DGs [70, 71, 72].

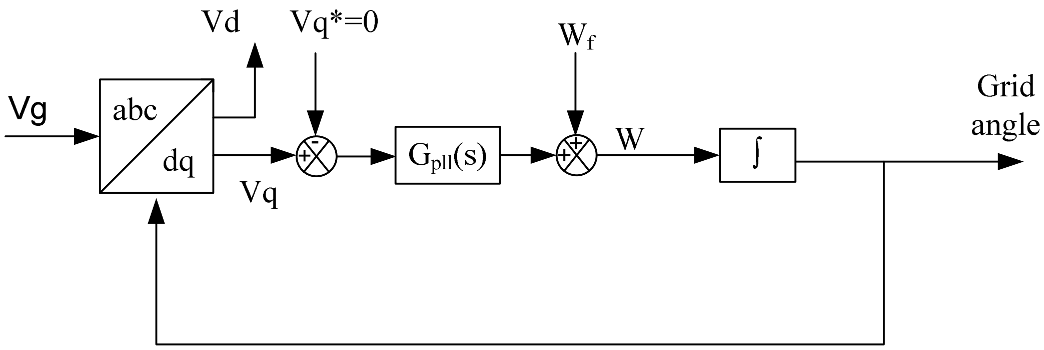


Figure 2.21 SRF-PLL block diagram.

Basically SRF-PLL Algorithm starts from measuring grid voltages and performs Park's transformation, *abc* to *dq* (see Appendix A). By using a PI controller the 'phase-lock' is realized by setting Vq=0. The output of the PI controller is the grid frequency, which, added to the feed-forward frequency and then integrated, provides the grid phase angle.

The transfer function of Proportional Integral (PI) controller is given by the following:

$$G_{pll}(s) = Kp * s + \frac{Kp}{T_i\, s}$$

K_p=250; T_i= 0.004s

Figure 2.22 shows the behavior of the SRF-PLL, simulated by using Matlab Simulink.

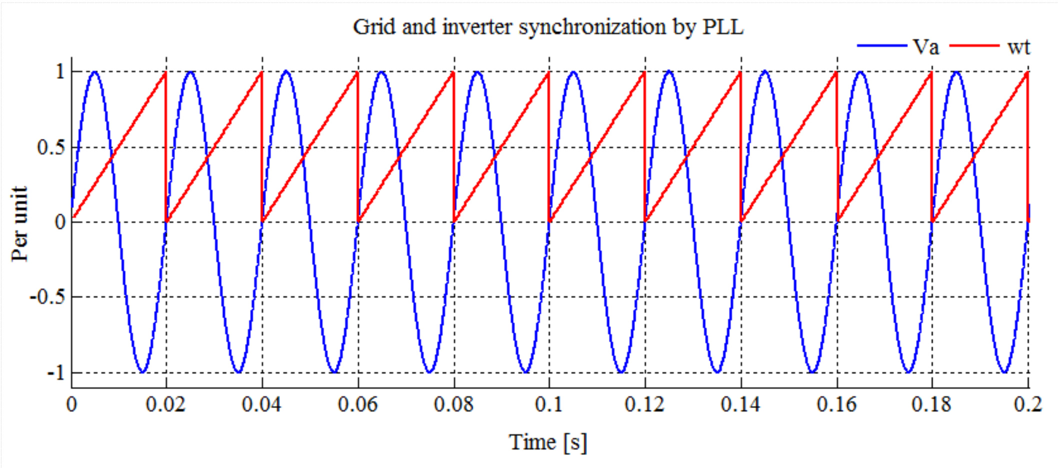


Figure 2.22 Grid voltage on phase a vs. *wt.*

Chapter 3 Renewable Energy Sources and Energy Storage

In this chapter a general overview of RE is briefly discussed, photovoltaic system characteristics and modeling with PV inverter configurations are explained. ESSs for grid integration overview, applications, technologies and technical characteristics have been illustrated.

3.1 Overview of Renewable Power Sources

RE generated by sustainable sources such as solar, wind, biomass, geothermal, hydro, wave and tidal. Figure 3.1 shows the generated energy from different renewable sources in Europe.

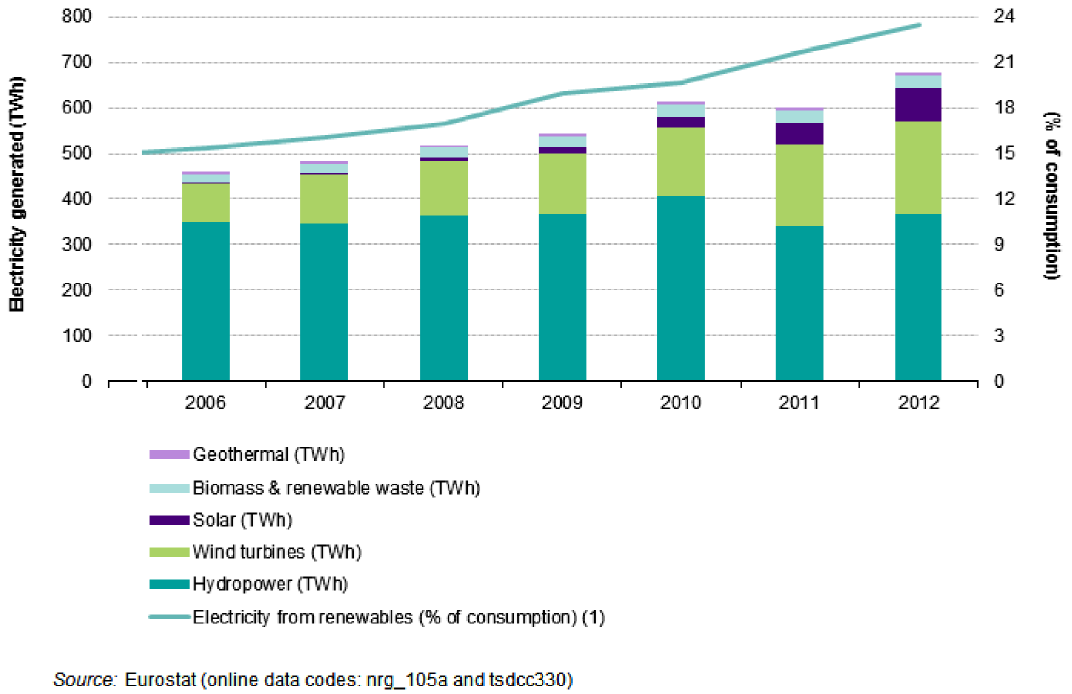


Figure 3.1 Electricity generation by RESs in Europe (2006 to 2012).

An overview on different renewable power sources are given on the following [73]:

3.1.1 Solar Energy

Solar energy can be utilized in two ways mainly, solar thermal and solar photovoltaic. The first can be utilized for heating purposes like solar water heating and also for generating electricity by using this heat for steam conversion. Radiant light or solar radiation can be used to generate electricity directly by using photovoltaic solar cells.

3.1.2 Wind Energy

Wind energy have been utilized by humans since many years ago. Mainly it can be used for electrical generation by movement of wind streams on the blades of wind turbine. In Figure 3.1 it can be seen that the percent of electricity consumption in Europe, which is generated by wind power sources, is high comparing to other sources. There are different types of wind turbines based on the place, on-shore and off-shore, also different types of electrical generators like Double Fed Induction Generators (DFIG) and synchronous generators can be used. Each type of generators requires power conversion and control systems in order to exceed the power generation efficiency.

3.1.3 Hydro, Geothermal and others

Hydro power is generated mainly by utilizing potential energy of water which moves the turbine and generator. The energy produced is proportional to the potential energy stored in dammed water. Wave and tidal energy is harnessing by utilizing the water movements in ocean. Geothermal is power extracted from heat stored in earth.

3.2 Photovoltaic Power Conversion

3.2.1 Photovoltaic Concept

Photovoltaic is the direct conversion of solar radiation into electricity by semiconductor materials which absorb photons of lights and release electrons charges or direct current. The solar cell is the main element in PV-generator which produces electricity when exposed to sunlight. This is a silent process because there are no moving parts so the tear and wear is low, which leads to increase the life time more than 25 years. However there is degradation due to ageing and the power generation capability may be reduced to 75% ~ 80% of nominal value [74].

3.2.2 Solar Cell Technologies and Efficiencies

The Crystalline Silicon (CS) solar cells are the most common representing about 90% of the market nowadays. The efficiency is between 14% and 22% for mono crystalline silicon. Poly crystalline cells have slightly lower conversion efficiency compared to the single crystal cells. Both are suitable for outdoor applications, like standalone and grid connected PV-systems. Other types are: thin-film amorphous silicon (η =10%), thin-film copper indium diselenide (η = 12%),and thin-film cadmium telluride (η = 9%).

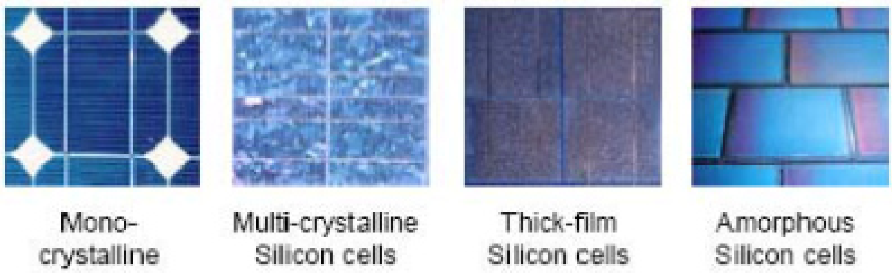


Figure 3.2 PV–cell technologies.

3.2.3 Electrical Model of PV Cell

The PV cell can be modeled with equivalent circuit as in following Figure 3.3. such model composites current source, diode, series resistance and shunt resistance [73].

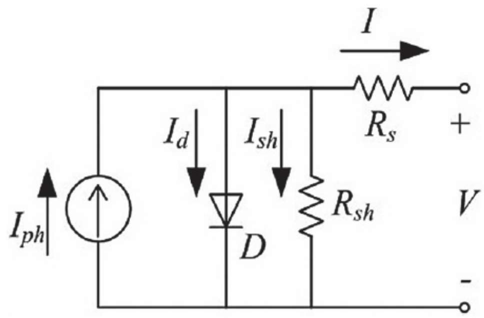


Figure 3.3 Solar cell equivalent circuit.

$$I = I_{ph} \; - \; I_s \; \left\{ \exp\left(\frac{q(V+IR_s)}{KT_cA}\right) - 1 \right\} - (V + IR_s)/R_{Sh} \qquad (3\text{-}1)$$

Where:

I_{ph} : photo – current generated by solar cell

I_s : Cell saturation of dark current

q : Electron charge 1.6 × 10e-19 coulombs

K : Boltzmann's constant (1.380 6488 x 10^{-23} J K^{-1}.)

T_c : Cell operating temperature

A : Ideal factor

R_s : Series resistance

R_{Sh} : Shunt resistance

3.2.4 Technical Characteristics of Photovoltaic

3.2.4.1 Voltage and Current Characteristics

The main characteristics of PV-cells are short circuit current, open circuit voltage and maximum power, which are the points I_{SC}, V_{OC} and MPP respectively shown in Figure 3.4. Normally these values are supplied by manufactures with Standard Test Condition (STC) which refers to global radiation 1000 W/m^2 incident perpendicularly on the cell or the module, cell temperature 25 °C and AM 1.5 (AM: Air Mass). The output power at V_{OC} and I_{SC} is zero as the current at V_{OC} equals zero and the voltage equals zero at short circuit.

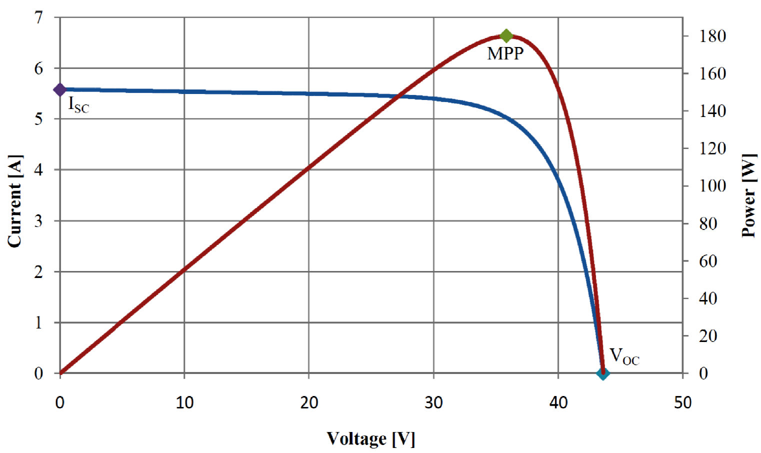


Figure 3.4 PV-Module I-V, P-V characteristics.

The Maximum Power Point (MPP) is the product of maximum current (I_{MPP}) and maximum voltage (V_{MPP}).

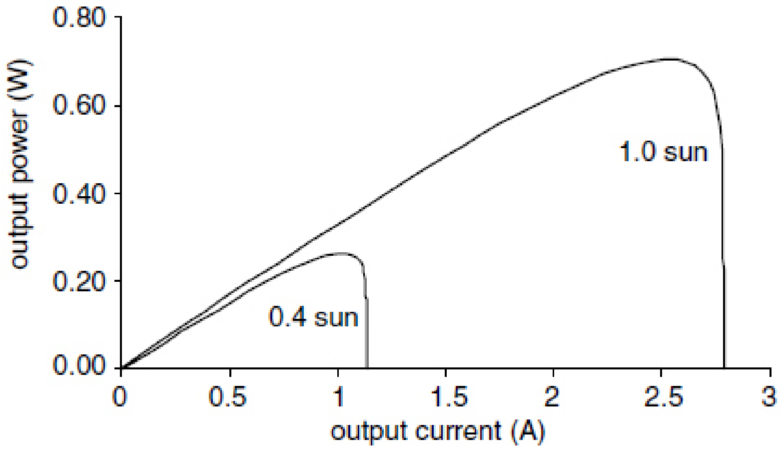
$$P_{MPP} = I_{MPP} \times V_{MPP} \tag{3-2}$$

The factor which is widely used to measure the solar cell quality is the fill factor, which is defined as the ratio of the actual maximum power P_{MPP} to the theoretical one $I_{SC} \times V_{OC}$ [75].

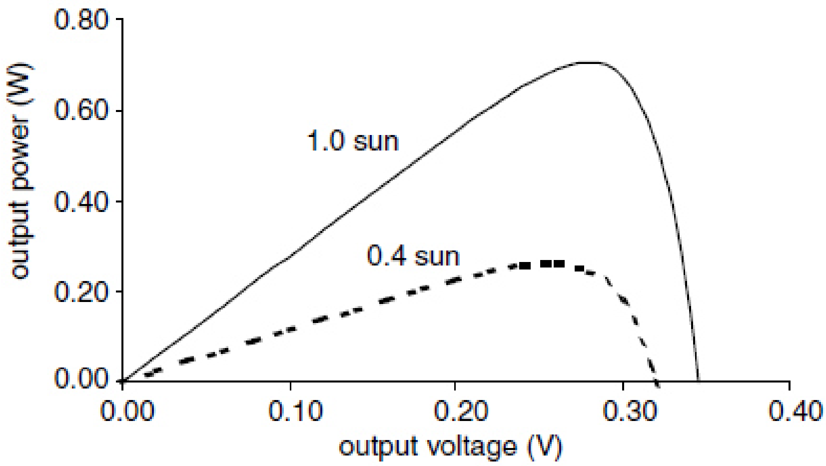
$$FF = \frac{I_{MPP} \times V_{MPP}}{I_{SC} \times V_{OC}} \tag{3-3}$$

3.2.4.2 The Irradiance and Temperature Effects [73]

The performance of the solar cell is affected by two main factors the temperature and the irradiance. Variation of the latter affects the current generated by a solar cell as in Figure 3.5.a: the higher the irradiance the higher the current, while the voltage variation is minimal, Figure 3.5.b. This is clear from the two Figures which shows the variation of power with solar irradiance variations, 1 sun =1000 W/m^2.



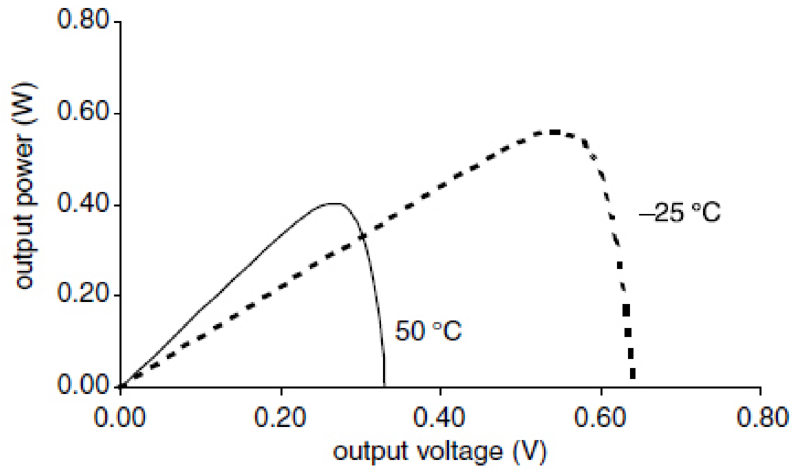
(a)



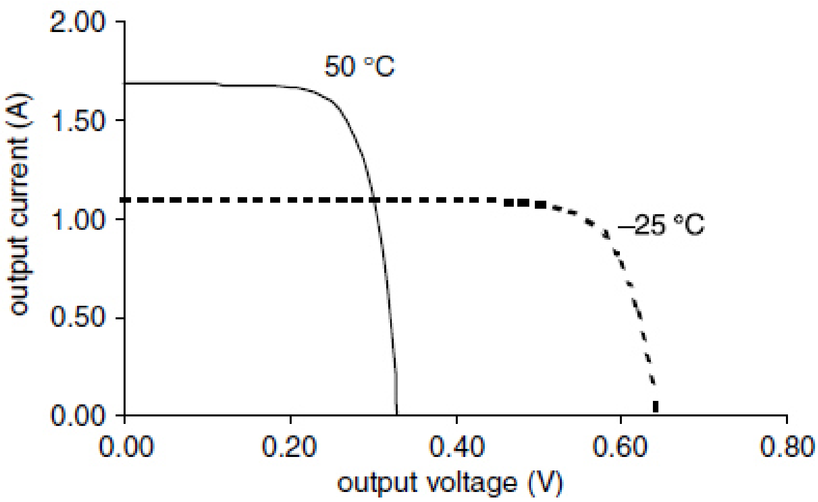
(b)

Figure 3.5 Effects of solar radiation level: (a) P-I; (b) P-V curves.

Solar cell voltage is highly dependent on the temperature as it is made by semiconductor materials. The reason is that increasing the temperature results in increasing the recombination of electron-hole pairs, as more charge carriers flow with more heat. As a result increasing the temperature will decrease the voltage, as shown in Figure 3.6, which leads to decrease the PV-cell efficiency.



(a)



(b)

Figure 3.6 Effects of the temperature: (a) P-V; (b) I-V curves.

The Normal Operating Cell Temperature (NOCT) is the temperature that the cells will reach when operated at open circuit in an ambient temperature of 20^{o} C at AM 1.5 irradiance conditions, G = 0.8 kW/m^2 and a wind speed less than 1 m/s. For variations in ambient temperature and irradiance, the cell temperature (in ^{o}C) can be estimated quite accurately with the linear approximation [75] as given in (3-4).

$$T_C = T_A + \left(\frac{NOCT-20}{0.8}\right) \times G \tag{3-4}$$

Where:

Tc: Cell temperature

Ta : Ambient temperature

NOCT: Normal operating cell temperature

G : Solar irradiance

3.2.4.3 PV Maximum Power Point

The maximum power may be given from deriving (3-5).

$$P_o = V_o \times I_o \tag{3-5}$$

$$\frac{dp_0}{dV_0} = V_0 + I_0 \frac{dV_0}{dI_0}$$

$$\frac{dV_0}{dI_0} = -\frac{V_0}{I_0} \tag{3-6}$$

Based on maximum power transfer theorem, load resistance should be equal to internal resistance of the source as a condition for delivering maximum power from source to load. Matching between the internal resistance of the source and the load resistance can be achieved by using DC-DC boost power converter which is connected between the PV cell or array and the load for the Maximum Power Point Tracking (MPPT), different MPPT techniques had been discussed in [76], to control the duty ratio of the converter.

3.2.5 PV Modules and Arrays

The output power of one solar cell is relatively small; around 2W at 0.5V. Therefore in order to increase the power, the cells are connected in series to make a module.

A typical PV module is made up around 36 or 72 cells connected in series and modules are then connected in series to form a string. Finally, the strings are connected in parallel to form a PV array. The number of modules in each string is specified according to the required voltage level of the array. Parallel strings is specified according to the required the array power rating as shown in Figure 3.7.

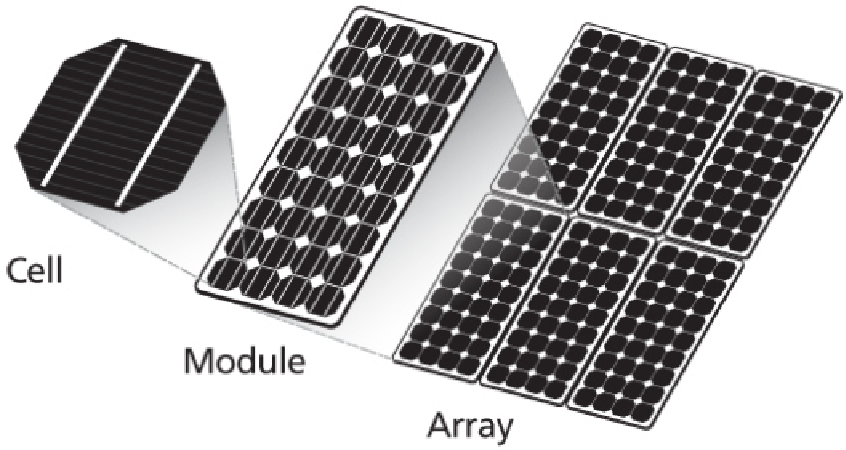


Figure 3.7 PV-cell; module and array.

3.2.5.1 Model of a PV Module Consisting of n Cells in Series

by assuming that the PV-cells connected in a module are identical, and this is very common because these cells are very similar in order to avoid circulation of internal currents among the cells, the equivalence of PV-Module as shown in Figure 3.8[73].

The respective output voltage and current of the group are:

$$V_o = n\, V_{oi} \qquad I_o = I_{oi} \tag{3-7}$$

Where V_{oi} and I_{oi} are, respectively, the average voltage and current in individual cell i. Compact form of the equivalent circuit is shown in Figure 3.9.

$I_{\lambda 1} = I_{\lambda 2} = \cdots = I_{\lambda n}$ $\qquad R_{s1} = R_{s2} = \cdots = R_{sn}$

$I_{d1} = I_{d2} = \cdots = I_{dn}$ $\qquad R_{p1} = R_{p2} = \cdots = R_{pn}$

$V_{d1} = V_{d2} = \cdots = V_{dn}$

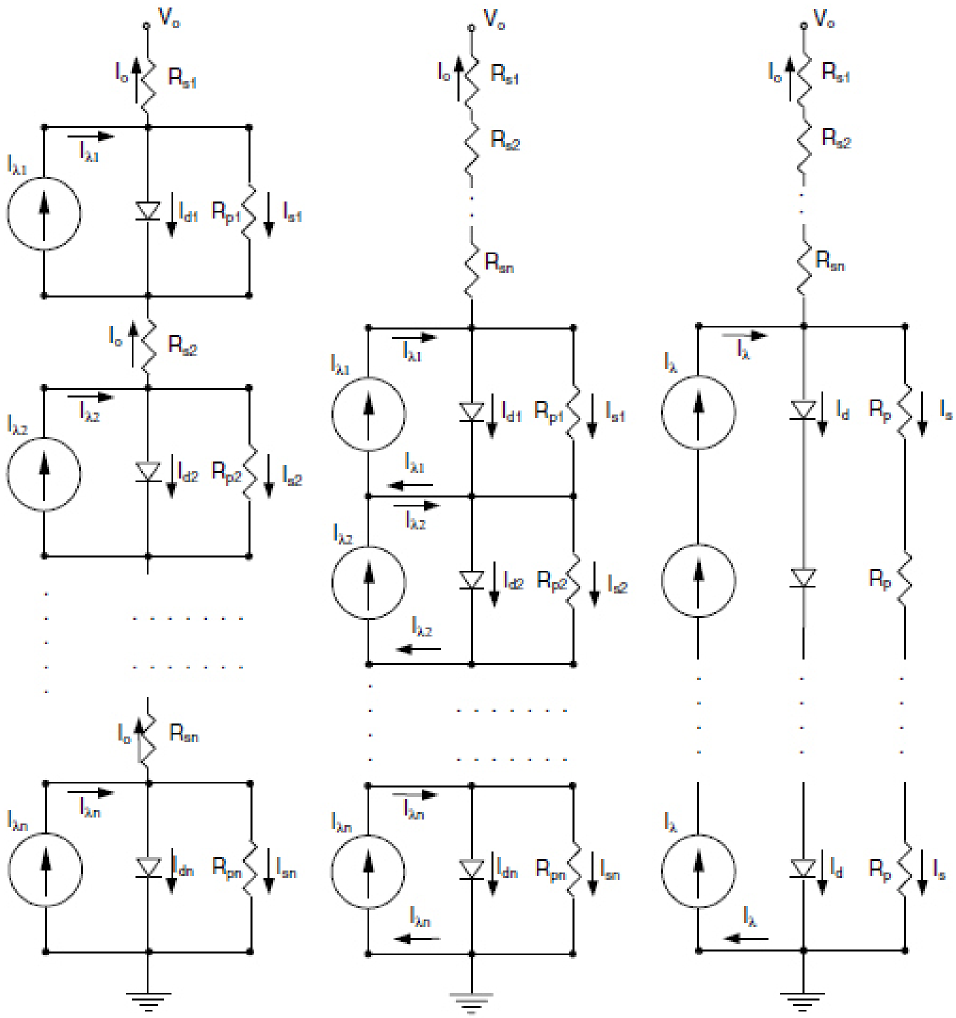


Figure 3.8 Equivalence evolution of a series PV cells in a module.

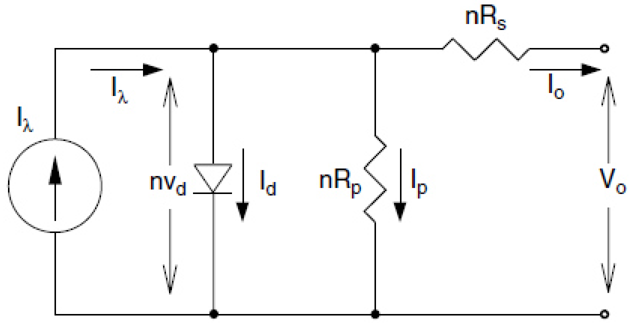


Figure 3.9 Equivalent model of a PV module with identical cells in series.

3.2.5.2 Model of a PV Panel Consisting of n Cells in Parallel

Assuming that the PV cells of a panel are connected in parallel across common terminals a and b as in Figure 3.10, it is obtained:

$$V_o = V_{oi} \qquad I_o = n \ I_{oi} \tag{3-8}$$

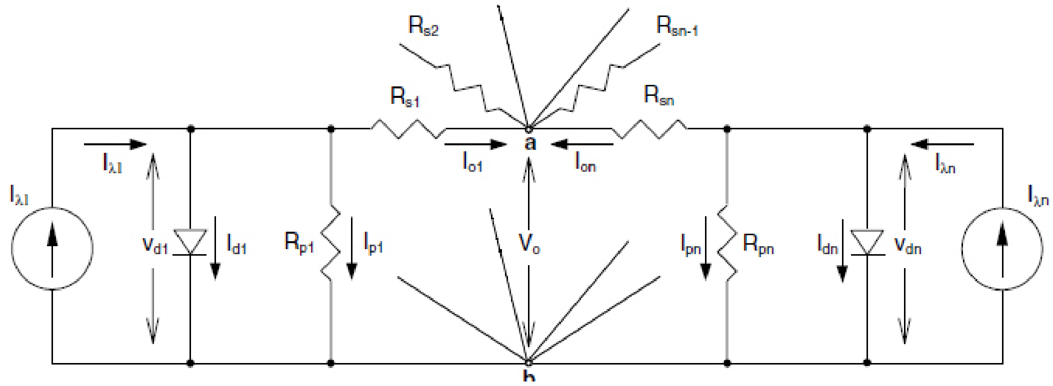


Figure 3.10 Group of identical PV cells connected in parallel.

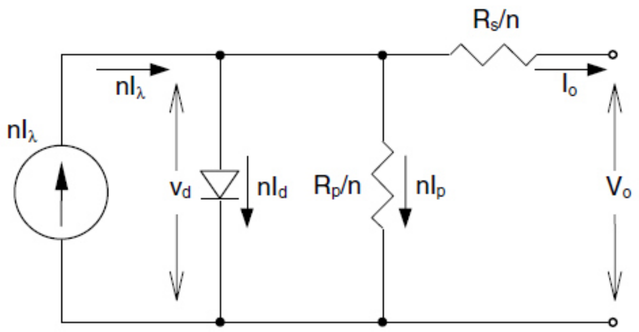


Figure 3.11 Equivalent model of a photovoltaic panel with cells in parallel.

3.2.6 Configurations of Grid Connected Photovoltaic Inverters

The integration of PV systems with electrical grid has different configurations. The classification of these configurations is shown in Figure 3.12 [74].

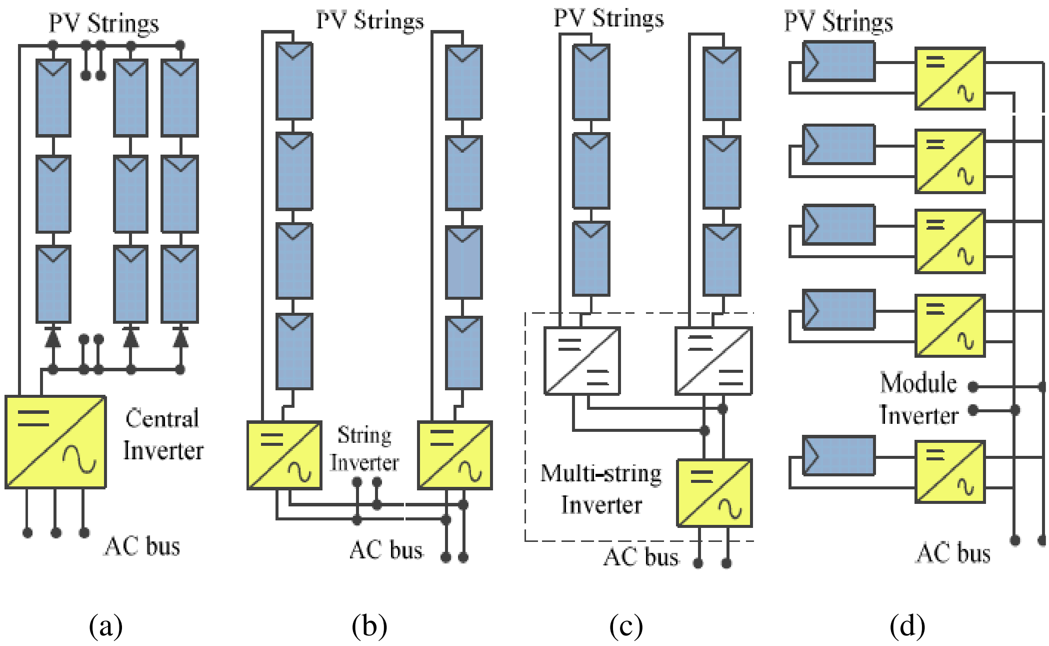


Figure 3.12 PV inverters grid connected schemes: (a) Central Inverters; (b) String Inverters; (c) Multi-String Inverters; (d) Module inverters.

3.2.6.1 Central Inverters

This configuration is used with PV plant (>10 kW), many parallel strings arranged to DC-side and connecting to a single central inverter as shown on the (Figure. 3.12.a). This topology has several advantages like high efficiency for power conversion, lowest specific cost and ease of the converter maintenance. However, the energy production the PV plant decreases due to module mismatching and partial shading conditions. Also the reliability of the plant is limited due to the dependence of power generation on a single central inverter: the failure of the central inverter results in the whole PV plant being out of operation [74].

3.2.6.2 String Inverters

The configuration is presented in Figure 3.12.b; in this topology each PV string is connected to a separate inverter. A DC-DC boost converter could be used to boost the DC output of PV to suitable levels. As each string is connected with each inverter the need for string diodes is eliminated which leads to reduce the total loss of overall system. String inverters have evolved as a standard in PV system technology for grid connected PV plants.

3.2.6.3 Multi-String Inverters

An evolution of the string technology applicable for higher power levels is the multi-string inverter [74]. It allows the connection of several strings with separate MPP tracking systems (via DC/DC converter) to a common DC/AC inverter as shown in Figure 3.12.c. Accordingly, a compact and cost-effective solution which combines the advantages of central and string technologies is achieved. This multi-string topology allows the integration of PV strings of different technologies and of various orientations (south, west and east). These characteristics allow time shifted solar power which optimizes the operation efficiencies of each string separately. For PV applications of 3-10 kW [74].

3.2.6.4 Module Inverters

In this topology one inverter is used for each module this configuration is shown in Figure 3.12.d. MPPT for each module optimizes, the energy yield for each module however less in overall efficiency, compared to other topologies. Moreover installing the inverter in the open air, with the PV module, will reduce the system lifetime, thus increasing its thermal stress. This concept can be implemented for PV plants of about 50 – 400 W peak.

3.3 Energy Storage Systems for RESs Integration with the Grid

3.3.1 Overview of ESSs

The generated power of RESs is highly dependent on climatic condition which makes the planning of electricity production more difficult without storage.

For example, wind and solar power sources have an intermittent nature in power generation which impacts the grid regulation, load following, power sources scheduling and power quality problems, for example PV output power during cloudy weather, for short time, fluctuates suddenly, therefore energy storage systems represent a solution for such fluctuations or sudden change in power generations [77].

With increasing the penetration level of integration RESs with the main grid, aforementioned impacts will increase more and more, hence more back-up energy storage is needed.

3.3.2 Applications of ESSs for RESs Integration with the Grid [77, 78]

- Grid forming units in MGs need energy storage batteries to provide the MGs with voltage and frequency.
- Enhance the performance of RESs by compensating the power fluctuations.
- Shifting peaks for different time periods.
- Supplying critical loads during power blackouts like UPS systems.
- Grid voltage and frequency support, the voltage support by provided by the stored power to the grid, to keep the voltage with acceptable limits which involves a trade-off between the amount of real energy produced by generators and the amount of reactive power produced. The grid frequency support means

real power provided to the electrical distribution grid to reduce any sudden, large load generation imbalance.

- Unbalanced Load Compensation.
- Other applications like reliability enhancing, power quality improvements, spinning reserve and ride through support.

3.3.3 Energy Storage Technologies

Technologies of ESSs can be classified based on size and discharge time, Figure 3.13 [79], shows different technologies for energy storage including batteries, Compressed Air Energy Storage (CAES), pumped hydro, flywheels, super capacitors and Superconducting Magnetic Energy Storage (SMES).

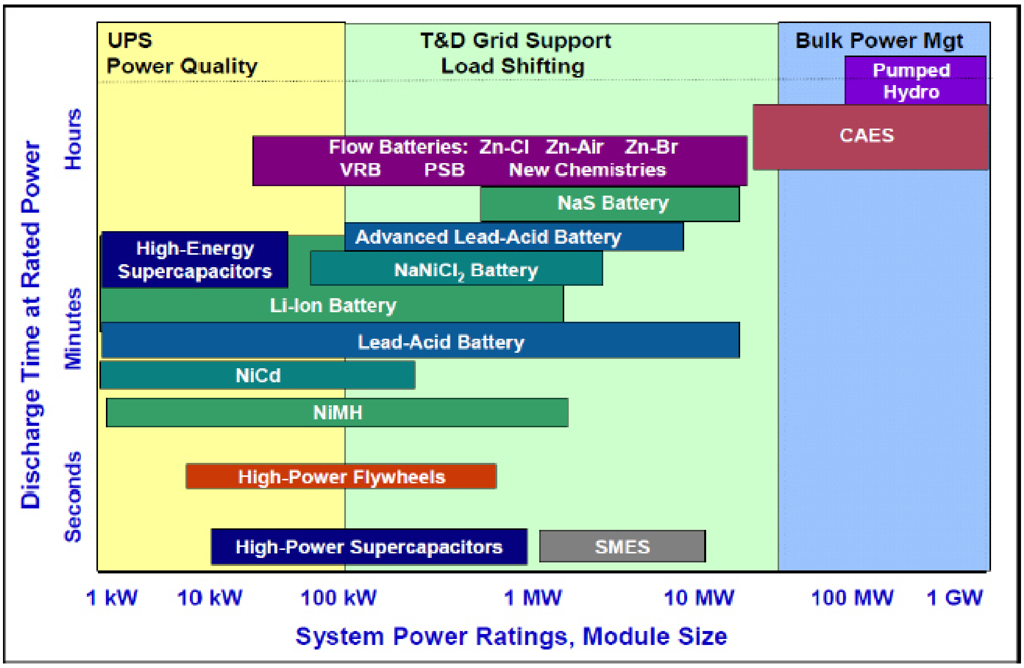


Figure 3.13 Power rating ver. Discharge time for various energy storage technologies.

3.3.4 Energy Storage Batteries

Batteries are considered an important backup sources for different energy applications. Table 3.1 summarizes the comparison between different types of batteries commercially available for renewable power sources [80].

Table 3.1 Comparison of battery technologies

Batteries	**Lead acid**	**NiCd***	**NiZn***	**Li/ion***
Energy/weight (Wh/kg)	40–50	60–75	50–60	150–200
Cell voltage (V)	2	1.25	1.5	3.7
Cycle number	600–1500	800–2500	500–1000	500–1000
Efficiency (%)	65–85	70–80	65–80	85–95

NiCd: Nickel-Cadmium (NiCd) batteries

NiZn: Nickel-Zinc batteries

Li/ion: Lithium-ion batteries (Li-ion)

Li-ion batteries have become very popular due to their high energy density, long life and their good performance even during low temperatures. Their disadvantage is the relatively expensive, high monitoring measures to control the cell in order to avoid explosion if they get too hot.

The best choice for batteries used in PV systems are lead acid batteries, Valve Regulated Lead Acid batteries (VRLA) and Nickel-Cadmium (NiCd). These batteries must have certain essential properties like low self-discharge, high charge-discharge efficiency, long life under cyclic charging and discharging, easiness of transport, low maintenance [80].

3.3.5 Technical Characteristics of Batteries

In general the main parameters of the battery are terminal voltage, rating capacity and State of Charge (SOC), the latter term is defined, a percentage of the available amount of energy over its maximum achievable amount. For example if we have a battery with 2 volt and 100 Ah then the rated capacity of this battery is 200 Wh, if this battery has 75 % SOC then the remaining energy in this battery is 150 Wh. In practice it is extremely difficult to measure exactly the state of charge. Figure 3.14 shows the variation of battery terminal voltage during charging and discharging taking into account different rates [73]. It can be seen that, during discharging with high current, the capacity of the battery will decrease, means 100 Ah with C/20 rating; increasing the discharging current more than 5A, this will lead to get less capacity than 100 Ah.

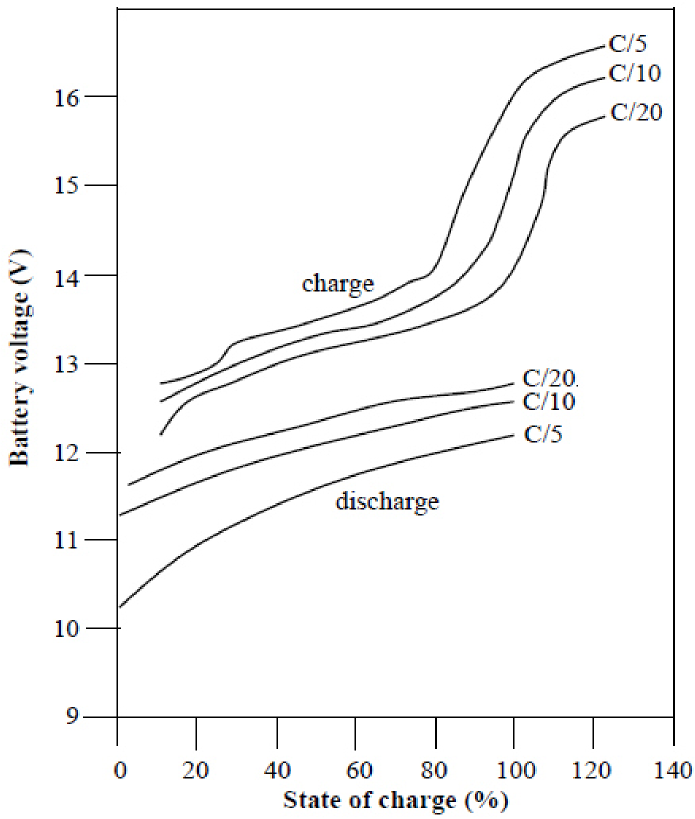


Figure. 3.14 Voltage as a function of charge-discharge rate and battery SOC.

Chapter 4 Control of Power Converters in MGs

This chapter presents a general overview and a classification of power converters control strategies in grid connected MGs, Control of non-dispatchable VSIs, active and reactive power control schemes also presented. MFPC control strategy is proposed with time domain simulation of different operating conditions.

4.1 Classifications of power converters in MGs

As mentioned before, MGs have the potential of working in both operation modes: grid connected and islanded mode. The power converters in MGs are classified in Table 4.1, based on the operation function [81]. In this work, a grid connected mode is considered, therefore the control strategy of power converters in grid connected mode will be discussed.

Table 4.1 Classifications of power converters in MGs.

Power Converter	MG mode	Function
Grid forming	Islanded Mode	Regulate the system voltage and frequency by balancing power generation and load demands.
Grid feeding	Islanded/Grid connected	Provide the active and reactive power dispatching requirements.
Grid supporting	Islanded/Grid connected	Supply active power from their primary energy source, and also provide ancillary services for the power quality improvement.
Grid parallel	Islanded/Grid connected	The grid parallel units are only responsible to feed as much power into the grid as possible, (MPPT).

4.2 Control of Grid Connected Converters

Grid connected VSIs are controlled with different control strategies. These control strategies are used to perform the control of the DC-link voltage, active and reactive power injected to the grid, grid synchronization and power quality of delivered power. Vector control strategies for three phase VSI are classified into three categories, based on synchronous reference frame control, stationary reference frame control and natural reference frame control. In this work, only the synchronous reference frame will be discussed and used.

In general two cascaded control loops are used to control VSIs, the inner loops for control the grid currents and the outer loops for control the voltage of the DC-link and the reactive power reference [82].

In synchronous reference frame, the three phase quantities of voltages and currents are transformed from $abc \rightarrow dq$ as shown in Figure 4.1, (the transformation is illustrated in Appendix A). The grid voltages and converter currents are converted to DC quantities, hence simple linear proportional integrator (PI) controllers can be used since it has infinite gain at zero Hz (DC variables). After controlling these variables, an inverse transformation $dq \rightarrow abc$ is performed, the latter three signals are inputs for PWM.

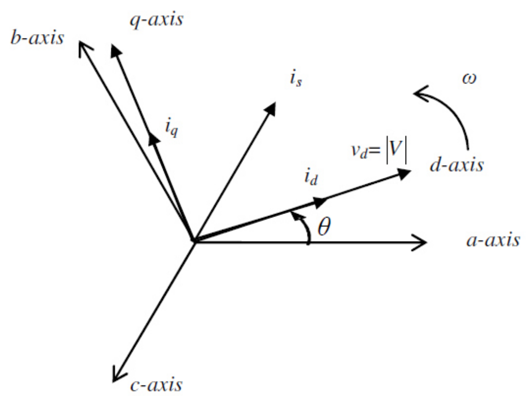


Figure 4.1 *abc* and rotating reference frame vectors.

4.3 Power Balance in dq Reference Frame

Power control of grid connected inverter is based on the dq reference frame theory, the instantaneous power in a three phase system is given by the (4-1).

$$p(t) = v_a i_a + v_b i_b + v_c i_c \tag{4-1}$$

Apparent power at the AC-side with dq reference frame can be given as [83]:

$$S = \frac{3}{2}\left(V_d + jV_q\right)\left(I_d - jI_q\right) \tag{4-2}$$

$$S = \frac{3}{2}\left\{\left(V_d \times I_d + V_q \times I_q\right) + j\left(-V_d \times I_q + V_q \times I_d\right)\right\}$$

Real part represents active power (P),

$$P = \frac{3}{2}\left(V_d \times I_d + V_q \times I_q\right) \tag{4-3}$$

imaginary part represents reactive power (Q).

$$Q = \frac{3}{2}\left(-V_d \times I_q + V_q \times I_d\right) \tag{4-4}$$

With the assumption that the d axis is perfectly aligned with the grid voltage, then $V_q = 0$ and active and reactive power equations can be simplified with the following:

$$P = \frac{3}{2}\left(V_d \times I_d\right) \tag{4-5}$$

$$Q = \frac{3}{2}\left(-V_d \times I_q\right) \tag{4-6}$$

From previous equations it is obtained that active and reactive power can be controlled by controlling direct and quadrature current components, respectively.

4.4 Control of Non-Dispatchable Grid Connected VSI

4.4.1 Grid Parallel Units

For grid parallel power converters, the main goal is to deliver all power produced by RESs to the grid to decrease the payback period of investment costs. The generated power is delivered first to the DC bus by using MPPT, which is achieved by DC/DC converters, then this power is delivered to the grid by VSIs. As shown in Figure 4.2 [84], the outer control loop is used for balancing the DC bus. From previous section the active power generated is given by (4-3).

$$P_{AC} = \frac{3}{2}\,(V_d \times I_d\,)$$

$$P_{DC} = V_{DC} \times I_{DC} \qquad (4\text{-}7)$$

With of assumption off no losses in the conversion, we can write: $P_{AC} = P_{DC}$

$$\frac{3}{2}\,(V_d \times I_d\,) = V_{DC} \times I_{DC} \qquad (4\text{-}8)$$

$$I_{DC} = \frac{3}{2}\,\frac{(V_d \times I_d\,)}{V_{DC}} \qquad (4\text{-}9)$$

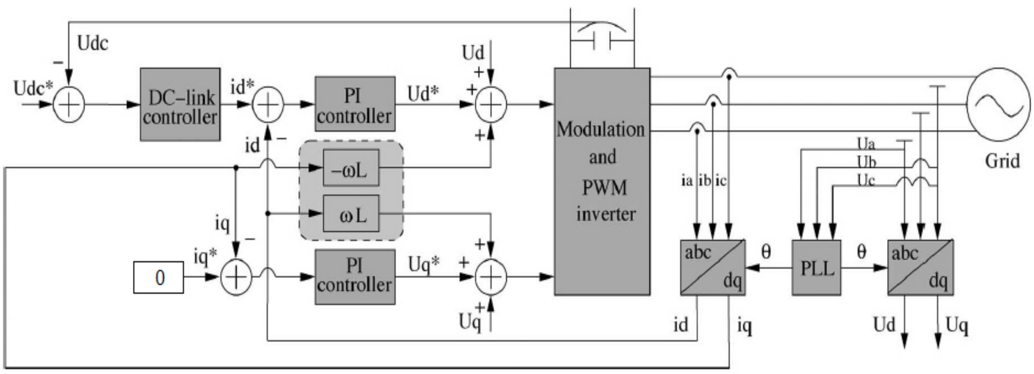


Figure 4.2 Structure for grid parallel synchronous rotating frame control.

As there are no storage batteries interconnected to these units they are considered a "non-dispatchable[1]" units. For example, in case of solar and wind power they are non-dispatchable (without adding storage), since the supply of sunlight or wind is periodic and cannot be predicted and controlled, therefore in such systems it is important to inject all power produced to the grid, in order to reduce the payback period of the investment costs.

4.4.2 Grid Supporting Units

Grid supporting units and grid parallel are quite similar, with one difference, that, the grid supporting units can deliver ancillary services like reactive power supplying to the main grid or other services, like providing power quality improvements, active filters by adding harmonic compensator in the control loops.

As shown in Figure 4.3 [84], the control loop for reactive power is used to control the reactive power, which can be supplied by these units. As an example, PV inverters during the night can be used to deliver the reactive power as there is no sun and no active power generation.

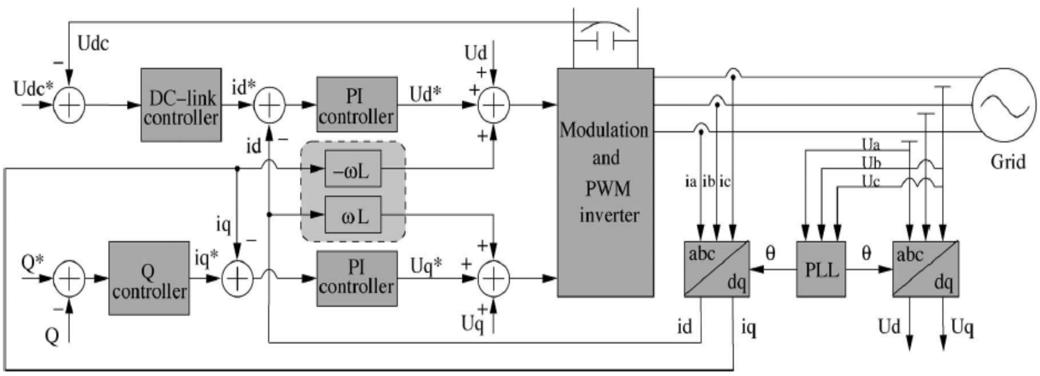


Figure 4.3 Structure for grid supporting synchronous rotating frame control.

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[1] In this thesis dispatchable term is referred to active power only.

4.5 Control of Dispatchable Grid Connected VSI

4.5.1 Operating Regions of Dispatchable VSIs

In case of ESS is utilized with VSI, these units become dispatchable units hence VSI active and reactive power are controlled by the grid operator, based on power management systems.

Dispatchable grid connected VSIs have the potential to work in four quadrant as shown in Figure 4.4, by control the active and reactive power independently, thanks to synchronous reference frame theory. These features give potential, for VSI, to deliver different services to the grid like unbalanced compensator, grid feeding and supporting functions.

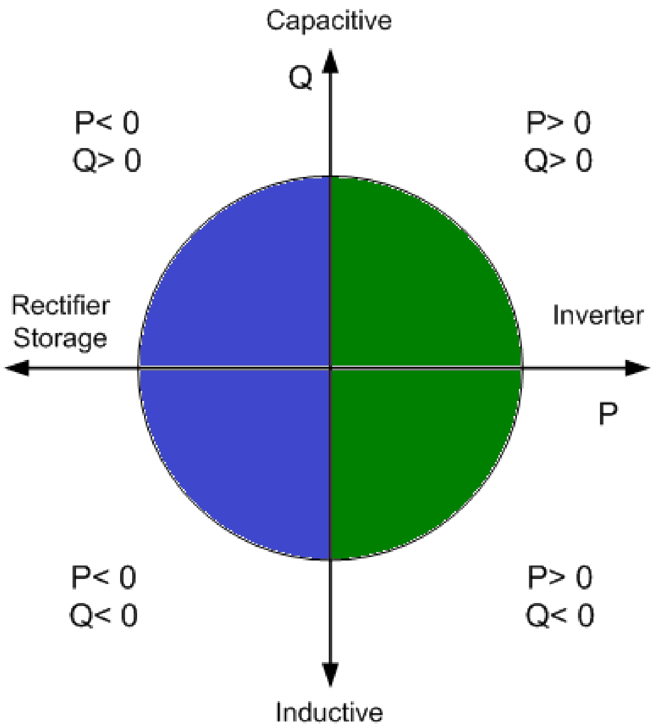

Figure 4.4 VSI real and reactive power operation regions.

4.5.2 Active and Reactive Power Control of VSIs

As mentioned before, VSIs active and reactive power are independently controlled based on synchronous reference frame, as mentioned before in equations (4-5) and (4-6). Active power is controlled by I_{dref} and reactive power is controlled by I_{qref}. By getting the reference values of active and reactive power from the grid operator, the two values of currents references can be calculated as previously given in equations (4-5) and (4-6). Later, these currents values are used to control the output power as shown in Figure 4.5.

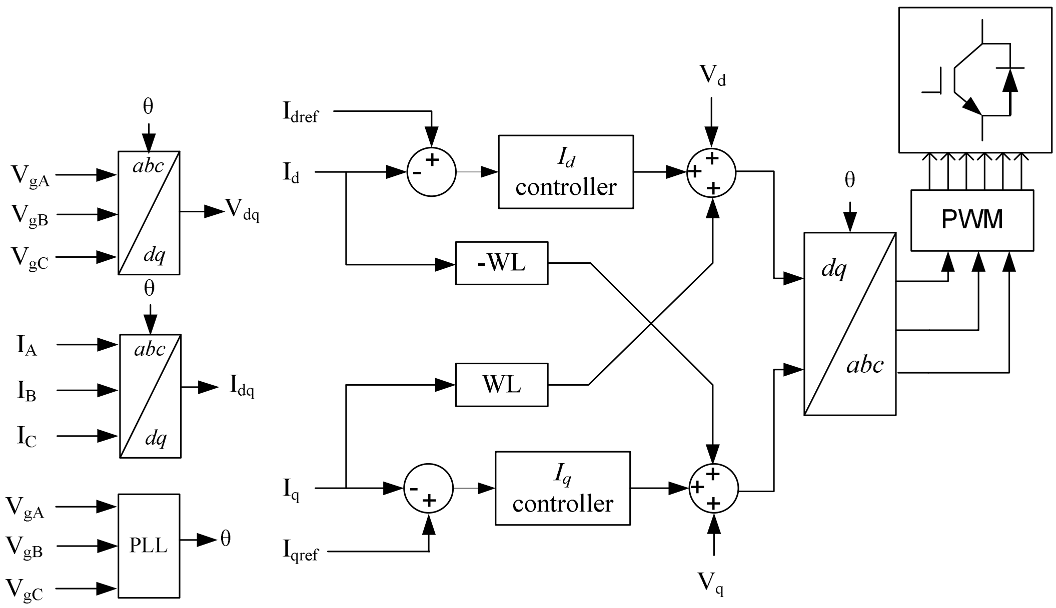

Figure 4.5 Current control block diagram.

The output power of VSIs can be controlled directly, by adding two cascaded control loops; the outer loops as shown in Figure 4.6 [81]. The reference values P_{ref} and Q_{ref}, are given by the grid operator or (SG) dispatcher. The output of PI controllers (I_{dref}, I_{qref}), are the inputs for the inner current control loops as shown in Figure 4.5.

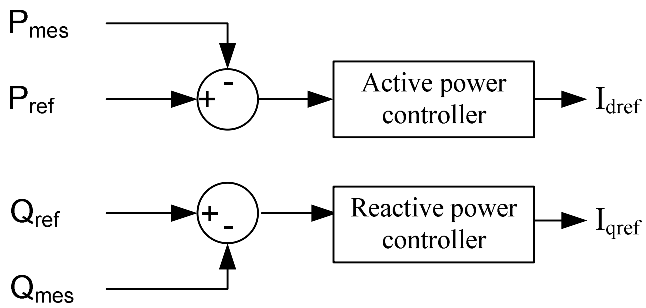

Figure 4.6 Outer control loops for active and reactive power.

The instantaneous active and reactive output power of VSIs Pmes and Qmes can be calculated for symmetrical and asymmetrical output as the following [85]: for balanced three phase systems, (4-10) is used for getting the active power and (4-11) is used for getting the reactive power.

$$P = V_a.I_a + V_b.I_b + V_c.I_c \quad (4\text{-}10)$$

$$Q = \frac{1}{\sqrt{3}}[(V_b - V_c).I_a + (V_c - V_a).I_b + (V_a - V_b).I_c] \quad (4\text{-}11)$$

For unbalanced three phase system each phase is measured separately and by summing the power for all phases, it is possible to obtain positive active power and positive reactive power for the three phases.

$$P = \frac{|V|}{\sqrt{2}} \times \frac{|I|}{\sqrt{2}} \times \cos\varphi \quad (4\text{-}12)$$

$$Q = \frac{|V|}{\sqrt{2}} \times \frac{|I|}{\sqrt{2}} \times \sin\varphi \quad (4\text{-}13)$$

$$\varphi = \angle \mathrm{V} - \angle \mathrm{I} \quad (4\text{-}14)$$

4.6 MFPC Control Strategy Based on Vector Control

As mentioned before a MFPC is proposed to perform different functions for MGs functionality improvements, for example, to be a compensator for unbalanced and reactive power compensation, on the other hand to be a dispatchable unit for feeding/absorbing power to/from the grid based on the grid operator. In this section the control strategy will be discussed only, and in chapter 5 the advantages of MFPC for grid connected MGs will be explained in details.

4.6.1 Proposed Control Strategy for MFPC

Vector control or (*dq*) control, can be employed in high-performance three-phase grid connected inverters, for delivering balanced output currents. The AC quantities are easily converted into DC by *abc/dq* transformation, hence simple PI-type controllers can be employed [86]. However, during unbalanced operation, the measured quantities are containing a double line frequency component due to the negative sequence components and a line frequency component due to the zero sequence components. Therefore it is not pure DC anymore. As well known a PI controller tracks the desired value if it is with zero Hz (DC) [86]. Therefore symmetrical components are used in [21, 87] to extract positive, negative and zero sequence components of currents and voltages and applying decomposition before PI controller. After the control stage, a sequence composition is applied as shown in Figure 4.7, hence the DC operating point for each channel can be obtained without disturbances. The current control loop composites transformation and control for each sequence components a already has been illustrated in Figure 4.5.

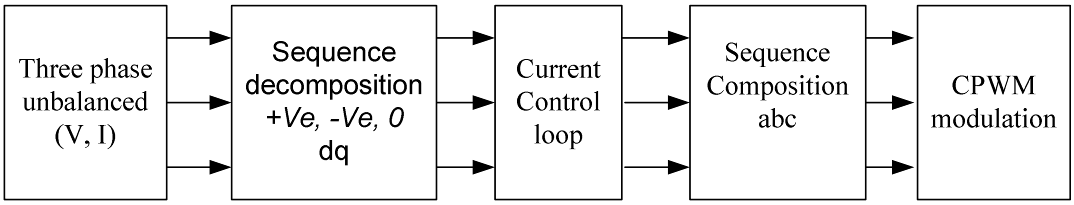

Figure 4.7 The control stages of MFPC in grid connected mode.

In this work symmetrical components are used for grid connected MFPC, the decomposition and composition the variables in positive, negative and zero sequence with conversion to dq coordinates for obtaining a DC variables are illustrated in Appendix B. After getting the dq variables, the control strategy is applied as shown in Figure 4.8. Positive sequence power can be controlled by an outer loop as previously has been described in Figure 4.6 or by calculating the reference positive current as given in (4-5). The negative and zero sequence loops are for compensating the unbalanced components.

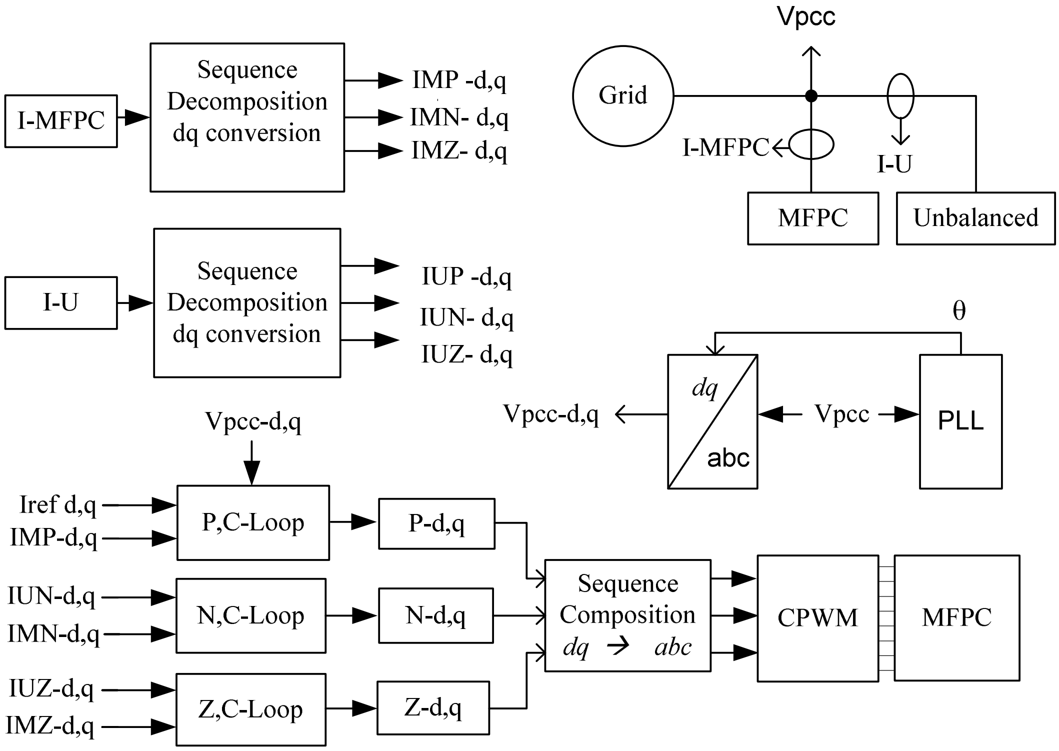

Figure 4.8 MFPC control strategy.

As mentioned before PI controllers have been used for current control loops. The transfer function of PI controller is given by the following:

$$G_{CL}(s) = Kp * s + \frac{Kp}{T_i\, s}$$

K_p=50 ; T_i= 0.025

The decomposition can be realized by using time delay of quarter period T/4 like what is proposed in [88, 89]. Adaptive Second Order Generalized Integrator (SOGI) as shown in Figure 4.9, is another approach to realize the orthogonal or beta components with a phase shift 90^o, has been proposed in [90]. The dynamic characteristic of SOGI is dependent on *K* (shown in Figure 4.9), being the value of $\sqrt{2}$ the tradeoff between settling time and overshot that can be realized [89].

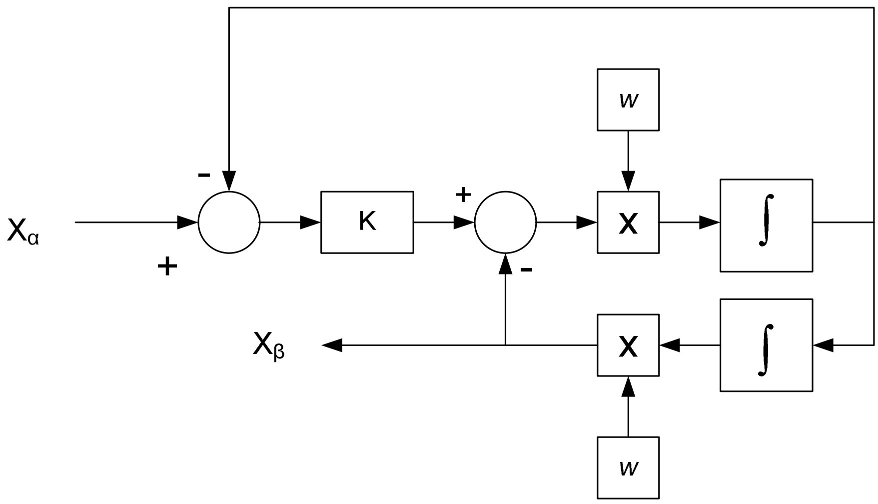

Figure 4.9 Generation of beta by SOGI.

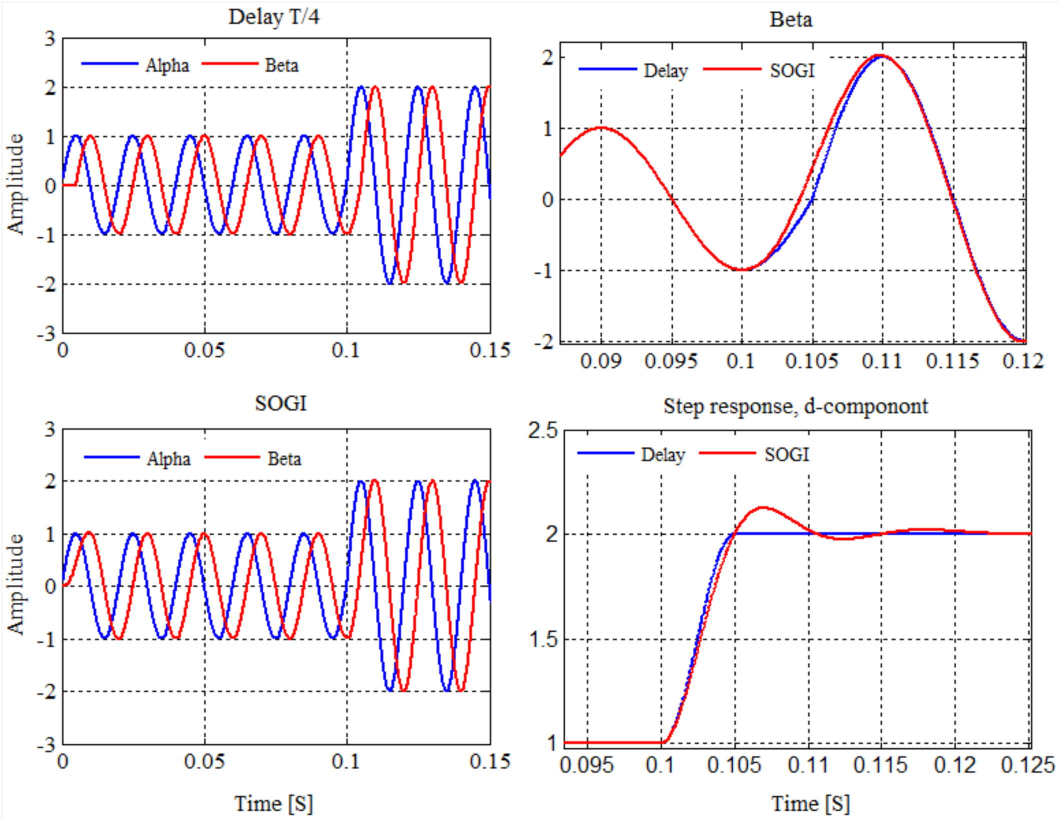

Figure 4.10 Comparison between SOGI and delay technique.

The comparison between delay technique and SOGI is shown in Figure 4.10, It can be observed that the step is applied at time t= 0.1s, with delay approach the settling time is 0.005s as expected. In case of SOGI, the settling time is 0.020s. It is clear that the delay approach with T/4 is three to four times faster than the SOGI approach. As a result by using delay approach the dynamic behavior of the whole control loop can be increased. Moreover with the assumption that the grid is working with a fixed frequency 50 Hz (stiff grid). The time delay is suitable as a MFPC control strategy is proposed for grid connected system.

4.6.2 Time Domain Simulation of MFPC Control Strategy

In order to evaluate the MFPC control strategy, different operating modes should be considered in simulation studies, for instance MFPC can work for [2]delivering power (inverter), charging the battery by [3]absorbing power (active rectifier) and [4]idle mode, neither positive sequence active power delivering nor absorbing by MFPC, therefore the losses of the MFPC is covered by the DC side (battery). In this chapter, these modes are considered in different simulation cases which will be discussed later in this chapter one by one.

4.6.2.1 System Components and Simulation Description

It can be seen in Figure 4.11 the diagram of the tested system. Four legs power converter (3P4L) has been used, as mentioned in chapter 2. each leg has two IGBT switches. The power converter is used for different functions mainly a compensator with storage capability.

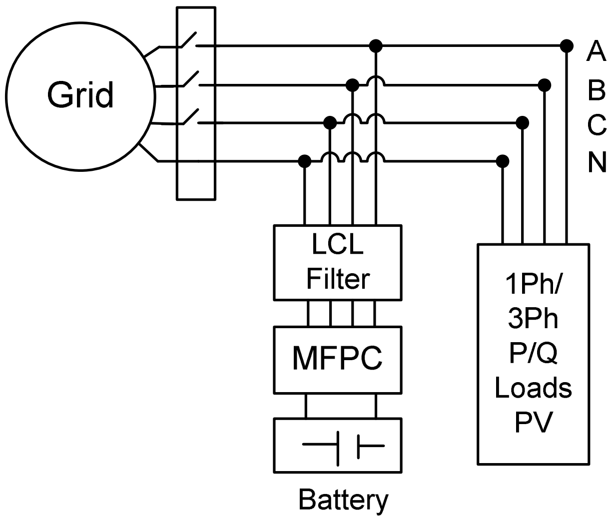

Figure 4.11 Tested system considered for simulation.

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[2] Positive sign in simulation figures.

[3] Negative sign in simulation figures.

[4] The positive sequence active power is zero

LCL filter and the way of calculating its elements have been already discussed in chapter 2. As mentioned, LCL is used for its advantages in MGs systems, filter elements are given in Table 2.2. The neutral inductor is selected to be equal to the converter side inductors, the bode plot of designed LCL filter is depicted in Figure 2.20 and THD analysis can be found in Figure 2.19.

The modulation strategy of MFPC is based upon a CPWM technique, which has been already explained in chapter 2, section 2.3.3.2.

SRF-PLL is used and it has been already explained and discussed in chapter 2.

The DC bus voltage for MFPC has been selected to be 800 $V_{dc.}$ The DC bus is usually regulated with a bidirectional DC-DC converter, like for example converter that has been already discussed in chapter 2 Figure 2.7, however the design and control of such converter is not considered in this work because we considered the DC bus with a fixed DC voltage.

In this work the grid is considered to be a stiff grid. Thus, the AC system is modeled by an ideal three phase voltage source, phase voltage of 230 V_{rms} and constant frequency 50 Hz as shown in Figure 4.12. The performance of the simulated system has been verified by means of simulations with Simulink/Matlab platform, (see the diagram in Appendix C).

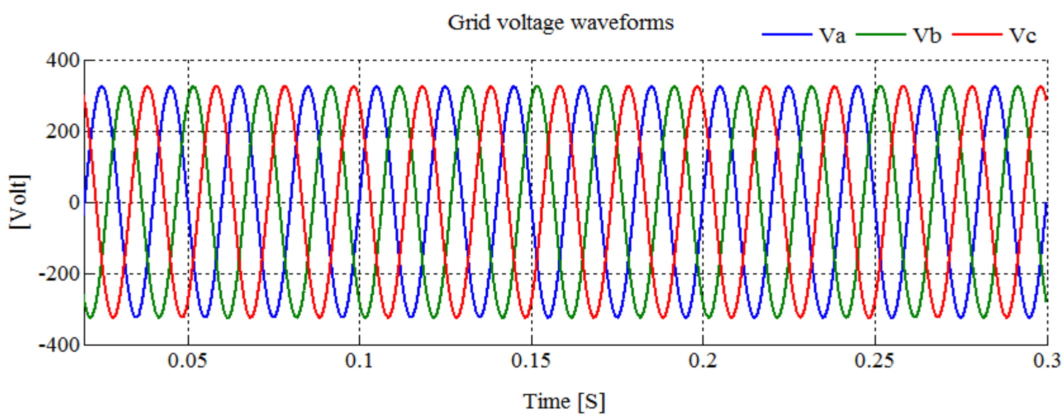


Figure 4.12 Voltage waveforms of the grid.

4.6.3 Simulation Results of MFPC Control Strategy

As mentioned before, three different cases should be considered in order to examine the performance of the proposed control strategy. Hereafter these explanations and discussions of these cases.

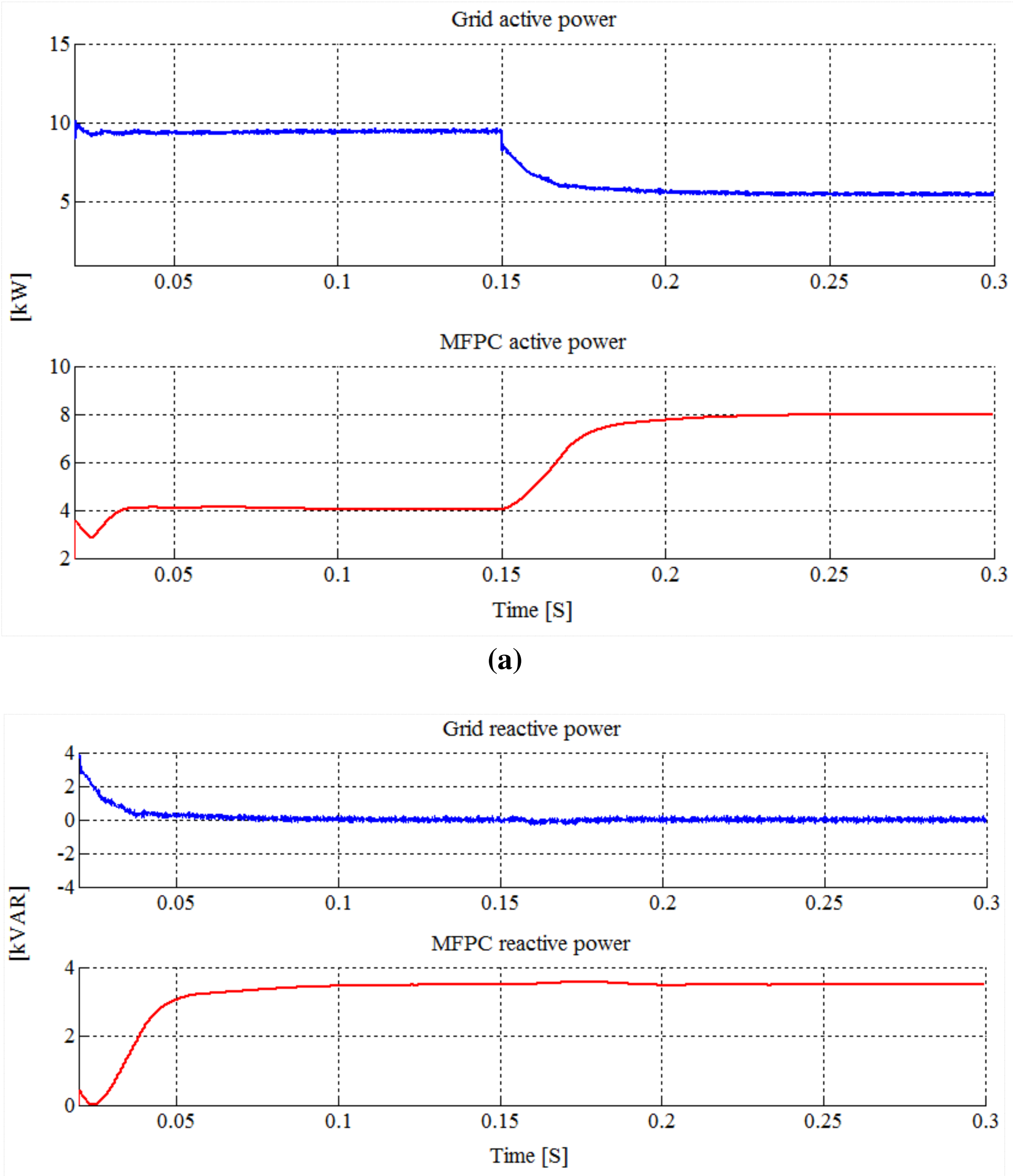
4.6.3.1 Case 1, MFPC During Discharging Mode with Step Response

This study is conducted to evaluate the performance of MFPC control strategy with unbalanced local loads, during discharging mode (delivering power) with step response. The local loads, active and reactive are unbalanced as given in Table 4.2. The step response is tested by changing the reference power of MFPC as shown in Table 4.2.

Table 4.2 Case 1, simulation parameters.

Local loads			
Power	**Phase (A)**	**Phase (B)**	**Phase (C)**
P [kW]	6	5.5	2
Q [kVAR]	1.5	0.5	1.5
MFPC power control			
Time	Start → 0.15s	0.15s → 0.3s	
Reference power	4 kW (delivered)	8 kW (delivered)	

It can be seen in Figure 4.13.a, the MFPC is delivering constant active power 4 kW from starting time until time 0.15s, at time 0.15s the output power of MFPC is increased to 8 kW. As a result the supplied power by the grid is decreased by 4 kW as expected. Figure 4.13.b shows that the reactive power is compensated by MFPC throughout the whole simulation period, as a result no reactive power is supplied by the grid (unity power factor).



(a) **(b)**

Figure 4.13 Case 1, positive sequence power of the grid and MFPC:

a) Active power; b) Reactive power.

As shown in Figure 4.14, The output active and reactive power supplied by each phase of MFPC are unbalanced. The *dq* components of load currents for positive, negative and zero sequence are shown in Figure 4.15.

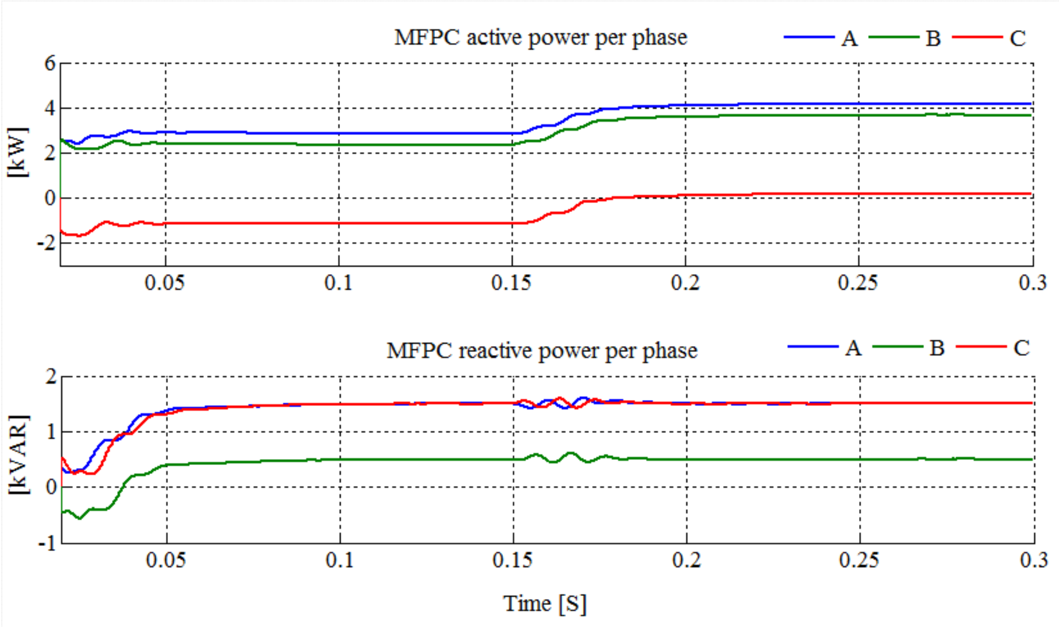


Figure 4.14 Case 1, per phase active and reactive power of MFPC.

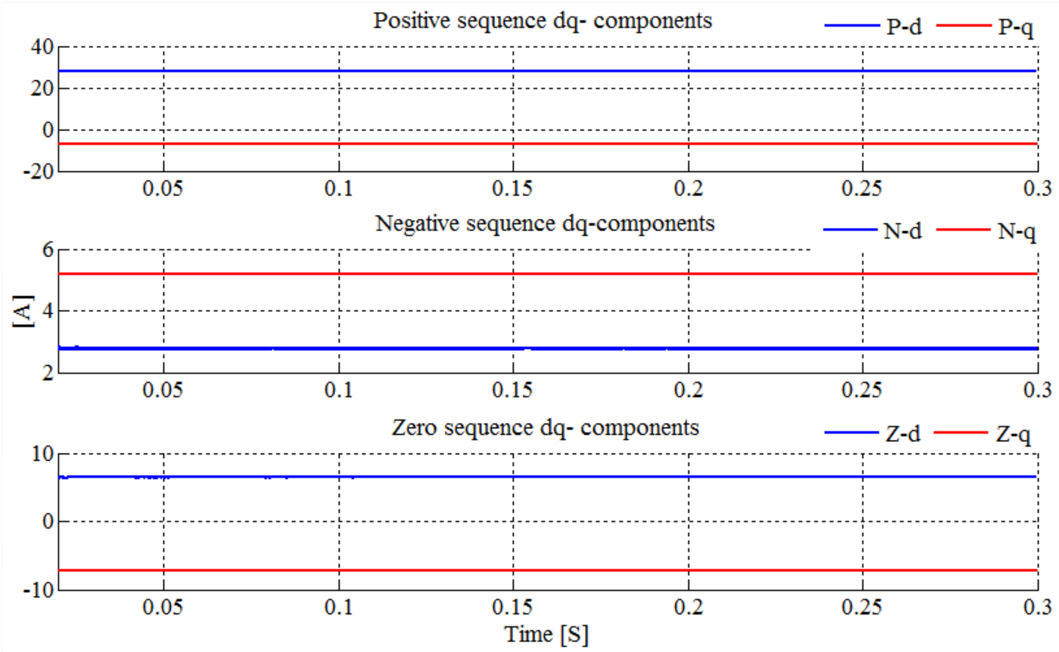


Figure 4.15 Case 1, sequence components of load currents.

Figure 4.16 shows the grid current waveforms are balanced with unbalanced current waveforms for loads and MFPC. At time 0.15s, the grid currents start decreasing because the power supplied by the grid is decreased.

In Figure 4.17 the grid neutral current is zero as expected, because the grid currents are balanced. MFPC neutral current is circulating in the neutral line.

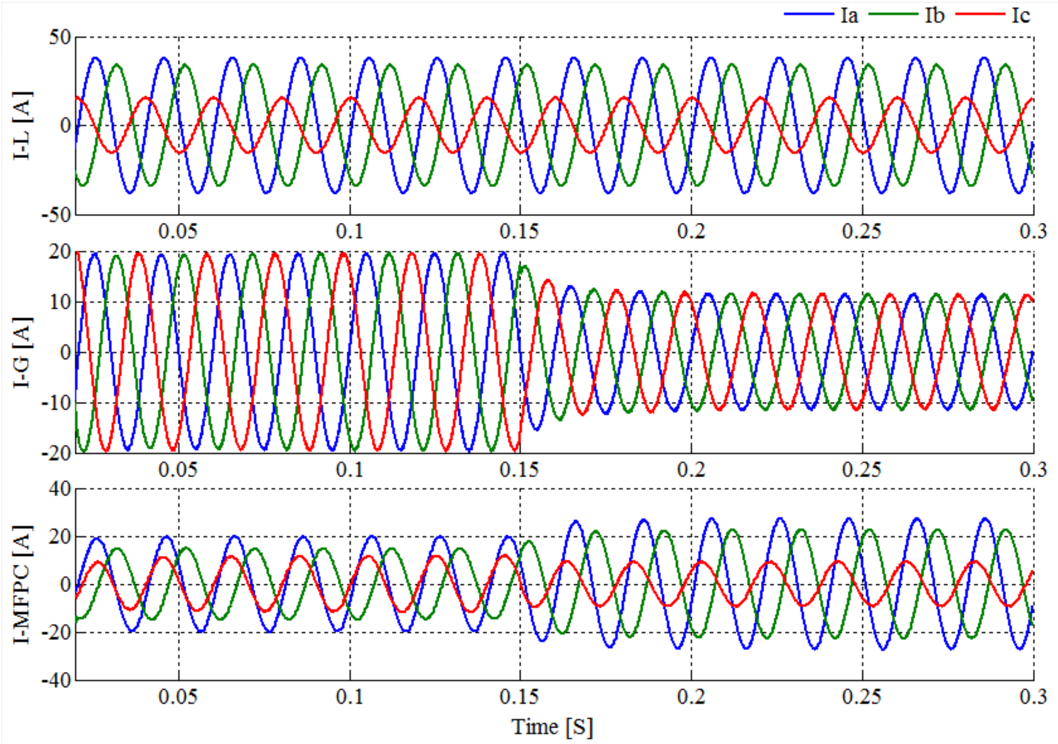


Figure 4.16 Case 1, current waveforms of loads, grid and MFPC.

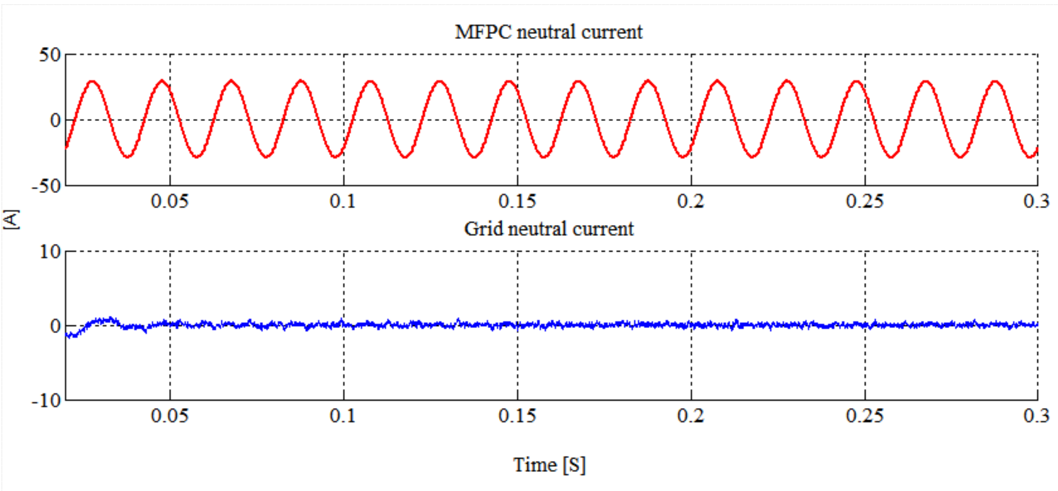


Figure 4.17 Case 1, neutral currents of MFPC and the grid.

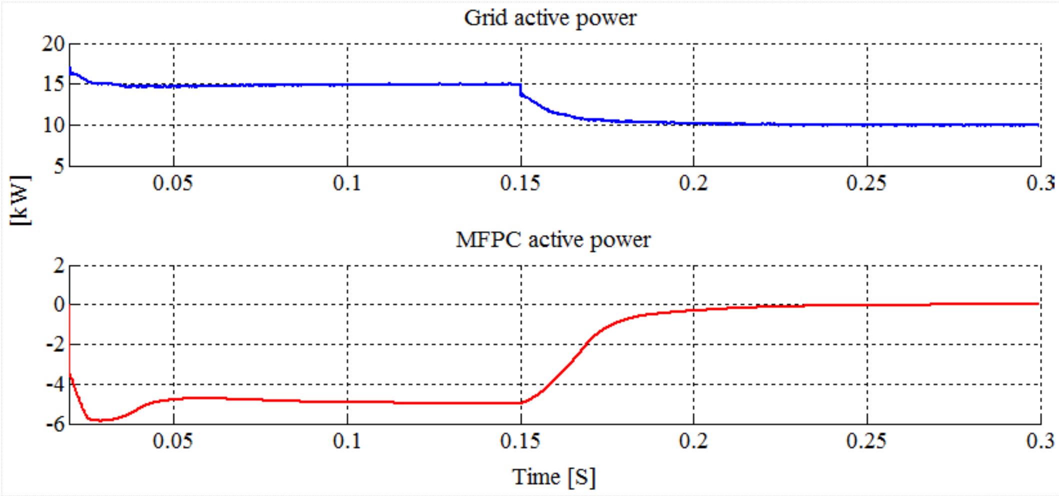
4.6.3.2 Case 2, MFPC During Charging and Idle Modes

In this simulation study the MFPC is working in charging and idle modes. Because MFPC is interfacing ESBs, this will add some restrictions and limits for its operation. For example, as mentioned in chapter three, the battery SOC should be maintained within the battery manufacturers recommendations, in order to extend the lifespan of the storage system which has high investment costs. Therefore idle mode is required to keep MFPC compensation functions working even ESSs are depleted or fully charged. Table 4.3 gives the values of unbalanced active and reactive loads. The step response is tested by changing the reference power of MFPC.

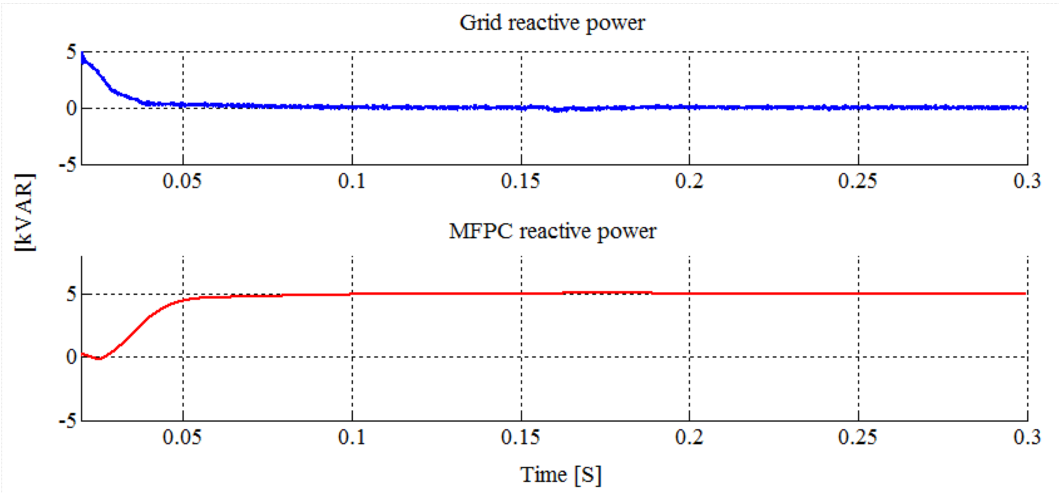
Table 4.3 Case 2, simulation parameters.

Local loads			
Power	**Phase (A)**	**Phase (B)**	**Phase (C)**
P [kW]	4	3.5	2.5
Q [kVAR]	2.5	1	1.5
MFPC power control			
Time	Start → 0.15s		0.15s → 0.3s
Reference power	5kW (Absorbed)		0 (Idle)

As shown in Figure 4.18.a MFPC absorbs active power (negative sign), from starting time until time 0.15s, after time 0.15s MFPC output power becomes zero. As a result the power supplied by the grid is reduced from 15 kW to 10 kW (the grid cover only the demanded load power). This can be occurred in some cases when the batteries reach certain limits either e.g. minimum SOC. In Figure 4.18.b, it can be seen that, the reactive power of grid remains zero, which means it is fully compensated by MFPC.



(a)



(b)

Figure 4.18 Case 2, positive sequence power of the grid and MFPC:

a) Active power; b) Reactive power

Figure 4.19 shows, that throughout the simulation period, the grid current waveforms are balanced with unbalanced currents for loads and MFPC. At time 0.15s the grid currents is start reducing, because the MFPC stop charging or absorbing power. During idle mode the grid currents continue to be balanced even with zero output power of MFPC (positive sequence). Figure 4.20 shows the neutral currents for grid and MFPC, with the same explanation of case 1.

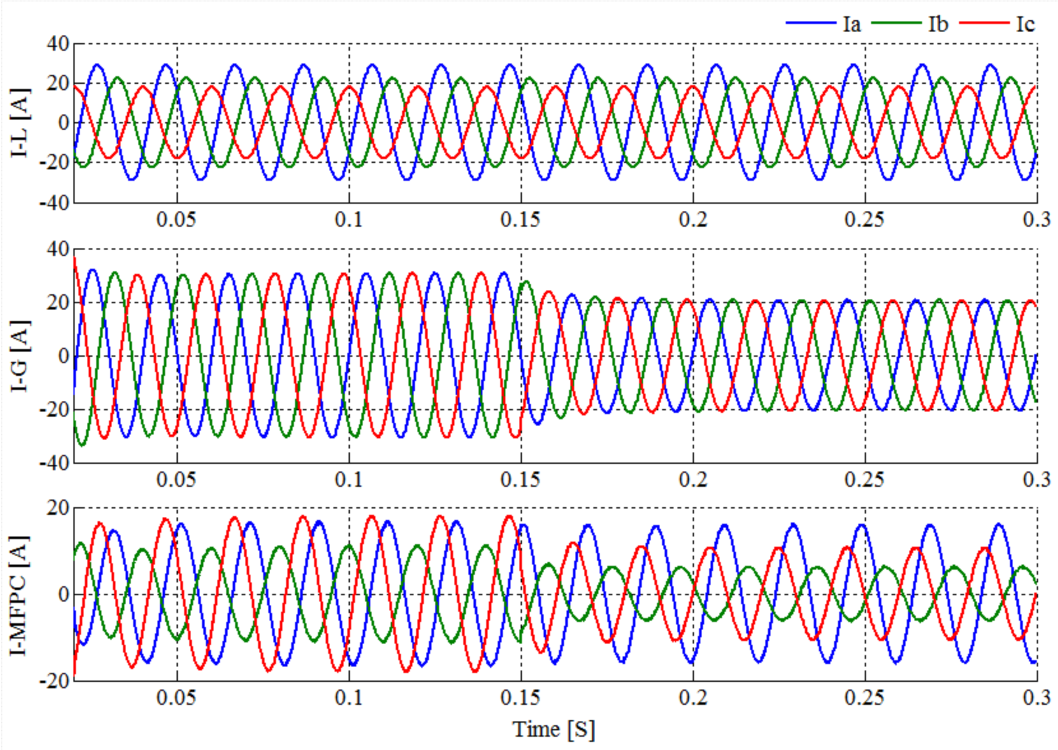


Figure 4.19 Case 2, current waveforms of the load, grid and MFPC.

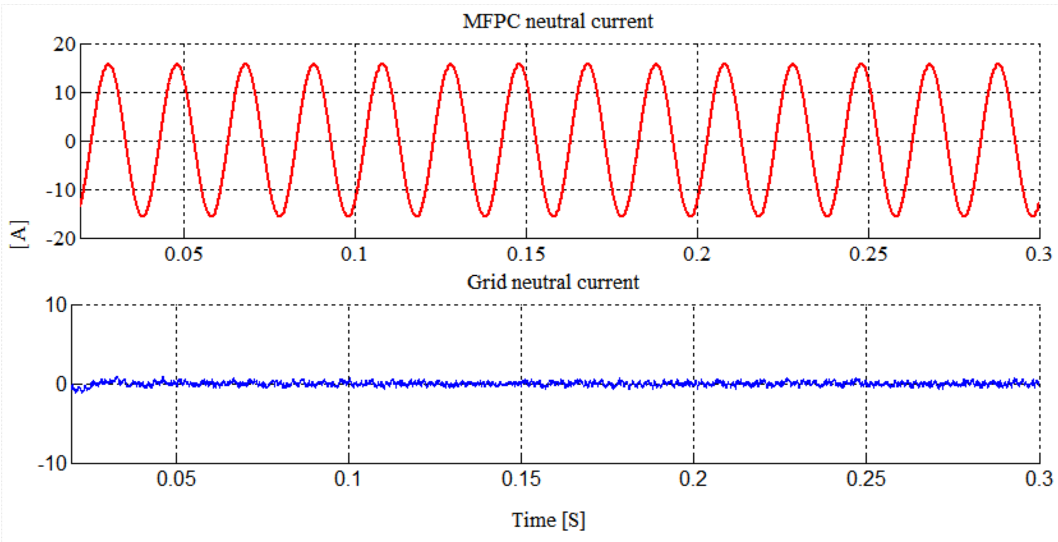


Figure 4.20 Case 2, neutral currents of MFPC and the grid.

4.6.3.3 Case 3, MFPC for Distributing Power between Unbalanced Phases

In this particular case MFPC is working to distribute the unbalanced generated power between phases. The generated power of single phase PV-inverter is distributed between unbalanced loads installed in different phases. The local loads are unbalanced as given in Table 4.4. A single phase inverter is connected in phase C with 6 kW rated power.

Table 4.4 Case 3, simulation parameters.

Local loads/inverters			
Power	**Phase (A)**	**Phase (B)**	**Phase (C)**
Load [kW]	3.5	1.5	1
PV[kW]	-	-	6
MFPC power control			
Time	Start →0.3s.		
Reference power	0 (Idle)		

It is interesting to observe in Figure 4.21, that no active power is absorbed or supplied either by the grid or MFPC (positive sequence). This means that the generated power of PV in phase C is distributed between the unbalanced local loads in different phases. For more explanation, in Figure 4.22. it is possible to observe that the MFPC is charging with 5 kW in phase C and at the same time, is discharging in the other two phases A and B with 3.5 kW and 1.5 kW respectively. Thus, the positive sequence power of MFPC is zero and no power is flowing into the grid.

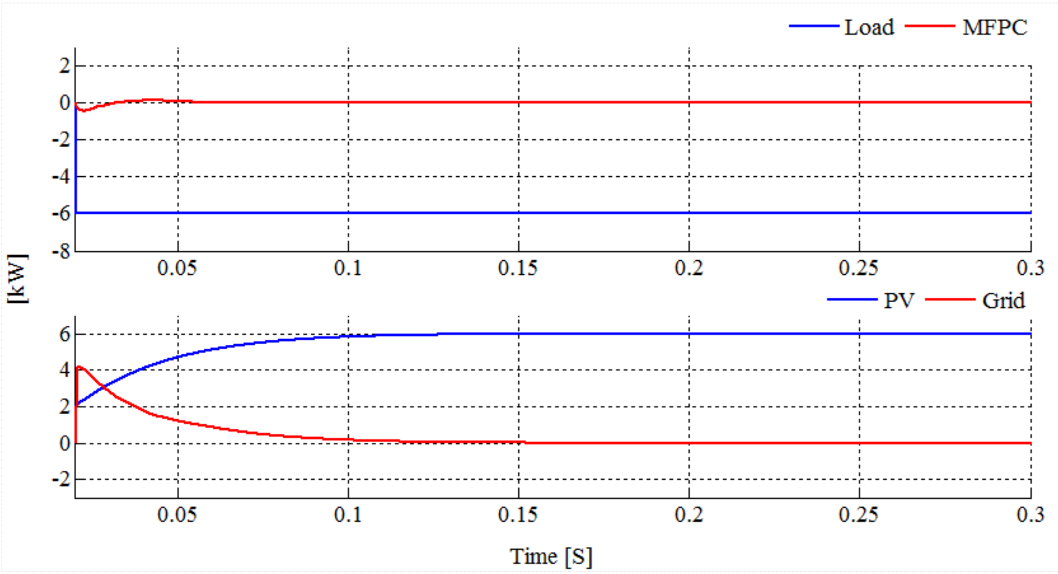


Figure 4.21 Case 3, positive sequence power of the loads, MFPC, PV and the grid.

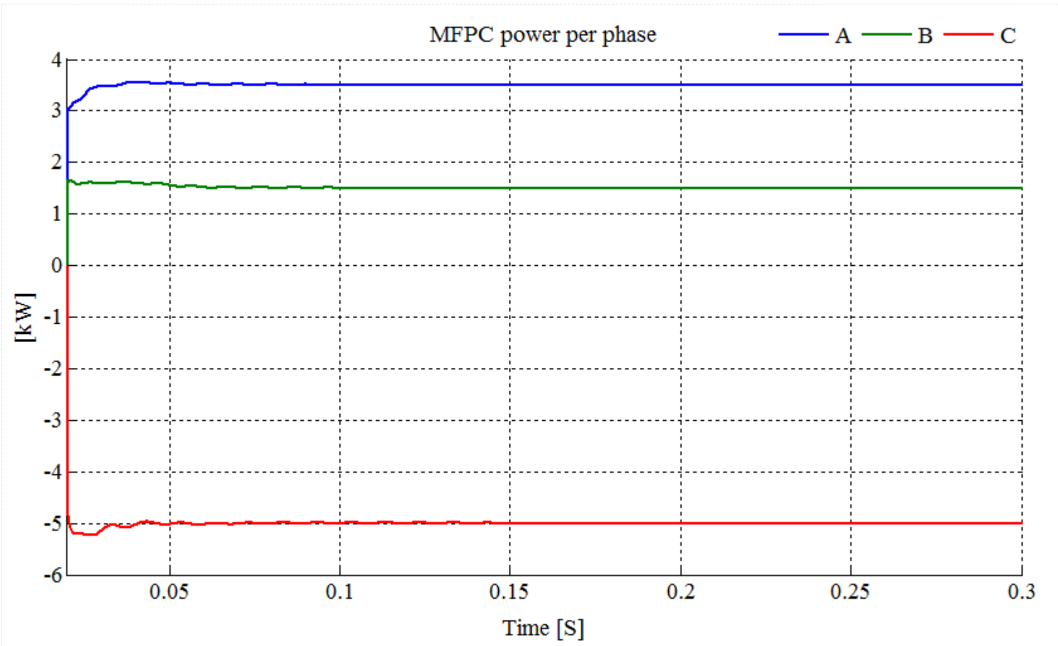


Figure 4.22 Case 3, MFPC active power per phase.

Figure 4.23 shows the current waveforms of loads, PV and MFPC. The load and MFPC current waveforms are unbalanced and PV current is only in phase C. Figure 4.24 shows the neutral currents of the grid and MFPC, the same explanation of case 1.

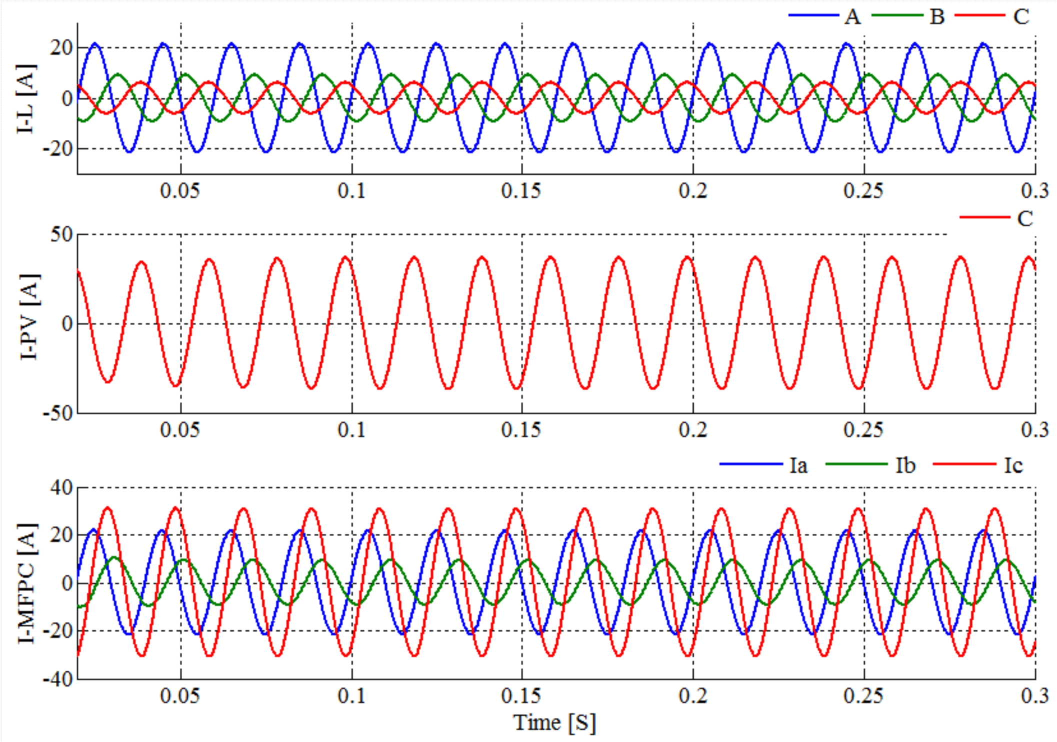


Figure 4.23 Case 3, current waveforms of the loads, PV and MFPC.

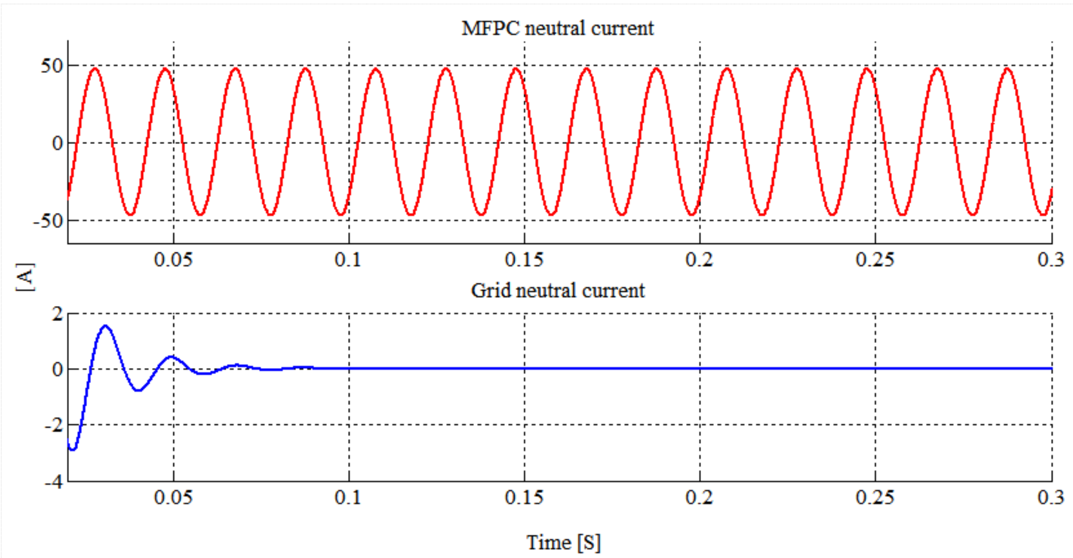


Figure 4.24 Case 3, neutral currents of MFPC and the grid.

Chapter 5 MFPC for Grid Friendly MGs

In this chapter the advantages of MFPC control strategy for grid connected LV MGs under unbalanced operating conditions will be illustrated by different simulations cases. The goal is mainly obtaining grid friendly MGs in presence of single phase generation/loads for different MG power management operating modes. Finally showing the advantage of MFPC for mitigation of unbalanced voltage drop/rise in LV MG.

5.1 Unbalanced Operation of MGs

As shown in Figure 5.1, the unbalanced operation of MGs may occur because of usage of single phase inverters, like for example PV rooftop inverters with configurations which already have been discussed in chapter 3. These inverters are commercially available in the market with high ratings e.g. 10 kW and high efficiency e.g. 98%. Imbalance can be caused also by single phase residential loads which are highly dependent on the end-users behaviors. Flowing unbalanced currents between the grid and MG will cause the voltage at Point of Coming Coupling (PCC) asymmetrical which will add problems for MGs, grid and three phase loads.

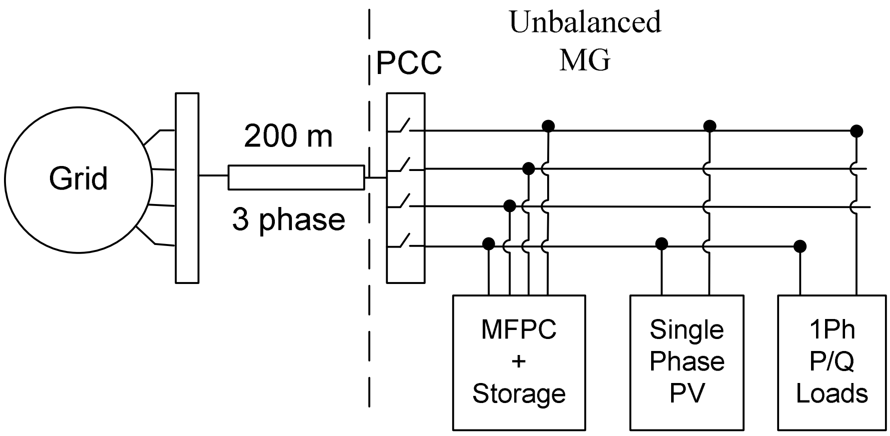


Figure 5.1 Tested MG for simulation case studies.

Asymmetrical voltages and unbalanced currents affect the behavior of MGs as well as add negative effects to the main grid. As mentioned before MG is supposed to be grid friendly when connected to the external grid. Therefore the power converters of MGs have to provide the zero sequence and negative sequence currents.

For unbalanced compensation in MGs, one solution could be controlling the loads of MG which is extremely difficult in case of residential loads. another solution maybe is disconnecting some DG units, which is uneconomical solution. As mentioned before in this work, MFPC that interfacing ESS with suitable control strategy has been proposed to make the MG "grid friendly", and to perform additional functions, which will be discussed in later sections of this chapter.

5.2 Grid Connected MGs Operating Modes

MG is assumed a dispatchable power unit, controlled by SG EMS. Therefore the EMS will select the desired operating mode, depending on the grid and MG conditions.

In order to evaluate the proposed control strategy, different operating modes of MG should be considered as shown in Figure 5.2. In this work, the performance of MFPC in different operating modes will be discussed to examine the system responses without designing the EMS. The tested MG is composed RESs mainly (single phase PV inverters), single phase loads and MFPC interfacing battery storage as shown in Figure 5.1.

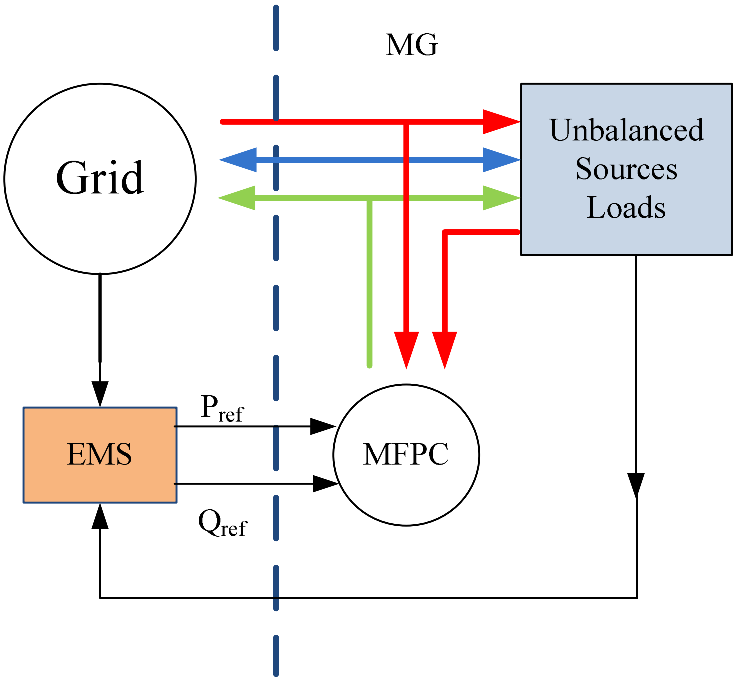


Figure 5.2 Operating modes of grid connected MGs.

MFPC works in different modes as described in Table 5.1, depending on MG operating mode.

Table 5.1 MFPC operating modes

Operating Mode	**Condition**	**MFPC Modes**
MG Supporting	Shortage of power generation or charging the battery during off-peak time	Charging and Idle
Grid Supporting	Supporting the grid during on-peak time	Discharging and Idle

5.3 Simulation of MGs Operating Modes

5.3.1 Simulation of MG Supporting Mode (MG-SM)

This simulation case study is for testing the performance of MFPC control strategy during MG-SM. In some cases MG needs to be supported by the main grid, for example in cases of power generation shortage and with ESBs SOC reaches the minimum recommended value. MFPC is working in two modes during this simulation period: charging and idle modes. MG local loads, active and reactive are unbalanced with no power generation from PV as given in Table 5.2.

Table 5.2 Simulation parameters of MG-SM.

Phase	**Phase (A)**	**Phase (B)**	**Phase (C)**
Load (kW)	3	5	1.5
Load (kVAR)	3.5	2.5	1
PV	No power generation		
MFPC control			
Time	Start → 0.2s	0.2s → 0.4s	
Power	5 kW (absorbed)	Idle	

Figure 5.3 shows the power consumed/supplied by the loads, MFPC and grid. MFPC is working in charging mode from starting time to 0.2s. At 0.2s MFPC stops charging and starts working in idle mode, therefore the delivered power by the grid is reduced, as no charging power is required. Idle mode may occur, for example, during charging the battery, if it reaches the Max. SOC. As shown in Figure 5.4 throughout the simulation period, the reactive power is fully compensated by MFPC, as there is no reactive power supplied by the grid.

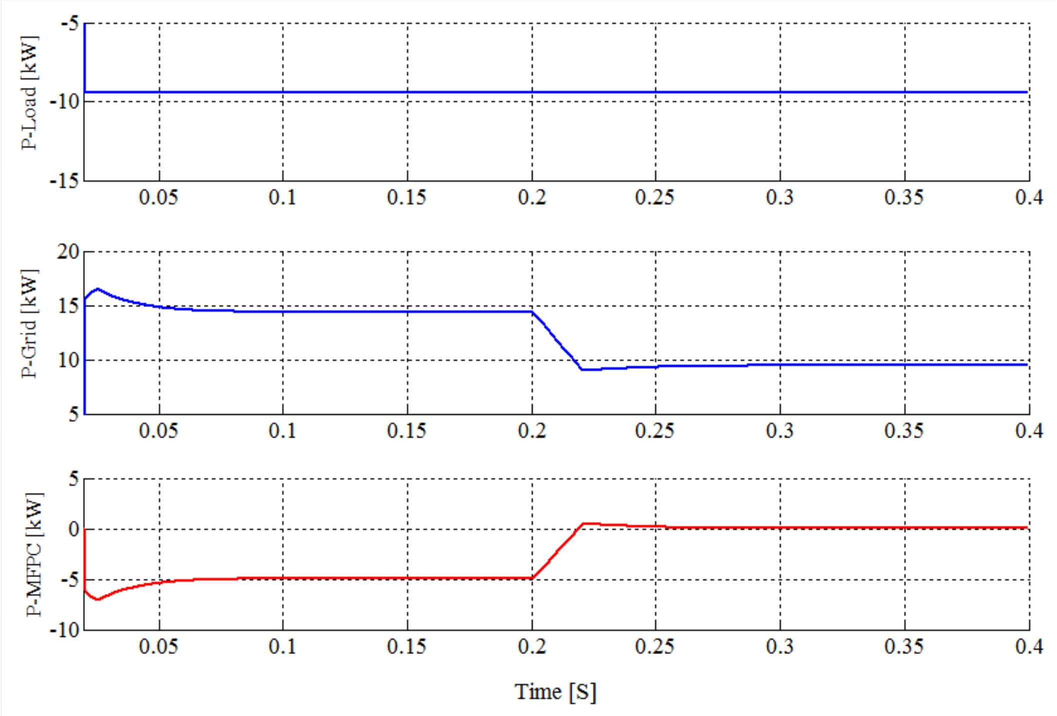


Figure 5.3 Positive sequence active power of loads, grid and MFPC (MG-SM).

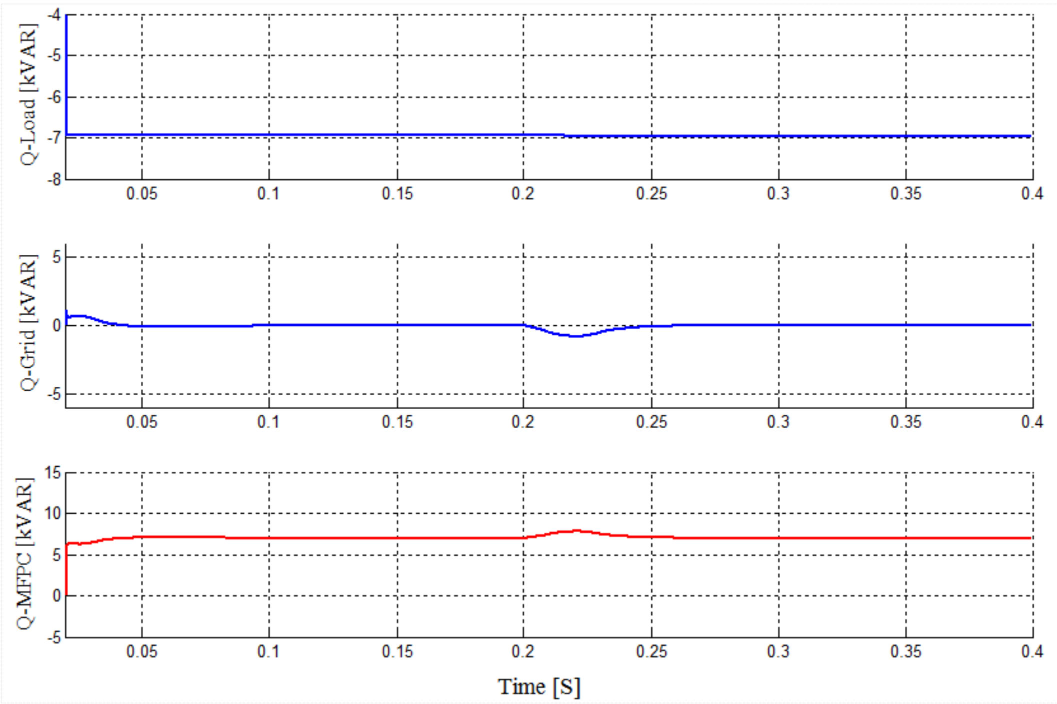


Figure 5.4 Positive sequence reactive power of loads, grid and MFPC (MG-SM).

Figure 5.5 shows the current waveforms of loads and MFPC are unbalanced with balanced grid currents throughout the simulation period. As a result the grid side neutral current is zero as shown in Figure 5.6. The main advantage of balanced grid currents is that the voltages at the PCC are symmetrical.

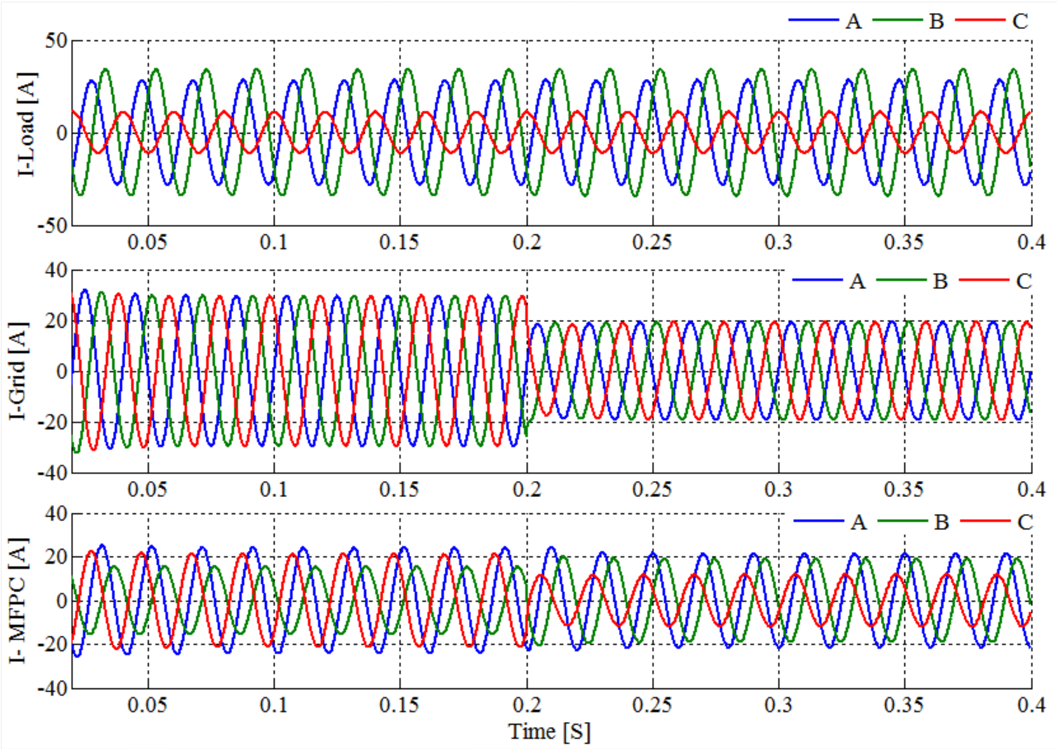


Figure 5.5 Current waveforms of loads, grid and MFPC (MG-SM).

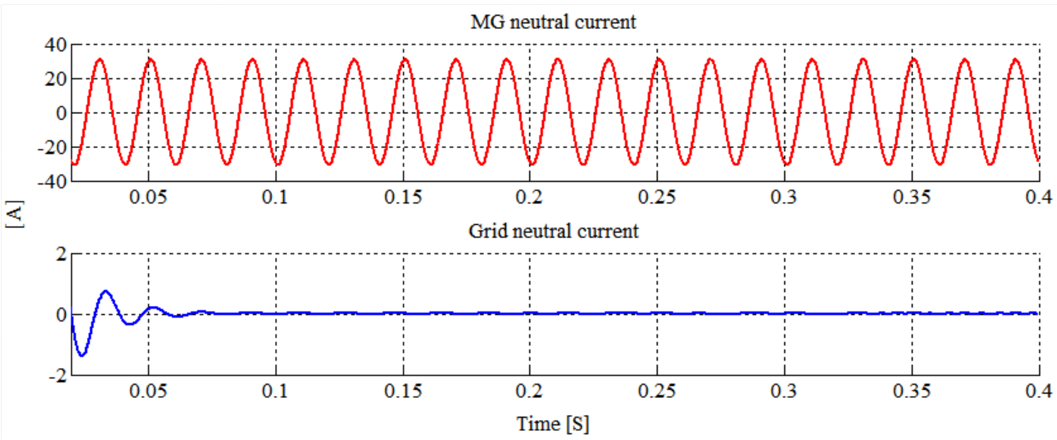


Figure 5.6 Neutral currents of MG and the grid (MG-SM).

5.3.2 Simulation of Grid Supporting Mode (Grid-SM)

In this simulation study, MG supports the grid with active and reactive power. The MFPC is working in two modes: discharging and idle modes. The latter is considered, because it may occurs during grid supporting mode, for example if battery SOC reaches its minimum limits during discharging. Therefore the idle mode is important for ESBs regulations. The local loads, active and reactive power values are unbalanced with PV single phase inverters are installed in MG as given in Table 5.3

Table 5.3 Simulation parameters (Grid-SM).

<table>
<tr><th>Phase</th><th>Phase (A)</th><th>Phase (B)</th><th>Phase (C)</th></tr>
<tr><td>Load (kW)</td><td>1</td><td>4</td><td>2</td></tr>
<tr><td>Load (kVAR)</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td>PV</td><td>4</td><td>6</td><td>2</td></tr>
<tr><td colspan="4">MFPC control</td></tr>
<tr><td>Time</td><td colspan="2">Start → 0.2s</td><td>0.2s → 0.4s</td></tr>
<tr><td>Power</td><td colspan="2">4 kW (delivered)</td><td>Idle</td></tr>
<tr><td>kVAR</td><td colspan="2">QL</td><td>QL+ 6 kVAR</td></tr>
</table>

Figure 5.7 shows the power curves, from starting time until 0.2s, the grid is suppurted by 9 kW; (5 kW) is from the excess PV generated power and (4 kW) is deliverd by MFPC. At 0.2s MFPC starts working in idle mode (stops delivering power), hence the delivered power to the grid is reduced as shown in Figure 5.7. At the same time, 0.2s, MFPC starts supporing the grid with reactive power (6 kVAR). Therfore a MFPC is required to supply the reactive power required by the load and the grid as shown in Figure 5.8. Figure 5.9 shows the current waveforms of the grid, loads, PV and MFPC. It is interesting to observe that MFPC makes the grid currents to be balanced, by distributing PV generated power between phases.

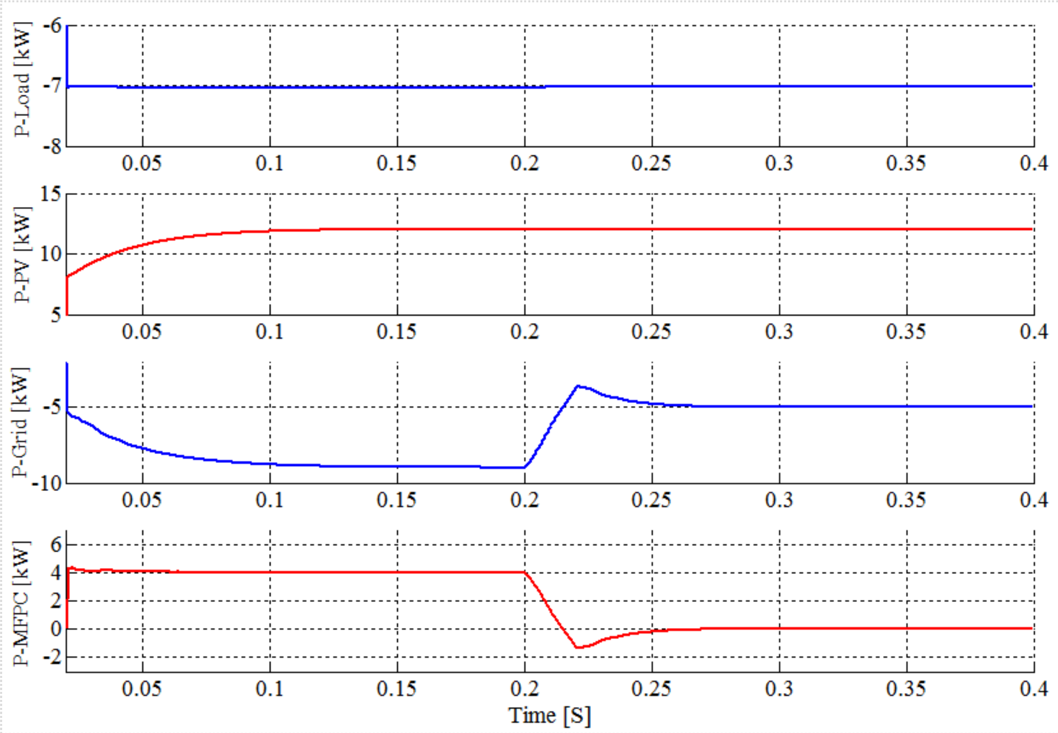


Figure 5.7 Positive sequence active power of loads, grid and MFPC (Grid-SM).

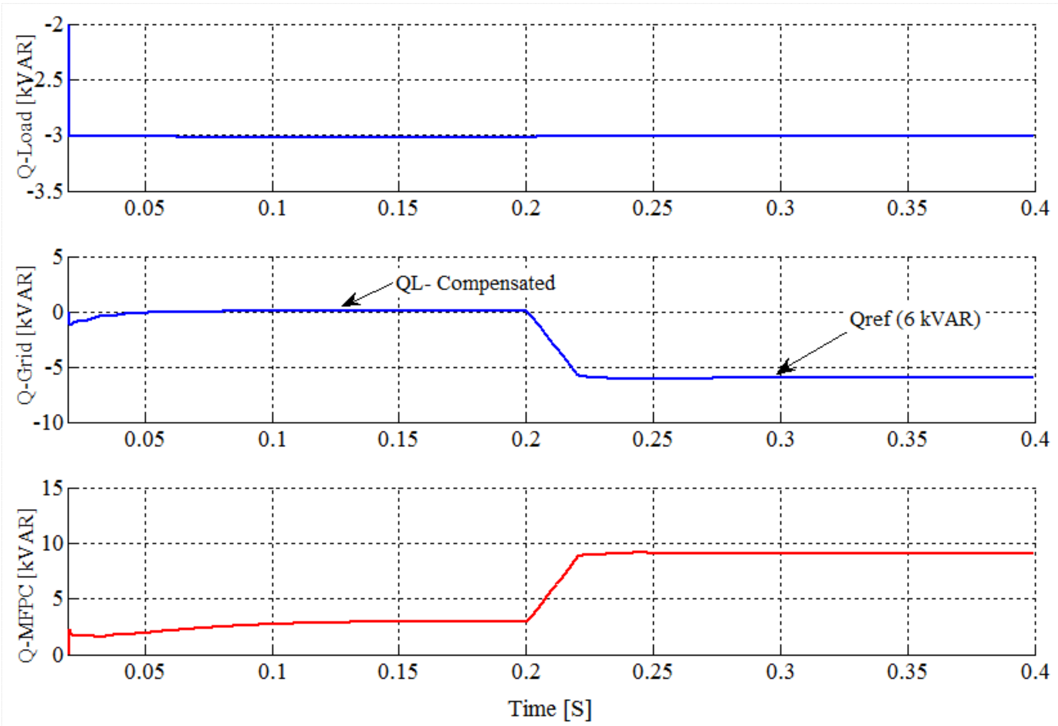


Figure 5.8 Positive sequence reactive power of loads, grid and MFPC (Grid-SM).

Therefore MG is injecting or supporting the grid with balanced currents, as a result the grid side neutral current is zero as shown in Figure 5.10. The main advantage of injecting balanced currents to the grid is that the voltages rise at PCC are symmetrical.

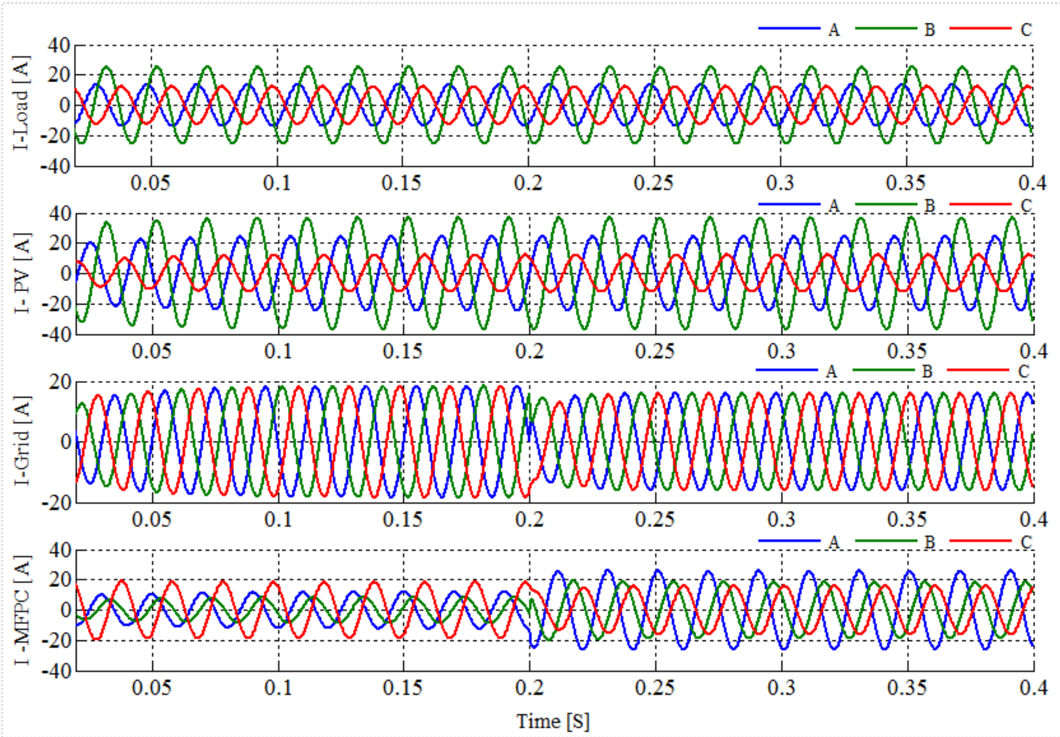


Figure 5.9 Current waveforms of loads, PV, grid and MFPC (Grid-SM).

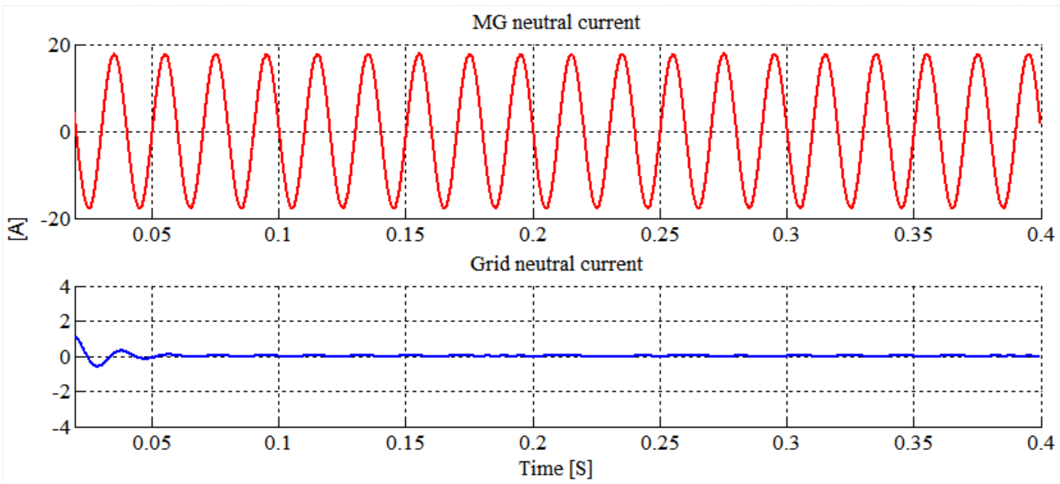


Figure 5.10 Neutral currents of the grid and MG (Grid-SM).

5.4 MFPC for MGs Voltage Quality Improvement

As illustrated in the previous cases MFPC makes the MG "grid friendly" by compensating negative and zero sequence currents. This case study is to investigate more advantages of MFPC control strategy, mainly for voltage quality improvements at PCC. As already shown in Figure 5.1 assuming that our MG is connected to LV network by a cable with impedance (0.1284 + j0.0166) Ω, (see Appendix D) for more details. Table 5.4 shows that the MG is highly unbalanced with generation and loads. It can be seen that the PV inverters are installed in phases A and C with no generation in phase B which is highly loaded. Percentage of Voltage Unbalance Factor (% VUF) is used to evaluate the unbalanced degree, as already described in chapter 1, equation (1-1).

Table 5.4 Simulation parameters of voltage quality improvement.

Phase	**Phase (A)**	**Phase (B)**	**Phase (C)**
Load (kW)	1	8	2
Load (kVAR)	2	0	4
PV	6	0	7
MFPC control			
Idle mode with unbalanced and reactive power compensation			

Figure 5.11 shows the voltage at PCC without compensation, it can be seen the voltage is low in phase B and high in phases A and C, as expected because the generation rises the voltage and consumption drops the voltage at PCC. In Figure 5.12 the % VUF (-) is equal to 1.2 % without compensation. Figure 5.13 shows the grid current waveforms are unbalanced without connecting the MFPC, as a result the voltage will be unsymmetrical as previously described.

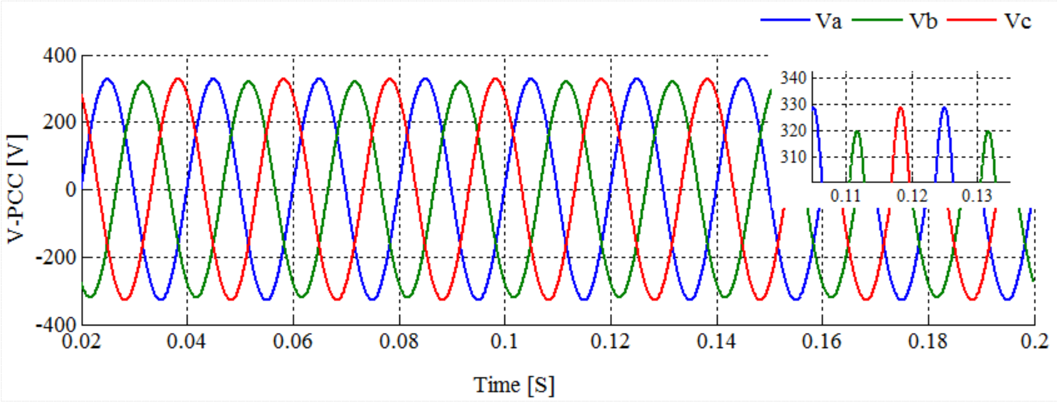


Figure 5.11 Voltage waveforms at PCC, without compensation.

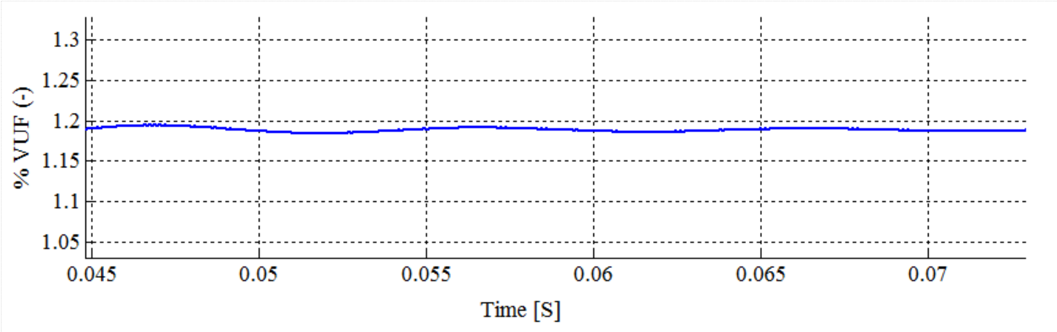


Figure 5.12 % VUF (-) without compensation.

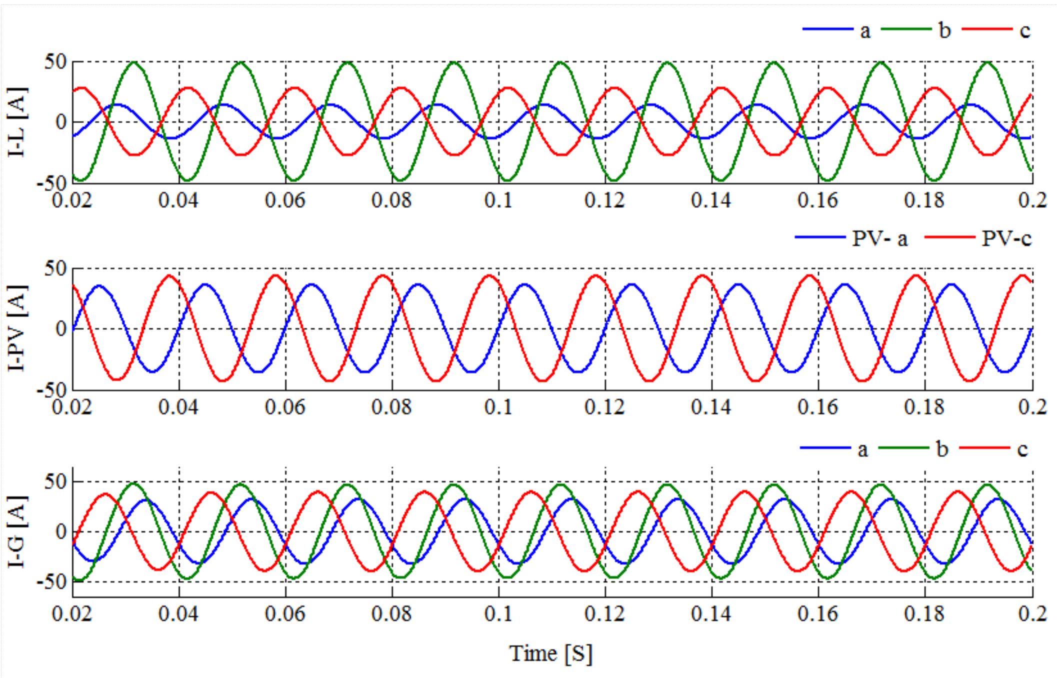


Figure 5.13 Current waveforms of loads, PV and the grid, without compensation.

As shown in Figure 5.14, it is interesting to observe that the voltages at PCC are balanced and the % VUF equal to zero as shown in Figure 5.15.

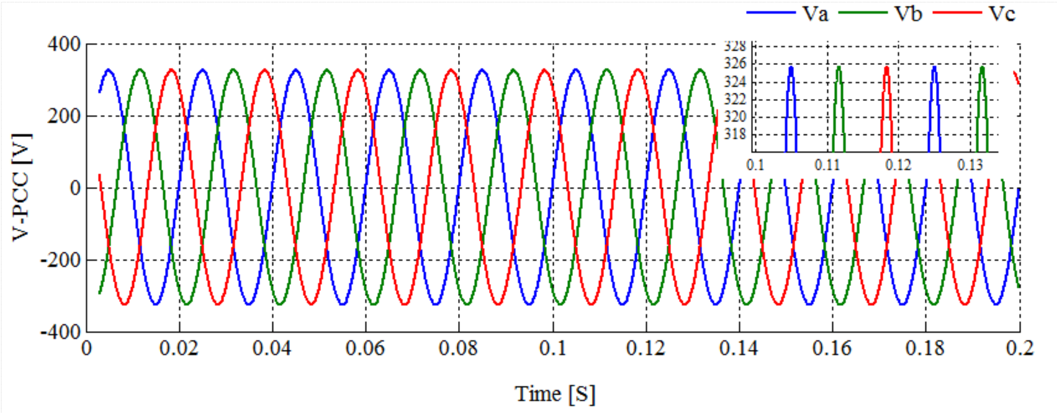


Figure 5.14 Voltage waveforms at PCC, with compensation.

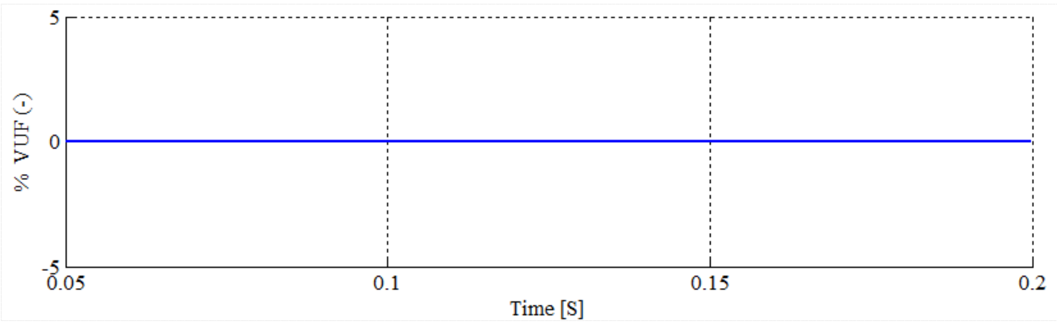


Figure 5.15 % VUF (-) with compensation.

Figure 5.16 shows that, the compensation is well done by MFPC; the grid currents are perfectly balanced with connecting MFPC with unbalanced waveforms for loads, PV and MFPC. As already discussed in previous simulation cases, MFPC can distribute power between phases and inject only balanced currents to the grid. In Figure 5.17 the grid side neutral current is zero, as expected because the grid currents are balanced.

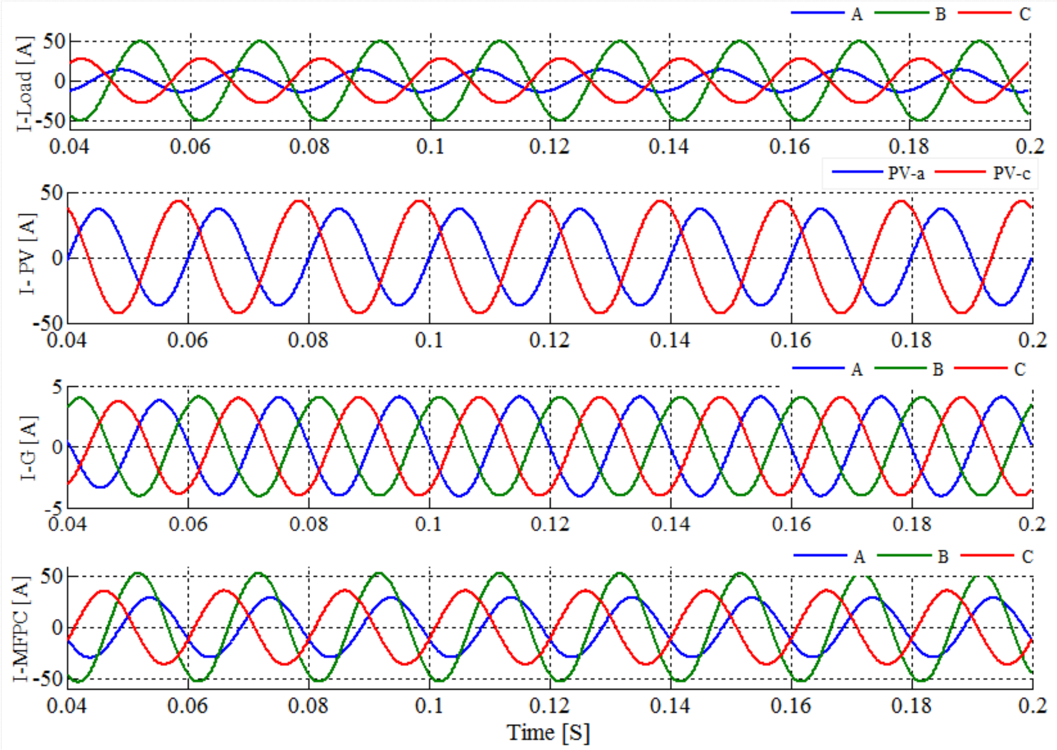


Figure 5.16 Current waveforms of the loads; PV; grid and MFPC with compensation.

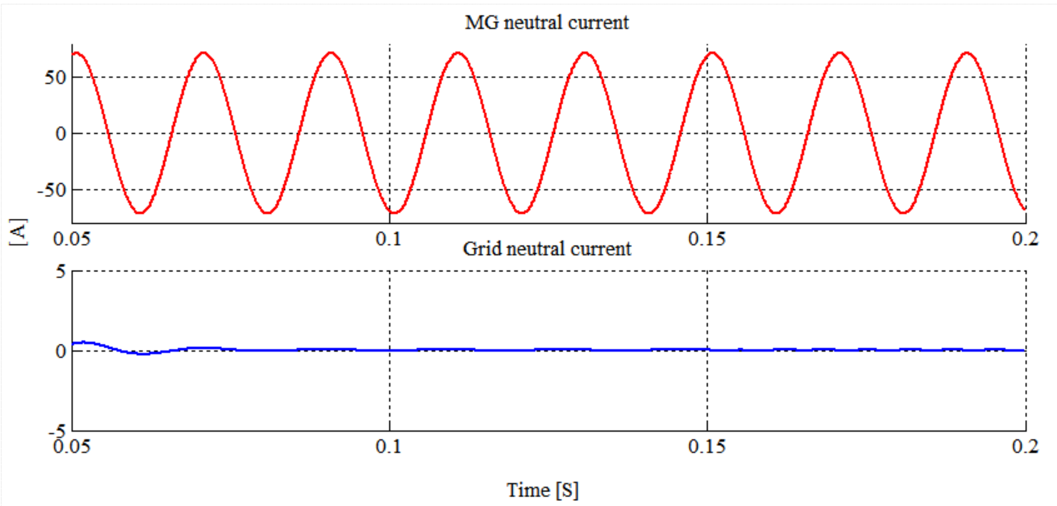


Figure 5.17 Neutral current of MG and the grid with compensation.

As mentioned before MFPC is working in idle mode, therefore (positive active power is zero). As shown in Figure 5.18, the excess power from PV (2 kW) after distributing PV generated power between phases is injecting to the grid. Reactive power is fully compensated by MFPC, as shown in Figure 5.19.

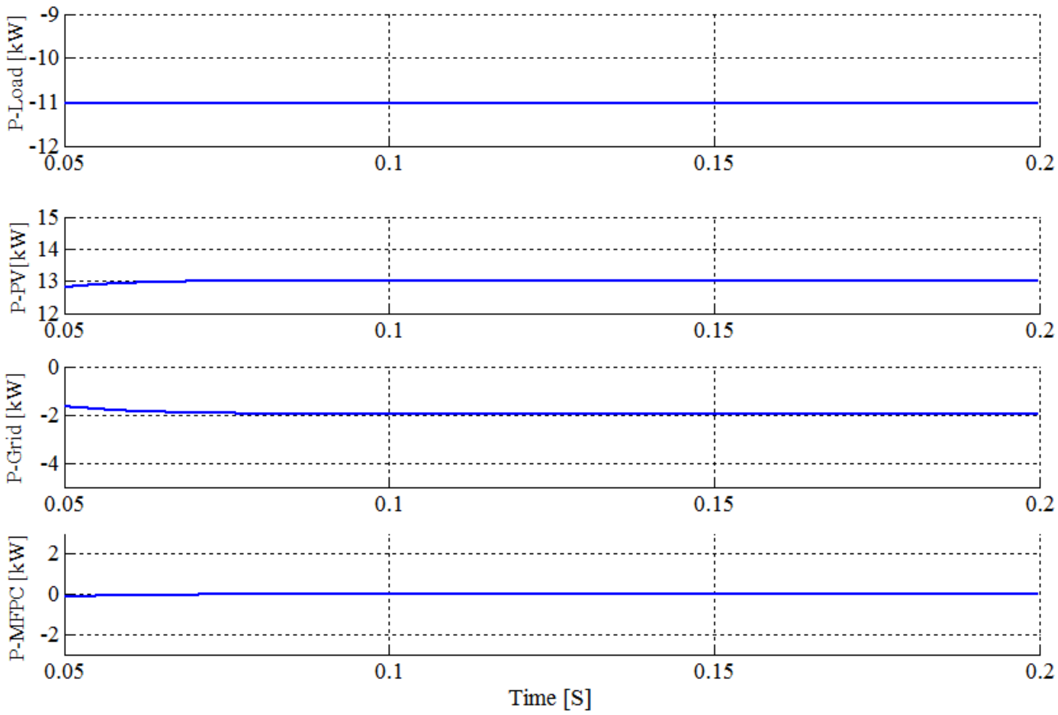


Figure 5.18 Positive sequence active power of the loads; PV; grid and MFPC.

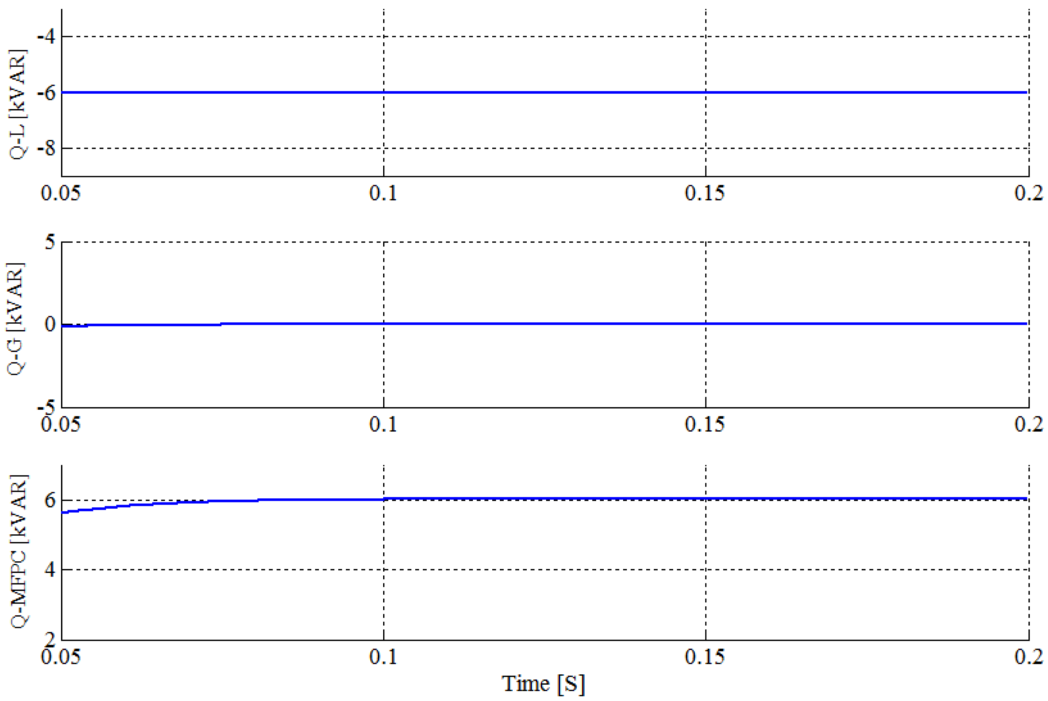


Figure 5.19 Positive sequence reactive power of the loads; grid and MFPC.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

Power converters with ESSs can be adopted to mitigate the negative effects of unbalanced grid connected MGs, however, they require suitable control strategies. In this thesis a control strategy for 4L3P inverter, based on vector control and symmetrical components is proposed to obtain grid friendly MGs under unbalanced operating conditions.

A brief introduction could help to understand different issues related to this kind of systems, is provided in chapter 1, discussing in general the EPSs, DG, MGs, SG and the imbalance with symmetrical components.

system components are required to be discussed in detail to fulfill deep understanding of the idea. For example, in chapter 2, the power conversion technology, power devices, power converters topologies, modulation strategy for three legs and four legs converters, LCL filter design and its transfer function and PLLs have been discussed.

Power sources and ESSs have been discussed briefly in chapter 3 to help in understanding a complete idea regarding the topic. For example, it is essential to know PV-inverters configurations and characteristics of batteries, because they have been used in this project.

In chapter 4, because of this research is focusing in MGs, it is important to investigate MGs power converters classifications, VSIs operating regions, and control of power converters in MGs.

A control strategy is proposed to obtain MFPC for unbalanced and reactive power compensation with grid supporting functions. The simulation case studies of

MFPC have been done for different operating modes; charging, discharging and idle mode. The idle mode can be used in case of ESBs regulations. Moreover MFPC control strategy provides a solution for unbalanced PV-inverters and loads in MGs by distributing the power between phases and injecting only the balanced currents to the grid. As a consequence the PV-penetration level can be increased.

In chapter 5 Simulation results for different cases and conditions, including reactive power compensation, unbalanced loads, grid supporting, MG supporting and voltage quality improvements have been presented to support the validity of proposed control strategy for mitigation the negative effects of grid connected MGs. to obtain “grid friendly” MGs even it is working under highly unbalanced and poor power factor conditions.

6.2 Future work

DC bus analysis and DC-DC converter control, represents an interesting future work for MFPC, because such unbalanced currents on the AC side inevitably leads to DC link voltage ripple or differential mode ripple in the DC bus [29], which needs more analysis and solutions to be discussed.

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APPENDIX A Mathematical Transformation

Stationary Reference Frame [91]

Three phase currents and voltages, can be transformed to stationary reference frame, in order to avoid coupled AC currents and voltages. Therefore voltage and current can be transformed from abc to α-β as follows:

$$\begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad (A-1)$$

Where X donates either current or voltage, By inverting the coefficient matrix the *abc* quantities can be found from α-β .

Synchronous Rotating Frame dq [92]

The transformation is made by using the Park transformation as shown in Equation A-2, where the stationary quantities can be found as a function of the synchronous quantities by inverting the coefficient matrix.

the dq0 (Park) components are deduced from αβ0 (Clarke) components as follows:

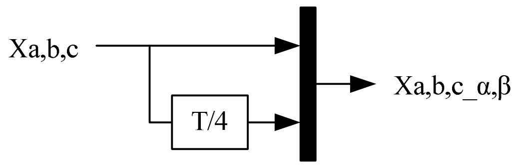
$$\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} \qquad (A-2)$$

The inverse transformation is given by

$$\begin{bmatrix} X_\alpha \\ X_\beta \\ X_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X_d \\ X_q \\ X_0 \end{bmatrix} \qquad (A-3)$$

Where θ is instantaneous phase angle, by this transformation, *dq* quantities are DC

APPENDIX B Sequence Decomposition/Composition



$$T = \frac{1}{f} = \frac{1}{50} = 0.02s$$

Figure B-1 Delay block [89].

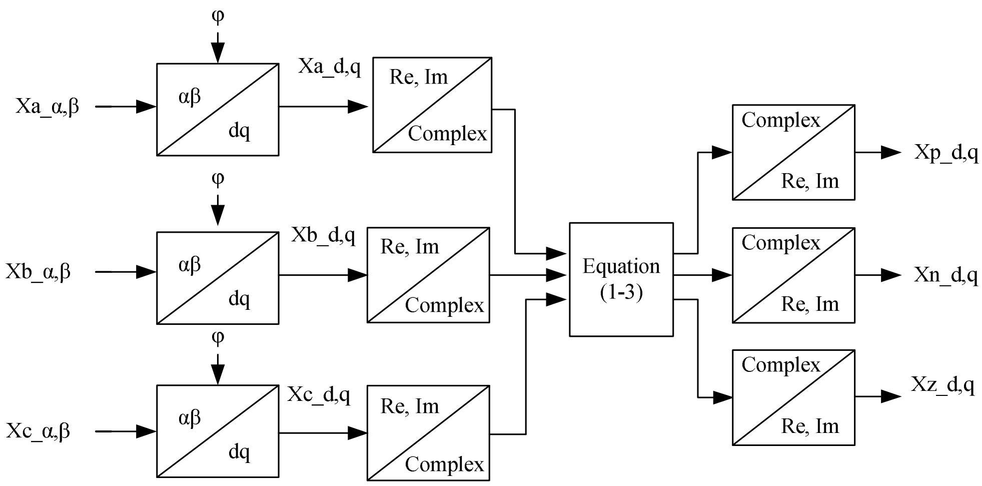


Figure B-2 Decomposition block [21]

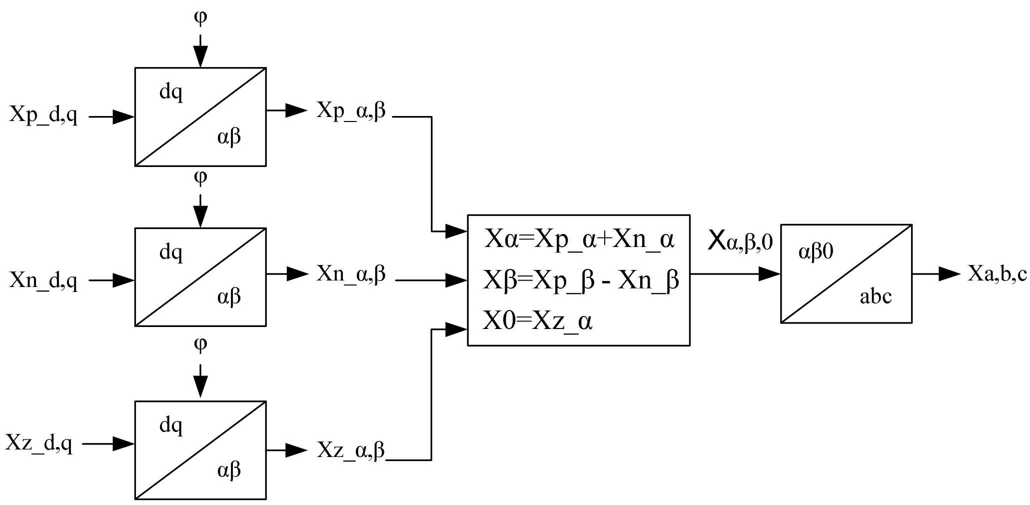


Figure B-3 Composition block [21]

Note: X, donates either current or voltage with unbalanced three quantities, as previously described in Figure 4.8. This technique is used for, unbalanced currents (I-U) and MFPC currents (I-MFPC).

APPENDIX C Simulink Diagram

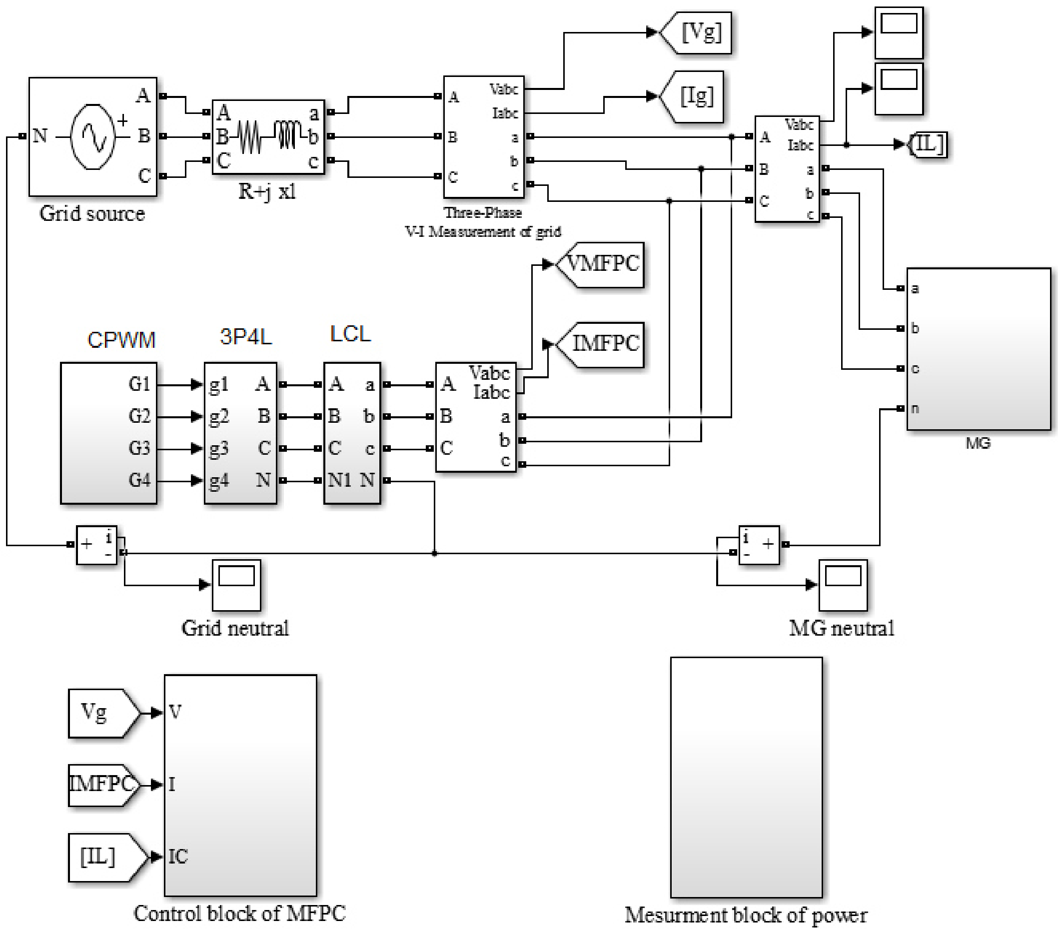


Figure C-3 Simulink model diagram.

APPENDIX D Line parameters

Table D-1 shows typical line parameters for LV and MV (Medium Voltage) [93].

Table D-1 Line parameters for different networks

Network type	R (Ω/km)	X(Ω/km)	R/X
LV	0.642	0.083	7.7
MV	0.161	0.190	0.85