



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY



AFRICAN CENTER OF
EXCELLENCE IN ENERGY FOR
SUSTAINABLE DEVELOPMENT

TOTAL ELIMINATION OF HARMONICS IN GRID-CONNECTED SOLAR ENERGY

By

MANISHIMWE Benedicte

Reg. N.0:220012106

A Thesis Submitted to the African Centre of Excellence in Energy for
Sustainable Development, College of Science and Technology (CST), University of Rwanda.

In Partial Fulfilment of the Requirement

For the Degree of Masters of Science

in

Renewable Energy Engineering

Supervisor: **Dr. Peter Moses Musau**

October 2022

Kigali-Rwanda.

DECLARATION

I, MANISHIMWE Benedicte declare that this thesis is my original work, and it has not been submitted for a degree at University of Rwanda or any other university. All sources of information utilized in the work have been properly acknowledge in academic format.

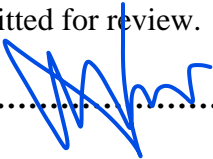
MANISHIMWE Benedicte

Signature

Submission Date:

With my approval as a university advisor, this thesis proposal has been submitted for review.

Dr. Peter Moses Musau Musyoki

.....


09-10-23

Thesis Advisor

Signature

DEDICATION

To My Family, and Friends, May God Bless you for your support to me during the studies period.

ACKNOWLEDGEMENTS

I would like to begin by thanking the Almighty God who has been my help and the source of my strength throughout the duration of my studies. I would like to express my sincere gratitude to my supervisor Dr. Musau Peter Moses for guidance, encouragement, and support throughout the course of this work. It was an invaluable learning experience for me to be one of their students. From them I have gained not only extensive knowledge, but also a careful research attitude. I express my gratitude to African Center of Excellence in Energy for Sustainable Development (ACE-ESD) staff for their commitment to make possible to study during world's pandemic crisis, COVID-19 and we finished the course work on time. My thanks are extended to my colleagues in cohort 3 who shown their contribution to build the friendly academic area at ACE-ESD.

ABSTRACT

Different technologies to harvest solar energy worldwide are being exploited as the sun supply about 1.8×10^{11} MW per year. The Photovoltaic (PV) distributed generators give a sustainable promise to the reliable electrical supply due to their environment-friendly character. IEEE 519-1992 and IEEE 1547-2003 must be fulfilled to integrate DRs into the grid. However, the power electronics devices (PEDs), converters are to connect the photovoltaic grid-connected systems to the power network and to regulate the voltage and frequency output of PV panels that might change due to the weather variation, are the harmonics producers in the electrical power system. Maximum Power Point Techniques impact the harmonics in PV grid-connected system; P&O algorithm is used to extract the maximum power output from PV array. The Hybrid Active Power Filters (HAPFs) with different control strategies of Active Power Filter to eliminate the harmonics in PV distributed generators connected to the grid but the authors considered the grid voltages as balanced, this makes the implementation of this control strategies quite difficult. The proposed control strategies of Modified p-q theory PLL circuit controls the active power filter of HAPF designed in this work reduces THD from 30.65% to 1.58% in MATLAB/Simulink.

Keywords: Harmonics, IEEE 519-1992 standards, IEEE 1547-2003 standard, Total Harmonics Distortion (THD), Hybrid Active Power filters (HAPFs), Pulse Width Modulation (PWM), modified p-q theory.

CONTENTS

DEDICATION	iii
ACKNOWLEDGEMENTS	iv
ABSTRACT	v
LIST OF FIGURES	viii
LIST OF TABLES	ix
LIST OF ABBREVIATIONS	x
CHAPTER 1. INTRODUCTION.....	1
1.1 Background	1
1.2 Problem Statement.....	1
1.3 Objectives.....	2
1.3.1 Main Objective	2
1.3.2 Specific Objectives:.....	2
1.4 Research Questions	2
1.5 Justification	2
1.6 Scope	2
1.7 Published Papers.....	3
1.8 Conceptual Framework	3
1.9 Proposal Organization	3
CHAPTER 2. LITTEATURE REVIEW	5
2.1 Introduction	5
2.2 Review on Harmonics in PV Grid-Connected System.....	5
2.3 IEEE 519-1992 Standard.....	6
2.4 IEEE 1547-2003 Standard.....	7
2.5 Pulse Width Modulation (PWM).....	8
2.6 Filters in Power System.....	9
2.6.1 Passive Filters.....	9
2.6.2 Active Power Filters	10
2.7 Literature Review on Power Filters in PV Grid – Connected	13
2.8 Problem Formulation.....	21
2.8.1 Problem Description.....	21
2.8.2 System Modelling.....	21
2.9 Chapter Conclusion	27

CHAPTER 3. METHODOLOGY.....	28
3.1 Introduction	28
3.2 Previous Methodologies	28
3.3 Methodology Approach.....	29
3.4 Proposed Methodology.....	29
3.4.1 DC Voltage Regulator for MPPT	29
3.4.2 Modified p-q Theory for SAPF	33
3.5 Simulation Tool: MATLAB/Simulink	35
3.6 Mapping the Methodology to the Problem.....	36
3.7 Chapter Conclusion	36
CHAPTER 4. RESULTS AND ANALYSIS	37
4.1 Introduction	37
4.2 Potential Photovoltaic Power in Rwanda	37
4.3 The proposed system modelling.	38
4.4 Result and Discussion.....	41
4.4.1 PV Maximum Power	41
4.4.2 Total Harmonic Distortion.....	42
4.5 Validation	44
4.6 Chapter Conclusion	45
CHAPTER 5. CONCLUSION AND RECOMMENDATION	46
5.1 Conclusion.....	46
5.2 Contribution.....	47
5.3 Future Work	47
REFERENCES.....	48
APPENDIX I: PUBLISHED PAPER.....	51
APPENDIX II: MATLAB FUNCTION OF CLARK'S TRANSFORMATION (ABC TO AB0) AXIS.....	55
APPENDIX III: MATLAB FUNCTION FOR PSO ALGORITHM	55
APPENDIX IV: MATLAB FUNCTION FOR P&O ALGORITHM	60

LIST OF FIGURES

Figure 1.1 Conceptual Framework of PV-HAPF	3
Figure 2.1 Passive Filters [16]	10
Figure 2.2 Classification of Active Power Filter	12
Figure 2.3 Hybrid Active Power Filters.....	13
Figure 2.4 PV-HAPF grid-connected System.....	21
Figure 2.5 PV Cell Equivalent Circuit [31]	22
Figure 2.6 MPPT Curve in Solar System [33].....	23
Figure 2.7 Electrical Circuit of Boost Converter [35]	23
Figure 2.8 Shunt Active Power Filter (SAPF) [16]	24
Figure 2.9 Equivalent Circuit of LCL Filter	25
Figure 3.1 P&O Algorithm for MPPT	30
Figure 3.2 PSO Algorithm for MPPT	32
Figure 3.3 PI Controller for VDC Regulator	33
Figure 3.4 Fundamental Circuit of Phase-Locked Loop.....	35
Figure 3.5 Modified P-Q Theory	35
Figure 4.1 Global horizontal irradiation map of Rwanda by 2018	37
Figure 4.2 Proposed Design	38
Figure 4.3 Voltage Source Converter	38
Figure 4.4 Design of P&O for PV MPPT in MATLAB	39
Figure 4.5 Design of PSO for PV MPPT in MATLAB	40
Figure 4.6. Maximum Power Point P&O Algorithm.....	41
Figure 4.7 Maximum Power Point using PSO Algorithm	41
Figure 4.8 Waveforms of Currents and Voltages at PCC when the p-q theory is applied	42
Figure 4.9 Distorted Source Voltages waveform.....	42
Figure 4.10 Output currents from the HAPF	43
Figure 4.11 Output Filter Current when the Basic p-q Theory is Applied	43
Figure 4.12 Output Filter Current when the Modified p-q Theory is applied	44
Figure 4.13. Grid Voltage distorted	45

LIST OF TABLES

Table 2.1 Voltage distortion limits at PCC according IEEE 519-1992 Standard [7]	6
Table 2.2 Current Distortion Limits for Distortion Systems (120V - 69kV).....	7
Table 2.3. Clearing Times for Abnormal Voltages [8].....	8
Table 2.4 Clearing Times for Abnormal Frequencies [9].....	8
Table 2.5 Summary review on the power filters in PV grid-connected system	17
Table 3.1 Mapping Table	36
Table 4.1 Boost Converter's Parameter.....	39
Table 4.2 HAPF Parameters	40
Table 4.3. Comparison of THD for Different Filters.....	44

LIST OF ABBREVIATIONS

AC: Alternative Current

APF: Active Power Filter

CSC: Current Source Converter

CSI: Current Source Inverter

DC: Direct Current

PCC: Point of Common Coupling

PEDs: Power Electronic Devices

PFs: Passive Filters

PI: Proportional Integral

PSO: Particles Swarm Optimization

PV: Photovoltaic

PWM: Pulse Width Modulation

SAPF: Shunt Active Power Filter

SeAPF: Series Active Power Filter

Shunt PFs: Shunt Passive Filters

TDD: Total Demand Distortion

THD: Total Harmonic Distortion

VSC: Voltage Source Converter

VSI: Voltage Source Inverter

CHAPTER 1. INTRODUCTION

1.1 Background

The electricity from renewable energy sources had been growing exponentially over the last two decades due to their environment-friendly characteristic and the focus on mitigation of climate change caused by greenhouse gas emissions. The power from hydro-power plants is used to be less than the power demand. Solar energy in alternative renewable energy is harvested worldwide using different technologies as the sun supply about 1.8×10^{11} MW per year; this is greater than world energy demand [1]. The most used to harvest solar energy is Photovoltaic (PV) conversion; the photovoltaic cells convert the conversion of the solar energy into electrical energy. Photovoltaic technologies market-focused firstly on the stand-alone (off-grid), then the grid-connected solar emerged in the last decade; the pilot projects of grid-connected solar energy are launched with their successful, different finance institutions finance the solar power plant's projects [2] [3] [4]. The increase in energy demand and environment-friendly character of renewable energy sources will be accelerated the integration of solar or wind energy generators into the electrical grid. The power electronics devices (PED) are used and different standards for power quality are followed to connect the renewable energy to the grid. Especially for solar energy; IEEE 519-1992 for harmonic limitation.

1.2 Problem Statement

The output of Photovoltaic (PV) panels is Direct Current (DC) but not constant; the power electronics devices (PEDs), the boost converters, and inverters are used to convert the output voltages of PV panels from DC into AC voltage which was an acceptable voltage by the grid, respectively. The inverters in PV grid-connected systems have the ability to filter the harmonics and compensate for the reactive power as active power filters do. However, weather variations, unbalanced grid voltages, and switching frequency decreased the filtering performance of inverters, this led to the harmonics in the output current of inverters in PV grid-connected system. Current harmonics caused heat and power losses in transmission lines and different devices in power networks; mainly the poor power quality of the grid was caused by the harmonics, the voltage sag, frequency disorder, etc. The mitigation of total harmonic distortion techniques in the grid-connected solar system are vital for power supply.

1.3 Objectives

1.3.1 Main Objective

This thesis aimed to eliminate the harmonics in PV grid-connected system using the hybrid power active filter (HAPF) with modified p-q theory control method.

1.3.2 Specific Objectives:

- i) Review the works related to eliminate the harmonics in PV grid-connected system using active power filter.
- ii) Design HPAFs to eliminate all harmonics.
- iii) Determine the impedance ratio of capacitor and inductor which gives the THDi is less than 5%.
- iv) To eliminate harmonics in PV grid-connected system with non-linear loads.

1.4 Research Questions

The following questions have been based on to meet the given objectives.

- i) Is it possible to eliminate the harmonics in grid-connected solar systems?
- ii) What are the deficiencies in the present designs?
- iii) Which standards concerning the harmonic limitation in the power system?
- iv) What is the percentage of Total Current Harmonic Distortion tolerance (THDi) of a solar power supply system?

1.5 Justification

The advancement of renewable energy integration into the grid as the distributed generation has provided sustainable energy sources with a disruption that degraded the power quality of the energy supply. Many studies had been carried out. The expected result of this thesis would be used in the design of PV-HAPF grid-connected systems to meet IEEE standards of power quality, IEEE 519-1992 and IEEE 1547-2003 Standards for the security and stability of the grid.

1.6 Scope

Almost PV systems are connected to point common coupling with loads at voltage rate of low or medium level. This work would give a technique method to mitigate the current harmonics injected non-linear loads into grid using hybrid active filters. The proposed design will be simulated in the environment MATLAB/Simulink to verify IEEE Standards (IEEE 519-1992 and IEEE 1547-2003).

1.7 Published Papers

The paper entitled “Design of Hybrid Active Power Filters (HAPFs) for Grid-Connected Photovoltaic Systems Using Modified p-q theory” was presented during 2022 IEEE PES/IAS Power Africa Conference, held 22th -26th August 2022 at Kigali, Rwanda.

1.8 Conceptual Framework

The Conceptual Framework depicted in Figure 1.1. The previous works on Active Power Filters in PV-GC system, the passive filters in PV-GC system, and the Hybrid Active Power Filters in PV-GC system are also reviewed. After modelling each component of the PV-HAPF system, a modified p-q theory control approach was used to control the APF. The proposed design was verified using a MATLAB/Simulink simulation.

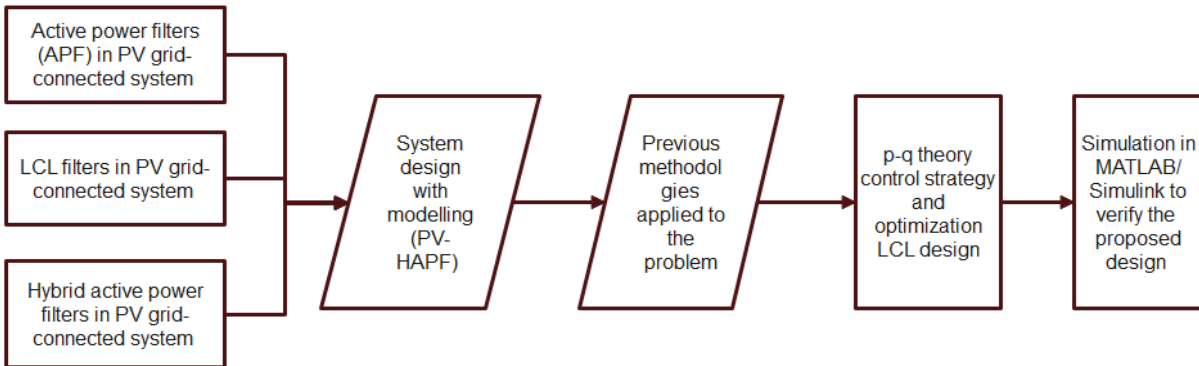


Figure 1.1 Conceptual Framework of PV-HAPF

1.9 Proposal Organization

The thesis is organized as follow:

Chapter 1 contains the background of the Photovoltaic grid-connected system (PV-GC), the current harmonic ‘s problem in the grid caused by the PV inverters, the main objective is the total elimination of harmonics using HPAFs and PWM controller in PV-GC, and, the validation of IEEE standards and simulation in MATLAB/Simulink is chosen as the scope of this project.

Chapter 2 focuses on the recap of harmonic in the grid, IEEE 519 and 1547standards, and PW control. Then the literature review on previous researches on power filters in PV grid-connected system. The research gaps had been highlighted in this chapter then the problem design is sorted out.

Chapter 3 details the method to collect the data, the previous technical methodologies applied to the problem, the new methodology was proposed in this chapter.

Chapter 4 contains the simulation and discussion of the proposed design of the hybrid active power filter.

Chapter 5 concludes this thesis along with the future work.

CHAPTER 2. LITTEATURE REVIEW

2.1 Introduction

Chapter2 covered the recaps of the harmonics on power systems, IEEE 519-1992 standards, the inverters with their topologies in PV grid connected system, and pulse width modulation (PWM). The review on previous research for power filters in PV grid-connected system with its highlighted gaps will be done in this chapter. From the gaps found in previous works on the power filters in PV grid-connected system, the proposed design was formulated which ended this chapter.

2.2 Review on Harmonics in PV Grid-Connected System

Harmonics are defined according to IEEE 519-1992 standards, the voltage or current distorted waveforms in power system. In perfect power system, the pure sinusoidal voltage received by the load, then the resulting currents are the pure sine waves. However, the power system is not pure sinusoidal practically, so voltage and current waveforms are distorted, their frequencies are multiples of the power system's fundamental frequency. The nonlinear loads connected to the electrical power system are principal producers of harmonics. The sources of harmonics include power electronics equipment, frequency converters, and rectifiers. Solar power converters convert DC output power to AC power and they are the interface units between the photovoltaic system and the grid but they inject the current harmonics into electrical power system. The current distortion causes electrical equipment to overheat and lose efficiency, among other things.

In [5], the authors detailed the types of harmonics found in PV inverters, they are in three categories:

- i) DC link voltage harmonics are produced by the change in output voltage from the PV modules known as DC link voltage. DC link ripples are responsible of the odd harmonics in the output current of inverters connected to PV system.
- ii) Grid voltage harmonics: the voltage grid contains the harmonics, and the harmonics injected into PV inverters are too low to be removed by filters. The amplitude of output current harmonics is increased by using this voltage grid.
- iii) Switching harmonics caused by the pulse width modulation (PWM).

There is a harmonic limitation as stated in standards and regulations such as IEEE 519-1992, ANSIC82.11, ANSI C82.14, and EN50160 to integrate the PV system to the grid, so the injected currents to the grid

have the waveform which is nearly to the pure sinusoidal form. Harmonics should not exceed 5% in medium voltage (MV) or low voltage (LV) networks, according to IEEE 519-1992 standards [6].

2.3 IEEE 519-1992 Standard

For electrical supply sustainability, IEEE standards 519-1992, commonly known as IEEE 519 standards, specified voltage and current harmonics limits based on the voltage at PCC and the grid's short-circuit current level, respectively [7], IEEE 519 gives the current harmonics limits of each electrical consumer and the voltage harmonics provided by the utilities. When the voltage at the PCC is less than 69kV, the electrical supply is defined as voltage harmonics with a 5 percent restriction, according to IEEE 519 guidelines. Table 2.1 showed the overall voltage harmonic and individual voltage harmonics based on the voltage rate at point common coupling (PCC). For the medium voltage level, 69kV, the individual voltage distortion is less than 3%, and total harmonic distortion is less than 5%. The THDv decreases as the bus voltage increases and the capacity increases.

Table 2.1 Voltage distortion limits at PCC according IEEE 519-1992 Standard [7]

Bus Voltage at PCC (kV)	Individual Voltage Distortion (%)	Total Voltage Harmonic Distortion (THD %)
Below 69	3	5
69 to 161	1.5	2.5
Above 161	1	1.5

According to ISC/IL ratio as shown in Table 2.2, the current harmonics distortion injected by nonlinear loads (TV, computer, etc) acceptable by the grid are limited by the IEEE 519-1992 standard. In most cases, the PV-GC are located in medium or low voltage transmission lines, $ISC / IL < 20$. Individual harmonics for the first eleven harmonics should be less than 4%, and for the highest harmonics (23-35h), the individual harmonics should be less than 0.6 percent. In Table 0.2, ISC is the Short-Circuit Current at PCC, IL is the maximum load demand current, and TDD is the total demand distortion. The even harmonics are about 25% of the odd harmonics, so they are not considered to affect the electrical power system.

Table 2.2 Current Distortion Limits for Distortion Systems (120V - 69kV)

Maximum Harmonics Current in Percent of IL						
Individual harmonic order (Odd harmonics)						
ISC/IL	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.6	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
* All power generation is limited to these values of current distortion, regardless of actual ISC/IL.						

2.4 IEEE 1547-2003 Standard

Standard IEEE 1547 called “the IEEE standard for interconnecting DERS to electrical power system, 2003”. IEEE 1547 focus on voltage and frequency requirement to connect DGs and DERs to PCC. The clearing time of abnormal voltage is adjustable shown in Table 2.3 [8]. Regarding frequency, the small systems (≤ 30 kW) have the same clearing time for over- and under-frequency. There are two under frequency trips allowed for systems more than 30 kW: one fixed at 57 Hz that has 0.16s to trip, and other is variable between 0.16s and 0.300s. The other configurable over the frequency ranges specified in Table 2.4 [9] [10] [11].

Table 2.3. Clearing Times for Abnormal Voltages [8]

Voltage range (per unit of base voltage ^a)	Clearing time(s) ^b
> 1.2	0.16
1.1-1.2	1
0.88 – 1.1	No requirement
0.5 – 0.88	2
< 0.5	0.16

The index a is base voltage calculated using the values from ANS C84.1 – 1995 as shown in Table 2.4. The index b is the maximum clearing time for DER less than 30 kW, and default clearing time for DER more than 30 kW.

Table 2.4 Clearing Times for Abnormal Frequencies [9]

DER Rating(kW)	Frequency (Hz)	Clearing time (s)
DER ≤ 30kW	> 60.5	0.16
	< 59.3	0.16
DER > 30kW	> 60.5	0.16
	< {57 – 59.8} (adjustable set point)	{0.16 – 300} (adjustable)
	< 57.0	0.16

2.5 Pulse Width Modulation (PWM)

PWM (pulse width modulation) is a technique for changing the width of a signal in a small proportional signal. The wider the control voltage, the more rectangular the output pulse becomes, which fluctuates depending on the average. Pulse width modulation (PWM), sinusoidal pulse width modulation (SPWM), and space vector pulse width modulation (SVPWM) are all PWM algorithms used in PV inverters [11]. The output voltage of three-phase VSI with low-order harmonics was controlled using SPWM and SVPWM approaches in refs [12] and [13]. SPWM is a rather simple and straightforward method. To adjust

the breadth of the output pulse waveform, this approach modifies the voltage amplitude and frequency to produce a sinusoidal waveform. Changing the signal's amplitude and frequency affects the pulse width. The sinusoidal output. If the switching frequency is increased, the output sinusoidal waves will be improved. When the sine waveform encounters the high-frequency triangle waveform, the switching state changes. The comparison of three-phase sinusoidal voltages (V_a , V_b , V_c) that are 120 degrees out of phase with the reference signal is used to perform SPWM in 3-phase VSI.

For a three-phase VSI, there are eight distinct switching patterns, each of which determines a voltage space vector [14]. The technique consisted of managing the current and the voltage source inverter utilizing controller in d-q frame, and the topologies give a good steady-state response with the extremely fast dynamic response, minimal current ripple, and highly sinusoidal waveform. The output voltage does not compare to any reference in Hysteresis PWM approaches, but it oscillates within the error band, known as the "Hysteresis band." The inverter output voltage does not saturate at the reference signal because the inverter output will constantly follow the route of the reference band. Switching losses are larger in this strategy than in the previous two. PWM with a hysteresis band is a VSC instantaneous feedback current controller in which the output current follows the real command current within a present hysteresis band. [14] and [15] opted to use Sinusoidal PWM in 3-phase Voltage Source Inverters (VSI) because it has a high output voltage efficiency with minimal harmonics that may be filtered using passive filters.

2.6 Filters in Power System

The harmonics in power system are cancelled or reduced through the power filters that are in three categories which are passive filters, active power filters, and hybrid active filters. These are discussed in subsections 2.6.1 and 2.6.2.

2.6.1 Passive Filters

The passive filters are to mitigate harmonics since at least four decades ago because they are simple to design, at low cost, reliable and used in hybrid filtering technologies. Capacitor, inductor, and resistor are used in passive filtering; According to where the capacitor and resistor are placed, they are either low-pass or high-pass. The capacitor follows the resistor in high-pass filters and operates at a frequency higher than the cut-off frequency. The source is connected to the resistor and the capacitor is in the output part of the low-pass filter, which allows frequencies below the cut-off frequency to pass through. Different types of passive filters, including tunable, first-, second-, and third-order, are possible as shown in Figure

2.1 where PFs filters the harmonics injected by the load. Main drawback of passive filters is to create harmful resonance frequency in power system which causes the instability in the grid [16].

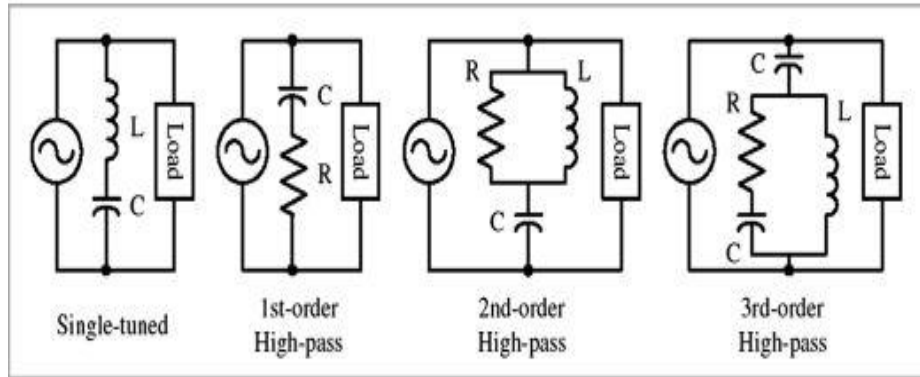


Figure 2.1 Passive Filters [16]

2.6.2 Active Power Filters

The active power filters mitigate the current harmonics in the power system by generating the compensated currents with the same amplitude, opposite direction of distorted current generated by the nonlinear loads. The inverters in photovoltaic (PV) system convert DC into AC, are connexion between PV system and the grid, and filter current harmonics presented into the grid and compensate the reactive power. Therefore, the inverters are considered as the active power filters [17].

Power electronics devices are the switches consist the inverters, for low voltage is MOSFETs, for medium and high voltage rate, the IGBTs switches are commonly used. The inverters are classified into three class; voltage source inverter (VSI) or voltage source converter (VSCs), current source inverter (CSI) or current source converter (CSCs), and Z source inverters (ZSI). VSI are most commonly utilized; the VSI is powered by DC voltage through capacitor. Meanwhile, CSI receives an adjustable current from a high-impedance DC voltage input source through inductance. VSI is better than CSI because of loss reduction, ease of control, reduced filtering requirements, and increased quality of its output voltage and current particularly in grid-connected systems. Authors in [18] proposed the three-phase inverters topologies: Three-phase inverters with stabilization, three-phase parallel inverters, three-phase three-wire inverters, three-phase four-wire inverters, three-phase five-wire inverters, three-phase six-wire inverters, and three-phase seven-wire inverters, diode-clamped multilevel inverter (DC-MLI), flying capacitor MLI(FC-MLI), cascade H-bridge MLI, three-phase inverter with stabilization, Three-phase parallel inverter. Then, the

authors of [19] added the number of stage in inverters' design (single stage or multi stage inverters), number of level, string and transformer (Transformer and transformer less inverters). The authors highlighted that the multilevel inverters and three-phase multi-string inverters are advantageous than other topologies as they give a high efficiency with pure sinusoidal waveform and minimum harmonic distortion because they have active filtering features.

The authors in [5] researched on PV grid-connected inverters, their working principles and their drawbacks which are harmonics with specifications according to the industrial inverters available on the market. In this work, the matrix formulation for each current control strategy was given. After the performance, the THD of the controllers under different conditions (steady, transient) is given.

The authors in [20] - [21] classified the Active Power Filters (AHFs) according to:

- i) Categories: Series, Shunt, or Hybrid.
- ii) A number of phases: Single- Phase and Three-Phase.

The authors in [22] and [23, 24] reviewed different technologies of the development of active power filters in order to mitigate the current harmonics in the grid and they detailed APF's structure: Series Active Power Filters (SeAPFs), Shunt Active Power Filters (SAPFs), and Hybrid Active Power Filters (HAPFs).

2.6.2.1 Shunt Active Power Filters (SAPFs) [25]

Shunt Active Power Filters (SAPFs) are most used Active Power Filters. A controllable voltage or current source constitutes a shunt APF. To accommodate greater currents, multiple shunt APFs can be connected in parallel, making this circuit appropriate for a wide range of power ratings. APFs generate the compensated currents that have the same amplitude but opposite direction with distorted currents to filter the harmonics caused by nonlinear loads.

2.6.2.2 Series Active Power Filters (SeAPFs) [26]

They are connected to power utilities by means of the transformer instead of inductor as in shunt active power filters do. Series APFs isolate the harmonics circulation between the non-linear loads and AC sources. Voltage harmonics (v_f) are injected across the interfacing transformer which filters third-order harmonics to keep the pure sinusoidal voltages across the nonlinear loads. Series APFs present resistor with high impedance for harmonic frequencies and with zero impedance for the fundamental component so the voltage or current harmonics can't flow AC source to the loads and vice versa. Series APFs deal mostly with load currents but this increases the power losses due the line's resistance of filters.

2.6.2.3 Hybrid Active Power Filters (HAPFs) [27]

Hybrid Active Power Filters (HAPFs) are combination of active power filters and passive filters; fast frequency for power electronic switches (IGBT or MOSEFT) used in the active power filters created switching noise that add the harmonics in the compensated source current. To level up the filtering characteristic of an active power filter, a passive filter is added in the circuit. The most passive filter used in HAPFs are LC and LCL filters. HAPFs have cost-effective benefits and more power quality improvement than passive power filters or active filters.

Figure 2.2 classified the Active Power Filters (APFs) where the hybrid filters which are the combination of Active Power filters (APFs) and Passive filters (PFs); they could both in series or in parallel, and Series and shunt vice versa.

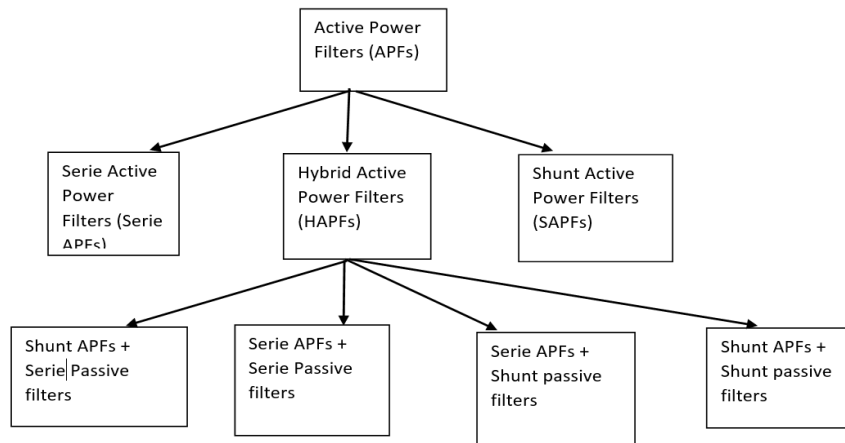


Figure 2.2 Classification of Active Power Filter

The most used hybrid active power filters are Shunt Active Power Filters + Shunt Passive Filters (SHAPF) and Series Active Power Filters + Shunt Passive Filters, they are illustrated in Figure 2.3.

i) Shunt Active Power Filters and Shunt Passive Filters (SHAPF): the filters are both connected parallel to the grid. The APF eliminate the high order harmonics while the low-order harmonics are filtered by the passive filter. Shunt passive filters are near to the main source.

ii) Series Active Power Filters and Shunt Passive Filters: Series APFs are series connected in to the grid by mains source through the transformer; they are harmonics isolator by forcing the current harmonics

from nonlinear loads to pass through shunt passive filters and offer high impedance to harmonics in power system.

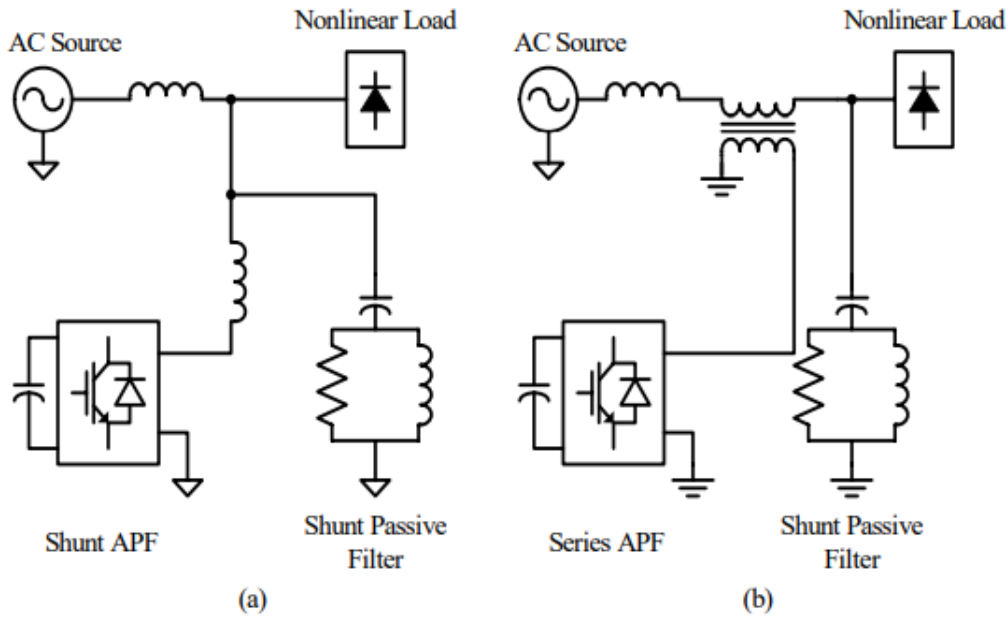


Figure 2.3 Hybrid Active Power Filters

In the next section focused on the literature review of filters used in PV-GC system in order to mitigate harmonics and to compensate the reactive power in a power system.

2.7 Literature Review on Power Filters in PV Grid – Connected

H. Kahlane, et al [14] worked on LCL filter design for Photovoltaic grid-connected system; LCL filters harmonics produced by the PV-inverters. In this work, the design procedure of LCL filters and m-file in MATLAB is written according to the formulas, the results give the LCL’s parameters where the bode diagram is range [0-50] db. **As mentioned in their work’s title LCL design for photovoltaic grid-connected systems, the authors didn’t interest to show the impact of solar radiation on the total harmonic distortion presence in PV inverters outputs.**

Moh. Jauhari et al [15] designed the control circuit using p-q theory for shunt active power filter in the photovoltaic grid-connected system. A three-phase VSC in PV system has abilities: to transfer the active power form PV array to electrical power network, to filter current harmonics and to compensate the reactive power. The p-q theory is applied to SAPF where it generates the compensated currents for current harmonics caused by nonlinear loads. To obtain the harmonic reference current to control SAPF, the p-q

Theory is applied currently. Without the PV arrays, SAPFs reduce from the current harmonics THD 27.22% to 1.05%, when PV array is connected, THD increases to 2.01%. **The authors didn't give any recommendations on how to reduce THD current when the SAPF injects the power from the PV system to the grid and the authors used the inductor coupling which make the PV system costly due to the needed of large size of the coupling inductor.**

Chandani M. Chovatia et al [18] designed SAPF of PV grid-connected system to improve the power quality. SAPF with VSI topology is used to mitigate the harmonics by following IEEE519 standards. To generate the signal gate of SAPF, a d-q control strategy is applied. To maintain THD under IEEE 519 - 1992 limit, the important items such switching frequency, current ripple should be optimizing at required level. Without the control of SAPF, the current harmonic level is about 27.32% which is decreased to 3.94% when the control of SAPF is applied. **However, there is harmonics of 5th, 7th, and 11th order which is above IEEE 519 standard as the presented inductor was for coupling instead to filter the low harmonics.**

Ayoub Benzahia et al [19] applied direct power control strategy for APF in their work to reduce current harmonics produced by the non-linear loads. This increased the power quality in PV-GC system. For MPPT method, the authors use the fuzzy logic technique. The simulation in MATLAB/Simulink show that the proposed methodology reduced THD is below 5%. **But in simulations, the authors didn't show the change of THD levels before the application of the methodology to certify the effective of their design and methodologies and also, they considered to filter the harmonics in outputs of inverters using RL filter which reduces more power injections from PV system because of Rf.**

Răzvan-Daniel Albu and Daniel Albu [20] worked on the Hybrid Active Power Filter connected to a solar power plant. The nonlinear loads cause current harmonics and consume more reactive power. The passive filter connected to PV-APF reduces the harmonics in the PV-APF outputs but this requires the large size which implies the cost. The improved pq theory is applied to SAPF to generate compensated currents and to allow the power transfer from the PV system to the grid. **This work doesn't present any electrical standard to follow, the control methodologies for the filters, this makes the simulations results not confirmed.**

In **Abdallah A. Smadi et al** [21], the authors aimed to reduce the harmonics in the distribution network using a solar power plant with Hybrid Active Power Filter. The HAPF controls circuit uses pq theory with hysteresis current controller, and P&O algorithm for the MPPT method. The usage of VSC as APFs in PV grid-connected systems allows the filtering of harmonics induced by nonlinear loads, the compensation of reactive power, and the power transfer from PV arrays to utility grids with THD currents below the IEEE 519-1992 limit. To eliminate the harmonics, present in the output current of VSC, self-tuned passive filters are interconnected with VSC and the power system, THD decreases from 20,2% to 3.21%. **The problem, the authors opt to overcome the drawback of LC at resonance frequency of VSCs.**

Rachid Belaidi et al [28] studied the Shunt Active Power Filter connected PV array. During sunlight, the P&O algorithm is utilized for the MPPT approach, and the PV arrays inject clean power into the grid, filter current harmonics in the power system, and adjust for reactive power. VSC ensures the filtering and reactive power correction capabilities when there is no solar insolation, DC sources supply the PV-APF. Synchronous reference frame (SRF) and carrier-based PWM are applied to produce the gate signal for APF. The simulation of the proposed system in MATLAB/Simulink shows a reduction on THD current from 32.31% to 2.87% when APF is applied. **However, the authors skipped the steps of PV arrays connected to DC-DC converters in Simulation and the use R_f in passive filter induced the power losses in PV system.**

Jihong Zhang and Hao Xue [29] designed the LCL filter for PV-inverters, they focused on reduction of total inductance of the filter. To reduce a total inductance for the filter according to the system's performance, the ratio between inductance branch and capacitance branch is elaborated of the power grid should be maintained. **This work didn't follow any standards for integrating RES into the grid, this makes the work suspicious even though the simulation works show a high improvement toward a pure sinusoidal wave when this method is applied, and moreover the design required the large size of total inductance as VSC had not the active filter capacities.**

T. Demirdelen, et al [30] worked on the SAPPF based on multilevel converters for large-scale solar energy system interconnection. In this paper, the P&O in MPPT method and the dq transformation for APF are applied. SAPF is coupled in series with LC filter turned to 5th and 7th order harmonic to form SHAPF. **The use of LC filters in large power applications makes the implementations of the proposed design quite difficult due to the resonance of LC filters with big nonlinear loads.**

Ayman Blorfan et al [31] used HAPF in their work titled "A Three-Phase Hybrid Active Power Filter with Photovoltaic Generation and Hysteresis Current Control". HAPF consisted of SAPF and Shunt high-pass PF, SAPF is connected to PV system. Detailed the theories to determine the reference current using either hysteresis current controller, or the extended p-q theory to generate current harmonics compensations. The performance of APF in their proposed configuration is improved the current harmonics from 30.09% to 1.95% and the switching frequency varied from 1kHz and higher to filter huge range of harmonics order. **PF used in this design doesn't require more calculation, the rest is to find its drawback compare to LCL filters.**

Xianyong Xu, et al [32] studied the control strategy of the inverters in photovoltaic generation grid-connected system. The proposed hybrid system mainly consisted of photovoltaic array, batteries, inverter, and passive filters. The maximum DC voltage of capacitor side of inverters was extracted using the MPPT algorithm, a recursive technique to calculate the reference current, PWM to regulate the VSC linked in shunt to the microgrid, and passive filters tuned 5th and 7th connected in shunt to the loads. PV grid-connected when there is enough solar insolation in this mode, the system ensures power supply, filtering harmonics, and reactive power compensation functionalities, and not connected PV system mode, the VSCs and PFs work as simple HAPFs to eliminate the reactive power compensation, and the DC link voltage is supplied by the grid. The impact of HAPFs in power systems is obvious when using PSIM6.0 to simulate. **The authors consider the voltage source as balanced which is not the case, the better is to consider also status of voltage source, and also the design of passive filters was not taken in count.**

B. Neelakanteshwar Rao et al [33] aimed in their work to mitigate the harmonics at point of common coupling when the PV power system is being integrated to the grid using SAPF with p-q theory. To validate the work, the authors simulated two cases; Case 1 is the PV -Inverter connected to nonlinear load only where the THD drops from 10.46% to 2.4%, and Case 2 is the PV grid-connected system, the VSI and Loads are the same as in Case 1 but for this case THD increases up to 4.14%. **This shows the existing harmonics in the grid even if the authors didn't consider that.**

Wajahat Ullah Tareen et al [34] highlighted the use of Inverters in renewables energies system as an active power filter to improve the power quality of electricity into grid; the harmonic's mitigation. In the MATLAB simulation, the THD meets the requirements of the renewable integration, IEEE-519 Standard. **However, in the simulation the authors didn't show the differences between the PV-grid connected system and the active power filter only, the integration of renewable energies is not well justified.**

Table 2.5 Summary review on the power filters in PV grid-connected system

Reference	Type of Filters	Objectives	The outcomes	The gaps to address
[14]	LCL	Design the LCL filters capable to eliminate the harmonics	To reduce the bonde diagram range to 0-50 dB	As mentioned in their work's title LCL design for photovoltaic grid-connected systems, the authors didn't interest to show the impact of solar radiation on the total harmonic distortion presence in PV inverters outputs.
[15]	SAPF	To achieve simultaneously current harmonic damping and reactive power compensation	The current THD is reduced from 32.31% to 2.87% when the proposed design is applied	The authors omit the PV array as input of DC-DC converter. The use Rf in passive filter induced the power losses in PV system.
[18]	Three-phase APF	To improve the power quality in power system, and same time delivery power from PV system and eliminate harmonics injected by nonlinear loads connected to the grid	SRF with FLC applied to APF reduce the harmonics to IEEE 519 standard.	In simulation, the authors didn't show the change of THD levels before to certify the effective of their design and methodologies. To use RL filter as passive filter which reduces more power injections from PV system because of power losses in Rf.

[19]	Active filter + single tuned passive filters (5 th , 7 th , 11 th).	HAPF improves the compensation characteristic of tuned passive filters by compelling harmonic currents to sink into passive filter, and it also eliminates the chance of series and parallel resonance using the p-q theory and Hysteresis current controller, respectively.	The application of shunt passive filters or active power filters only give THD which is above the required limit, SHAPF gives the output power with THD of 2.02% for sources current.	The parameters of simulation are not highlighted; this is quite to prove the proposed design of HAPF.
[20]	LCL	To optimize LCL filter's parameters in PV grid-connected system	The total inductance of LCL filters reduces the total inductance of passive filter in PV grid-connected system to eliminate current harmonics injected inverters	No specified standards followed to verify the validity of the proposed design. VSC had not used as the active filter .
[25]	LCL	To interconnect the PV inverters and the utility grid, and to filter the harmonics in PV system	The active damping of LCL filters to reduces the resonance frequency using m-file in MATLAB.	The impacts of variant solar radiations on the PV inverter's output.

[26]	SAPF	To supply the PV power, eliminate the current harmonics and compensate the reactive power	Without SAPF, PV inject the current with 21.75%, when SAPF is applied to PV system, THD reduces to 2.02%	PV system increase THD of the output. The authors didn't try to reduce it. The presence of the harmonics in PV system's outputs due to use inductance for coupling only.
[28]	SAPF	To improve power quality and mitigate harmonic to IEEE 519-1992 limit	SAPF with SRF theory is applied to PV grid connected system, current from 27.32% to 3.49%.	Even if the output of SAPF has overall harmonics under IEEE 519-1992 standard, it still present high harmonics on 5 th ,7 th ,11 th harmonic order because the Lf was for coupling only instead to be a passive filter.
[21]	Tuned to 5 th and 7 th order PF connected in shunt and Shunt APF	To mitigate harmonics in distribution network, supply the power and reactive power compensation.	Tuned to select frequency LC filters improve the filter characteristics of SAPFs.	The problem is the resonance of LC filters at resonance frequency of VSCs.
[30]	SAPF is connected in series with LC filters turned to 5 th and 7 th order harmonics to form SHAPF	To model and control of grid interfaced large scale photovoltaic system with embedded hybrid active power filter functions.	The inverter part of SHAPF is utilized to inject power generated from photovoltaic source to the grid and also to act as hybrid active power filter to compensate harmonics and reactive power demand	The use of LC filters in large power applications makes the implementations of the proposed design quite difficult due to the resonance of LC filters with big nonlinear loads.

[31]	APF+ high-pass PF.	The proposed configuration improves the filtering performance of the conventional APF, and at the same time supplies the power from the PV arrays to the loads and the utilities using extended p-q theory.	The performance of APF in their proposed configuration is improved where current THD of the source is reduced from 30.09 % to 1.95 %.	PF used in this design doesn't require more calculation, the rest is to found its drawback compare to LCL filters.
[33]	SAPF	to mitigate the harmonics at point of common coupling when the PV power system is integrated to the grid using shunt active power filter with p-q theory.	THD is reduced under 5%	This shows the existing harmonics in the grid even if the authors didn't consider that.
[34]	APF	Use Inverter in PV grid-connected as an active power fitter to mitigate the harmonics in the grid	The THD is under IEEE 519-1992 standard when the APH is connected to the grid	In the simulation the authors didn't show the differences between the PV-grid connected system and the active power filter only, the integration of renewable energies is not well justified.

2.8 Problem Formulation

2.8.1 Problem Description

The previous research used the voltage sources as balanced and the resonance attenuation between LCL filters and the grid decreased the filtering characteristics of hybrid active filters. This section covered the system modelling of the parts constitute PV-HAPF grid-connected systems. The aims of this proposal was to eliminate the harmonics in PV grid-connected system using Hybrid Active Power Filter. The block diagram of the proposed design is in Figure 2.4 where PV arrays are connected to a boost converter to step up a DC output power from PV arrays, the VSC convert power outputs form AC to DC. Final, the passive filters eliminated the harmonics in the power outputs from the inverter.

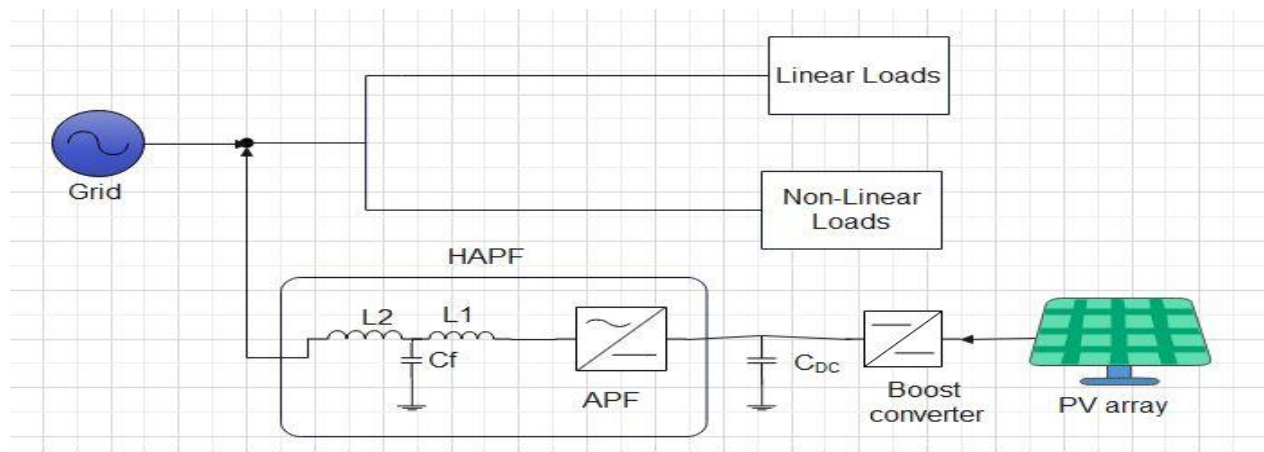


Figure 2.4 PV-HAPF grid-connected System

2.8.2 System Modelling

2.8.2.1 PV Modelling

When sunlight strikes the surfaces of a photovoltaic cell (PV), a P-N junction generates electricity. The equivalent circuit of a PV cell is shown in Figure 2.5, which comprises series and shunt resistors as well as a parallel diode. Depending on the solar cell's composition, the voltage of a single solar cell can range from 0.5 to 0.7 V. The number of series and parallel cells connected to PV modules corresponds to the PV power's rating. The equivalent circuit of a PV cell (R_{sh}) consists of a current source, an anti-parallel diode (D), a series resistor (R_s), and a parallel resistor [30]. According to the Kirchhoff laws, Figure 2.5 gives the relationship between output voltage (V) and output current (I) for the single-diode equivalent circuit of a solar cell, which can be described by Eq. 2.1.

$$I = I_{ph} - I_0 \left\{ \exp \left[\frac{q(V+IR_s)}{AkT} \right] - 1 \right\} - \left(\frac{V+IR_s}{R_{sh}} \right) \quad \text{Eq. 2.1}$$

Where I_{ph} is the photocurrent of a solar cell, I_0 is its saturation current, A is the curve fitting factor of a solar cell, k is Boltzmann constant (1.381023 J/K), and T is the temperature ($^{\circ}\text{K}$)

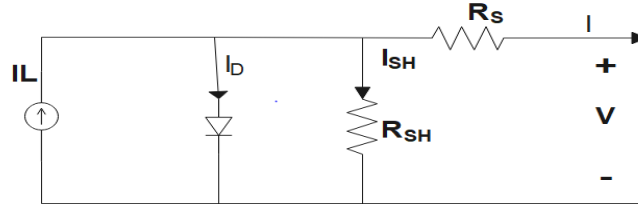


Figure 2.5 PV Cell Equivalent Circuit [31]

At short-circuit conditions, where the slope of the I-V characteristics is almost zero, the value of R_{sh} can be assumed to be infinite in [32]. I_{ph} equals short circuit current (I_{sc}) in this scenario, and the PV array has N_p and N_s series linked solar cells. Then Eq. 2.1 becomes Eq. 2.2.

$$I = N_p I_{sc} - N_p I_0 \left\{ \exp \left[\frac{q \left(V + I \left(\frac{N_s}{N_p} \right) R_s \right)}{N_s A k T} \right] - 1 \right\} \quad \text{Eq. 2.2}$$

2.8.2.2 Maximum Power Point Tracking

Each PV array has the maximum power output but it is not constant due to the weather conditions, the output voltage and current oscillate around the maximum point, this gives nonlinear V-I curve as shown in Figure 2.6. PV output currents and voltages converge to maximum power point, this gives the maximum power output in Eq. 2.3, the output power is direct proportional to the solar radiations which affects more the output current than voltage output. Different techniques are developed to extract maximum power point which are detailed in next chapter. MPPT controller is between PV array and DC-DC converter.

$$P_{mp} = I_{mp} * V_{mp} \quad \text{Eq. 2.3}$$

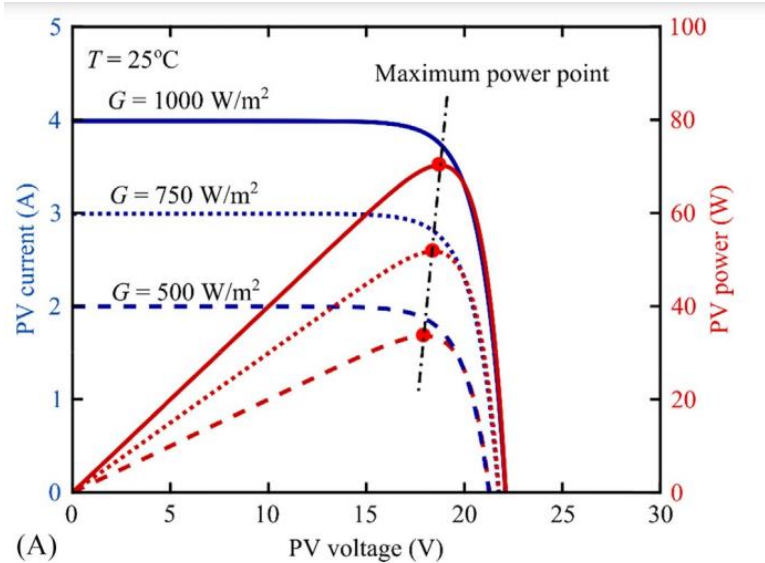


Figure 2.6 MPPT Curve in Solar System [33]

2.8.2.3 Boost Converter [35]

Because the PV array's output power is low, the step-up converter is required before sending the PV output voltage to the inverter and MPPT controller for the DC-DC converter in order to extract the maximum power from the PV array. A diode (D), a Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) switch, an inductor (L), and a capacitor make up a DC-DC converter (CDC). When the switch is closed, current flows through the diode and is stored in the capacitor as direct current, resulting in V_{dc} , according to the circuit analysis in Figure 2.6. Duty circle (D) gives the relationship between V_{in} (V_{pv}) and V_{out} (V_{dc}) of DC-DC converter, is in Eq. 2.4.

$$D = 1 - \frac{V_{in}}{V_{out}} \quad \text{Eq. 2.4}$$

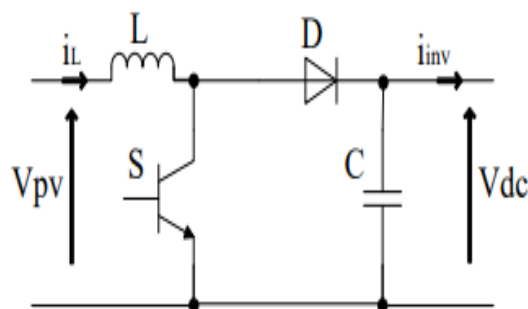


Figure 2.7 Electrical Circuit of Boost Converter [35]

2.8.2.4 Active Power Filter

As shown in Figure 2.8, the Active Power Filter comprises a voltage source converter, coupling inductor (L_f), and link capacitor (C_{dc}). Power electronics switches are used in voltage source converters. SN, which can range from 1 to 6 (S1, S2, S3, S4, S5, and S6), produces particular currents that cancel out the harmonic currents created by the nonlinear load. Sn generates compensated current harmonic currents in the opposite direction of nonlinear loads' injected harmonic currents. The compensated current is obtained using Kirchoff current law (KCL) in Figure 2.8, then Eq. 2.5 is given.

$$I_f = I_s - I_L \quad \text{Eq. 2.5}$$

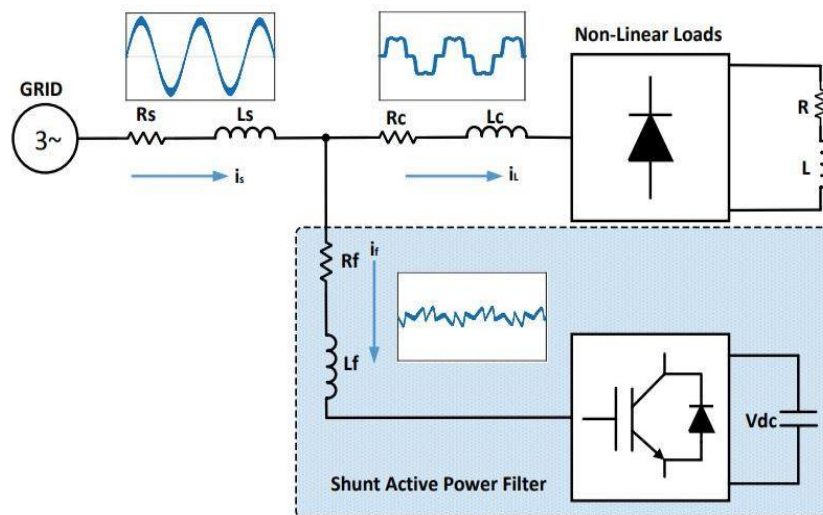


Figure 2.8 Shunt Active Power Filter (SAPF) [16]

2.8.2.5 LCL Filters

The grid-side inductance (L_2), inverter-side inductance (L_i), and capacitance (C_f) of LCL filters are designed to decrease high-order harmonics induced by DC/AC converter frequency switching [34]. The corresponding circuit of a single line diagram is shown in Figure 2.9, where an input voltage of the LCL filter is the output voltage of VSI and an input current of the LCL filter is the output current of VSI.

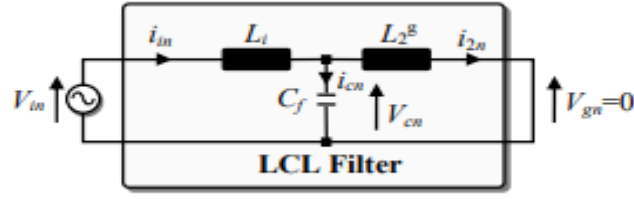


Figure 2.9 Equivalent Circuit of LCL Filter

2.8.2.5.1 Resonance Frequency (f_{res}) and Ripple Current (I_{ripple})

The L_i is in parallel with L_2 , the equivalent inductance is given in

$$L_f = \frac{L_i * L_2}{L_i + L_2} \quad \text{Eq. 2.6}$$

The resonance frequency (f_{res}) is calculated as shown in Eq. 2.7.

$$f_{res} = \frac{1}{2\pi\sqrt{L_f C}} = \frac{1}{2\pi} \left(\frac{L_i + L_2}{L_i * L_2 C} \right) \quad \text{Eq. 2.7}$$

The resonance frequency selected is half the switching frequency and 10 times the grid frequency as shown in Eq. 2.8. This is for a better filtering characteristic without resonance problems.

$$10f_g \leq f_{res} \leq \frac{1}{2}f_{sw} \quad \text{Eq. 2.8}$$

Where f_{sw} is the switching frequency, f_g is the grid frequency, and f_{res} is the resonance frequency.

The ripple current attenuation derived in Eq. 2.9 determines the ratio between grid-side and inverter-side inductance.

$$I_{ripple,peak} = \sqrt{\frac{2}{3}} * \frac{P}{V_f} \quad \text{Eq. 2.9}$$

Where P is the rate active power of the grid while V_f is equal to output voltage of bridge inverter.

2.8.2.5.2 Capacitance

The capacitance C_f is computed using the reactive power's maximum permitted change in the Point of Common Connection (PCC). The reactive power exchange is typically 5-7 percent of the inverter's capacitance rated output. As a result, it can be calculated using in Eq. 2.10.

$$C_f = 5\% * C_{base} \quad \text{Eq. 2.10}$$

$$\text{Where } C_{base} = \frac{P_{gL-L}}{W_g * V_g} \quad \text{Eq. 2.11}$$

And, P_{gL-L} is Line to line active power of grid, W_g is the grid frequency and V_g is the grid voltage.

2.8.2.5.3 Inverter Side Inductance (L_i)

Due to the power electronics switching of IGBTs, the ripple current (I_{ripple}) of VSI is in Eq.2.12, and the minimum and maximum value of L_i depend on it as described in Eq. 2.13 and Eq. 2.14 respectively.

$$\Delta i_{max} = 10\% * I_{ripple,peak} \quad \text{Eq.2.12}$$

$$L_{i_{min}} = \frac{V_{DC}}{(6 * f_{SW} * \Delta i_{max})} \quad \text{Eq. 2.13}$$

$$L_{i_{max}} = \frac{(\delta V_{gL-L})}{(W_0 * \sqrt{2} I_{max})} \quad \text{Eq. 2.14}$$

Where δ is set to be about 5%.

2.8.2.5.3 Grid Side Inductance (L_2)

The grid side inductance is designed to restrict grid current harmonics in accordance with IEEE 519-1992 standards and grid code requirements, where THD must be less than 5% [35]. The total sum of the LCL filter inductor values should be less than or equal to ten percent of the values of the inductance reactance base in per unit, as calculated in Eq. 2.15. This also improves the system's speed and dynamics.

$$L_{Tmax} = (L_i + L_2)_{max} = 10\% L_{Tbase} \quad \text{Eq. 2.15}$$

$$\text{Where } L_{Tbase} = \frac{V_g^2}{W_g * P_{gL-L}} \quad \text{Eq. 2.16}$$

The relationship between inductances on the converter and grid sides is defined as r and is stated in Eq. 2.17.

$$L_2 = r L_i \quad \text{Eq. 2.17}$$

Where $0 \leq r \leq r_{\max}$ and $r_{\max} = (L_{T-\max})/L_i - 1$

r is always less than 1, this implies that L_2 is less than L_i .

The proper control strategy for this design is required to reduce resonance frequency of passive filters, different methods are employed to reduce the resonance between filter and grid.

2.9 Chapter Conclusion

This chapter covered the literature review. Section 2.2 gives the recap of the harmonics in power, IEEE519-1992 standard is in section 2.3 while the Section 2.4 covers IEEE 1547-2003 standard. Section 2.4 is for the pulse with modulation (PWM). Section 2.6 focus on the filters in the power system which are subdivided into active filters and passive filters. The literature review of power filters in PV grid-connected with the related gaps is in Section 2.7. Section 2.8 is for the problem formulation of the proposed design with its modelling system.

CHAPTER 3. METHODOLOGY

3.1 Introduction

This chapter covers the methodology and algorithm to apply to the proposed design. The proposed methodology has more advantages than the previous ones applied to PV grid-connected systems with Hybrid Active Power Filter features. The mapping section shows how the proposed methodology and algorithms are related to the solutions of the problem. The except outcome solutions are highlighted in this chapter.

3.2 Previous Methodologies

Moh. Jauhari [15], M. Chovatia [18], A. Smadi, et al [21], and Ayman Blorfan [31] used the pq theory method to control the SAFs to generate the compensated current with hysteresis current control for the PV inverters in order to mitigate the harmonics and supply clean power to the grid, simultaneously. When the voltage sources are balanced, the p-q theory allows the SAPF to draw constant instantaneous power from the source, draw sinusoidal current from the sources, and have little power loss; however, when the voltage sources are not balanced, the SAPF can only do one of the above. SAPF input current is practically sinusoidal with HCC methods, which regulate and stabilize DC-link voltage. The load current is compared to the current band limit using the HCC approach. When the load current passes the upper band limit, the switch shuts off; when the load current crosses the lower band limit, the switch switches on. This necessitates a high switching frequency as well as significant switching losses. The output of SAPF still presents harmonics due to the variation of voltage sources and switching frequency.

Rachid Belaidi [28], T. Demirdelen [30] and XianyongXu [32] applied the P&O algorithm to track the maximum PV output power. The authors of [24] use SRF theory to generate current references for SAPF PWM, but they leave out PV generation in simulation. SAP only has the functionality to eliminate current harmonics and compensate for reactive power in this work. The SRF controls the APF to generate compensated currents. Using the cosine and sine functions, the SRF approach converts stationary three-phase grid voltages and load currents into the D-Q frame. A phase-locked loop (PLL) senses the phase angle of grid voltage, is extensively employed to make this transition. PI controllers are required to reduce the non-linearity and local D-Q coupling. DC signals limit AC values within the main reference values. The SRF method is easy to implement; the generation of reference currents doesn't require the

voltage grid but the necessity of phase angle is critical of this performance but it requires a large number of voltage and current transducers to filter the harmonics. Moreover, when the voltage sources are unbalanced, the PI controller couldn't satisfy the SRF performance.

3.3 Methodology Approach

Different approaches used in this work to meet the main objective:

3.3.1 Data Collection: Many different tools were used during the data collection process. Recording devices and note books were employed to collect enough data for this study.

3.3.2 Quantitative Approach: the measurement of the data is essential in engineering design where affect the identification, definition and measurement of the required data. The reliability of the data was taken account during this research.

3.3.3 System Design: Different abovementioned controller methods are followed to design the experiment test for this work.

3.3.4 Data Analysis: To validate the work, the data analysis will be occurred in the next chapter.

3.4 Proposed Methodology

This section covered a new methodology for the proposed design, the advantages of the proposed methodology are highlighted also. From the aforementioned applied methodologies to the power filters in PV grid-connected system to mitigate the harmonics, the variations of input of DC voltage link due to solar radiation variations, the demonstrate of power injection from PV are omitted, the HAPFs ensured the harmonics mitigation and reactive power compensation. From this a gap found on control of MPPT, and control for SAPF.

This work aimed to use PV-inverters as active power filter with ability to supply the power simultaneously. The proposed methodology will be verified in MATLAB/Simulink for the combination of P&O and PSO algorithm for MPPT to improve response time and convergence to maximum power point, the modified p-q theory in SAPF controller.

3.4.1 DC Voltage Regulator for MPPT

3.4.1.1 Perturb and Observe (P&O) Algorithm

Perturb and Observe (P&O) algorithm, which operates on the principle of perturbing the system's operational point in order to generate maximum output power. A small increment is added to the PV output power until the maximum power point is attained, as illustrated in

Figure 3.1. P_t (power output) is first computed by measuring the solar module's V_t and I_t values and recorded, P_{t-1} is calculated using V_{t-1} and I_{t-1} , the change on output power of PV array is determined by ΔP (comparing present output power P_{t+1} to the previous one P_t). If ΔP is null, the maximum power point is reached. If ΔP is positive, the system will continue to perturb in the same direction; otherwise, V_{t-1} is reduced by ΔV to return the output power value to the maximum power point by adding a negative increment. The system operating point begins to oscillate regularly about the maximum power point after the maximum power point is reached. The DC-DC converter will track this operational point and step it up to the required voltage values for the APF's DC link capacitor.

This method is easy to implement. However, it has a significant disadvantage: Constant oscillations at the maximum power operating point causes power losses., delayed dynamic response when using a tiny increment value and a low sampling rate, and instability when irradiance levels change rapidly [37].

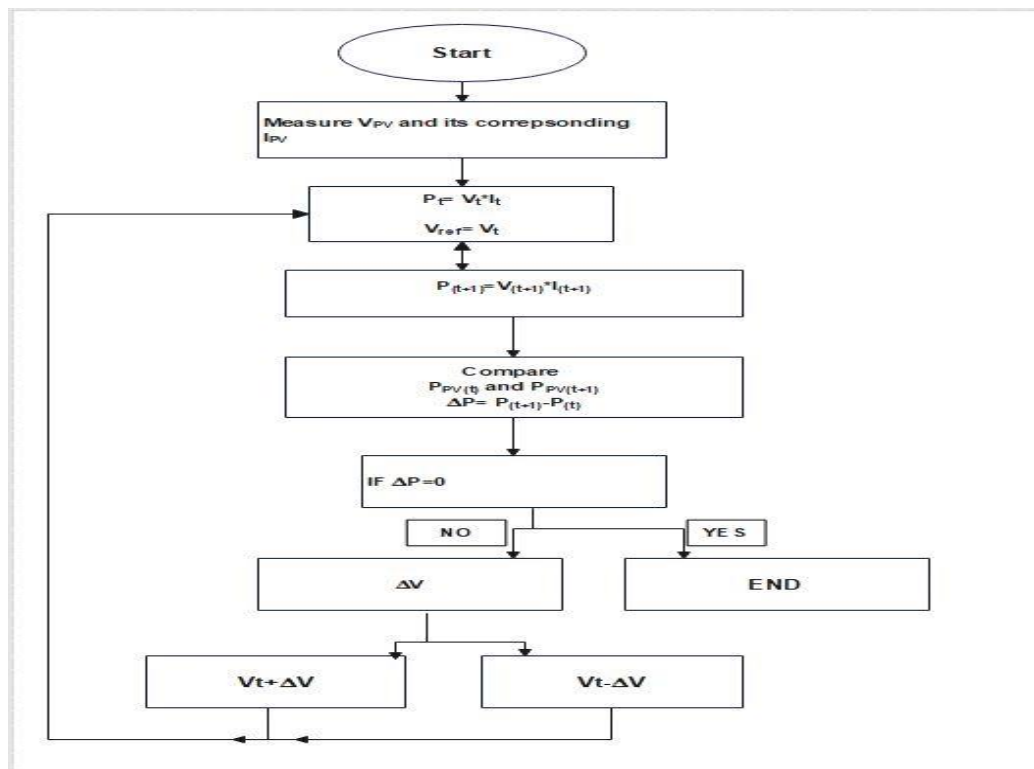


Figure 3.1 P&O Algorithm for MPPT

3.4.1.2 Particle Swarm Optimization (PSO) Algorithm

Eberhart and Kennedy proposed the PSO algorithm in 1995. It is a swarm-based stochastic optimization technique in which the PSO algorithm simulates the social behavior of animals

such as insects, cattle, birds, and fish. These swarms follow a cooperative food-finding strategy, with each member of the swarm modifying the search pattern in response to its own and other members' learning experiences. PSO also employs a swarm mode, which allows it to simultaneously search a huge section of the optimized objective function's solution space. Using the PSO algorithm, one can stimulate natural social behavior and the dynamic movement of creatures such as insects and birds to discover the optimal solution that can be represented as a point or on a surface. Particle best value (Pbest) and global best value (Gbest) influence particle placements. The PSO algorithm is represented mathematically by Eq. 3.1 and Eq. 3.2, in which particle velocity (θi^{k+1}) and location $(X i^{k+1})$ change in terms of particle best value Pbest and global best value Gbest.

$$\theta i^{k+1} = w i^k + c1 r1 [Pbest - X i^k] + c2 r2 [Gbest - X i^k] \quad \text{Eq. 3.1}$$

$$X i^{k+1} = X i^k + \theta i^{k+1} \quad \text{Eq. 3.2}$$

Where r1, r2 are random numbers, Pbest is the particle best value, and Gbest is the global best value. k is the current iteration, w is the inertia weight, c1 and c2 are learning parameters (cognition and social parameters), r1 and r2 are random values, Pbest is the particle best value, and Gbest is the global best value.

Three key concepts of the PSO algorithm are to maintain particle inertia, alter the condition based on its most optimistic position, and change the condition based on the swarm's most optimistic position. According to [36], Figure 3.2 depicts all steps of the PSO algorithm for using the MPPT method in a PV system:

- i) The particles and parameters are selected in search space randomly,
- ii) Position and velocity of the selected particles are determined using Eq. 3.1 and Eq. 3.2, respectively.
- iii) Compute the fitness values of each particles using Eq. 2.1, voltage and current of PV are found and evaluate the best values to find global best value (Gbest),
- iv) Update the position and the velocity of each selected particle with respect to the Gbest,
- v) Check if the present global best value (Gbest(t)) is equal to previous global best value (Gbest(t-1)).
- vi) If step 5 is negative, repeat Step 3 & 4 till the optimum solution is reached, the maximum iteration number is set at 60. Whether or not the iteration meets the termination condition, which is that the population exceeds the maximum number of iterations.

vii) Gbest at the end of the last iteration gives the optimized value (maximum power point) using Eq. 2.3.

In the MPPT methodology, this strategy is utilized to optimize the output power from PV. Local maxima trapping owing to random population initialization, increased tracking time, greater search space exploration, output power fluctuations, and longer settling time are some of the drawbacks. To solve those drawbacks of the previously mentioned MPPT algorithm, this suggestion proposes combining P&O and PSO to increase the performance of each algorithm.

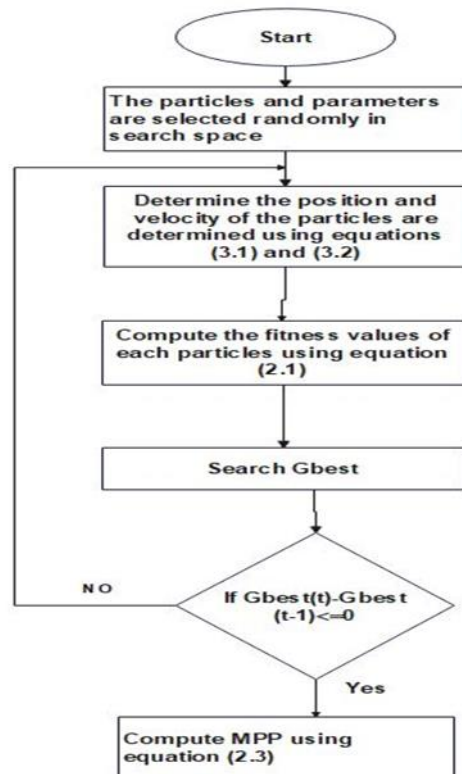


Figure 3.2 PSO Algorithm for MPPT

3.4.1.3 DC Voltage Regulator of DC Link Capacitor

To sustain a constant voltage level at capacitor link, PI is required the DC voltage regulator controller with an anti-windup configuration. K_i and K_p are used in the PI controller, the proper configuration of K_i and K_p affects the transient of voltage at capacitor at APF, and K_p is less than K_i . The transfer function is written in Eq. 3.3, From Figure 3.3, PI controller stabilizes the average dc-bus voltage at predefined level. The output of PI controller is I_{ac} to energize C_{dc} . PI controller is preferred to PID, PR and RC controllers as it allows the power exchanger between the PV system and the grid.

$$H(s) = K_p + \frac{K_i}{s} \quad \text{Eq. 3.3}$$

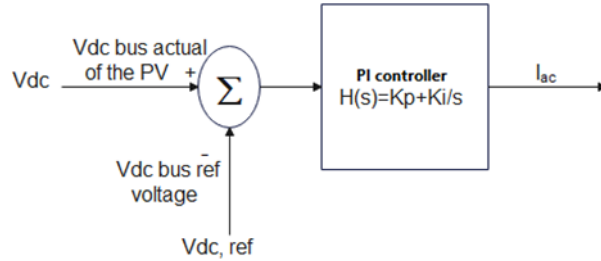


Figure 3.3 PI Controller for VDC Regulator

3.4.2 Modified p-q Theory for SAPF

Instantaneous reactive power theory known as the p-q theory was first put forth by Akagi in 1983. In this theory, the matrix transformation of ABC to is referred to as Clark's transformation. Instantaneous voltages (V_0, V_α, V_β) are mapped from the three-phase voltages (V_a, V_b, V_c). The p-q theory controller has several benefits, including: easy to install, the compensation algorithm is very flexible and gives the sinusoidal waveforms from the source. This section covers the mathematical model of basic p-q and the one of modified p-q theory with their respective algorithms. The modified p-q theory is selected for this work due it works both in balanced and unbalanced voltage sources.

In Clark's transformation, the grid voltages (V_a, V_b, V_c) and load currents ($i_{L_a}, i_{L_b}, i_{L_c}$) are transformed into in $0\alpha\beta$ axis to give V_0, V_α, V_β , and I_0, I_α, I_β in Eq. 3.4 and Eq. 3.5, respectively. In three-phase four-wire system, V_0 and I_0 are omitted in matrix transformation.

$$\begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \quad \text{Eq. 3.4}$$

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \quad \text{Eq. 3.5}$$

The resulting Clark's transformation voltage and current produce instantaneous power real power (p), and imaginary power (q) as given Eq. 3.6.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad \text{Eq.3.6}$$

P and Q have the oscillating imaginary parts (\widetilde{p} , \widetilde{q}) and real parts (\bar{p} , \bar{q}) as highlighted in Eq. 3.7.

$$\begin{aligned} \text{real power } p &= \bar{p} + \widetilde{p} \\ \text{imaginary } q &= \bar{q} + \widetilde{q} \end{aligned} \quad \text{Eq. 3.7}$$

By viewing them as functions of active and imaginary power and voltage of the power system, Eq. 3.8 may be used to calculate the current contained in instantaneous power, giving powers in pq theory a physical meaning.

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \frac{1}{v\alpha^2 + v\beta^2} \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad \text{Eq. 3.8}$$

The compensated i_α and i_β are transformed into compensated current (i_{ca} , i_{cb} , i_{cc}) by inverting Clark's transformation to inject the compensated current into the grid for eliminating the harmonic currents from nonlinear loads. The same process occurs to voltages. The compensated voltages and currents are calculated based on Eq. 0.9 and Eq. 3.10.

$$\begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} \quad \text{Eq. 3.10}$$

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad \text{Eq. 3.11}$$

The control algorithm is presented in Figure the input voltage and current are mapped from abc axis to $0\alpha\beta$ axis, the results of this transformations produce instantaneous powers which are used to selected which component to compensate. To get the three-phase current and voltages compensated, they inverse the Clark transformation.

The resulting of Clark's transformation voltage in Eq. 3.4 contains the 5th and 7th harmonics due to the unbalanced voltage sources. A self-tuning low pass filter is required to filter harmonics content in $\alpha\beta$ voltages.

3.4.2.1 Phase-Locked Loop

The source voltages at PCC are unbalanced and distorted. The PLL is to track continuously the fundamental frequency of the grid voltages. The appropriate design of the PLL in Figure 3.4.

allows a proper operation under distorted and unbalanced voltage waveforms. This synchronizing circuit (PLL circuit) determines automatically the system frequency and the phase angle input signal. The PLL enables the sinusoidal compensated currents rather than the constant power. The algorithm is based on a fictitious instantaneous active power, the positive-sequence detector blocks which extracts instantaneously the fundamental positive-sequence voltages V'_a , V'_b , and V'_c that correspond to the phasor V_{+1} of the grid voltage V_a , V_b , and V_c .

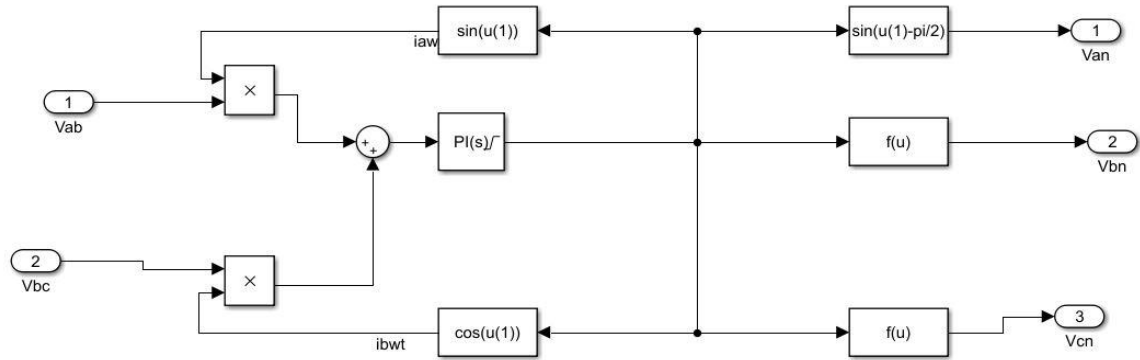


Figure 3.4 Fundamental Circuit of Phase-Locked Loop

Figure 3.5 illustrated the modified p-p theory algorithm for a shunt active power filter connected to PV array. This method aimed to filter the voltage sources in order to give the sinusoidal source currents.

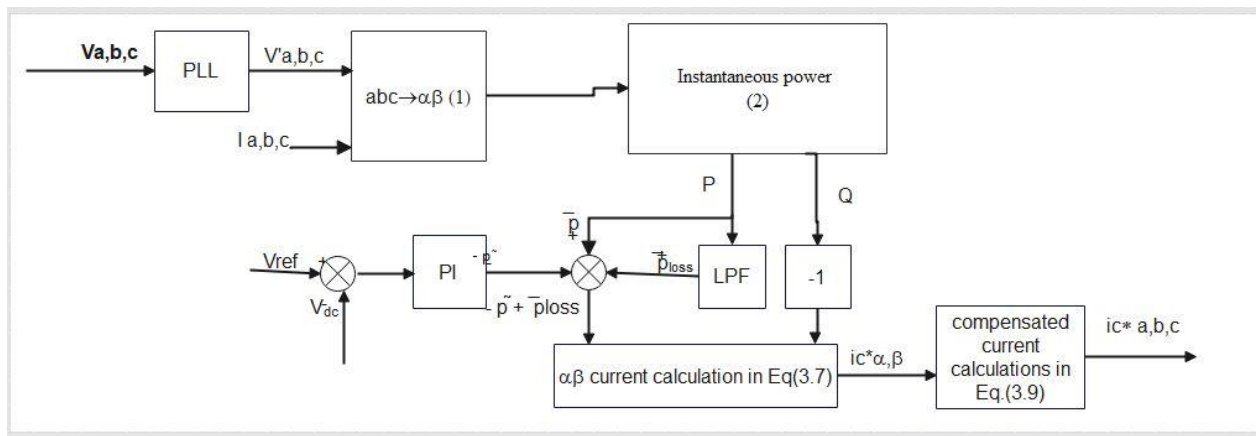


Figure 3.5 Modified P-Q Theory

3.5 Simulation Tool: MATLAB/Simulink

MATLAB stands for Matrix Laboratory. Simulink is an embedded software of MATLAB that provides an essential means to model, simulate, and analyse electrical systems through inputs and outputs. MATLAB is the matrix analysis, design for electrical circuits. It also supports

linear and nonlinear systems that are represented in continuous time as well as sampled time on cross systems. Simulink transforms your computer into a laboratory for analysing and modelling electrical engineering systems.

MATLAB has a number of advantages: Easy to understand, easy to use, built-in functionality, and some sort of orient object. However, it has drawbacks, such as a long compiling time and the inability to connect with computer languages.

3.6 Mapping the Methodology to the Problem

This work aimed to eliminate the harmonics in PV grid-connected system in all solar insolation conditions. The proposed MPPT controller P&O algorithm is compared to PSO algorithm in order to get the maximum power point with the reduced oscillations. PI controller was to stabilize direct voltage required for V input of APF and simultaneous allowed the transfer from PV array to the grid. To eliminate harmonic distortion in output of PV-HAPF, the modified p-q theory enabled the filtering of harmonics contents even the voltage sources were distorted, and the proper control strategies of HAPF-PV ensured the filter features during sunlight and no solar insolation time.

Table 3.1 Mapping Table

Objective	Method	Reason
Extract maximum power from PV array	Compare P&O to PSO algorithm	To have accurate, precise and fast convergence power to MPP
Required level of V_{DC} for C_{DC}	PI controller for V_{DC} regulator	To maintain the V_{DC} at required level and transfer stably the power from the PV array to the grid
Reduce Harmonic distortion in PV system	Modified p-q theory	To filter the harmonics under sources voltages distorted

3.7 Chapter Conclusion

In this chapter, the previous methods applied to the problem had been underlined in Section 3.2 while Section 3.3 gave different approach to meet the objectives. Then, the new methodology to the problem had been proposed in Section 3.4. Section 3.5 defined MATLAB/Simulink as simulation tool and chosen methodologies are mapped to the problem in Section 3.6.

CHAPTER 4. RESULTS AND ANALYSIS

4.1 Introduction

This chapter contains the description of PV power potential in Rwanda, then covered the simulation of different components of the proposed design in MATLAB/Simulink.

4.2 Potential Photovoltaic Power in Rwanda

The data obtained from global solar apps showed that Rwanda has the solar radiation vary from 4.2kW to 5.4 kW per day, referee to Figure 4.1 this gives the feasibility of many solar power plant sites. The big solar power plant in Rwanda is located in Rwamagana district, Eastern province, has power capacity of 8.5 MW and is grid-connected power plants. The coordinates of the power station are: 2°01'34.0"S, 30°22'38.0"E (Latitude: 2.026111; Longitude: 30.377222).

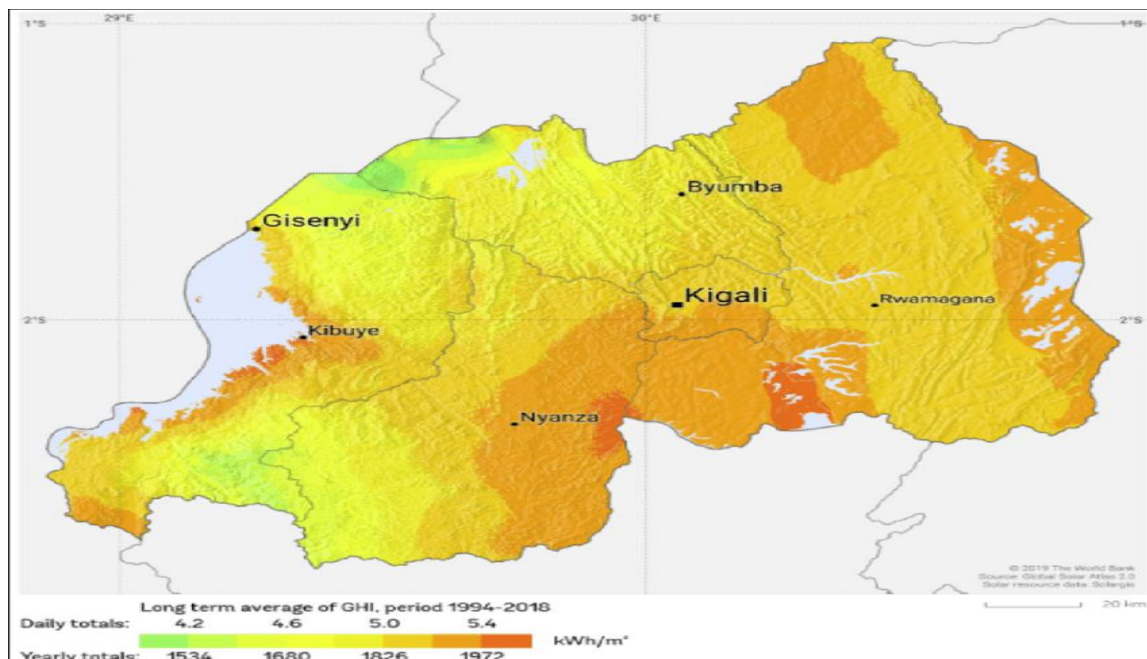


Figure 4.1 Global horizontal irradiation map of Rwanda by2018

Rwanda has the annually maximum temperature of 27.5°C, average sunshine of 5hours. This gives the feasibility study of the solar power plant in different sites in Rwanda. In this work, the solar radiation varies from [4.2-5.4] kW and the temperature of [25-27] in Celsius degree. It is possible to install a small PV grid-connected system to supply the power for 50 houses that consume 20W daily. The simulation is done according the modelling formulation done in Chapter 2 and by follow the step by step of the algorithms and methods defined in Chapter3.

4.3 The proposed system modelling.

In this thesis, the proposed model had three components in MATLAB Simulink in Figure 4.2 where the PV array is connected to a shunt HAPF with the grid, the modified p-q theory generates the gate signals for PWM circuit, the three-phase source is connected in parallel with the non-linear load which is composed by the rectifier.

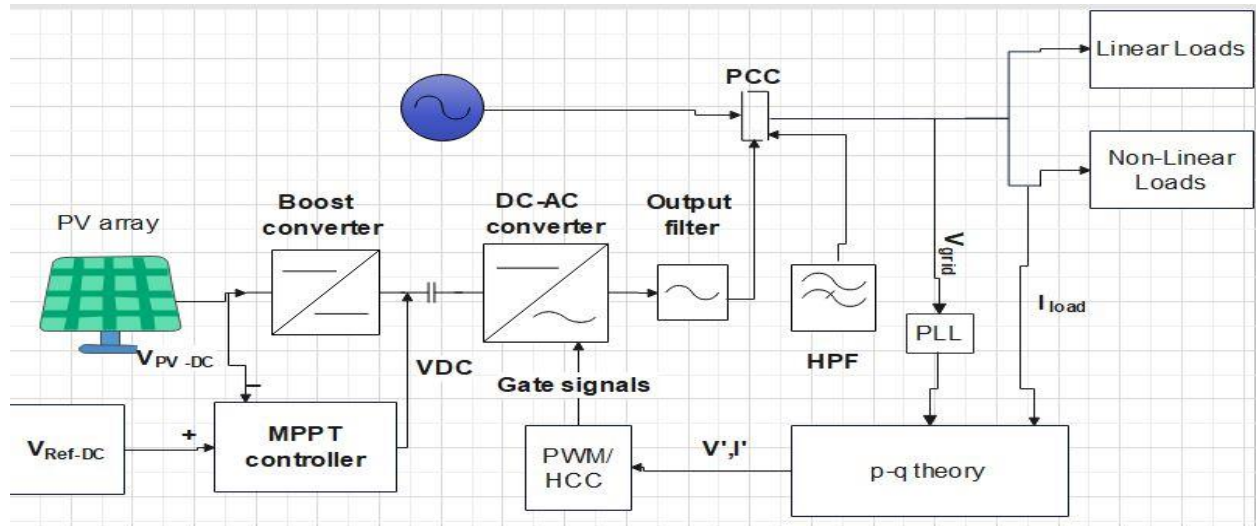


Figure 4.2 Proposed Design

4.3.1 PV-HAPF which was in charge of PV power transfer from PV to the grid, and the power quality improvement. SAPH is 6-switches IGBT as shown in Figure 4.3, the PWM is used to control the VSC (APF) where switching frequency is set at 2kHz.

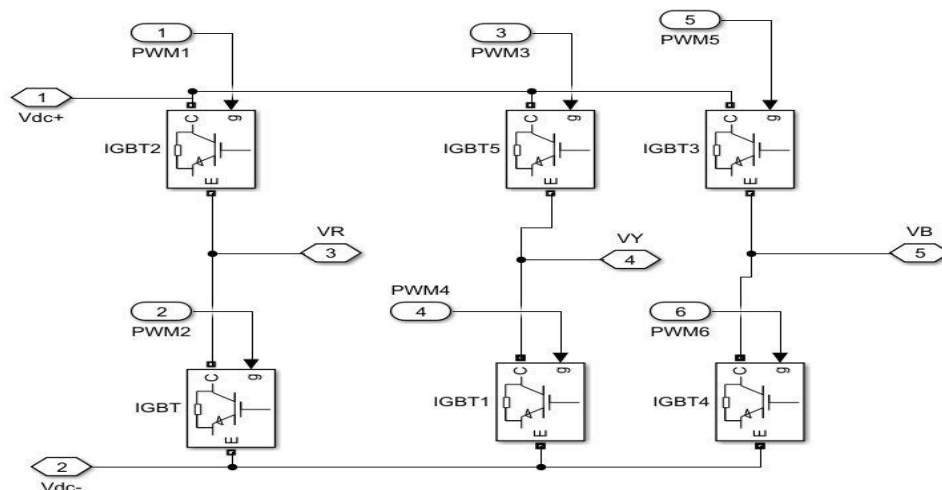


Figure 4.3 Voltage Source Converter

4.3.2 Main source voltages: A three-phase power supply which had the voltage magnitude of 220V, the equal phase angle of 120° and the unity power factor.

4.3.3 Point of common coupling (PCC) is the V-I measurement blocks.

4.3.4 Nonlinear Load is mainly a rectifier supply a resistive load.

4.3.5 DC-DC Boost Converter: The duty cycle (D) is key element to optimize the boost converter output voltage. D is defined in Section 2.8.2.3, the DC-DC converter contains an inductor, a capacitor, a diode, and an IGBT as it is a high-frequency switch. It produces a higher voltage during power supply to the load. Based on the switch duty cycle, the output voltage is changed. The parameters of the boost converter circuit are in Table 4.1.

Table 4.1 Boost Converter's Parameter

Parameter in S. I	Quantity
Input voltage, $V_{in}(V)$	250
Output Voltage, $V_o (V)$	500
Rate Power, $P_r (W)$	10e3
Switching Frequency (fs)	5e3
Resistive Load(Ω)	10
$\Delta V(V)=1\%V_o$	5
$I_o(A)=P_r/V_o$	200
$\Delta I(A)=5\%*I_o*(V_o/V_{in})$	20
$L(H)= V_{in} (V_o-V_{in})/ (\Delta I*fs*V_o)$	125e-3
$C_o(F)=I_o (V_o-V_{in})/ (fs* \Delta V*V_o)$	400e-6
$D=1-(V_{in}/V_o)$	0.5

4.3.6 Maximum Power Point Tracking Algorithms: Different techniques of MPPT in Solar PV system are defined in Section 3.4.1. P&O algorithm and PSO algorithm are simulated their designs in Matlab are attached in Figure 4.4 and Figure 4.5, respectively.

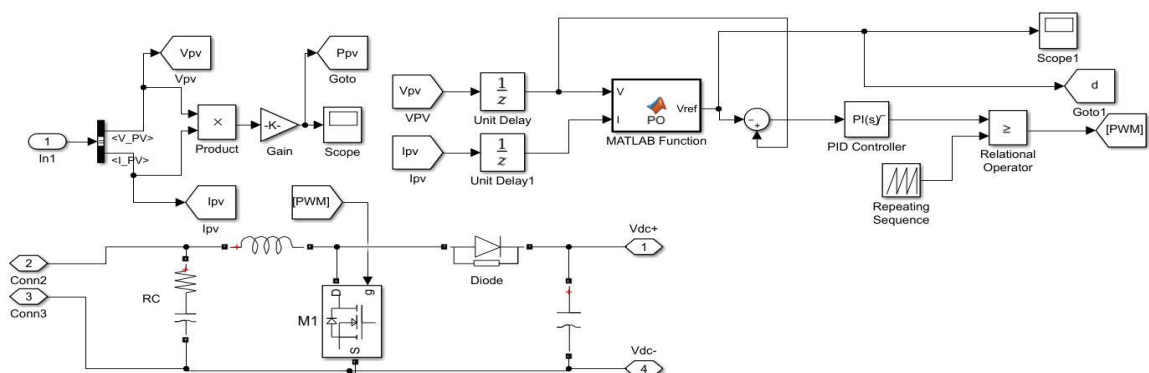


Figure 4.4 Design of P&O for PV MPPT in MATLAB

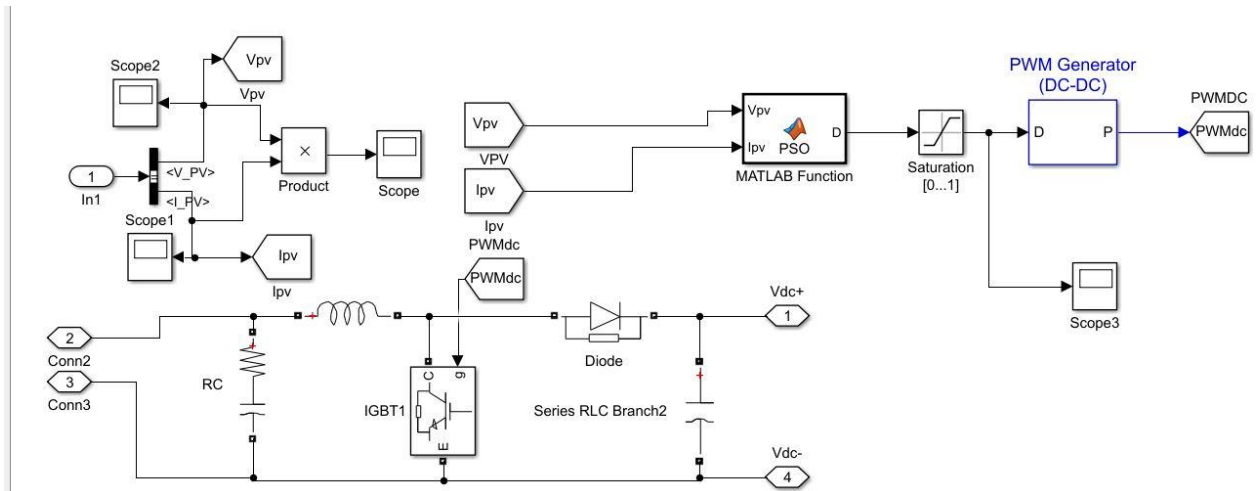


Figure 4.5 Design of PSO for PV MPPT in MATLAB

4.3.7 LCL Filters: The filter in this thesis was the Hybrid Active Power Filters (HAPF) composed by a shunt APF and LCL filter where the SAPF is connected to PV system, LCL filters the harmonics contained in the outputs of SAPF. The model of PV-HAPF is attached in Figure 4.2 and the parameters of the filter are listed in Table 4.2.

Table 4.2 HAPF Parameters

Parameter in S. I	Quantity
DC link voltage (V)	500
Grid voltage in r.m.s (V)	311
Grid frequency (Hz)	50
Switching frequency (Hz)	2000
IL max (A)	10
Power capacity of the inverter (W)	10,000

Calculation of LCL filter.

Using Equation (2.10) -(2.16), we got:

$$C=5\% * C_{base}= 5\% *(Pg L-L)/wg*(Vg)^2= 465e-6 F.$$

$$L\text{-inverter}= 5\% Vgl-l / (w0*li_max\sqrt{2}) = 35e-4H$$

$$L_T \text{ Base}= Vg^2/ (wg*Pg L-L) = 3.6 e-2H$$

$$(L_i+L_2)_{max}=L_T \text{ max} =10\% L_T \text{ Base}= 36e-4H$$

$$L_2= [(L_T \text{ max}/L_i)-1] *L_i= (3.6-3.5) e-3H=103e-6H.$$

4.4 Result and Discussion

4.4.1 PV Maximum Power

P&O gives a stable maximum power point when it reaches the duty while there was a significant oscillation when PSO is applied. More number of iterations, more the maximum power point varies. The graph of MPPT using P&O presented in Figure 4.6 has a unique duty cycle while the power of PSO varies its duty cycle as shown in Figure 4.7.

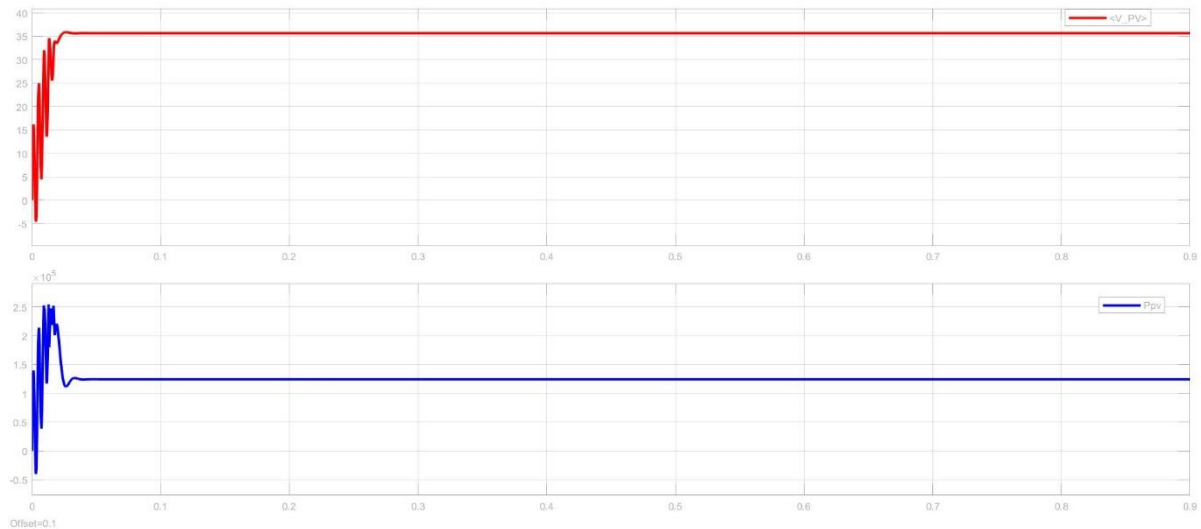


Figure 4.6. Maximum Power Point P&O Algorithm

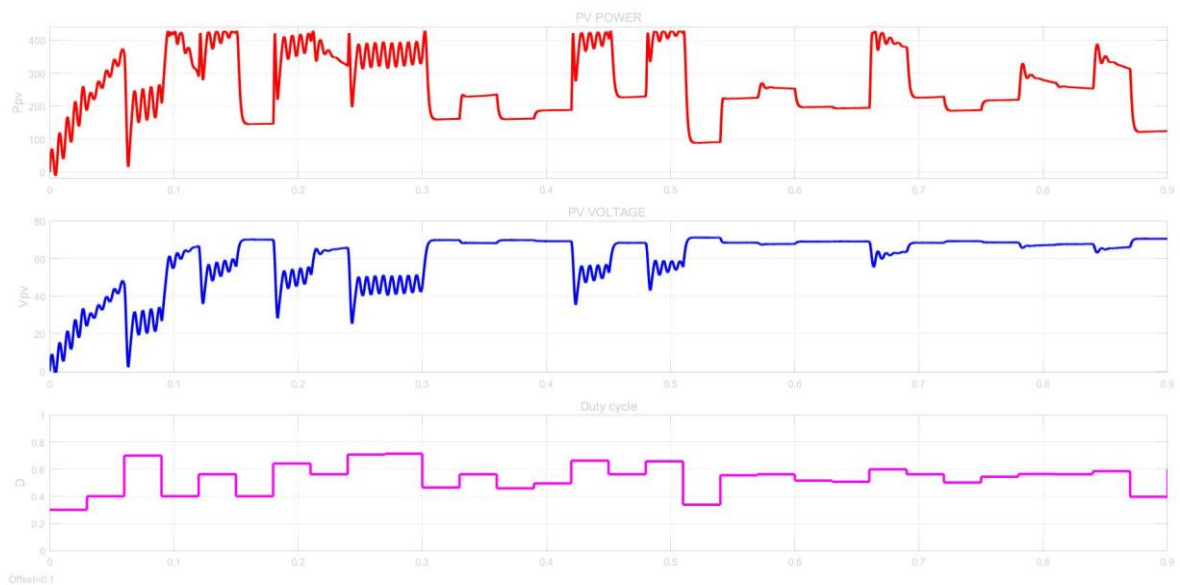


Figure 4.7 Maximum Power Point using PSO Algorithm

4.4.2 Total Harmonic Distortion

The waveform characteristics of the source's voltages, load currents, and filter currents are defined once the control circuit is connected SAPF. Figure 4.8 contains the wave characteristic of different points of the proposed design but the source voltages present the distortion as highlighted in Figure 4.9. The need of LCL is emphasized by the waveform of output current from the filters as stated by T. Demirdelen, et al [29].

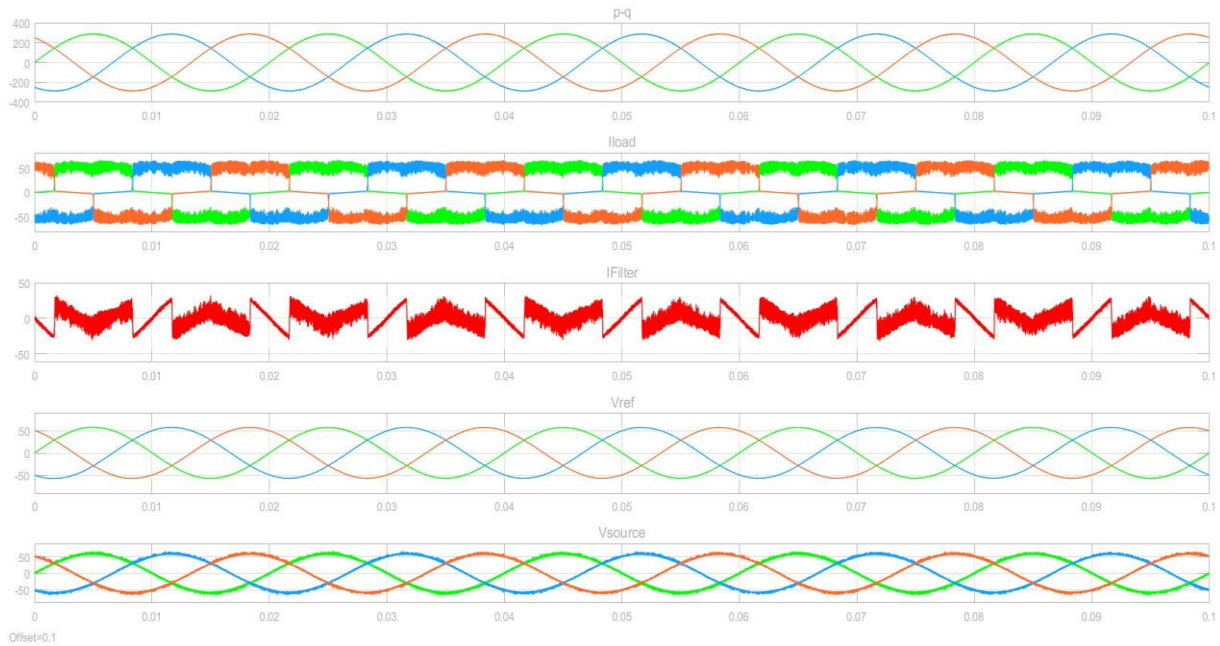


Figure 4.8 Waveforms of Currents and Voltages at PCC when the p-q theory is applied

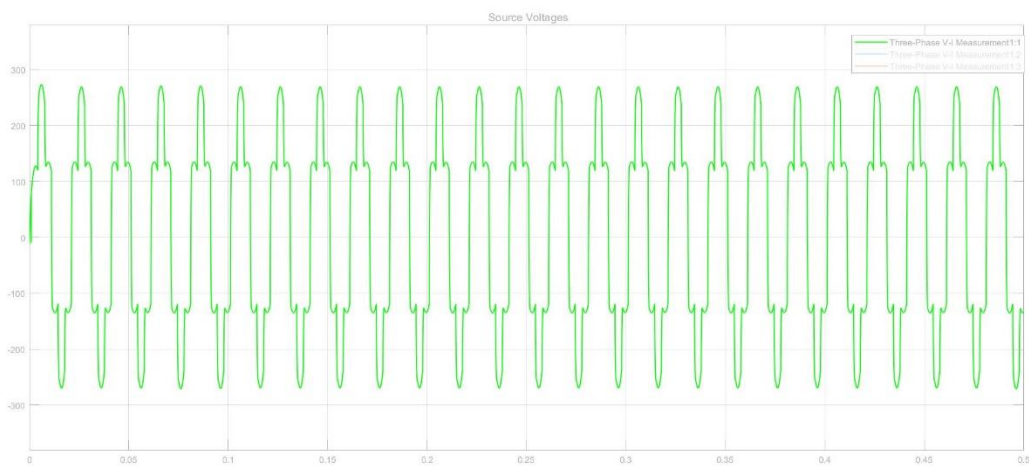


Figure 4.9 Distorted Source Voltages waveform

PLL circuit tracks the positive-sequence voltages of the grid (V_{abc}) before Clark's transformation. Without the control of SAPF, the current THD at PCC is 30.65% which is above the IEEE-519 limit as shown in Figure 4.10.

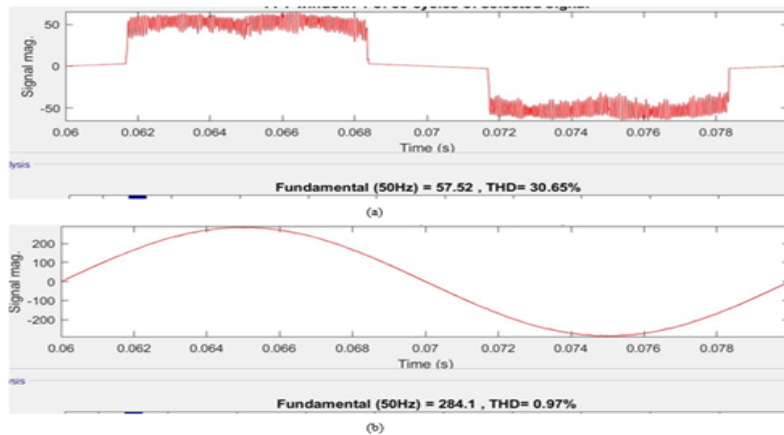


Figure 4.10 Output currents from the HAPF

To validate our simulation, the comparison of FFT analysis between basic p-q theory and modified p-q theory is done.

i) Basic p-q Theory: the control method for the PV-VSC using p-q theory is modelled, then reduced the current distortion significantly, THD was under IEEE 519 limits but the distortion in main sources cause the high THD in the output current from PV-HAPF. p-q theory control for VSC decreases significantly THD at PCC as shown in Figure 4.11 where THD decreases from 34.9% to 4.68% and previously worked in [23,25,28,30].

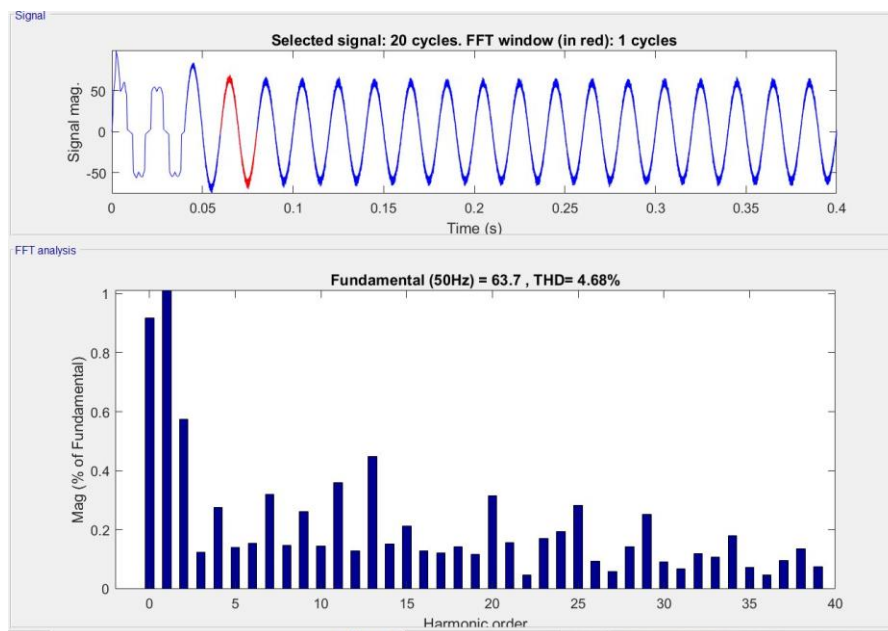


Figure 4.11 Output Filter Current when the Basic p-q Theory is Applied

ii) **Modified p-q Theory:** it gave the lowest THD compare to basic p-q theory model where THD of 1.25% is obtained. The waveform in Figure 4.12 was almost pure sinusoidal output current supply for the grid from PV system under distorted voltages.

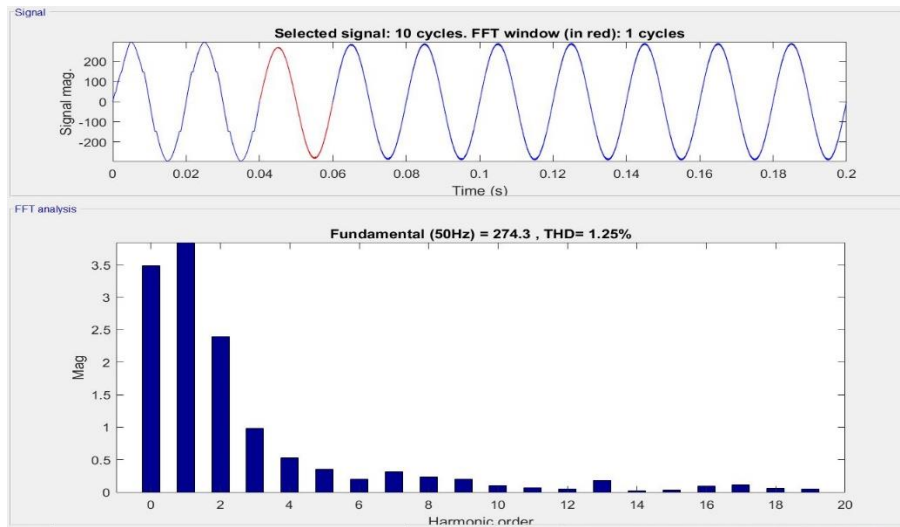


Figure 4.12 Output Filter Current when the Modified p-q Theory is applied

4.5 Validation

the results of chosen hybrid filter in this thesis are compared to other types of filters to highlight the benefits of using the proposed design, the parameters are same as shown in Table 4.2. the results of the simulation of power filters are in Table 4.3 and the SHAPF (SAPF+LCL) give a better Harmonic limitation than others. To meet the lowest THD, others filters require a big size of passive filters.

Table 4.3. Comparison of THD for Different Filters

Filters	THD (%)
SAPF+ L_f	4.9
SAPF+L	3
SAPF + LC	2.2
SAPF+ LCL	1.25

The integration of renewable energies distribution generators should meet the following standards:

IEEE 519-1992 Standard: The application of the proposed design reduces THD under Harmonic's limit (THD < 5%).

IEEE 1547-2003 Standard: According Table 2.3, there is no clearing time required because the distorted voltage is [0.8-1.1] of base voltage. In Figure 4.13, the base grid voltage is about 300V, the distortion cause the voltage drops to 250V.

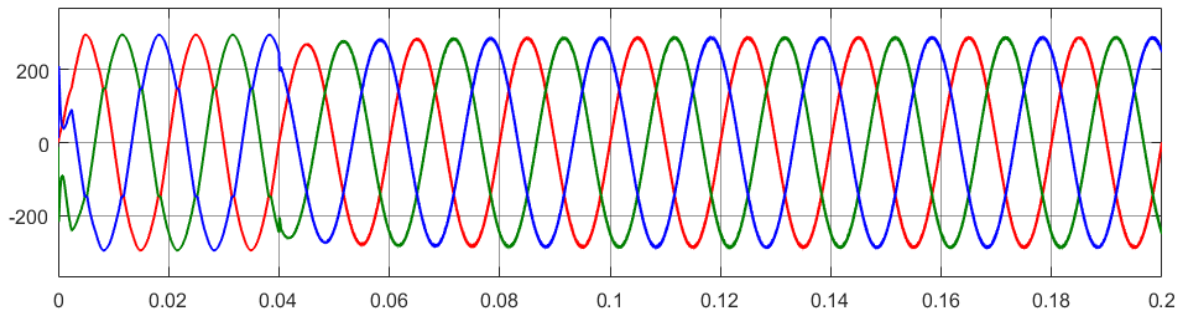


Figure 4.13. Grid Voltage distorted

4.6 Chapter Conclusion

In this chapter, the design of different parameters is defined, then the values of the mentioned parameters are calculated using the formulas defined in Chapter2 to validated the proposed design, the defined methodology is simulated in MATLAB Simulink as highlighted in Chapter3. The discussion of the obtained results is done to verify the given objects in Chapter1. The final conclusion will be given in next chapter.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The integration of Solar energy to the grid intensifies the energy supply capacity to the loads. The solar energy requires DC to AC conversion which involves the use of power electronics devices. In this work, the inverter is used as power active filter to mitigate the current harmonics in the grid. But without the proper control strategy, the Voltage Source Inverters (VSI) are also the source of the harmonics in the grid. It was highlighted in the literature review that the grid voltages harmonics, the high switching harmonics and DC link voltage harmonics are presented in VSC for solar grid-connected system

The conceptual framework was proposed in order to eliminate totally the harmonics in solar grid-connected system, to limit the harmonics in order to meet the international harmonics limitation's standards (IEEE519-1992 and IEEE 1547-2003). The work done on harmonics mitigation using different types of filters: Passive Filters (PF), Active power Filters (APF) and Hybrid filters are reviewed in the literature. For this work, VSC (Three-level/ Six switches) is the active power filter and the LCL passive filters active form the proposed hybrid active power filter (HAPF) in which the active power filters is connected in shunt to the grid eliminates the high-order harmonics and compensate the reactive powers while the passive filters, LCL filters the low-order harmonics. Before the simulation of the chosen design, the modelling of the PV-HAPF's parts are done.

MPPT is the important key for the quality of solar panels power output under variations weather conditions instantaneously. In results of P&O algorithm and PSO algorithm in Matlab/SIMULINK shown that the P&O algorithm has the easy implementation and less power losses, P&O tracks quickly the maximum power point quickly and successfully irrespective of fluctuations while PSO algorithm requires complex adjustment and had some significant power losses.

The time domain is preferred to frequency domain in this thesis. The instantaneous p-q theory is reviewed deeply, and the sinusoidal PWM is for gate signal for VSC. During MatLab/SIMULINK; the PV-HAPF without control system of APF presented total harmonic distortion of 34.4%. Once the basic p-q theory is applied, THD is reduced to 4.68%, THD is decreased more to 1.25% when the Modified p-q theory is used to control the APF of the proposed design of PV-HAPF. As long the THD is closely to zero percent, the outputs current of VSC is sinusoidal which has a power factor (P.F) near to unit this means a good compensation of the reactive power. It can conclude that the proper control of VSC plays an important role in the

integration of distributed generation to the grid though harmonic's limitations at point of common coupling (PCC) when the renewable energies are available, then the VSC can be the APFs and compensate the reactive power in absence of power supply from renewable energy. This works is limited only on MatLab/SIMULINK simulation.

5.2 Contribution

i) Rwanda energy sector strategic Plan 2023/2024 target is to provide 100% for electric access for household, with the increase number of connection to the national grid. This will increase the number of the power plants connected to the grid. As the harmonics are the main challenges for the grid, hybrid active filter in 250kW solar power grid-connected system is a good feasibility project for the micro-grid with the better harmonics limitation. Thus, this study will assist in reducing losses in the commercial sector's transmission, distribution, and distribution networks as well as in achieving the ESSP's high level goal aim on improving the reliability of the energy supply.

ii) The design of control system of HAPF which works under balanced grid voltages and distorted one as the solar power plants are under start up projects .

5.3 Future Work

The design power filters in solar energy grid-connected has the multi-functionality for the power quality on the power system. However, the Power transfer from PV panels to the grid pass through power converters which presents a quantity of power losses and quite expensive. The following recommendations for future works are given at end of this work:

i) The study on to maximize the power transfer from solar energy so they will be dependable source of energy.

ii) To reduce the power filters of harmonics mitigation only in power system in order to reduce the nonlinear loads connected to the grid.

iii) To simulate the design in hardware for the solar power plant project in the future.

REFERENCES

- [1] Bhubaneswari Parida et al, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, Elsevier, vol. 15, no. 1, pp. 1625-1633,, January 2011.
- [2] Agmar F. et AL, "Economic Overview of the Use and Production of Photovoltaic Solar Energy in Brazil," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 181-191, 2018.
- [3] Chowdhury A. H et al, "System and Cost Analysis of Stand-Alone Solar Home System Applied to a Developing Country.," *Sustainability*, MDPI, vol. 11, no. 1403, pp. 1-13, 2019.
- [4] Blaabjerg et al, "Power Electronics and Reliability in Renewable Energy Systems," *IEEE International Symposium on Industrial Electronics*, pp. 19-30, 2012.
- [5] Olusayo A et al, "Harmonic Control Strategies of Utility-Scale Photovoltaic Inverters," *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH*, vol. 8, no. 3, pp. 1355-1368, 2018.
- [6] Eklas Hossain et al, "Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices," *IEEE Access*, 2018.
- [7] Peter Musau Moses, "Renewable Energy Integration , lecture notes," *ACEESD/CST/Univeristy of Rwanda*, 2021.
- [8] Kamran Zeb et al, "A Comprehensive Review on Inverter Topologies and Control Strategies for Grid- Connected Photovoltaic System," *Renewable and Sustainable Energy Reviews*, pp. 1120 - 1141, 2018.
- [9] Edjadessamam AKORO et al, "Different Topologies of Three-Phase Grid Connected Inverter for Photovoltaic Systems, a Reveiw," *Sciences Appliquées et de l'Ingénieur*, vol. 2, no. 2, pp. 33-41, 2017.
- [10] Bhim Singh et al, "A Review of Active Filters for Power Quality Improvement," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 46, no. 5, pp. 960-971, 1999.
- [11] Andalib Bin K et al, "Harmonic Mitigation Through Advanced Control Methods for Grid- Connected Renewable Energy Sources," *2017 IEEE- Industry Applications Society Annual meeting*, pp. 1 -12, 2017.
- [12] Zainal Salam et al, "Harmonics Mitigation Using Active Power Filter: A Technological Review," *ELEKTRIKA*,, vol. 8, no. 2, pp. 17-26, 2006.
- [13] Hao Xue and Jihong Z, "Optimum Design of LCL Filter Parameters for Photovoltaic Inverters," *Advances in Computer Science Research (ACSR), 3rd International Conference on Computer Engineering*,, vol. 49, pp. 455 -458, 2019.
- [14] H. Kahlane et al, "LCL Filter Design for Photovoltaic Grid -Connected Systems," *Revue des Energies Renouvelables SIENR'14 Ghardaïa*, pp. 227-232, 2014.

- [15] Jauhari M. et al, "Control Design for Shunt Active Power Filter Based on p-q Theory in Photovoltaic Grid- Connected System," *International Journal of Power Electronics and Drive System (IJPEDS)*, vol. 9, no. 3, pp. 1064 - 1071, September 2018.
- [16] Rachid Belaidi et al, "Shunt Active Power Filter Connected to a Photovoltaic Array for Compensating Harmonics and Reactive Power Simultaneously," *IEEE, 4th International Conference on Power Engineering, Energy and Electrical Drives*, pp. 1482-1486, 2013.
- [17] Irfan Ali et al, "Control Techniques for Active Power Filter for Harmonic Elimination & Power Quality Improvement," *International Journal Of Electrical, Electronics And Data Communicati*, vol. 4, no. 10, pp. 25-31, Oct.-2016.
- [18] Chandani M. Chovatia et al, "Power Quality Improvement in a PV Panel Connected System Using Shunt Active Filter," *International Journal of Computer Technology and Electronics Engineering (IJCTEE)*, vol. 2, no. 4, pp. 41 -45, August 2012.
- [19] Ayoub Benzahia et al, "A PV Powered Shunt Active Power Filter for Power Quality Improvement," *Global Energy Interconnection Development and Cooperation Organization*, vol. 2, no. 2, pp. 143-149, 2019.
- [20] Răzvan-Daniel Albu and Daniel, "Hybrid Active Power Filter Connected to a Photovoltaic Array," *Journal of Electrical and Electronics Engineering*, vol. 2, no. 1, pp. 109- 112, 2009.
- [21] Abdallah A. Smadi et al, "Distribution System Harmonic Mitigation Using a PV System with Hybrid Active Filter Features," *IEEE, North American Power Symposium (NAPS)*, 2019.
- [22] Zainal Salam et al, "Harmonics Mitigation Using Active Power Filter: A Technological Review," *ELEKTRIKA*, vol. 8, no. 2, pp. 17-26, 2006.
- [23] Kamran Zeb et al, ""A Comprehensive Review on Inverter Topologies and Control Strategies for Grid- Connected Photovoltaic System," *Renewable and Sustainable Energy Reviews.*, vol. 94, pp. 1120-1141, 2018.
- [24] B. Kavya Santhoshi et al, "Critical Review of PV Grid-Tied Inverters," *energies, MDPI*, vol. 12, no. 1921, pp. 1-26, 2019.
- [25] Musa Yusup Lada et al, "Simulation a Shunt Active Power Filter using MATLAB/Simulink," *The 4th International Power Engineering and Optimization Conf. (PEOCO2010)*, pp. 371-375, June 2010.
- [26] Luis Morán, "41. Active Power Filters," in *Power electronics HandBook (Fourth Edition)*, ScienceDirect, 2018, pp. 1341-1377.
- [27] Unnikrishnan A. K. et al, "Shunt hybrid active power filter for harmonic mitigation: A practical design approach," *Indian Academy of Sciences*, vol. 40, no. 4, pp. 1257-1272, June 2015.
- [28] Rachid Belaidi et al, "Shunt Active Power Filter Connected to a Photovoltaic Array for Compensating Harmonics and Reactive Power Simultaneously," *IEEE, 4th International Conference on Power Engineering, Energy and Electrical Drives*, pp. 1482-1486, 2013.

- [29] Hao Xue and Jihong Zhang, "Optimum Design of LCL Filter Parameters for Photovoltaic Inverters," *Advances in Computer Science Research (ACSR), 3rd International Conference on Computer Engineering Information Science & Application Technology (ICCIA 2019)*, vol. 90, pp. 455-458, 2019.
- [30] T. Demirdelen et al, "Simulation Modelling And Analysis Of Modular Cascaded Multilevel Converter Based Shunt Hybrid Active Power Filter For Large Scale Photovoltaic System Interconnection," *Simulation Modelling Practice and Theory*, vol. 71, pp. 27-44, 2017.
- [31] Ayman Blorfan et al, "A Three-Phase Hybrid Active Power Filter with Photovoltaic Generation and Hysteresis Current Control," *IEEE*, pp. 4316-4321, 2016.
- [32] XianyongXu et al, ""Control Strategy of Photovoltaic Generation Inverter Grid-Connected Operating and Harmonic Elimination Hybrid System," *2nd International Conference on Power and Renewable Energy*, pp. 886-890, 2017.
- [33] B.Neelakanteshwar Rao et al, "Mitigation of Photovoltaic Solar System Harmonics using Shunt Active Power Filter," *e Fourth International Conference on Computing Methodologies and Communication (ICCMC 2020)*, pp. 566-571, 2020.
- [34] Wajahat Ullah Tareen et al, ""Active power filter (APF) for Mitigation of Power Quality Issues in Grid Integration of Wind and Photovoltaic Energy Conversion System," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 635-655, 2017.

Design of Hybrid Active Power Filters (HAPFs) for Grid-Connected Photovoltaic Systems Using Modified p-q theory

Manishirwe Benedict
*African Center of Excellence in
 Energy for Sustainable Development,
 University of Rwanda,
 Kigali, Rwanda
 benoit251@gmail.com*

Peter Mwanu Moses
*Department of Electrical
 and Information Engineering,
 South Eastern Kenya University,
 Kitui, Kenya
 pmrasyoki@seku.ac.ke*

ABSTRACT: DC-AC converters in PV grid-connected systems are for power conversion and the interface point to the grid. They are also the active power filters because of their ability to eliminate the harmonics in power systems and compensate the reactive power for the nonlinear loads connected to the grid. However, the active power filters present disadvantages to the grid. To overcome its drawbacks, the hybrid active filters are introduced but without a proper control strategy of active power, the passive part of the hybrid active filter requires a big size which causes the resonance problem between the inductance and the grid. In this paper, the modified p-q theory control strategy of active power filter is applied where MATLAB/Simulink gives a THD current of 0.97% which meet IEEE 519-1992 standards to connect solar PV systems to the grid.

KEYWORDS— harmonics, hybrid active power filters, modified p-q theory

I. INTRODUCTION

Solar energy technologies are being developed since they are a renewable energy source that gives a promise sustainable energy. Sunlight emits about 1.8×10^{11} MW on the earth's surface per day which is great than worldwide energy consumption [1]. The photovoltaic (PV) system is on the top for solar energy conversion to electrical energy. The solar off-grid systems entered the market before the grid-connected solar systems.

The integration of Renewable Energy Generators (REGs) occurs in the grid. The power DC-AC converter is the interface point of the PV system to the Point of Common Coupling (PCC). The power converter classified as an Active Power Filter (APF) is an inverter that could be connected in shunt or in series to the grid depending on the type of harmonics to filter [1, 2, 3, 4]. The inverter in a PV grid-connected system is an APF. The output currents of inverters have harmonics due to the high switching frequency of power electronic switches used in power converters. The harmonics in the power system are a critical challenge for the power quality of the grid. Passive Filters (PFs) are used to filter the harmonics in the beginning, but those filters present the disadvantages of the big size of inductances and high cost. In the '90s, the power converters started being used as APFs

because they can filter the harmonics present in the power system, but they still have harmonics in their outputs.

The combination of APF (PV-inverter) and PF forms the Hybrid Active Power Filter (HAPF) in a PV grid-connected system. The Hybrid Active Filter is the best solution as the large size of the Passive Filter is reduced, and the Passive Filter eliminates the harmonics from the inverters. To integrate solar PV systems into the grid, IEEE 519-1992 standard should be met, without a control strategy of APF, the abovementioned drawbacks of PFs will appear. This paper proposes the application of modified p-q theory control in three-phase HAPFs as it presents benefits in harmonic mitigation in PV grid-connected systems.

Contribution: This paper aims to mitigate harmonics in solar PV grid-connected using hybrid active filters with modified p-q theory.

Organization: The present work is organized as follows; Section I is the background and problem statement of HAPFs in PV grid-connected to meet IEEE 519 requirements, Section II covers the literature view, and Section III presents the methodology and algorithm for the proposed design, then Section IV detailed the proposed design with its control circuits. The results of MATLAB simulation with related discussion are presented in Section V. Lastly, Section VI is for the conclusion of the work.

II. LITERATURE REVIEW

A. Harmonics in PV Grid-Connected System

The harmonics have the frequency which are the multiples of the fundamental frequency (50 or 60 Hz). The high switching frequency of PED switches and the harmonics coming from the nonlinear loads are the major sources of harmonics in solar power plants. The Total Harmonics Distortion (THD) at PCC should not exceed 5%.

B. Active Power Filters

For the active part of HAPF in PV grid-connected, Shunt Active Power Filter (SAFP) is most used than Series Active Power Filter (SAAPF) because SAFP has the current harmonics filtering and reactive power compensation abilities [6, 7, 8, 9]. The APF receives a firing signal according to the sensed grid voltages and load currents to generate the compensated current to harmonic currents with the shift of 180° . [10] detailed the topologies APF: three-

phase three wires inverter, three-phase four wires inverter, three-phase five wires inverter, three-phase six wires inverter, three-phase seven wires inverter, Multilevel Inverter Diode Clamped (DCMLI), Flying Capacitor MLI(FCMLI), cascade H-bridge MLI, three-phase inverter with stabilization, Three-phase parallel inverter. The authors in [11] classified the PV-inverters according to the inverter's stage: single-stage or multi-stage.

APF in a PV system has three main control circuits to ensure active filtering characteristics and supply power from the PV array, which are:

DC-Link Voltage Control: to keep the V_{dc} at the required level for reference voltage, the circuit uses one of the controllers (PI, PR, RC, sliding mode) depending on the current controller according to the authors in [5] but the PI and Sliding mode controllers are preferred as they allow the power transfer between the PV array and the grid.

Current Control Circuit: the generation compensating current controller which is either frequency domain or time domain. Fast Fourier Transform (FFT) is a common control technique used in the frequency domain to generate reference current while the time domain uses basically Synchronous Reference Frame (SRF), Fuzzy Logic, and Instantaneous reactive power theory known as p-q theory, to generate the reference currents and voltages [12, 13, 14, 15].

Signal Conditioning: the generation of the firing signal uses either the Pulse Width Modulation (PWM) techniques or Hysteresis Current Control (HCC) to generate the gate signals [15]. Refs [16, 17, 18, 19] use PWM techniques while authors in [9] use the HCC techniques.

C. Passive Filter

The passive filtering part of HAPF is composed of the resistor (R), inductor (L), and capacitor elements (C). PFs are for eliminating the low order harmonics in outputs of APF and coming from load currents of nonlinear loads. They are low pass or high pass according to the emplacement of the capacitor to the resistor. For High Pass Filters (HPF), the resistor is followed by the capacitor and its operating frequency is higher than the cut-off frequency. In a Low Pass Filter (LPF), the source is connected to the resistor, the capacitor is in the output port, and the frequency below the cut-off frequency passes through it. Passive filters could be in different forms; tuned, first-order, second order. Inductance-Capacitance-Inductance (LCL) type of filter is more used than inductance (L) type of filters because LCL has small total inductance than the L-type filters of the same rate to avoid the resonance problems between grid and filter, the damping resistance are proposed for passive filter [20, 21, 22, 23].

The aim of this work is to control the APF of PV-HAPF using the p-q theory in distorted voltage sources to eliminate harmonics in PV grid-connected systems. PI controller gives the best choice as it enables the power exchange between the PV system and grid while other controllers consider PV the

stem as a DC source only. The control strategies of APF are proposed in the next section.

III. METHODOLOGY

Many control methods of PV-HAPF had been studied to minimize the Total Harmonics Distortion of APF. The previous methodologies applied are discussed in this section, and the present methodology is mapped to the problem.

A. Previous Methods

The studies on harmonic mitigation in power systems using hybrid power filters are done. The control strategies of Shunt APFs in PV grid-connected are studied in order to give the Voltage Source Inverter (VSI) of the system the injection of active power abilities plus harmonics mitigation and reactive power compensation. The authors in [5, 6, 8, 15, 16, 19] used p-q theory control for VSI where THD in outputs of SAPP is less than 5% to affect the power network. The multilevel VSI gives a good performance for solar systems, in [6], the HAPF reduces THD from 29.9% to 1.44%, the generation firing angle is done by HCC [8] and Carrier-based PWM [19]. The simulation gives a good result even if the grid voltages are considered balanced and sinusoidal.

B. Mapping the Method to the Problem.

The integration of renewable sources into the grid aims to supply stable and sinusoidal power. Voltage Source Converters (VSCs) in PV systems are for power conversion of the PV system from DC to AC, ensuring reactive power compensation and current harmonics mitigation. The p-q theory was introduced firstly by Akagi in 1983, this theory consists of matrix transformation of a,b,c to 0, α , β known as Clark's transformation, three-phase voltages (V_a, V_b, V_c) are mapped into instantaneous voltages (V_0, V_α, V_β) [24]. The p-q theory controller offers various advantages: easy implantation, flexibility, instantaneous calculation of power, selection of undesirable power components to be compensated, drawing a sinusoidal current from the source [25], and the separation of zero-sequence components into the zero sequence axis. It is impossible to optimize those advantages simultaneously using p-q theory when the voltages at PCC are unbalanced or/and distorted. The current technique available is a Phase Lock Loop (PLL) technique [26]. The best option for ensuring the decoupling of current and distorted voltages at the PCC is PLL, which detects the positive sequence of distorted voltages(V^+). This means that the PLL circuit eliminates the effect of other loads on the performance of the shunt filter. The p-q algorithm gives either constant instantaneous power instantaneously or a sinusoidal current from the PV system to maintain the unit power factor.

IV. PROBLEM FORMULATION

This section contains the basic p-q theory and the modified p-q theory where the basic p-q theory is modified by inserting the PLL circuit at inputs of the grid voltages. This works under distorted /unbalanced voltages.

A. Mathematical Model of Basic p-q Theory

In Clark's transformation, the source voltages (v_a, v_b, v_c) and load currents (i_{La}, i_{Lb}, i_{Lc}) have similar transformations. v_a, v_b, v_c are transformed into (v_0, v_α, v_β) and similarly the

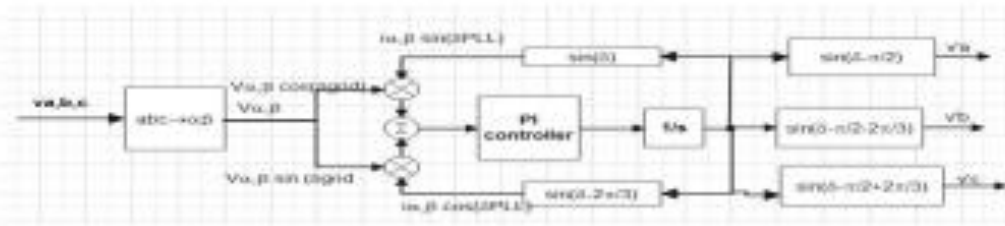


Fig. 1. PLL Circuit

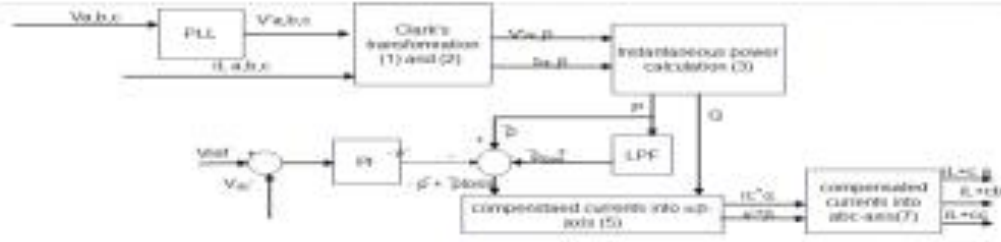


Fig. 2. Modified p-q theory

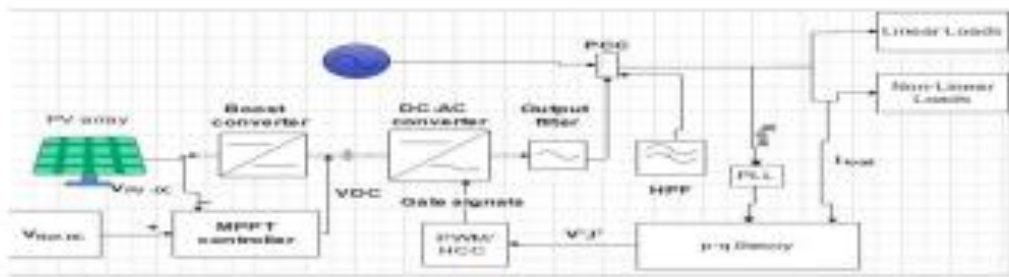


Fig. 3. Proposed PV-HAPF design

There is a significant change in waveforms when the p-q theory is applied to the designed HAPF as highlighted in Fig. 4. Where the distorted current waveform (look case a) becomes a sinusoidal one (look case. b) with huge reduction in THD current.

TABLE I. RESULTS OF THE SIMULATIONS

Filtration Characteristic	Total Distortion Current (%)	Harmonic
Without Filter	30.65	
Hybrid Active Power Filter with basic p-q theory	1.25	
Hybrid Active Power Filter with modified p-q theory	0.87	

VI. CONCLUSION

The p-q theory control method is applied in the proposed HAPF so they could give the sinusoidal and balanced currents to compensate for the presented current harmonics in the power system. The distorted balanced grid voltages lead to the power quality problem of addition harmonics in HAPFs, this reduces this performance in harmonic elimination for the power system. Modified p-q theory control gives the best optimal THD compared to basic p-q theory to control the active filter of HAPF designed as stipulated in IEEE519 standards to interconnect Distributed generation to the grid. The compensated current from HAPF's is nearly sinusoidal as THD is under IEEE 519.

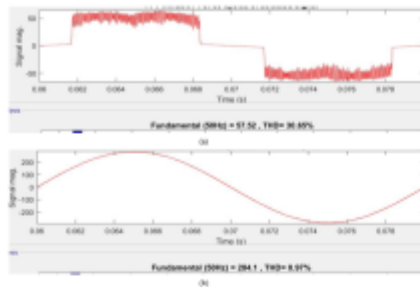


Fig. 4. Comparison of current waveform: case(a) Hybrid Active Power Filter without control and case (b) Hybrid Active Power Filter with modified p-q theory controller.

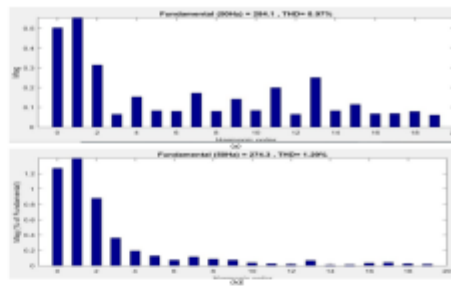


Fig.5. Comparison of Total Harmonic Distortion Currents between the application of modified p-q theory case(a) and basic p-q theory case.(b)

REFERENCES

- [1] Olusayo Adekunle et al, "Harmonic Control Strategies of Utility-Scale Photovoltaic Inverters," *International Journal of Renewable Energy Research*, vol. 8, no. 3, pp. 1354-1368, 2018.
- [2] S. e. al, "Characterisation and Assessment of the Harmonic Emission of Grid-connected Photovoltaic Systems," *IEEE Russia Power Tech*, pp. 1-7, 2008.
- [3] B. K. S. e. al, "Critical Review of PV Grid-Tied Inverters," *MPDI*, vol. 12, no. 1921, pp. 1-26, 2019.
- [4] A. V. e. al, "Invertet and PWM Control Technique suitable for Renewable Energy Applications," *International Conference-RARE 2020*, pp. 1-7, 2020.
- [5] X. L. a. Andalib-Bin-Karim, "Harmonic mitigation through advanced control methods for grid-connected renewable energy sources," *IEEE-Industry Applications Society Annual meeting*, vol. 8, no. 1, pp. 1-12, 2017.
- [6] Wajahat Ullah Tareen et al, "Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 635-655, 2017.
- [7] Sabir Ouchen et al, "Fuzzy-predictive direct power control implementation of a grid-connected photovoltaic system, associated with an active power filter," *Energy Conversion and Management*, vol. 122, pp. 515-525, 15 August 2016.
- [8] M. Tunay et al, "Simulation modeling and analysis of modular cascaded multilevel converter based shunt hybrid active power filter for large scale photovoltaic system interconnection," *Simulation Modelling Practice and Theory*, vol. 71, pp. 27-44, 2017.
- [9] V.N Jayasankar and U Viratha, "Advanced control approach for shunt active power filter interfacing wind-solar hybrid renewable system to the distribution grid," *Journal of Electrical Systems*, 2018, *Vol.14*, 2, pp.88-102, vol. 14, no. 2, pp. 88-102, 2018.
- [10] Kamran Zeb et al, "A comprehensive review on inverter topologies and control strategies for grid-connected photovoltaic system," *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 1120-1141, 2018.
- [11] Edjessam AKORO et al, "Different topologies of Three-phase grid-connected inverter for photovoltaic systems, a review," 2017.
- [12] P. M. Balasubramaniam et al, "An efficient control strategy of shunt active power filter for asymmetrical load condition using the time-domain approach," *Journal of Discrete Mathematical Sciences and Cryptography*.
- [15] Harneek Singh et al, "A Review on Shunt Active Power Filter Control Strategies," *International Journal of Engineering & Technology*, vol. 8, no. 4, pp. 121-125, 2018.
- [16] Demirdelen T. et al, "Review of Hybrid Active Power Filter Topologies and Controllers," *4th International Conference on Power Engineering, Energy and Electrical Drives Istanbul, Turkey*, pp. 587-592, 13-17 May 2013.
- [17] B. Kavya Santhoshi et al, "Critical Review of PV Grid-Tied Inverters," *energies*, *MDPI*, vol. 12, no. 1921, pp. 1-26, 2019.
- [18] Atal Viswas et al, "Inverter and PWM Control Technique suitable for Renewable Energy Applications," *International Conference - RARE 2020*, pp. 1-7, 2020.
- [19] R. Belaidi et al, "Improvement of the electrical energy quality using a Shunt Active Filter supplied by a photovoltaic generator," *Energy procedia*, vol. 6, pp. 522-530, 2011.
- [20] Vishwakarma et al, "A Comparative Study of PWM SchGrid-Connected Connected PV Cell," *7th International Conference on Power Electronics and Drive system*, pp. 1769-1775, 2007.
- [21] R.Raja et al, "Designing of LCL Filter and Stability AnalyThree-PhaseGrid-ConnectedConnected Inverter System," *International Journal of Science, Engineering and Technology Research (IJSETR)*, vol. 5, no. 1, pp. 306-312, January 2016.
- [22] Mohammad Hossein Mahlooji et al, "A review on modeling and control of grid-connected photovoltaic inverters with LCL filter," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 563-578, 2018.
- [23] Camilo C. Gomes et al, "Damping techniques for grid-connected voltage source convertes based on LCL filter: An overview," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 116-135, 2018.
- [24] R.N. Tripathi et al, "Design and control of LCL filter interfaced grid-connected solar photovoltaic (SPV) system using power balance theory," *Electrical Power and Energy Systems*, vol. 69, pp. 264-272, 2015.
- [25] Mariem Tajari et al, "Cascaded Multilevel Inverter for PV-Active Power Filter Combination into the Grid-Tied Solar System," *International Journal Of Renewable Energy Research*, vol. 10, no. 4, pp. 1-10, December 2020.
- [26] Ali et al, "Three-phase phase-locked loop synchronization algorithms for grid-connected renewable energy systems," *Renewable and Sustainable Energy Reviews*, 90, 434-452, vol. 90, pp. 434-452, 2018.

APPENDIX II: MATLAB FUNCTION OF CLARK'S TRANSFORMATION (ABC TO AB0) AXIS

```
function[V_alpha,V_beta, I_alpha,I_beta]= bctobeta(Va,Vb,Vc,ILa,ILb,ILc)
```

```
V_alpha=(Va-Vb/2-Vc/2)*sqrt(2/3);
```

```
V_beta=(Vb-Vc)/sqrt(2);
```

```
I_alpha=(ILa-ILb/2-ILc/2)*sqrt(2/3);
```

```
I_beta=(ILb-ILc)/sqrt(2);
```

Matlab Function of instantaneous power calculation

```
function [P,Q]= instantenousPower(V_alpha,V_beta, I_alpha,I_beta)
```

```
P= V_alpha*I_alpha + V_beta* I_beta;
```

```
Q= -V_beta* I_alpha + V_alpha*I_beta;
```

Matlab Function of inverse of Clark's transformation ($\alpha\beta 0$ to abc axis)

```
function [Ica,Icb,Icc] = compensatedcurrent(V_alpha,V_beta, P,Q)
```

```
I_alpha=(V_alpha.*P+V_beta.*Q)/(V_alpha.^2+V_beta.^2);
```

```
I_beta=(V_beta.*P-V_alpha.*Q)/(V_alpha.^2+V_beta.^2);
```

```
Ica=sqrt(2/3)*(I_alpha);
```

```
Icb=sqrt(2/3)*(-I_alpha/2+sqrt(3)*I_beta/2);
```

```
Icc=sqrt(2/3)*(-I_alpha/2-I_beta*sqrt(3)/2)
```

APPENDIX III: MATLAB FUNCTION FOR PSO ALGORITHM

```
function D = PSO(Vpv,Ipv)
```

```
%#codegen
```

```
persistent u;
persistent dcurrent;
persistent pbest;
persistent p;
persistent dc;
persistent v;
persistent counter;
persistent gbest;
if(isempty(counter))
    counter=0;
end
if(isempty(dcurrent))
    dcurrent=0.5;
end
if(isempty(gbest))
    gbest=0.5;
end
if(isempty(p))
    p=zeros(4,1);
end

if(isempty(v))
    v=zeros(4,1);
end

if(isempty(pbest))
    pbest=zeros(4,1);
end
if(isempty(u))
    u=0;
end
if(isempty(dc))
    dc=zeros(4,1);
    dc(1)=0;
```

```

    dc(2)=0.3;
    dc(3)=0.5;
    dc(4)=0.9;
end
if(counter>=1 && counter<300)
    D=dcurrent;
    counter=counter+1;
    return;
end
counter=0;

if(u>=1 && u<=4)
    if((Vpv*Ipv)>p(u))
        p(u)=Vpv*Ipv;
        pbest(u)=dcurrent;
    end
end
u=u+1;
if(u==6)
    u=1;
end
if(u==1)
    D=dc(u);
    dcurrent=D;
    counter=1;
    return;
elseif(u==2)
    D=dc(u);
    dcurrent=D;
    counter=1;
    return;
elseif(u==3)
    D=dc(u);
    dcurrent=D;

```

```

    counter=1;
    return;
elseif(u==4)
    D=dc(u);
    dcurrent=D;
    counter=1;
    return;
elseif(u==5 )
    [m,i]=max(p);
    gbest=pbest(i);
    D=gbest;
    dcurrent=D;
    counter=1;
    %update velocity and duty cycle
    v(1)=updatevelocity(v(1),pbest(1),dc(1),gbest)
    v(2)=updatevelocity(v(2),pbest(2),dc(2),gbest)
    v(3)=updatevelocity(v(3),pbest(3),dc(3),gbest)
    v(4)=updatevelocity(v(4),pbest(4),dc(4),gbest)
    %update duty cycle
    dc(1)=updateduty(dc(1),v(1))
    dc(2)=updateduty(dc(2),v(2))
    dc(3)=updateduty(dc(3),v(3))
    dc(4)=updateduty(dc(4),v(4))

    return;

else
    u
    y='hello'
    D=0.1

end

end

```

```

function vfinal=updatevelocity(velocity,pobest,d,gwbest)
% PSO Parameters
w=0.4;
% w=(1.1-(pobest/gwbest));      % Inertia Weight
    % Inertia Weight Damping Ratio
c1=1.2;    % Personal Learning Coefficient
c2=2;     % Global Learning Coefficient

% If you would like to use Constriction Coefficients for PSO,
% uncomment the following block and comment the above set of parameters.

% % Constriction Coefficients
% phi1=2.05;
% phi2=2.05;
% phi=phi1+phi2;
% chi=2/(phi-2+sqrt(phi^2-4*phi));
% w=chi;    % Inertia Weight
% wdamp=1;  % Inertia Weight Damping Ratio
% c1=chi*phi1; % Personal Learning Coefficient
% c2=chi*phi2; % Global Learning Coefficient
vfinal = (w*velocity)+(c1*rand(1)*(pobest-d))+(c2*rand(1)*(gwbest-d));
end

function dfinal=updateduty(d,velocity)
dup=d+velocity;
if(dup>1)
    dfinal=1;
elseif(dup<0)
    dfinal=0;
else
    dfinal=dup;
end
end

```

APPENDIX IV: MATLAB FUNCTION FOR P&O ALGORITHM

```
function Vref= PO(V,I)
Vrefmax=1;
Vrefmin=0.5;
Vrefinit=0.0;
deltaVref=1e-5;
persistent Vold Pold Vrefold;

dataType='double';
if isempty(Vold)
    Vold =0;
    Pold=0;
    Vrefold=Vrefinit;
end

V=29;
I=7.35;
P= V * I;
dV=V- Vold;
dP= P- Pold;

if dP ~=0
    if dP<0
        if dV<0
```

```

    Vref =Vrefold+deltaVref;
else
    Vref =Vrefold-deltaVref;
end
else
if dV<0
    Vref =Vrefold-deltaVref;
else
    Vref =Vrefold+deltaVref;
end
end

else Vref=Vrefold;
end
if Vref >=Vrefmax |Vref<=Vrefmin
    Vref =Vrefold;
end
Vrefold= Vref;
Vold= V;
Pold= P;

```

APPENDIX V: TURNITIN REPORT



UNIVERSITY of RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY



AFRICAN CENTER OF EXCELLENCE ENERGY FOR SUSTAINABLE DEVELOPMENT

TOTAL ELIMINATION OF HARMONICS IN GRID-CONNECTED SOLAR ENERGY

By

MANISHIMWE Benedicte

Reg. N.0:220012106

A Thesis Submitted to the African Centre of Excellence in Energy for Sustainable Development (ACE-ESD)

College of Science and Technology (CST), University of Rwanda

In Partial Fulfilment of the Requirement

BENEDICTE

ORIGINALITY REPORT

21%

SIMILARITY INDEX

13%

INTERNET SOURCES

15%

PUBLICATIONS

8%

STUDENT PAPERS

PRIMARY SOURCES

1

Manishimwe Benedicte, Peter Musau Moses. "Design of Hybrid Active Power Filters (HAPFs) for Grid-Connected Photovoltaic Systems Using Modified p-q theory", 2022 IEEE PES/IAS PowerAfrica, 2022

Publication

3%

Manishimwe Benedicte
09/10/23