HARMONICS ELIMINATION TECHNIQUES IN SOLAR ENERGY INTEGRATION INTO SMART GRID

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ABSTRACT

HARMONICS ELIMINATION TECHNIQUES IN SOLAR ENERGY INTEGRATION INTO SMART GRID

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(MSc Sustainable Environment and Energy Systems)

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Energy availability is a growing concern of the 21st century worldwide and generating this energy should not affect the envinment and its inhabitants negatively. The modern energy transmission and distribution system became more interesting with the advent of smart grid and integrating renewable energy sources into the grid creates a challenging problem of managing harmonics. To effectively integrate renewable energy as well as minimizing harmonics content in the power system smart grid importance was highlighted, with value of harmonic current content measured by the total harmonic distortion (THD) based on electrical system rated current value. This thesis is aimed towards reviewing the available techniques in reducing the harmonic distortions for effective and efficient transmission of renewable energy in smart grid integration. The use of an improved control strategy was proposed which significantly improves the effectiveness of harmonic elimination in smart grid systems. The two-level and there-level inverters in solar integration to the smart grid were studied, thereby presented a controlled hydrid filtering technique that implemented three-level inverter, that provides effective means of harmonics elimination. There was significant improvement of over twenty percent in the use of three-level inverter against two-level, even with the about 25% reduction in cost, the two-level inverter losses over forty percent of power as compared to three-level. With tens of thousands of grid connected inverters globally, the cost of three-level ineverter will achieved over 15% lower cost compared with the two-level topology in just a year. Matlab/Simulink software was use to simulate the model using passive, active and hybrid filter with and without control and the hybrid method with control showed the lowest THD value, which was within acceptable limits.

KEYWORD Hybrid filter, Total Harmonic Distortion, Transmission & Distribution System, Smart Grid

ÖZ

Enerji mevcudiyeti, dünya genelinde 21. yüzyılda artan bir endişedir ve bu enerji üretiminin çevreyi ve onun sakinlerini olumsuz yönde etkilememesi gerekmektedir. Modern enerji iletim ve dağıtım sistemleri akıllı şebekenin ortaya çıkmasıyla daha ilginç hale geldi. Yenilenebilir enerji kaynaklardan elde edilen kesintili enerjiyi şebekeye entegre etmek harmoniklerden kaynaklanan kalite sorunları yaratır. Bundan dolayı, bu çalışmada yenilenebilir enerjiyi etkili bir şekilde entegre etmek ve güç sistemi içindeki harmonik içeriğini en aza indirmek için, elektrik sistemi anma akımı değerine dayalı olarak toplam harmonik bozulma ile ölçülen harmonik akım içeriğinin değeriyle vurgulanmıştır. Bu tez, sunulan tekniklerin etkinliğini artırmak için kontrol stratejisinin kullanılmasını içeren akıllı şebeke entegrasyonunda yenilenebilir enerjinin etkin ve verimli iletimi için harmonik bozulmaların azaltılmasındaki mevcut tekniklerin gözden geçirilmesini amaçlamaktadır. Akıllı şebekeye güneş enerjisi entegrasyonunda iki seviyeli ve orada seviyedeki invertörler daha iyi incelenmiş ve böylece harmoniklerin ortadan kaldırılması tekniklerinin etkili araçlarının bir incelemesini sunmuştur. Üç seviyeli invertör kullanımında, iki seviyeye oranla yüzde yirmiden az harmonic oluşumu gözlemlenmiş; ayrıca üç seviyeli invertörlerin, güç kayıpları bazında, iki seviyeye kıyasla yüzde kırkın üzerinde kayda değer bir gelişme gösterdiği gözlemlernmiştir. Çalışma içerisinde pasif, aktif, hibrit filtreler ile filtresiz simülasyonları tamamlamak için MATLAB / Simulink yazılımı kullanılmış ve en düşük harmonic bozulma değerini göstermiştir.

Anahtar Kelimeler: Hibrit filtre, Toplam Harmonik Bozulma, İletim ve Dağıtım Sistemi, Akıllı Şebeke.

DEDICATION

To the memory of my late father May Almighty Allah have mercy on him (Aamin).

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ABBREVIATION

AC	Alternating current
AMI	Advanced metering infrastructure
CSI	Current source inverter
CSP	Concentrated solar power
DC	Direct current
Gtoe	Gigatonne of oil equivalent
HRES	Hybrid renewable energy sources
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistor
IMP	Internal mode principle
kW	kilowatt
MOSFET	Metal oxide semiconductor field effect transistor
MPPT	Maximum power point tracking
MW	Megawatt
PF	Power factor
PV	Photovoltaic
PWM	Pulse width modulation
RES	Renewable energy source

SHEPWM	Selective harmonic elimination pulse width modulation
SMT	Solar module tester
STC	Standard test condition
TD	Transmission and distribution
TDD	Total demand distortion
THD	Total harmonic distortion
VSI	Voltage source inverter

CHAPTER 1

INTRODUCTION

1.1 Background

The most important issue in managing electricity is having effective and efficient transmission and distribution (TD) system, that would accounts for the most of energy losses (Navani, Sharma, & Sapra, 2012). In general TD system refers to the various steps in moving generated electricity from generating stations to the end user. Transmission is actually the bulk carrying of electrical energy from its generating station, for example, from power plant to electrical power substation. Distribution is the step of carrying electricity from a substation to end users or can be referred to as the last step in electrical power delivery. The main aim of the transmission system is the interconnection of power generating systems efficiently to end users or loads (Padiyar, 2007). The networking of all steps involved in power generation and its final delivery to consumers is made possible by the electrical grid, which has been overstretched about 9200 worldwide, supplying over 1 million megawatts daily and over three hundred thousand miles connections of transmission lines (Ahmed Abdulkadir & Al-Turjman, 2018; Khan & Riaz, 2016). These ever increasing burdens on the grid with the need to have improved efficiency in energy management led to the development of an effective and robust grid that provides two-way information called the smart grid.

Smart grid is defined as a network that intelligently integrates the power generators with customers to transmit electricity efficiently. It allows for sufficient distribution of electricity in terms of better area coverage, reliability, adequate capacity, safety, economic, as well as in sustainability (Ahmed Abdulkadir & Al-Turjman, 2018). The smart grid system consists of four mojor parts namely; generating stations, transmitting systems, distributing systems and end-users or consumers. The smart grid allows the integration of renewable sources of power generation such as solar and wind. The advent of the Advanced Metering Infrastructure (AMI) enables the smart grid to achieve two-way communication that benefits both the utility providers and consumers. Energy losses resulting from long-distance transmission of energy is significantly lowered by utilizing the High Voltage Direct Current (HVDC) technology, which can provide high efficiency in the transmission of energy at distances beyond hundreds of miles (Ahmed Abdulkadir & Al-Turjman, 2018; Lavanya G, Dr K Sambath, Sudha S, Sindhu S, 2016).

World energy demand is continuously increasing as countries globally aim to boost their economic growth. Renewable energy will improve global energy requirements significantly as conventional energy sources constantly fall short as its availability is decreasing (Chow, 2003; Johansson, Kelly, Reddy, & Burnham, 1993).

Presently renewable energy sources provide over 10% of total energy consumed in the world as shown in Figure 1, and, before the end of the 21st century, renewable energy will provide more than half of the electricity requirements globally with the reduction of more than one-third of the reliance on fuel as well as over two-third of the pollution resulting from CO_2 (Chow, 2003; Johansson et al., 1993). Renewable energy sources include solar, biomass, wind, geothermal and tidal energy sources (Alrikabi, 2014), these energy sources will provide continued energy when harnessed as these sources will be vastly distributed along large geographical areas which do replenish themselves by natural means.

Renewable energy is efficient as well as cost effective having little or no environmental impact. Therefore, is critical to integrate it safely into the smart grid due to its unpredictable nature. Although renewable energy introduces several harmonics when thousands of RESs are integrated into the smart grid system, this requirement of effective control is paramount to preventing instability that might lead to the eventual failure of the grid.

The most promising renewable energy generation mechanisms at present are photovoltaic (PV) cells and wind energy. However, there is more emphasis on the PV solar energy generation; control methods and its optimization were presented in this thesis.

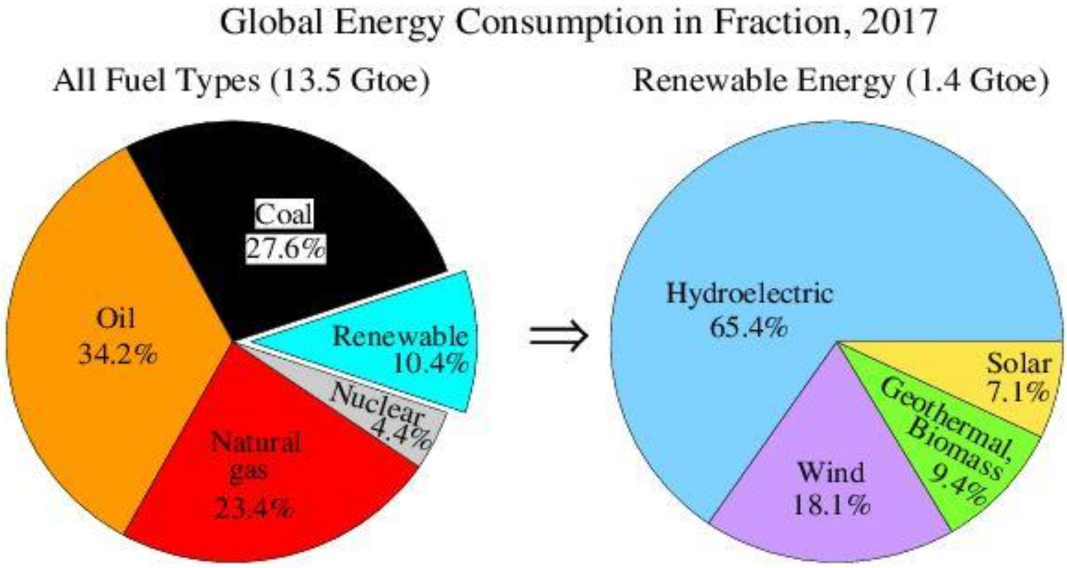


Figure 1: Energy consumption by sources(Alrikabi, 2014)

Solar energy is surely enormous and can provide the needed energy globally forever (Eric McLamb, 2011). The method of harnessing this energy for generation of electricity differs and such means of generated energy is termed as solar energy or solar electricity. The major way of utilizing the sun radiations to generate electricity are as follows:

1.1.1 Solar panels (Photovoltaic modules, PV)

This is the most common method of generating electricity from the sun. PV panels mainly use semiconductors that easily give out electrons when they absorb heat from the sun to produce what is called solar energy or simply electricity. These have been used in powerhouses, industries and the largest PV generating plant is the 290MW plant in Arizona U.S.A. (Ahmed Abdulkadir & Al-Turjman, 2018).

1.1.2 Solar thermal (concentrated solar power, CSP)

Despite not being very popular, solar thermal energy generation can produce far more electricity compared to the PV modules approach. However, it can not be used for residential consumption due to its significant high cost, which makes it better preference for utility plants. The largest facility using this technology to generate electricity is the 377MW plant in the California desert. The Concentrated Solar Power (CSP) has three different technologies that vary only in the means of collecting the energy from the sun (Ahmed Abdulkadir & Al-Turjman, 2018). These are dish engine technology, parabolic trough, and tower focal point concentrated solar power.

In the dish engine method, power is produced from the use of dish-shaped parabolic mirrors where gas is heated in a chamber with collected energy from the sun and the heated gas drives a piston of a generator, thereby producing electricity. For more efficiency, the dish is mostly attached to a tracking system that maximizes the use of the sun radiation (Ahmed Abdulkadir & Al-Turjman, 2018).

The parabolic trough uses trough-shaped mirrors that are long enough to concentrate the sun energy to a tube filled with liquid which collects heat as it focuses the sun rays, thereby heating the liquid in the tube connected to a heat exchange system where water is heated to steam that is used in a steam turbine generator to generate electricity. This operates in continuos recycling process, as the heated fluid transfer its heat, the steam cools and condenses. Then the same process is continuously repeated. Heated fluid can also be stored for a long period of several months and then be reused when sunshine is not available for over thirty years (Ahmed Abdulkadir & Al-Turjman, 2018) .

The focal point CSP technology utilizes a large area of flat computer-controlled mirrors that constantly moves to recieve maximum sun reflection throughout the day onto a tower that has a collecting tank. Molten salt moves in and out of the tank and is heated to a temperature of 537.8˚C (1000˚F). The heated fluid is then sent to a steam boiler, where the inherent heat in the molten salt propels a steam turbine, thereby producing electricity (Ahmed Abdulkadir & Al-Turjman, 2018).

1.2 Integrating Solar Energy to the Grid

As solar technology continues to improve in efficiency and become more popular the cost is expected to decrease significantly. Thus the payback period of a PV system that stands at an average of 20 years now can be expected to drop to 10 years (Ahmed Abdulkadir & Al-Turjman, 2018; Denholm, Ela, Kirby, & Milligan, 2010; Oberhofer & Meisen, 2012). Major equipment, referred to as balance of system used to integrate a state utility to the smart grid or a national smart grid includes: 1) power conditioning equipment, 2) safety equipment, and 3) instrumentation and meters. Power conditioning equipment practically changes DC to AC as electronics devices use electricity in AC mode. The major power conditioning types of equipment are:

- Constant DC power to oscillating AC power conversion
- The frequency of the AC cycles should be 50 or 60 cycles per second
- Voltage consistency is the range allowed for the output voltage to fluctuates

- Quality of the AC sine curve, regardless of the fact that AC wave shape is jagged or smooth.

Some electric appliances can operate regardless of the electricity quality while others need stabilizers to operate. Inverters are devices required to stabilize the intermittent electricity so that the electricity harmonizes with the requirements of the load in the grid.

Safety equipments are devices that provide protection to stand-alone system and on-grid integrated electricity generated through solar or wind source from being destroyed or endangering people during natural phenomina such as storm, lightning, power surges, or fault that can result from faulty equipment. Instrumentation and meters are equipments that provide the homeowner with the ability to view and manage their electricity, the battery voltage of his system, the quantity of electricity one is consuming and also the strength of the battery in terms of charge/discharge (Ahmed Abdulkadir & Al-Turjman, 2018).

The most difficult challenge in the smart grid technology is the integration of renewable energy into the modern smart grid efficiently. Renewable energy is by nature intermittent and can cause power quality problems such as harmonics, frequency, and voltage fluctuation.

This research utilizes the IGBT converter in the proposed model to achieve the interface of renewable generation into a smart grid, as IGBT converters have the inherent ability of a two-way power flow in the antiparallel diode.

Harmonics are sinusoidal currents or voltages that have frequencies which are integer multiple of the fundamental frequency, which is the frequency at which the power system is designed to operate at either 50 Hz or 60 Hz. The most important aspect of power generation is that it should be generated, transmitted and delivered with high-quality power factor (PF). The power factor in power generation, transmission and distribution systems are related to issues ranging from AC-DC converters that introduce large current or voltage harmonics value and high values of total harmonic distortion thus affecting power quality. Similarly, thyristors and diodes add current harmonics that results in reduced power factor in alternating current (AC) line causing distortion which leads to input current and voltage phase shift (out of phase) (Hersley, 2005; Radhakrishnan, 2016). Power quality issues arise in power systems with the advent of nonlinear loads. In a system providing stable sinusoidal voltage, the nonlinear loads unilizes the nonsinusoidal current, creating large and alarming power quality challenges in the systems, in the form of harmonics. These loads include converters, rectifiers, adjustable speed drives and inverters (Yusof & Rahim, 2009).

The term *surge* and *transient* have being used interchangeably by people referring to harmonics but for the power system experts, they can only be used to describe what actually occurs as these terms could surely be meaning different situation (Robert G. Ellis, P. Eng., 2001). Surge does happen in power system as well as transient. However, it is important not to mix surge with the transient. A surge is a sudden, unexpected rise in voltage or current that is not controlled and is for a certain period in power system, such voltage spike, outburst of car engine and so on. A transient on the other hand is a sharp increase in power system or electrical circuit which results in induced power and communication lines as well. Majorly, it is characterized by a very high voltage which sends enormous amounts of current to power systems. While harmonics are disturbance created from the fundamental wave at integer multiples of the fundamental waves, and can as well be described as a uniform occurrence that duplicates at every fixed frequency of 60Hz or 50 Hz cycles (Martzloff, 1970; Robert G. Ellis, P. Eng., 2001; Suryanarayanan, Mancilla-David, Mitra, & Li, 2010).

Harmonics exists in power systems and they cause in power loss. Direct current rectified with the aid of a rectifier introduces harmonics to the voltage signal that is applied to a load. This load will contain harmonic contents at multiples of the rectifiers pulse rate and the least harmonic will be that of the rectifiers pulse rate. The pulse rate will increase the current harmonic, in amplitudes, in the applied load at the same frequency, thus contributing significantly to loss of power in the system as well as waveform distortion (Lander, 1993).

Harmonics are associated with power electronics components due to the inherent nature that exists in present semiconducting devices. It is observed that ideal waveforms are sinusoidal but waveforms generated as a result of electronics systems are non-sinusoidal thereby indicating the presence of harmonics. Waveforms could consist of a fundamental pure sine wave and harmonics that are mostly integer multiples of the fundamental. The sum of these pure sine waves gives a non-sinusoidal wave that is generally complex and can be mathematically expressed as shown in Eq. (1), which can eventually be resolved into Fourier series, similarly indicated by Eq. (2)

$$V = V_0 + V_1 \sin(\omega t + \Phi_1) + V_2 \sin(2\omega t + \Phi_2) + \\ V_3 \sin(3\omega t + \Phi_3) + V_n \sin(n\omega t + \Phi_n) \tag{1}$$

Where V expresses the instantaneous value of a complex wave, V_0 represents the mean value, V_1 represents the maximum value of fundamental components, V_2 represents the maximum value of the 2nd harmonic component, V_3 represents the maximum value of the 3rd harmonic component, and V_n represents the maximum value of the nth harmonic component.

Conveniently replacing the independent and dependent variables with X and Y respectively in Eq. (1),, the Furies Series can be obtained as shown in Eq. (2).

$$Y = f(x) = A + a_1, \sin x + a_2 \sin 2x + a_n \sin nx + \\ b_1 + \cos x + b_2 \cos 2x + b_n \cos nx \tag{2}$$

Further simplifications of Eq. (1), the total root mean square (RMS) value can be derived for a complex wave as shown in Eq. (3)(Ned Mohan, Tore M. Undeland, William P. Robbins, 2007).

$$V_{rms} = \sqrt{V_{1(rms)}^2 + \ V_{2(rms)}^2 + V_{3(rms)}^2 + V_{4(rms)}^2 + \dots + V_{n(rms)}^2} \tag{3}$$

Similarly

$$I_{rms} = \sqrt{I_{1(rms)} + I_{2(rms)} + I_{3(rms)} + I_{4(rms)} + \dots + I_{n(rms)}} \tag{4}$$

Also,

$$Total\ power = V_{n(rms)} I_{n(rms)} \cos \Phi_{\mathrm{n}} \tag{5}$$

Eq. (3) expresses the total RMS value in terms of voltage while for current it is expressed in Eq. (4) with Eq. (5) representing power flows to a given system with both complex voltage and complex current.

Hence, from the onset, (6) represents the total harmonic distortion factor that is a ratio of the RMS value of the total harmonic contents to that of the RMS amplitude of the fundamental wave form.

Total Harmonic Distortion Factor =

$$V_{rms} = \frac{\sqrt{V_{2(rms)}^2 + V_{3(rms)}^2 + V_{4(rms)}^2 + \dots + V_{n(rms)}^2}}{V_{1(rms)}} \tag{6}$$

This provides a simplified way of calculating the total harmonic distortion factor in a power system, as well as looked at the presence of these harmonies components; provide its effect in the supply as well as the load side. The methods use in eliminating harmonic contents or reducing the amplitude of the harmonics to an acceptable limit was also presented. One method of achieving this elimination or reduction harmonies in power systems is by the use of filters.

For a power system that contains these harmonics it is very important to remove or reduce these harmonics to acceptable limits. Thus, it is important to understand how much of these harmonics is present in a power system to effective manage the harmonic contents. The two major techniques used to measure distortion in power systems or harmonic contents are Total Harmonic Distortion (THD) and Total Demand Distortion (TDD)(Radhakrishnan, 2016). THD is defined as the ratio of the harmonic content to the fundamental content. The total harmonic distortion is either voltage THD or current THD and can be calculated using Eq. (7) and Eq. (8) respectively (Radhakrishnan, 2016).

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_f} \tag{7}$$

Where f represents the fundamental frequency = 1

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_n^2}}{I_f} \tag{8}$$

Harmonics occur as even and odd numbers multiples of the fundamental. Even numbered harmonics are absent in AC line and the THD is usually represented as a percentage (Radhakrishnan, 2016).

Total Demand Distortion (TDD) is referred to as the moving average of Total Harmonic Distortion based on the value of the system rated current, as a system can operate at a significantly high load than others, the magnitudes of the system harmonics becomes more important.

1.3 Problem Statement

This thesis is motivated by the need to decrease the harmonics as the renewable energy generation and its associated conversion systems power capacity is drastically increasing. Therefore, to optimize the integration of solar energy to the national grid, the sources of harmonics in smart grid systems was studied. The reviewed literature presented in Chapter 2 helps identify the gap in previous research works. This thesis looked into the possibility of reducing energy loss as a result of conversion in power systems due to a significant change in weather conditions. Hence, harmonics elimination techniques were studied for conversion systems for better optimization.

1.4 Thesis Organization

Chapter 2 will review the literature on harmonics elimination techniques, passive filters, active filters, hybrid filters, and modulation techniques. The review presented the advantages and disadvantages of each technique as well.Chapter 3 will present the methodology used for the simulation of the renewable energy system in MATLAB/Simulink for modeling solar power integration to a smart grid to analyze harmonics content in the system. The proposed harmonic elimination technique that is resilient and efficient in harmonics reduction was presented. Chapter 4 presents the results from the model and Chapter 5 presents the conclusion with future research expected to improve on this work.

CHAPTER 2

LITERATURE REVIEW

2.1 Filters

Direct Current (DC) generated by solar array systems contains both even and odd numbered harmonics, which can be reduced or eliminated by employing filters. A filter is an electronic device that utilizes passive (RLC) or active components (op amplifiers, transistors) to allow or deny passage of a specific range of frequencies. Filters are divided into three types: passive, active, and hybrid (Amol Anandrao Patil, , Ranjeet Narayan Katkar , Patil Abhinandan Ajit , Chougule Pratik Vijay, , Pallavi Pradeepkumar Patil, & , Sushant. V. Patil, 2017; Radhakrishnan, 2016; Shaikh, Lashari, & Ansari, 2015).

2.1.1 Passive filters

Passive filters are utilized in electronic systems to protect such systems from harmonic distortion. This protection is usually achieved in a systemic way by creating a reduced impedance path that denies harmonic entrance into the power system. This type of filter consists of passive components such as resistors, inductors, and capacitors. Passive filters are categorized into a low pass and high pass filters, that are usually connected in either shunt or series topology. Passive filters are the most utilized type of filters due to its efficiency and significantly low cost. However, passive filters have disadvantages of being bulky, lack flexible control, creates resonance, and power factor problems, as only a specific harmonic order is being reduced using passive filter. Several passive filters need to be utilized to achieve a unity power factor.

A low-pass filter can be single-tuned or doubled-tuned filter. This is a technique of eliminating a particular current harmonic by tunning a low-pass filter to a specific frequency that uses low impedance such as 5th multiples or 7th multiples harmonics of the fundamental. Figure 2 a) and b) shows the configurations of single-tuned and double-tuned low-pass filters respectively. A single-tuned passive filter is a series filter consisting of resistor, inductor and capacitor in a circuit tuned to a specific frequency while double-tuned filter is that tuned at two frequencies (Shaikh et al., 2015).

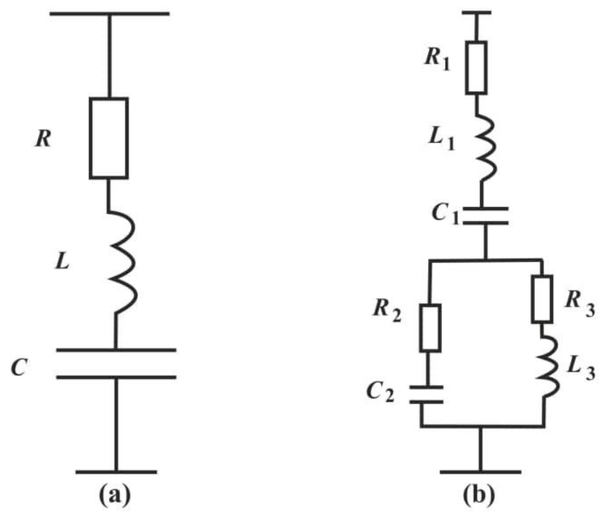


Figure 2: Passive filter (a) single-tuned (b) double-tuned(Shaikh et al., 2015)

High-pass filters on the other hand also consist of passive components with less impedance for harmonics at specific frequencies thus filtering all harmonic present with higher frequencies. These filters can be configured as first order, second order, third order and fourth order high pass filters. Figure 3 shows types high-pass passive filters. The first order filters is the simplest form of high-pass filters, containing only one active component. The order of the high-pass determines the number of component(s) contained in the filter and the higher order provides better stability to the power system.

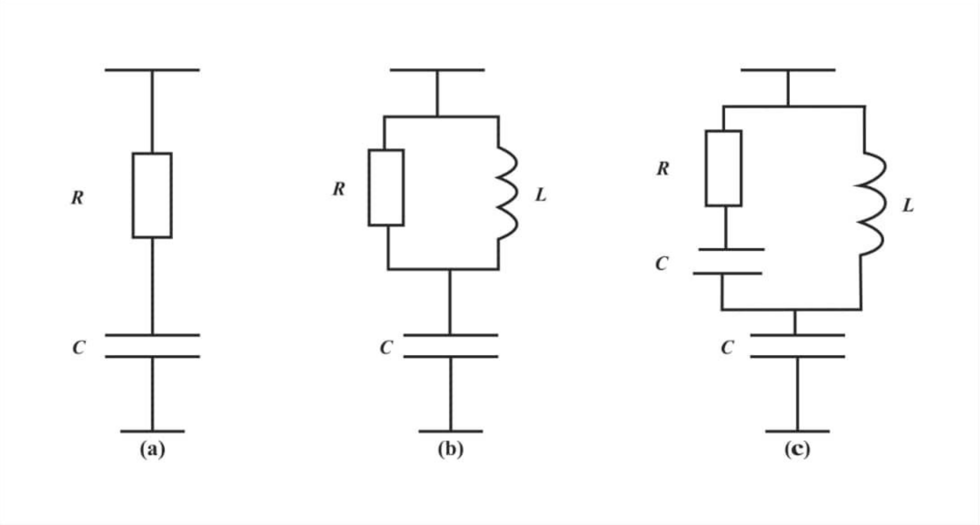
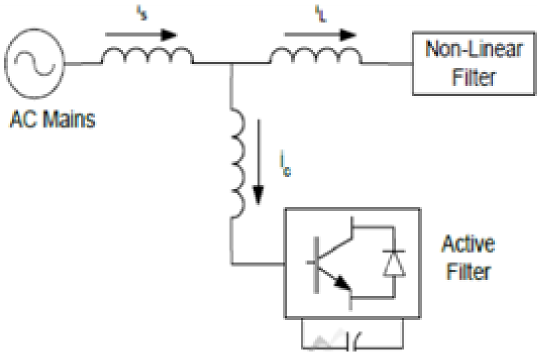


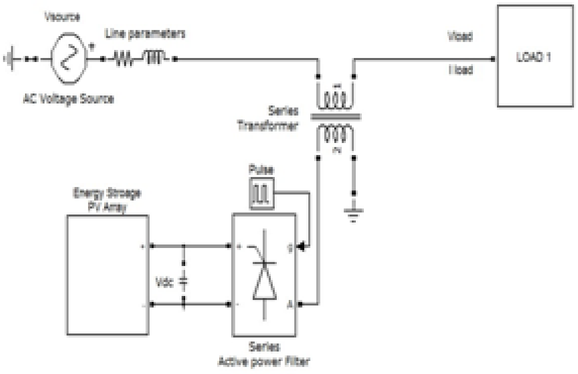
Figure 3: High-pass filter (a) first order (b) second order (c) third order(Shah, 2014; Shaikh et al., 2015)

2.1.2 Active Filters

Active filters are filters made by connecting resistors, capacitors and active components such as operational amplifier or transistors in a ciruit. The active filter solves power factor problem of a passive filter as well as becomes an improved substitute for passive filters. Active filter is smaller in size compared to passive filters, solves flickering challenges resulting from fluctuations in power systems. Active filters can eliminate more multiple harmonics reaching up to the 50th multiples of fundamental and is the basis for future improvement in the harmonics elimination techniques. Active filter provides reactive power compensation, however, more expensive compared to passive filter and shunt active filters are not suitable for large systems and also have complex control issues. Reactive power occurs in an alternatin current power system as a result of phase shift of voltage and current waveform. Reactive power is an essential part of the total power in TD system, measured in watts and expressed as a var (volt-ampere reactive) unit (Baste & Patil, 2010; I. Bhattacharya, Deng, & Foo, 2010; A. Martins, Ferreira, & Azevedo, 2011; Page, 1980).

Active filters eliminate harmonics by creating similarly harmonic distortion introduced by the load into the system but in a 180 degrees phase shift (Bagde, Ambatkar, Bhure, & Rakhonde, 2017; Shah, 2014). Active filters are used in two types of configurations, in series or in parallel as shown in Figure 4. The parallel or shunt active filter configuration eliminate harmonic by adding similar harmonic of 180 degrees phase shift, that operates as a current source. The series active filter operates as a voltage regulator and reduces harmonic content by isolating the distortion content between the load and the power system.





(a) (b)

Figure 4: Active power filters (a) Parallel Active filter (b) Series Active filter(Annapoorani, Samikannu, & Senthilnathan, 2017; Choudhary & Gaur, 2015)

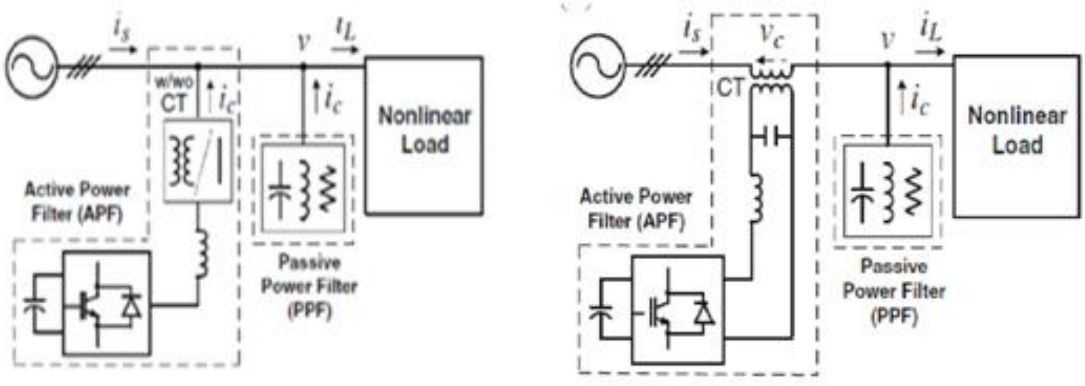
2.1.3 Hybrid Filters

The limitations of active filters such as large switching frequencies; their high cost as a result of complex electronics usage. And the high performance controlling technique as well as high rating combined with the challenges of passive filters, the resonance issue with the impedance problems led to development of the hybrid filter. These filters provide an improved filtering of harmonics, thereby achieving increased power quality. It combines advantages of both active and passive filters to provide effective harmonic elimination. Overcoming the resonance issues of passive filters and significantly reducing expensive nature of active filter (Bagde et al., 2017; Shah, 2014).

Hybrid filter can be utilized in power systems in the following combinations:

- A shunt active filter with a shut passive filter
- An active filter in series with a shunt passive filter
- And in series active power filter with a shut passive filter

These hybrid filter configurations are less expensive compared to the active filter (Nair & Sankar, 2015). Figure 5 shows two such configurations.



(a) (b)

Figure 5: Hybrid filter configurations (a) Shunt active filter with shut passive filter (b) Series active power filter with shunt passive power filter(Nair & Sankar, 2015)

2.2Photovoltaic Plant Harmonic Sources

The increase in global energy demand has significantly raised the number of photovoltaic power plant installations (Alrikabi, 2014). Similarly, usage of inverters that connects the photovoltaic and the grid together in different stages, that is, the transmission stage, as well as distribution stages, did increase (Ajeigbe, Chowdhury, Olwal, & Abu-Mahfouz, 2018). Also, inverters settings vary, depending on the type of PV module used in a power plant, such as multi-string, AC module, central and string inverters. These inverters do inject harmonics into the systems that can also result in resonance even though recent development in techniques allowed several manufacturers to produce PV inverter with reduced harmonic addition tendency. Furthermore, photovoltaic plant in a much wider perspective introduces harmonics into the grid in the form of grid voltage harmonics, DC link voltage harmonics and switching harmonics (Ajeigbe et al., 2018). Table 1 (Wang, Duarte, Hendrix, & Ribeiro, 2011) and

Table 2 reproduced from (Wang et al., 2011), show the accepted limits for both voltage and current harmonics according to ICE 51727 and IEEE 1547 (Ajeigbe et al., 2018), respectively.

Table 1: Limits for voltage Harmonics reproduced from(Wang et al., 2011)

Odd Harmonics		**Even Harmonics**	
Harmonic Order	**Relative Voltage percentage (%)**	**Harmonic Order**	**Relative Voltage percentage (%)**
3	5.0	2	2.0
5	6.0	4	1.0
7	5.0	6	0.5
9	1.5	8	0.5
11	3.5	10	0.5
13	3.0	12	0.5
15	0.5	14	0.5
17	2.0	16	0.5
19	1.5	18	0.5
21	0.5	20	0.5
23	1.5	22	0.5

Table 2: Limits for Current Harmonics reproduced from (Ajeigbe et al., 2018)

Odd harmonics order	**Distortion limits (percentage)**
From 3rd to 9th	Less than 4.0
From 11th to 15th	” 2.0
From 17th to 21st	” 1.5
From 23rd to 33rd	” 0.6
And higher than 33rd	” 0.3
Even harmonics	” 25.0 of odd harmonics

The intermittent nature of photovoltaic power sources introduces harmonics by causing ripples to be generated at the DC link voltage, majorly because in power electronics designs of PV inverters, it is always assumed that the voltage at the DC link is constant which in reality it is never been the case. Several researchers have attributed the presence of harmonics, odd harmonics at the output current of photovoltaic inverters to DC links voltage (Ajeigbe et al., 2018; Du, Lu, Chu, & Xiao, 2015; Freddy, Rahim, Hew, & Che, 2015; Wang et al., 2011). Similarly, some instrument used in measuring control system, affect harmonic generation in power systems. Switching losses is one of the two losses inherent in semiconductor, the second losses is the conduction losses.

Switching losses occurs as a result of the on and off switching of the semiconductor, it depend also on the semiconductor charesteristics, the commuted current as well as the voltage applied. The most difficult and challenging harmonic in photovoltaic output current introduced to power systems is the switching harmonics. This occurs majorly due to the discrepancy that resulted in the generated switching pulses and thus necessitates improve system control design to avoid significant swiyching losses as well as ensure stability in the power system (Ajeigbe et al., 2018; Du et al., 2015).

2.2.1 Converters

Converters are critical devices in power systems, used either to increase or decrease the output in respect of the input power in a power system. They are the example of devices that act as a nonlinear load as well in the power TD systems, nonetheless, are useful in regulating switch modes DC in power supply systems. This includes non-isolated DC-to-DC converters, isolated converter, high voltage direct current (HVDC) converters, multilevel converters, cyclo-converters, resonant converters, and matrix converters. Step-down or Buck, Boost or step-up, buck-boost or step-down / step-up, Cuk and full–bridge converters are some examples of non-isolated converters while fly-back, push-pull and forward converters are few examples of isolated converters (Albarbar & Batunlu, 2018). To achieve the desired use of any of these converters, an efficient control topology should be applied.

The two-level and three-level inverters are examples of a conventional converter and multilevel converter topology respectively. The three-level inverters have significant advantages over the conventional two-level converters in that their output voltage contains little distortion with a reduced problem of electromagnetic compatibility due to its staircase waveform. The three-level inverter also generates less common-mode voltage thus reducing stress in bearings of motor drives, as well as draws input current with reduced distortion achieving higher efficiency. Common-mode voltage is the voltage that is common to the inverting and the non-inverting inputs of a amplifier. Figure 6 and Figure 7 show the two-level and multilevel converters topology (Albarbar & Batunlu, 2018).

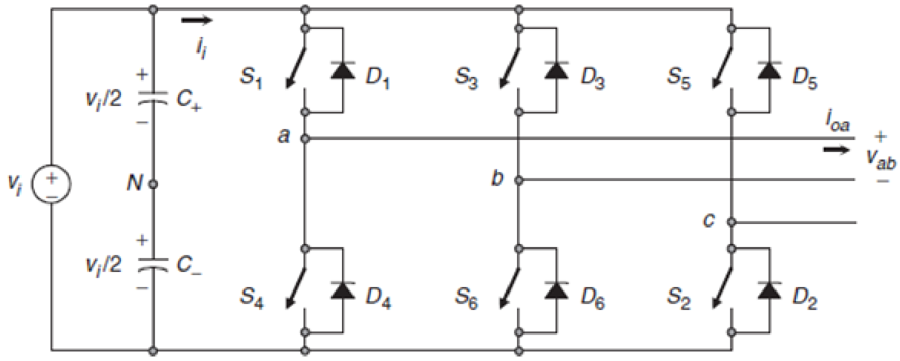


Figure 6: Switching in two-level inverter topology(Albarbar & Batunlu, 2018)

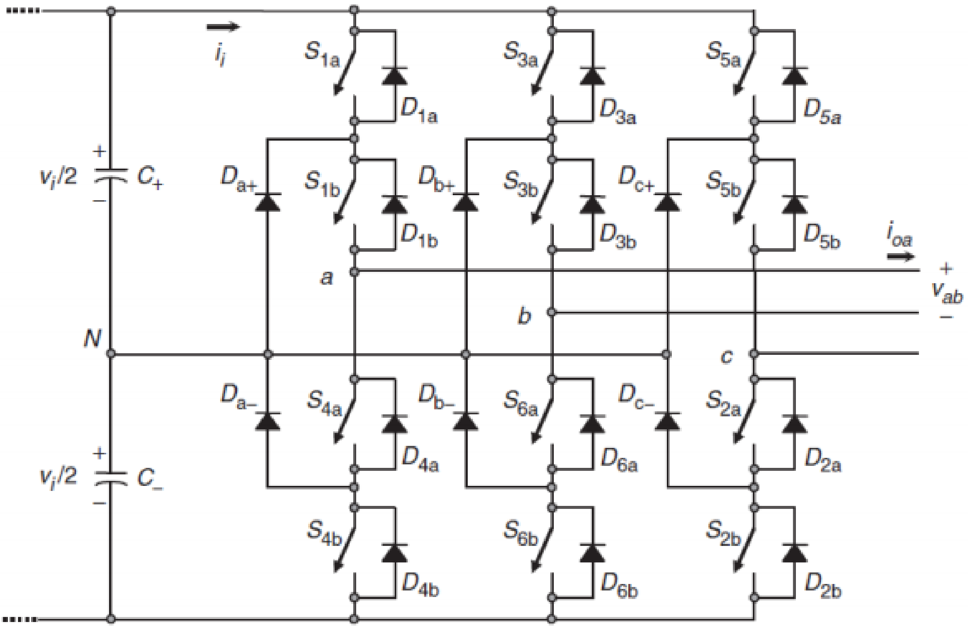


Figure 7: Switching in multilevel inverter topology (Albarbar & Batunlu, 2018)

Multilevel converters provide better performance in terms of waveform quality, stress and bearing in motor drives, input current harmonic distortion and switching frequency but having a major challenge in obtaining the proper switch pattern required. The multilevel inverter gained popularity in the application of various field including renewable energy generation as depicted in Figure 8 (Albarbar & Batunlu, 2018; Z Ye, A Chen, S Mao, T Wang, D Yu, X Deng, 2018).

Modulation is an important technique needed to obtain a suitable switching signal for an electronic power device. In the multilevel converter, two types of modulating techniques are used. These techniques are:

1. High switch frequency pulse width modulation (PWM)
2. Fundamental switch frequency

The high switch frequency PWM technique includes space vector PWM, selective harmonic elimination PWM, and sinusoidal PWM. On the other hand, the fundamental switching frequency techniques are space vector control and selective harmonic elimination. Improved modulation index, as well as efficient harmonics elimination, is achieved utilizing the high-frequency PWM that employing the fundamental switch frequency strategy (Broeck, Skudelny, & Stanke, 1988; Ned Mohan, Tore M. Undeland, William P. Robbins, 2007).

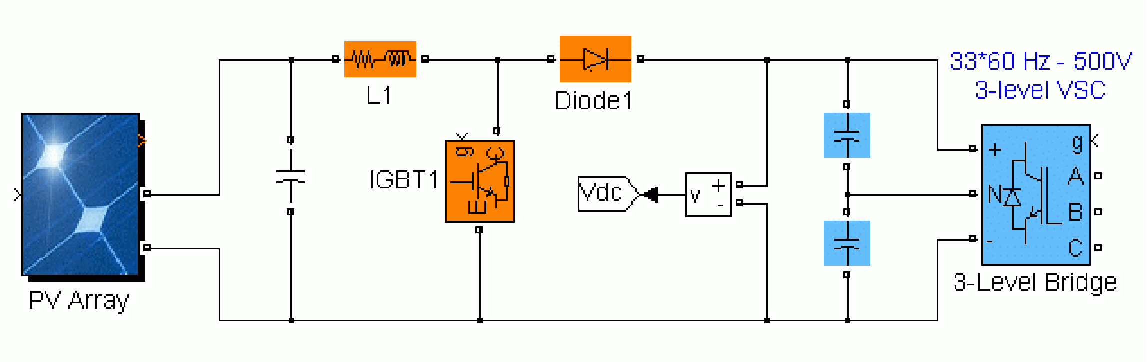


Figure 8: Application of Converter in Renewable energy Generation(Albarbar & Batunlu, 2018; Z Ye, A Chen, S Mao, T Wang, D Yu, X Deng, 2018)

A resonant converter is another important development in power electronics, it is defined as the utilization of both converter topology and a switching strategy in achieving a zero current switching, zero voltage switching or both (Ned Mohan, Tore M. Undeland, William P. Robbins, 2007) as shown in Figure 9.

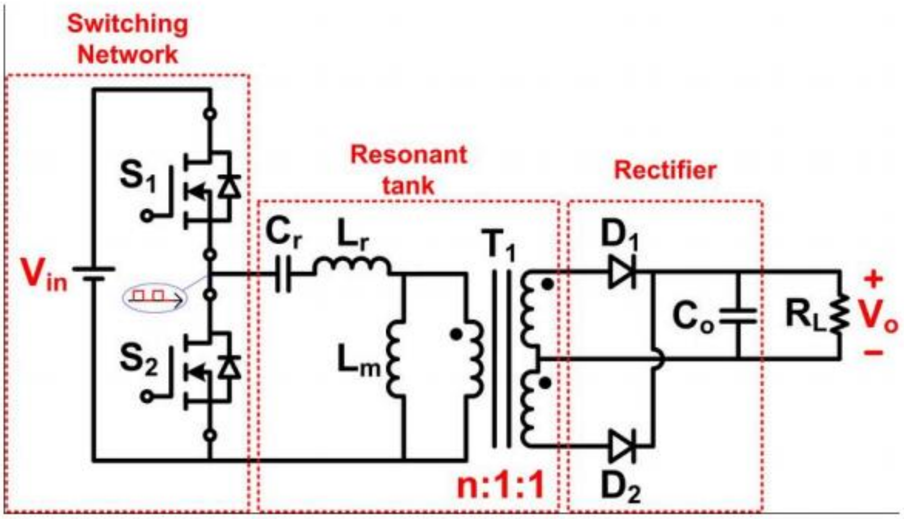
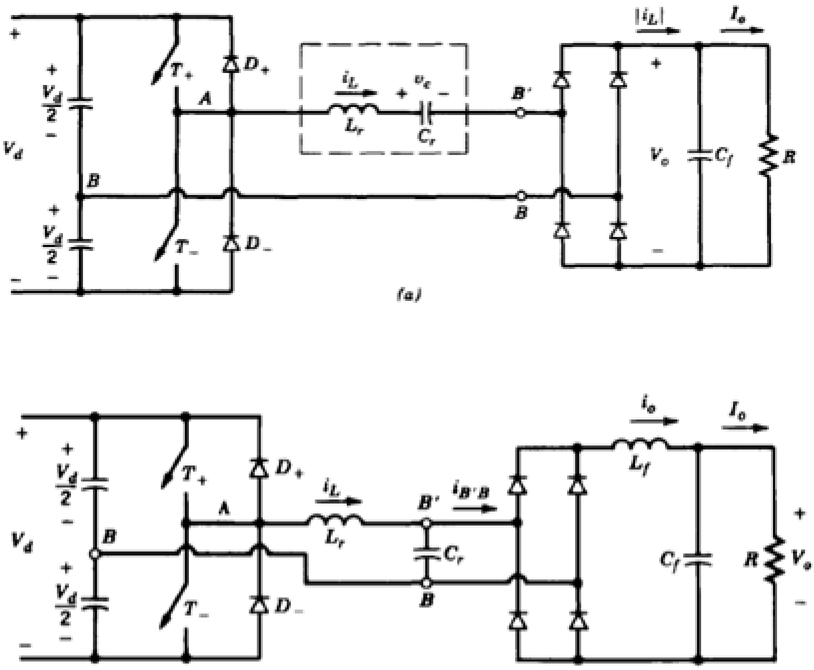


Figure 9: Resonant Converter (Ned Mohan, Tore M. Undeland, William P. Robbins, 2007)

The resonant converter is divided into three stages; the switching network, the resonant tank and the rectifier stage. Two switches are employed; the resonant tant utilizes a resonating inductor and capacitor with a transformer turn ratio of one ratio one, the rectifier stage is half-bridge, connected in center-tapped manner to the transformer.

Resonant converters are grouped into four categories, which are; a) Load-Resonant-converters b) Resonant-Switch Converters c) Resonant-DC-Link Converters and d) High-Frequency-Link integral Half-Cycle converters. The load-resonant converter is regarded as a voltage-source series resonant, current-source parallel resonant and class E and subclass E resonant converters. The series-loaded resonant, parallel-loaded resonant and hybrid resonant converters are different forms of voltage-source series resonant converters while zero-voltage-switching, zero-current-switching, and zero-voltage-switching clamped-voltage converters are types of resonant-switch converters. The series-loaded resonant converters and the parallel-loaded resonant converters differ in the connection of the resonant tank to the output. For the series-loaded resonant converter, the output part is connected serially with the resonant tank while in the parallel-loaded resonant the output is connected in parallel with the resonant tank as shown in Figure 10 (a) and (b) respectively [30].



(b)

Figure 10: Load-Resonant Converter; (a) series-loaded resonant converter (b) parallel-loaded resonant converter [30]

2.2.2 Inverters

An inverter is a device that changes direct current (dc) to an alternating current (ac) by inversing. Inverters are also referred to as DC-AC converters, with a DC input voltage source the inverter is termed voltage source inverter (VSI) and when the current source is applied at the input it is a current source inverter (CSI), therefore controlling directly the output voltage and current. These types of devices introduces harmonics in power systems, the harmonic content though differs from one manufacturer to the other. The harmonic contents are transmitted into distribution networks in power systems, thereby causing damages and worries to end users connected to the network (Dartawan, Hui, Austria, & Suehiro, 2012). The quality of the inverter determines the total harmonic distortion introduced into the system, as advanced inverters generate low harmonics. Inverters are categorized into two classes; the single-phase inverters and the three-phase inverters.

2.2.3 Type of Inverter

In terms of connectivity, inverters that are commercially available can be divided into string inverters, micro-inverters and hybrid inverters or simple power optimization systems even though their principles of operation are identical. To connect generated power from the photovoltaic plants to the grid, a high-power inverter is utilized. Figure 11 shows the THD block diagram of the proposed model

2.2.4 High-power photovoltaic inverters

The high-power inverters are grouped based on configurations into central inverters, string inverters, ac module inverters, and multi-string inverters, as shown in Figure 12 (Ajeigbe et al., 2018; Kirubasankar & Kumar, 2016).

Central inverters are large scale utility based configuration; central inverters use an IGBT device and have the highest conversion efficiency reaching almost 99%. The capacity of central inverters stands at 850 kW but can be improved with a dual connection to reach 1.6 MW with a power rating that can attain a maximum of 2.5 MW. The maximum power point tracking (MPPT) is lower compared to other types of inverters, as an MPPT is connected to PV array. The central inverters are not flexible, but also uses a blocking diode (Ajeigbe et al., 2018; Kouro, Leon, Vinnikov, & Franquelo, 2015).

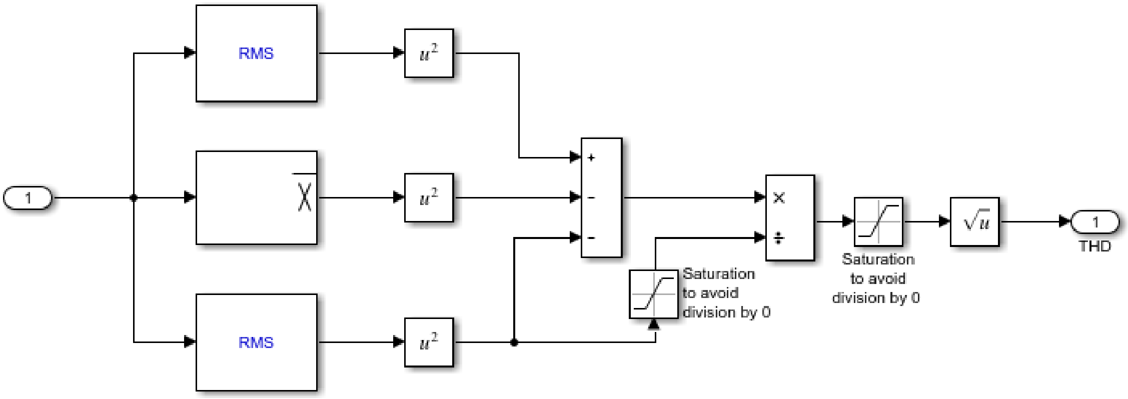


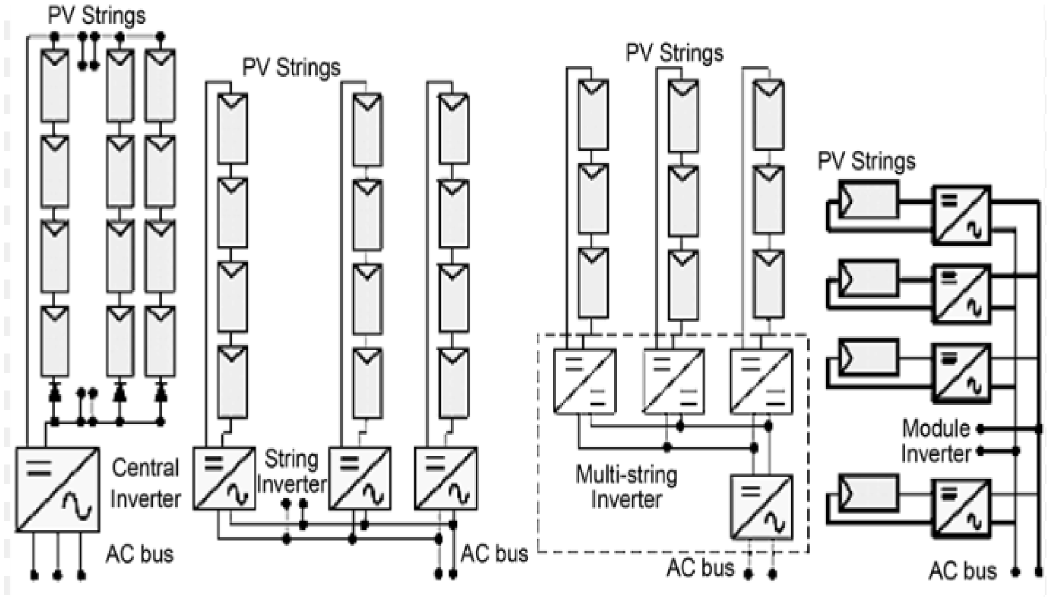
Figure 11: THD block

As the inverter operates at every particular condition, maximum power point efficiency is arrived at, which is simply the ratio of extracted power to that which is available (Batunlu, Alrweq, & Albarbar, 2016).

For medium-scale applications, both string and multi-string inverters are used. The string inverter has a power range below 10 kW and it combines the metal oxide semiconductor field effect transistor (MOSFET) and insulated gate bipolar transistor (IGBT). Its conversion rate is about 98% with a better MPPT efficiency compared to central inverters. This improvement is achieved by increasing the number strings, thereby providing a string to a module. This type of inverter is mostly available without a transformer (Ajeigbe et al., 2018; Kouro et al., 2015).

The multi-string inverter on the other hand, has a higher power rating of below 500 kW and uses the same device combination of both IGBT and MOSFET. It is an improvement on string inverters with a higher MPPT efficiency achieved by the use of one small string to one MPPT which slightly increases its conversion to about 98%. It is flexible, less expensive to build but requires two compulsory stages (Ajeigbe et al., 2018; Kouro et al., 2015).

The ac module inverters are utilized for small-scale applications. Its power rate is low compared to multi-string inverters; this power rate is below 350kW. The ac module inverter uses MOSFET device and has the highest MPPT efficiency in addition to a conversion efficiency of approximately 97%. The ac module has some setbacks such as high losses, expensive and it has two compulsory stages (Ajeigbe et al., 2018; Kouro et al., 2015).



(a) (b) (c) (d)

Figure 12: Photovoltaic Inverters (a) central inverter (b) string inverter (c) multi-string inverter (d) ac module inverter (Kirubasankar & Kumar, 2016)

2.2.5 Control strategies

The rapid increase in photovoltaic power plant installations globally calls for an efficient control methods to optimize harmonic reduction techniques. The conventional control method, which involves the use of either passive or active filters and also the utilization of both in hybrid configuration, has shortcomings in its harmonic elimination abilities. This shortcomings causes continuous losses of large power as well as the destruction of numbers of power equipment and facilities, such as transformers, generator as well as cables (Ajeigbe et al., 2018). Several approaches employing PV inverters have been developed to improve power quality and reduce harmonic content in power systems.

- LOOP CONTROL STRATEGY: This strategy is a control method, that uses cascaded loops one from each side of the DC link. Before the DC link, a voltage control loop resolving the PV inverter input voltage and at grid side of the DC links a current control loop is applied to avoid fluctuation in its output current to the grid. The current control loop reduces the current harmonic content at the output.
- PROPORTIONAL INTEGRAL (PI) CONTROL: In this control method, the use of a PI controller that depends on a dq control framework is used to improve the nature of the current waveform. The synchroneous reference framework control strategy is used in decoupling power into its active and reactive components; this synchromeous reference framework is also referred to as dq. This improvement is realized by rotating the current and grid voltage

in a dq control framework, thus decoupling the AC power into its active (Id) and reactive (Iq) components. Figure 13 show the PI control schematic (Ajeigbe et al., 2018; Parvez et al., 2016), (Larsson & Hägglund, 2012)-(Marufuzzaman, Reaz, Rahman, & Chang, 2014).

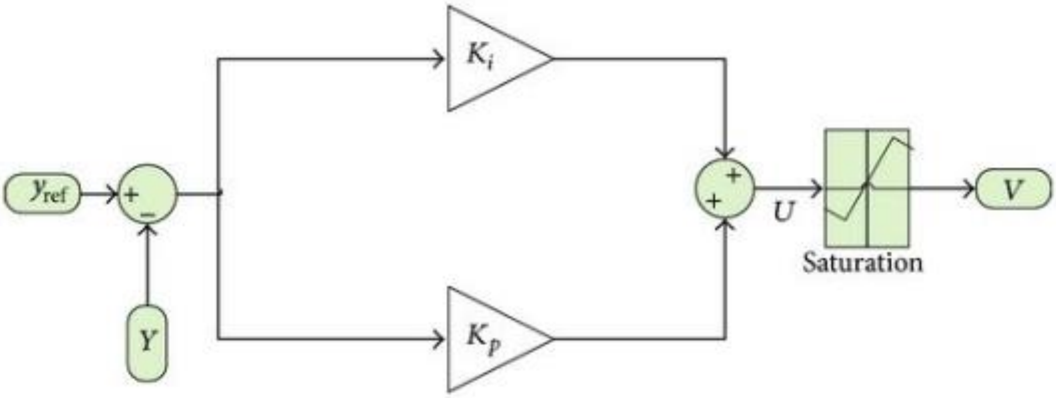


Figure 13: PI control schematic(Ajeigbe et al., 2018; Camacho et al., 2007b)

- PROPORTIONAL RESONANT (PR) CONTROLLER: In this control technique a $abc - \alpha\beta$ module is used to change the current at the grid from the natural frame *abc* to a reference stationary frame αβ, which improves the performance of the system. Phase error as well as the magnitude of the steady state, which is a challenge in PI control strategy are overcomed (Ajeigbe et al., 2018; Camacho et al., 2007a, 2007b; Hassaine et al., 2014; Parvez et al., 2016). Figure 14 shows the use of PR control strategy for controlling current in a three-phase grid inverter (Blaabjerg, 2006).

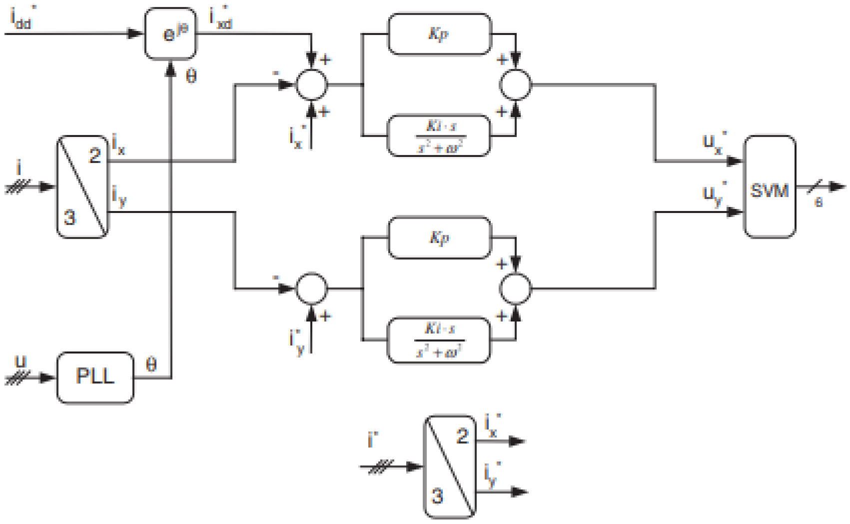


Figure 14: Proportional Controller in three- phase grid inverter(Blaabjerg, 2006)

- REPETITIVE CURRENT (RC) CONTROLLER: This control scheme utilizes the IMP (internal mode principle) in mitigating harmonics in power systems. By controlling IMP parameters in a regular period eliminates steadystate error and the system attains an improved gain at multiple of the fundamental frequency. The RC control technique effectively eliminates harmonic contents at 11th and 13th order but causes instability in the system as a result of the delay tendency due to dynamic response (Ajeigbe et al., 2018). Figure 15 shows the utilization of repetitive current in a three-level inverter.

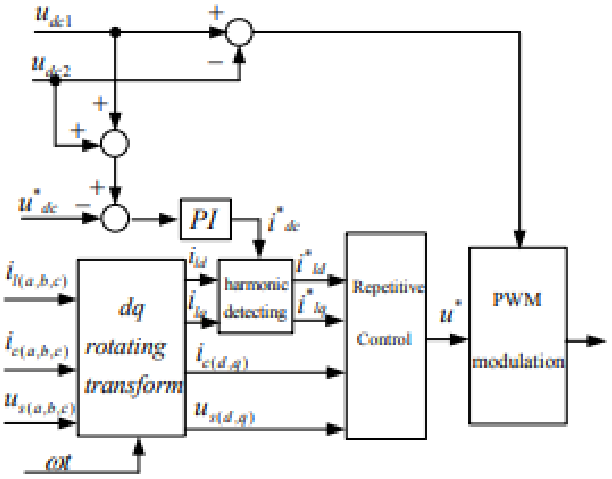


Figure 15: Repetitive controller in three-level inverter(He, Liu, Wang, & Zou, 2009)

2.3Harmonic Elimination Techniques

In the smart grid system, lots of electronics devices including a variety of converters such as the thyristor and static power converters, which acts also as nonlinear load, thereby introduces current harmonics that eventually affect the quality of the power delivered to the consumer. To mitigate this and provide the end user and connected appliances high quality generated energy some harmonic elimination or reduction techniques are applied, such as the following;

2.3.1 Filters

The conventional method of reducing harmonics in power systems is the use of passive filters, active filters, filters in shunt orientation and even hybrid filter. Several researchers have reported the use of a filter as the best means of harmonic mitigation in power systems. The researchers (Amol Anandrao Patil, et al., 2017), reported the use of a series active filter to mitigate harmonics in voltage but proposed passive filter, as an efficient method for reducing harmonic content in both the current and voltage. This harmonic reduction technique according to the researchers, is cheaper compared to the use of active filter and easy to implement. The most used passive filter in harmonic mitigation is that which consist of tuned series inductive-capacitive (LC) circuit.

For improved harmonic elimination (Kececioglu, Acikgoz, & Sekkeli, 2016), proposed an advanced passive filter that does not only mitigates harmonic content but also improves the reactive power in the system. On the other hand (Shaikh et al., 2015), presented some shortcoming of passive filters, as using such filters cause difficulty in achieving flexible control. Also, the use of passive filter, causes a situation which results in resonance and the very large passive filters have to be use to mitigate harmonic effectively. The researcher proposed the utilization of three passive filters, a high pass filter to mitigate higher order harmonic contents and two single-tuned filters that are tuned at the frequencies of the 11th and 13th order harmonics.

Furthermore (Soomro, Sahito, Halepoto, & Kazi, 2016), presented a technique that applies the six pulse multiplication converter in single-tuned shunt configuration passive filters to reduce power losses, increase power systems general efficiency. The authors eliminated the 3rd order harmonic which is quite a dominant harmonic resulting in significant power quality loss as well as the 5th and 7th order current harmonics.

Again as in most cases, when an applied voltage in pure sine wave or sinusoidal, the nonlinear loads will continuously draw a non-sinusoidal current, due to the nonlinear load varying impedance, thus polluting the system with harmonics and distorting the voltage. The researchers (A. Martins et al., 2011) proposed an experimentally validated active power filter that can be utilized not just for eliminating harmonics in power systems but also to improve power factor issues as well as balance loads in both the linear and non-linear systems. Similar, (A. P. Martins, 2003) presented a prototype of three-phase active filter for harmonic mitigation.

While (Paul, 2011), proposes the use of active filters in two different topologies (in series and shunt active) to mitigate the challenges caused by matrix converters of power system pollution.

In the research presented by (Yusof & Rahim, 2009), a method using a synchronous reference frame for controlling a three-phase hybrid active and passive filters was proposed for reducing harmonics in a power system. This method achieved improved mitigation of current source harmonics, as the active and passive filters complimented each other's effectiveness.

2.3.2 Pulse width modulation

The paper presented by (C & Sharma, 2016) reported the usage of Passive filters, Active filter and Pulse Width Modulation (PWM), for reducing harmonics in grid systems. Stating the challenges of passive filters has being bulky as well as the introduction of resonances into the system while active filters provide a solution to these problems and gives improved efficiency. The researchers state that the most common methods for recent times have been the PWM method, which employs a voltage source inverter. The improvement in the decoupling techniques, led to the instantaneous real and reactive current technique (id-iq) that is used mostly and gives wonderful outcome when used with a proportional integral controller, which was used for several grid situations integrating, with hybrid renewable energy sources (HRES) as well as without HRES.

The researchers (Ito et al., 2010), employ a technique called disturbance compensation control. They classified controlling methods for harmonics reduction into two categories: feedback-based current control and disturbance compensation control. Examples of feedback-based current control techniques include hysteresis control, deadbeat control, and the specific frequency components current control method. Each of the foregoing, have the challenges that is overcomed by the disturbance compensation control method. The authors stated that shut active filter reduces harmonics resulting from hysteresis but not in systems using L-C-L filters where special consideration is required, as the L-C-L output current is associated with quite a massive ripple current. While the deadbeat requirement of the instantaneous state variable values makes systems having analog filters, that need long time constants for circuits sensing, unsuitable. Also according to the researchers in (Ito et al., 2010), reducing harmonics by resonant current compensators and current controllers in addition to outer compensators (usually a voltage loop), which are examples of specific frequency controlled technique, creates strong interference that will result in overall poor efficiency of the system.

2.3.3 Selective elimination pulse width modulation

The recent improvement in power system, with fast switching IGBTs, make semiconductor device less attractive in inverter configurations such as inverters connected in series, inverters connected in parallel, multilevel reactive power compensator, multiple rectifiers, neutral point clamp and optimization inverters(Li, Czarkowski, Liu, & Pillay, 2000). (Li et al., 2000) presented two methods of harmonics elimination. First, is the Selective Harmonics Elimination Pulse Width Modulation (SHEPWM) technique that implements phase-shift harmonic suppression, while the second method utilizes mirror harmonic reduction techniques. Both methods are series connected voltage source PWM inverters. (Li et al., 2000) noted other control techniques such as space vector PWM, sinusoidal PWM, non-sinusoidal carrier PWM, mixed PWM, and SHEPWM. The SHEPWM will provide the hihest quality among all the PWM methods. Other techniques are single and three-phase half-bridge voltages source inverter type and its corresponding full-bridge version. There also are square wave modulation techniques, unipolar and bipolar PWM techniques (Namboodiri & Wani, 2014).

Rectifiers are critical devices in power electronics and semiconductors used in such devices are classified into uncontrolled rectifiers (e.g. dodes used as switches), phase-controlled rectifiers (e.g. silicon controlled rectifier) and pulse width modulation rectifiers (e.g. insulated gate bipolar transistors and metal oxide field-effect transistors) (M. Bhattacharya, 2014). In electricity distribution network, excellent performance, reduced distortion, good power factor, better regulation of voltage, flickers and loads balancing can be optimized by pulse width modulation rectifiers (M. Bhattacharya, 2014; C & Sharma, 2016; Ito et al., 2010; Li et al., 2000).

2.4Motivation

There is a significant amount of work conducted to mitigate harmonics in power systems, most of which looked at the non-sinusoidal harmonics introduced by loads (Amol Anandrao Patil, et al., 2017; Radhakrishnan, 2016; Shaikh et al., 2015). Solar energy harvesting was well studied including solar energy integration to the grid system. So far, no literature was found on harmonics, as a result of adverse weather, which is the gap this study aimed towards achieving. The solar energy generation depent significantly on the solar irradiance and maximum irradiance relies on the clear weather. Also, the advantages of three-level again the conventional two-level inverters were presented as reviewed studies did not relate the same in terms of photovoltaic energy system integration to the smart grid. Solar energy generation is increasing and several thousands of solar power plants integrated to grid will sure generate several harmonics which will lead to significant energy loss if not looked into.

The effective mitigation methods were looked at in view of applying the same to better improve energy generation as well as solving harmonic arising due to bad weather as power components convert energy from one form to the desired form.

CHAPTER 3

METHODOLOGY

3.1Solar panel

The efficiency of generating electricity using solar panels is greatly influenced by the irradiance and relates to the variation in temperature. A study to verify effect of irradiance was coducted by (Salim, Najim, & Salih, 2013), in which irradiance was varied between 100 W/m^2 to 1050 W/m^2. Similarly, (Dr.P.Sobha Rani & , Dr.M.S.Giridhar, Mr.R.Sarveswara Prasad, 2018), observed the importance of irradiance for optimized performance of photovoltaic with the aid of a solar module tester (SMT). The theoretical analysis of the performance of the solar cell and solar module was conducted with relationship to maximum power point tracking (MPPT), fill factor, temperature and irradiance will affect its effectiveness.

3.1.1 Irradiant Energy Content

The energy delivery of a solar panel is dependent on the intensity of energy the solar radiation the penel received. This content of energy is expressed in equation (9).

$$W = hf \tag{9}$$

But, $c = f\lambda$ Substituting for f, Eq. (9) can be rewritten as Eq. (10)

$$W = \frac{hc}{\lambda} \tag{10}$$

Where h represents Planck's constant = 6.6261 × 10^{-34} Joules/second, f is frequency measured in hertz, c is light velocity which is 2.998 × 10^{8} m/s and λ is $wavelenght$

The total incident irradiant does not produce Photovoltaic (PV) effect on the solar panel as can be seen in Figure 16, some of the incident radiations will be reflected, others will pass through the panel and some will result in electron-hole combination.

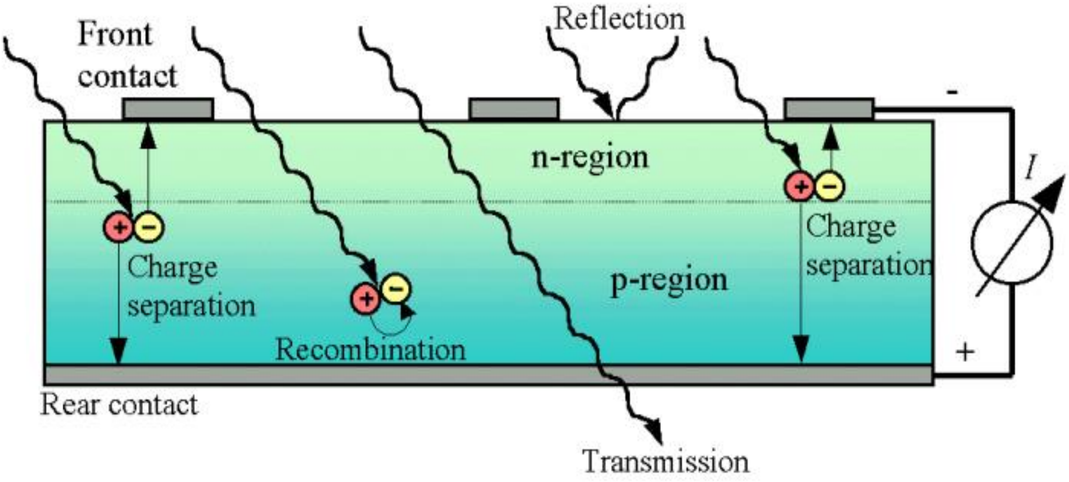


Figure 16: Irradiant incidences on PV panel(Freddy et al., 2015)

The eventual energy produced by a PV array system can be calculated using (11). The efficiency of a PV is measured based on ideal conditions, such as standard test condition (STC) as well as capacity utilization factor. The capacity utilization factor is a metric that evaluates PV annual performance, capacity utilization factor, is a simple ratio of gross energy generation to maximum gross energy generated as represented in Eq. (12), using a minimum of one-year data (Verma & Singhal, 2015).

$$E = A \times r \times H \times PR \tag{11}$$

Where E represents Energy output, A stands for panel's total area in (m^2), r stands for panel's yield, H stands for yearly solar radiation of installed tilted panel, and PR stands for the performance ratio.

$$\text{Efficiency} = \frac{\text{gross energy generation}}{maximum\ gross\ energy\ generation} \tag{12}$$

The efficiency of a PV panel is measured as a ratio of electrical power of 1PV (kWp) to the area of the same panel. For example, the efficiency of a 0.25 kWp photovoltaic module, with a panel area of 1.60 m^2 will be 15.6%.

Also, with a capacity utilization factor of 18%, 1MW PV array plant yield will be approximately 0.18 MW, at the following STC radiation (irradiance) = 1000 W/m^2, Cell temperature = 25^{o}C, Wind speed = 1 m/s, and AM = 1.5 (Verma & Singhal, 2015).

PV generation encounter losses, the losses are presented in the following percentage ranges as shown in Table 3

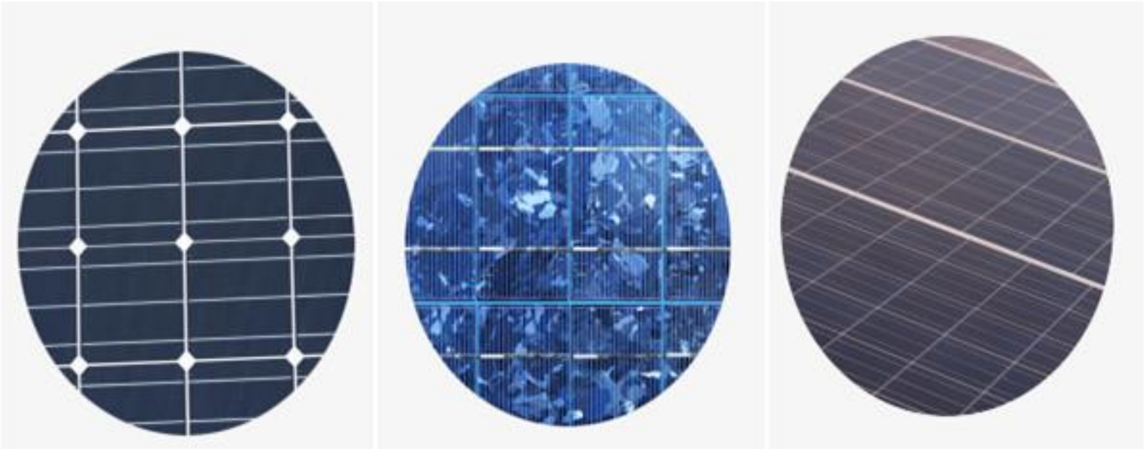
Table 3: PV generation losses

Inverters losses	Range
Inverter losses range	4% to 10%
AC and DC cables losses	1% to 3%
Temperature losses	5% to 20%
Weak radiation losses	3% to 7%
Snow and dust losses	0 to 2%
Shading losses	0 to 80%

3.1.2 Photovoltaic (PV) Panel Types

Different types of PV panel exists in market such as monocrystalline, polycrystalline, amorphous thin film and the concentrated solar cell as illustrated in Figure 17 (Ned Mohan, Tore M. Undeland, William P. Robbins, 2007; “Types of Solar Panels (2019) | GreenMatch,” 2019). Other solar panel types have been reported in literature. For example, Bio-hybrid Solar cell with very high efficiency that is expected to be over 1000 times than the efficiencies of monocrystalline, polycrystalline and amorphous thin film. The Cadmium Telluride which provides a lower cost of manufacturing as well as utilizes a lower quantity of water but with a dangerous setback of emitting Cadmium which is toxic and reported to cause cancer and other health challenges to human (Mohammad Bagher, 2015).

The Monocrystalline, Polycrystalline, and Amorphous thin-film solar panel are the most used in photovoltaic power generation and these panels are made from silicon. For an electron to be liberated into the energy gap in silicon about 1.08eV of energy is required, therefore, the radiation that has the tendency to liberate electrons in silicon should have a wavelength which is below 1150nm (Albarbar & Batunlu, 2018). Again, in the wavelength spectrum of solar radiation, wavelength above the 23% will either be a loss in the solar cell junction, converted to heat as a result of being absorbed or penetrates through the panel due to its long wavelength.



(a) (b) (c)

Figure 17: Types of PV panel (a) Monocrystalline (b) Polycrystalline (c) Amorphous thin film (Verma & Singhal, 2015)

There also exists a concentrated photovoltaic cell; which has an improved efficiency of approximately 41%. Its short-coming is the relatively high cost and that they requires solar trackers, cooling systems to attain the expected high-efficiency performance (Albarbar & Batunlu, 2018).

3.2MODELLING

MATLAB Simulink was used to model a smart grid integrated with a PV model. The model has the following sub-systems; PV array, 3level IGBT bridge controller, Pulse Width Modulation (PWM) generator, controller, filters and Grid as illustrated in Figure 18.

The temperature was fixed while the irradiance was varied and the distortion was observed at very lower irradiance. The Total Harmonic Distortion (THD) block was used to measure the harmonic content.

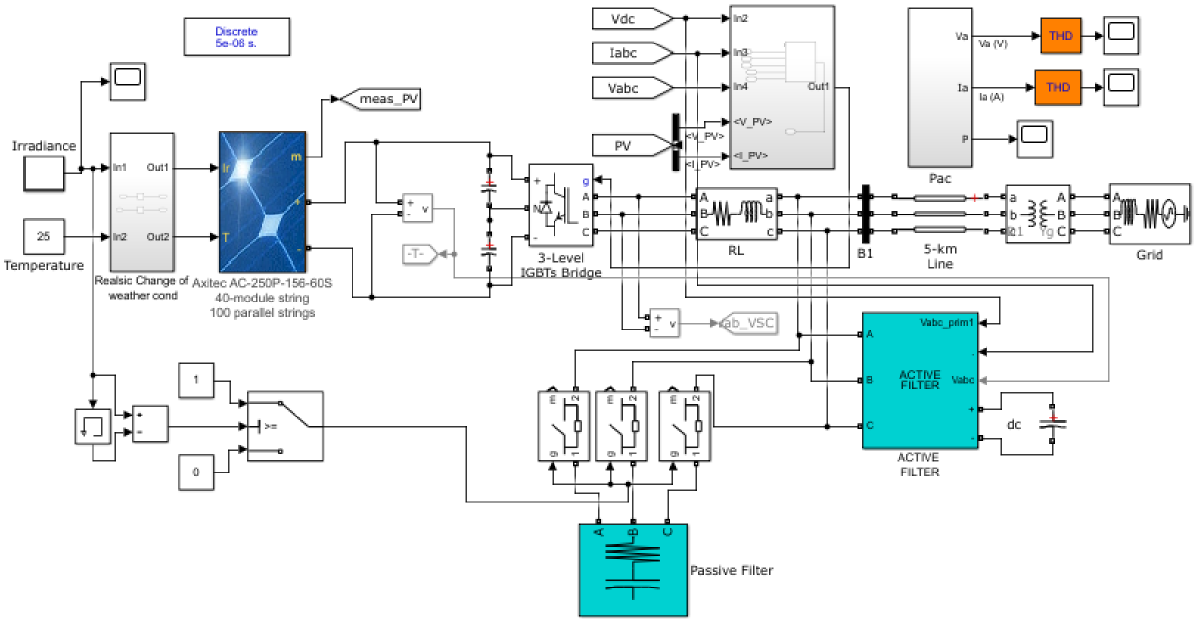


Figure 18: General structure of model

3.2.1 Irradiance

The irradiance of the PV panel was monitored and measured noting its effect on the efficiency of generation at a fixed temperature. Maximum power point tracking (MPPT) was implemented but at a lower irradiance significant amount of energy is lost.

Solar radiation beamed to the earth’s surface is the combination of the direct radiation from the sun and the scattered radiation from the atmosphere. The intensity of solar radiation reaching the earth’s surface depends on both direct and scattered radiations. During clear weather conditions, the intensity depends mostly on the direct solar irradiance and when there is cloud covering the solar irradiance intensity relies on the diffused (scattered) irradiance. Therefore, observing greater intensity of solar radiation depends on position of clouds in relation to the Sun's position, as the irradiance intensity reduces when the atmospheric condition is covered with clouds (Matuszko, 2012). Figure 19 shows the variation of irradiance received by the PV array which dropped from an initial of 1000W/m^2 to 200W/m^2 at 0.3seconds.

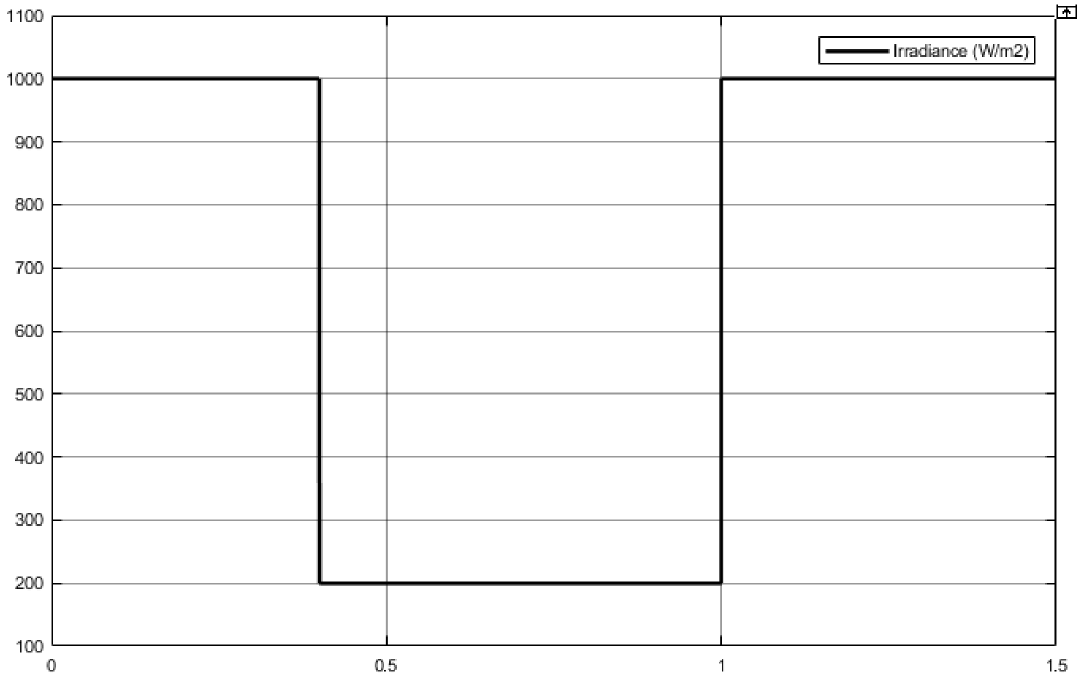


Figure 19: PV irradiance

3.2.2 Shading effect

The shading effect is another challenge that affects the efficiency of a PV system. This effect significantly reduces the power output of a solar module, as when a single cell is shaded in a PV module containing 18 cells, with maximum power generation of 100W, for example, the output power of the PV drops to below 30W losing about 70% of its power generation with only about 2% of cell shading. This means the wasted or lost power is dissipated in the shaded cell (Ekpenyong, E.E and Anyasi, F.I, 2013).

3.2.3 Two-level and Three-level inverters

The use of switches in the multi-level inverter is necessary for achieving the desired optimization in power systems in terms of speed, size and economic value. These are possible with the advent of switches with the low-voltage utilized in three-level inverters but is lacking in the two-level inverter that utilizes high-voltage. The multi-level inverter employs the three-level inverters in series connection to attain a improved sinusoidal wave than that provided in the usage of two-level inverters. This gives the three-level inverters output voltage ability to contain lower THD, reduced switching and conduction losses, thereby, increased voltages is achieved. The major advantage of the level inverter is its ability to generate three-level output current or voltage (positive Vdc, negative Vdc or Zero) whereas the two-level inverter generate two-level output current or voltage (positive and negative Vdc) as shown in Figure 20 and Figure 21 respectively but it is much expensive than the two-level inverter (Honade et al., 2016; Ikonen, Laakkonen, & Kettunen, 2005; Jokinen & Lipsanen, 2005).

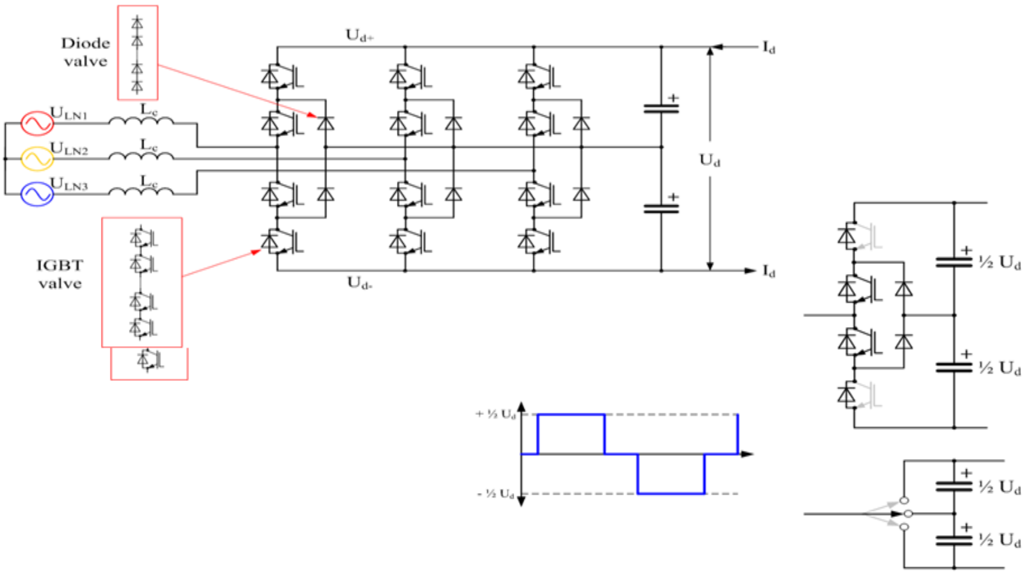


Figure 20: Three level inverter output(Albarbar & Batunlu, 2018; Ikonen et al., 2005)

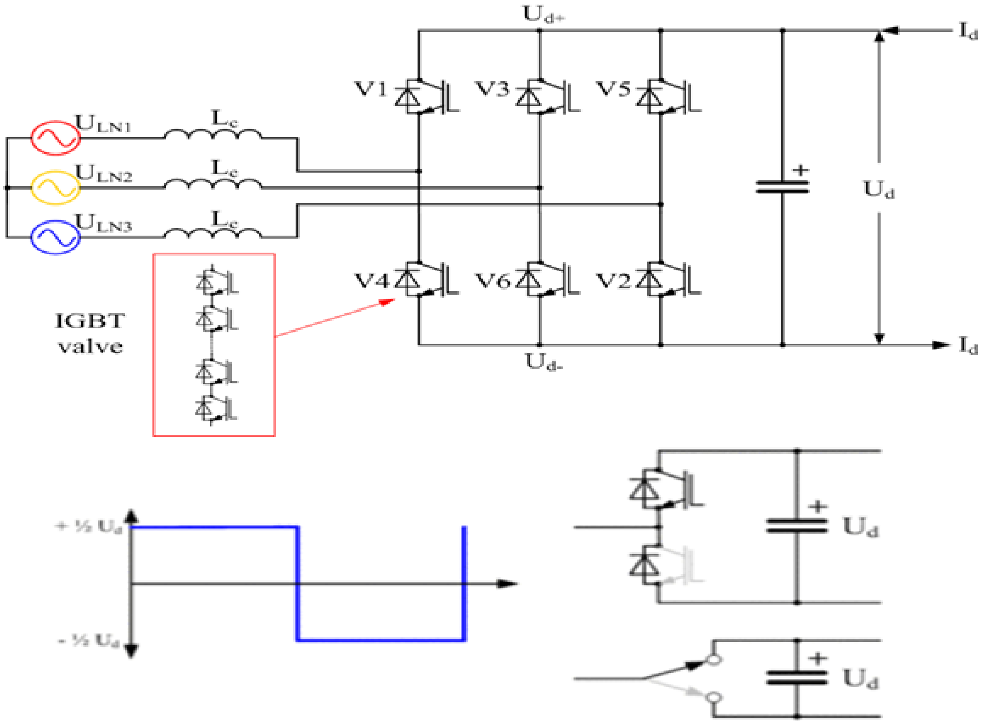


Figure 21: Two-level inverter output(Honade et al., 2016; Ikonen et al., 2005; Jokinen & Lipsanen, 2005)

As earlier explained, inverters can be grouped into single-phase or three-phase inverters depending on a chosen switching pattern. Figure 22 shows a full-bridge single-phase inverter, and Figure 23 shows three-phase inverter that is a bridge-types of inverters with improved efficient in high power rating requirement (Honade et al., 2016).

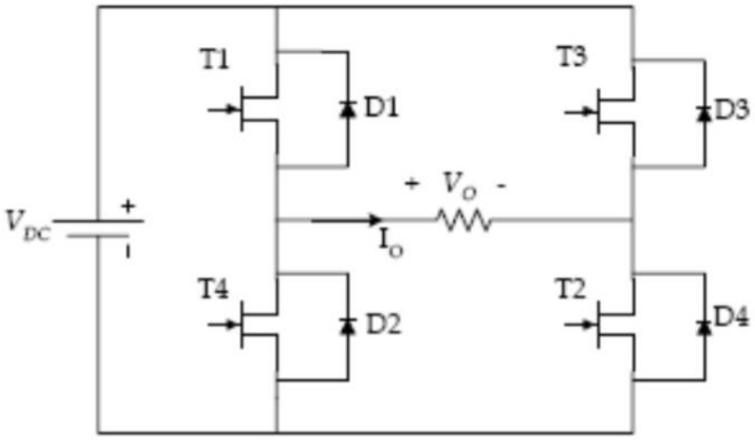


Figure 22: Single-phase full bridge inverter (Honade et al., 2016)

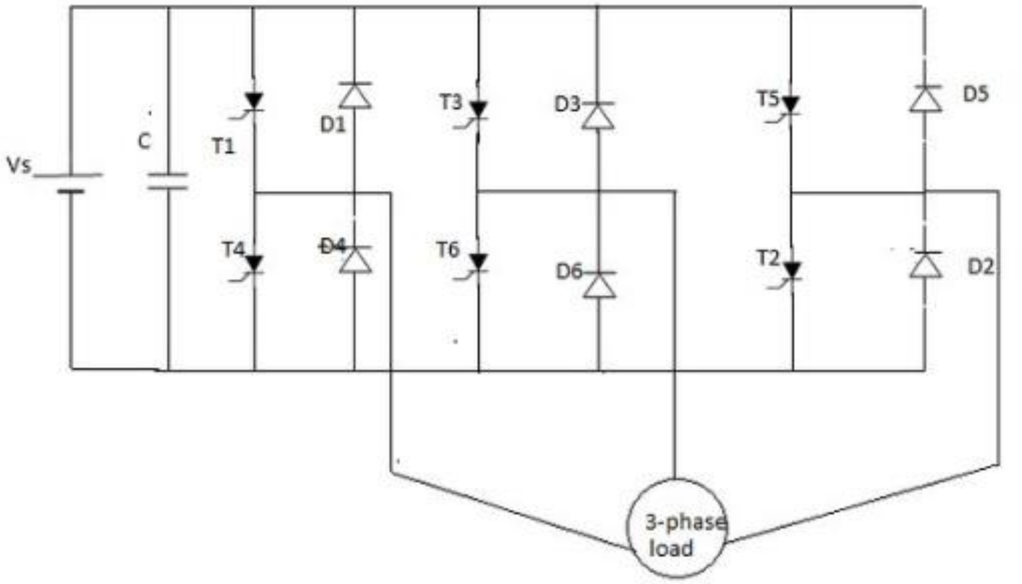


Figure 23: Three-phase full-bridge VSI (Honade et al., 2016)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Filters

The use of filters in mitigation of harmonics in power systems is continuously increasing with much emphasis placed on the control. The use of a hybrid filter was examined in different topology as well as in two-level and three-level inverters.

4.2 Simulations

The simulation result for the designed model was run in different scenarios; Figure 24 shows the effect of a passive filter (Appendix I) while Figure 25 shows the effect without the passive filter when the irradiance input shown in Figure 19 is applied. These two shows significant distortion during the time change in the transient but was less during the usage of passive filter. As it can be observed, without any filter, there is almost 65% of harmonic distortion when the irradiance level is very low. With the passive filter the distortion is lowered down to below 10%, however during the transition high oscillations are observed.

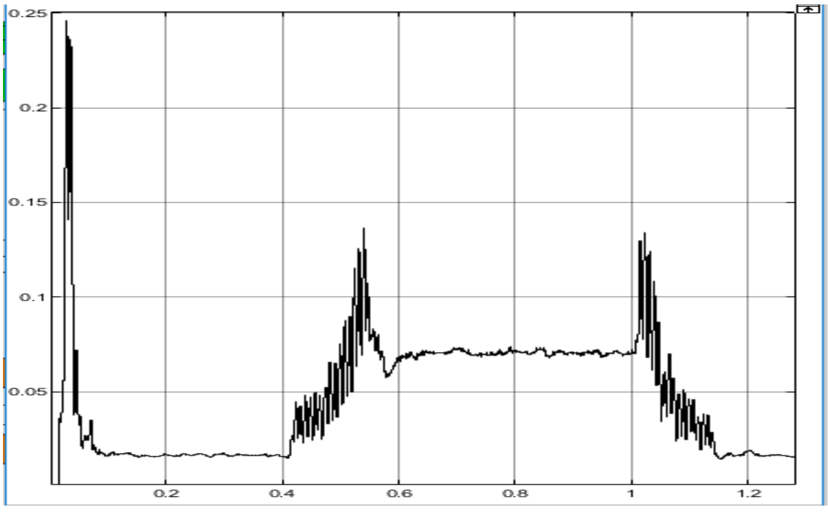


Figure 24: Harmonic Distortions with passive filter

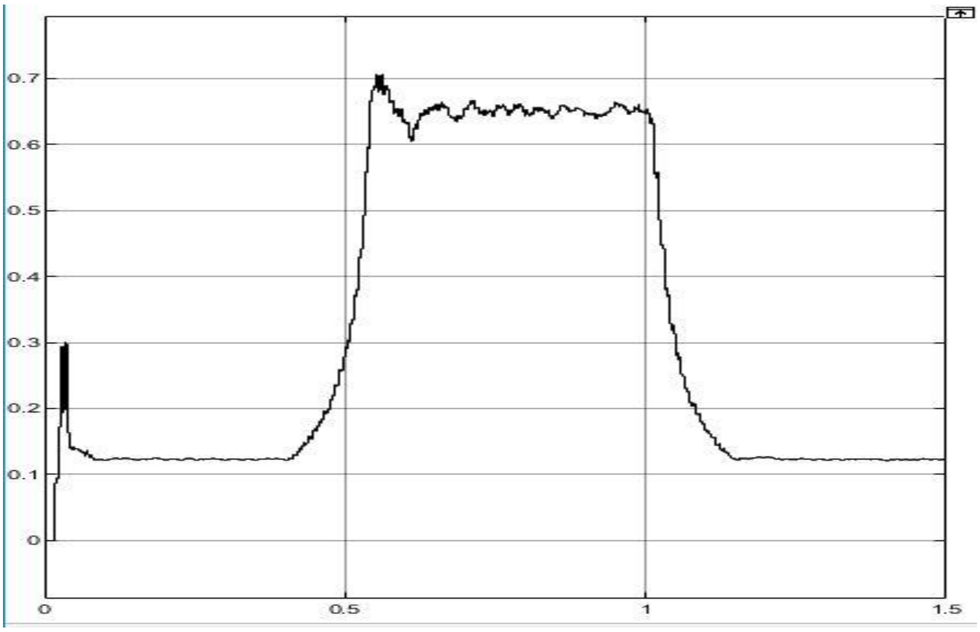
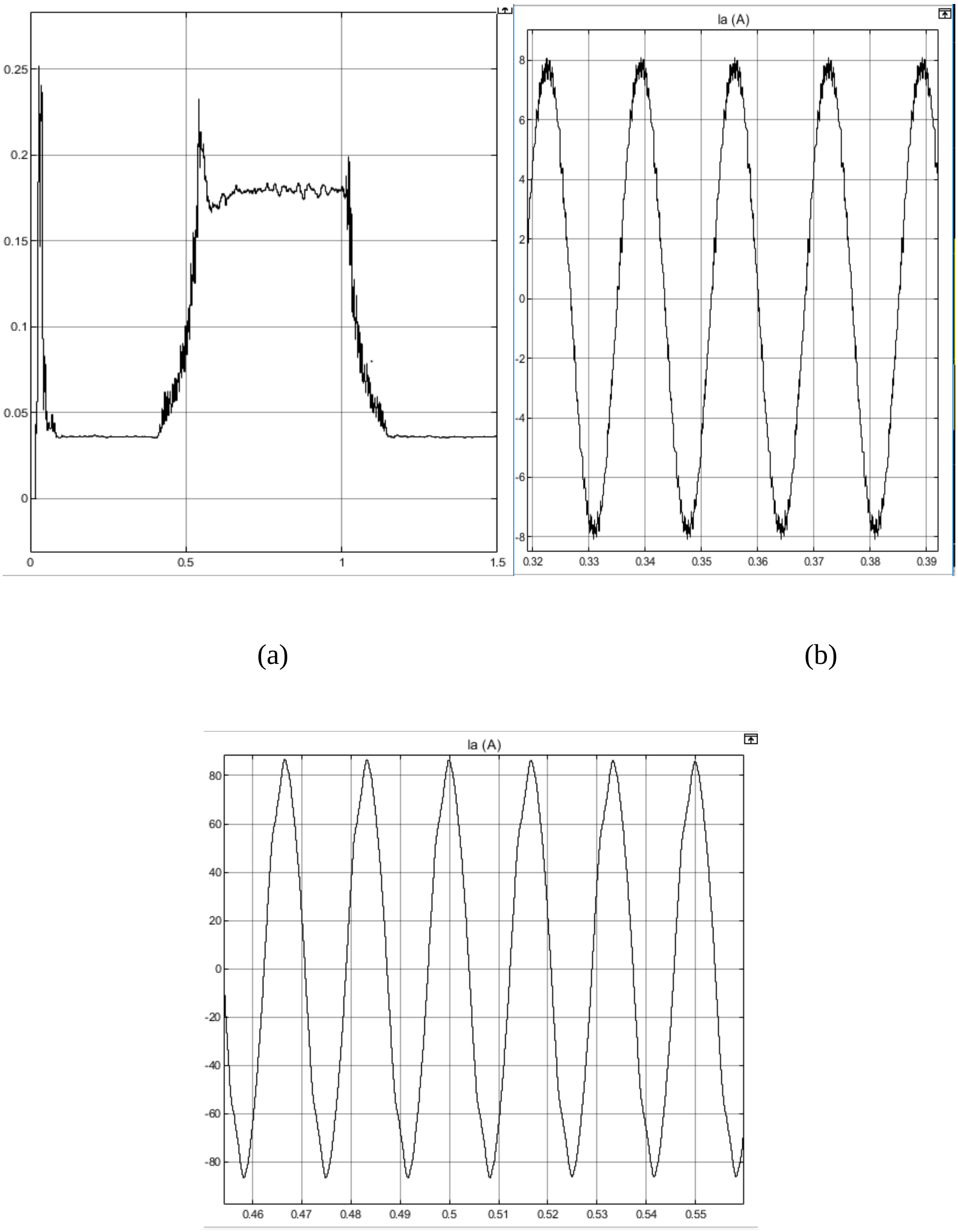


Figure 25: Harmonic distortions without a filter

The active filter was implemented in the model (can be depicted in Appendix II) and Figure 26 (a), (b) and (c) show the content of harmonic distortion with active filter, current distortion at peak of current waveform, current distortion absent at peak of current waveform and spectrum of current distortion with active filter furrier transform of transient variations respectively. The usage of the active filter, shows that the transition harmonic distortions are reduced around 0.4 seconds up to 0.55 seconds and between 1 – 1.2 seconds respectively. Compared to the passive filter usage, the reduction is significant in terms of transient characteristics; however the steady state amplitude between 0.55 – 1 second is around 18%. With the same light level applied, compared to the passive filter usage there is around 12% distortion increment occurring with the active filter usage; from 6% to 18%. It can be commented that the passive filter is better in the steady state however; active filter is much efficient in the transition characteristic, during the irradiance change condition.

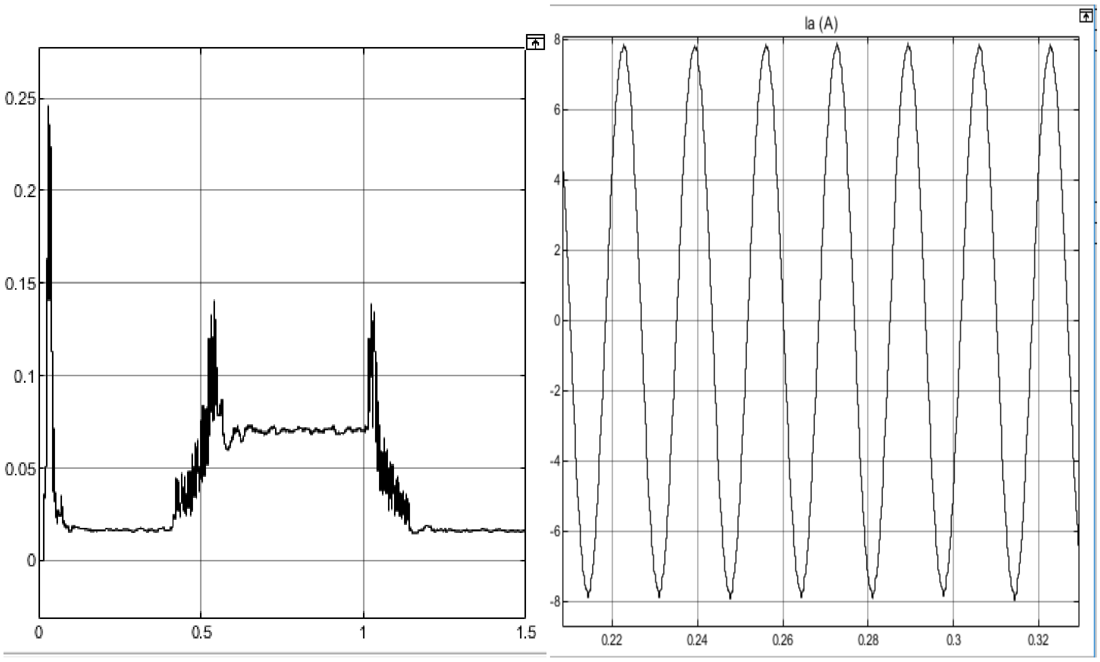


(a) (b)

(c)

Figure 26: (a) total harmonic distortion with active filter (b) Current distortion at peak of current waveform (c) Current distortion absent at peak of current waveform and

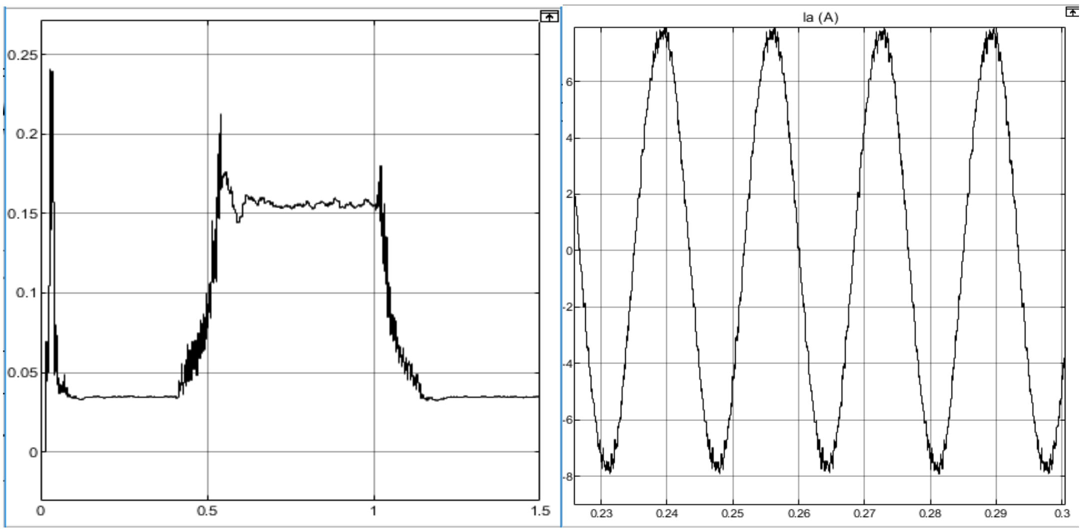
Further analyses are provided when the active and passive filters applied together to the inverter side of the system. The model can be seen in the Appendix III section. A hybrid of a passive and an active filter was implemented without control. The scheme is in allowing the two filters to work continuously. Figure 27 shows these variations in (a) Total harmonic distortion, (b) current distortion waveform. It can be depicted in the Figure 27 (a) that, if both active and passive filters are active all the time, the transient is slightly better compared to the passive filter only usage, as shown in Figure 24, previously. In the steady state condition, there was no significant change observed. It can be commented that, usage of the active and passive filters all the time is not very efficient in terms of total harmonic distortion elimination as their individual advantages are being eliminated in this approach.



(a) (b)

Figure 27: Hybrid filter (a) Total harmonic distortion (b) current waveform

Therefore, the last scenario was in control of the hybrid of two filters, active and passive. The active filter has a better outcome in term of transient efficiency, so during changes active is continuously used and until there is a constant situation the control of the passive filters remains off and it is switched on by the control system when the steady state is again reached. The controller keeps both actrive and passive filters on all the time and when there is a significant irradiance change is detected, the passive filter is turned off so that only active filter smooths the distortion. Figure 28 shows this total harmonic distortion, current harmonic waveform, and Fourier transform respectively.



(a) (b)

Figure 28: Hybrid filter (a) Total harmonic distortion (b) current harmonic waveform (c) current distortion waveform

It can be seen from the Figure 28 (a) that the both transient and steady state characteristic of the total harmonic distortion characteristics are much better compared to the non-controlled ones, previously discussed. The measured differences between the various topology modeled to obtain the better outcome in filtering were tabulated as shown in Table 4. The results showed higher value of THD equivalent to the calculated value expected for a square waveform while the lowest THD was measured for the proposed combination of active and passive filters with the controlling of passive as at when required during an increased transient.

Table 4: Comparison of result

Type of filters	With control	Current Waveform	THD (%)
3-level without filter	0.777	Very high transient -	78.72
2-level without filter	0.810	Very high transient	80.09
3-level with passive filter	0.183	Very high transient	18.84
2-level with passive filter	0.40	High transient	40.01
3-level with Active filter	0.18	High transient	18.00
2- level with Active filter	0.36	Medium transient	36.40
3-level with Active/passive filter	0.15	Medium transient	14.92
2-level with Active/passive filter	0.20	Low transient	19.42
3-level with active and controlling Passive	0.07	Low transient	7.11
2-level with Active/passive filter + RL	0.145	Low transient	14.47

4.3 Hybrid Controlled Filter for Active-Passive Filter

In the proposed model, Proportional Integral (PI) control was used, as the implementation of a better and more effective control strategy is the key to improved harmonic mitigation, even with the advancement in inverters from two-level to three-level. Researchers have continued to investigate on better control strategies, a Hysteresis control strategy is considered the easiest but has issues resulting from frequency switching, which is due to variation in switching frequency, thereby producing a continuous harmonic spectrum. Figure 29 show the active filtering usage with an appropriate firing pulse sequence is applied to transistor, the waveform of the input current can be controlled to follow a sinusoidal reference, as can be observed in the positive half-wave of current. The Figure clearly shows that the on- (off-) state of transistor produces an increase (decrease) in the inductor current. Figure 30 shows the control block of the proposed model.

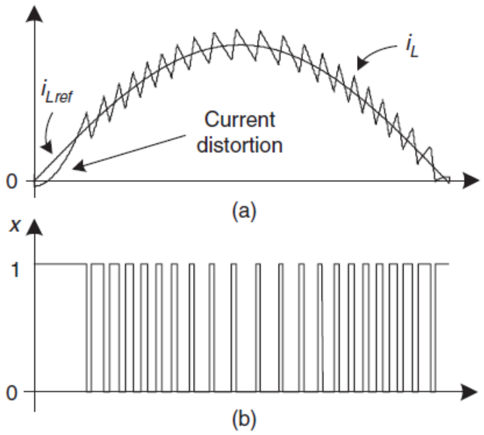


Figure 29: Active Filtering control

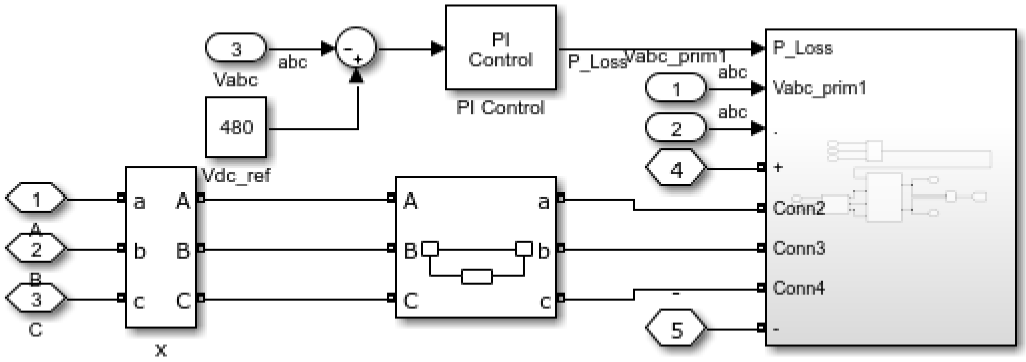


Figure 30: Block of the proposed model control strategy

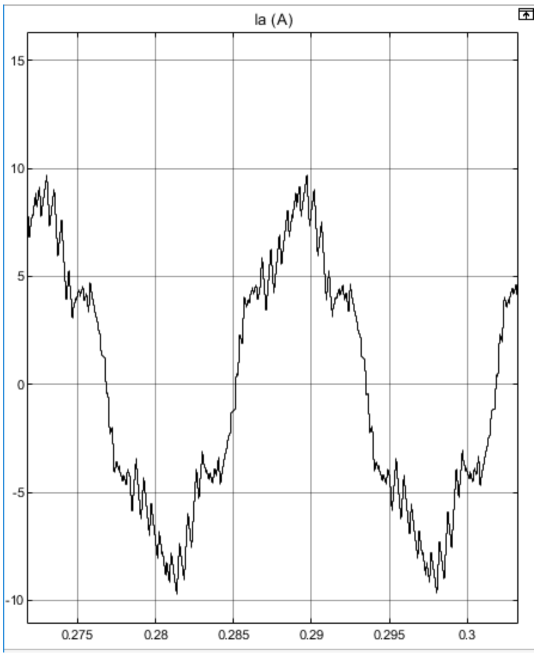
Repetitive control has witnessed advancement as (He et al., 2009) presented an advanced repetitive control strategy that provides a much-improved output current using a three-level active filter. It utilizes a norch zero phase shift to reduce significantly the harmonic content with appreciable lowered gain at both low and medium frequencies range.

Also, (Grino, Cardoner, Costa-Castello, & Fossas, 2007) proposed a different repetitive control called the digital repetitive controller for shunt active filters, making this topology of active filtering quite robust with lesser total harmonic distortion and power factor improvement to near unity.

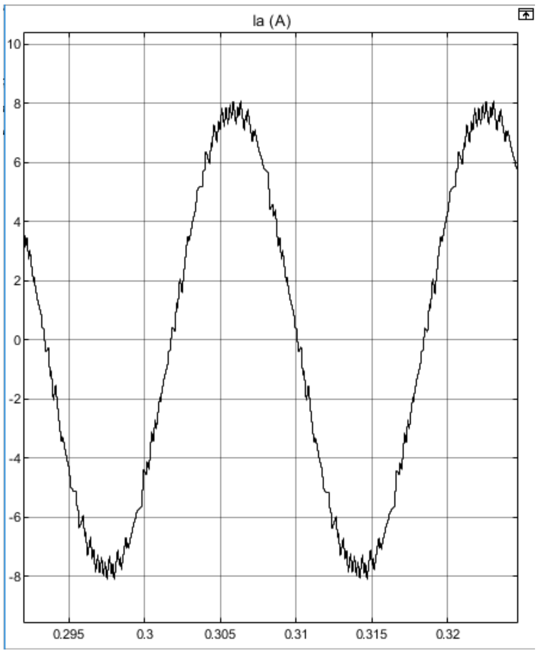
Similarly, (Pandove & Singh, 2018) presented a modified repetitive control scheme for shunt active filter topology that provides amplitude reduction in sensitivity function, which as well implemented a norch variable of either high or lower at reduced and increased frequency ranges.

4.4 Analysis of results

The result is analyzed using Matlab/Simulink; the first case was the use of a resistive-inductive load as shown in Figure 31, the current waveforms contain significant harmonic distortion. The case was compared for both two-level and three-level inverters, the three-level showed a lesser harmonic content.



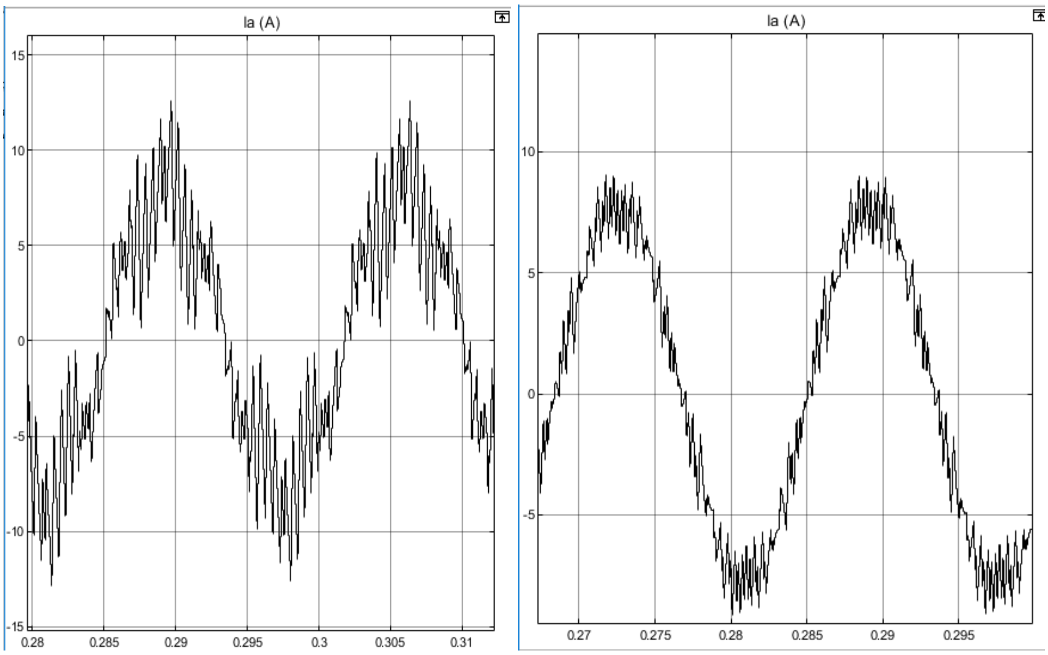
Two-level



Three-level

Figure 31: With Resistive-Inductive scenario

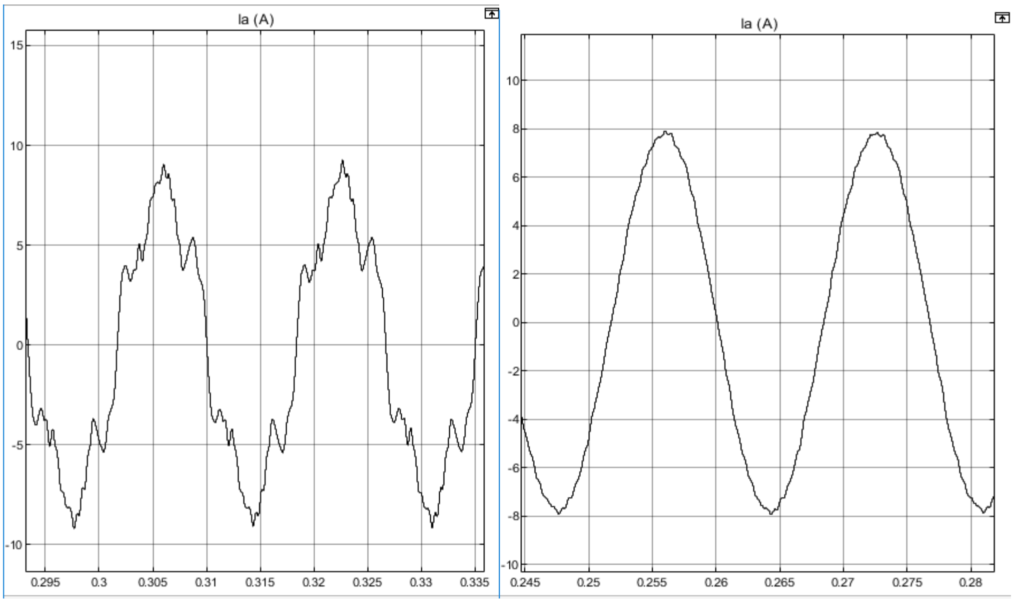
The next case was simulated without the use of any filter and also removing reductive-inductance applied to the output of the two-level and three-level inverters as shown in Figure 32 The waveform shows distortion which is more pronounced than that of the observed two-level inverter.



Two-level Three-level

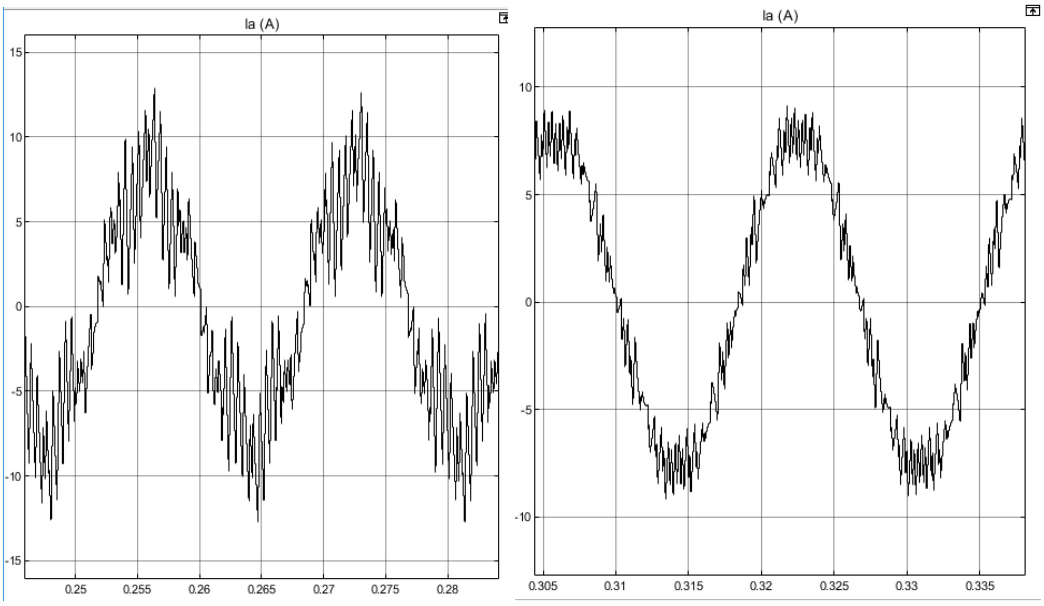
Figure 32: Without both Resistive Inductance and filter

The following case shows the effect of a passive filter in reducing harmonic contents on the current waveform as depicted in Figure 33 for both two-level and three-level. In another simulation shown in Figure 34 and Figure 35, the RL was removed allowing the use of active filter alone and the combination of active and passive filters respectively. The waveform was better only in amplitude both contained several distortions.



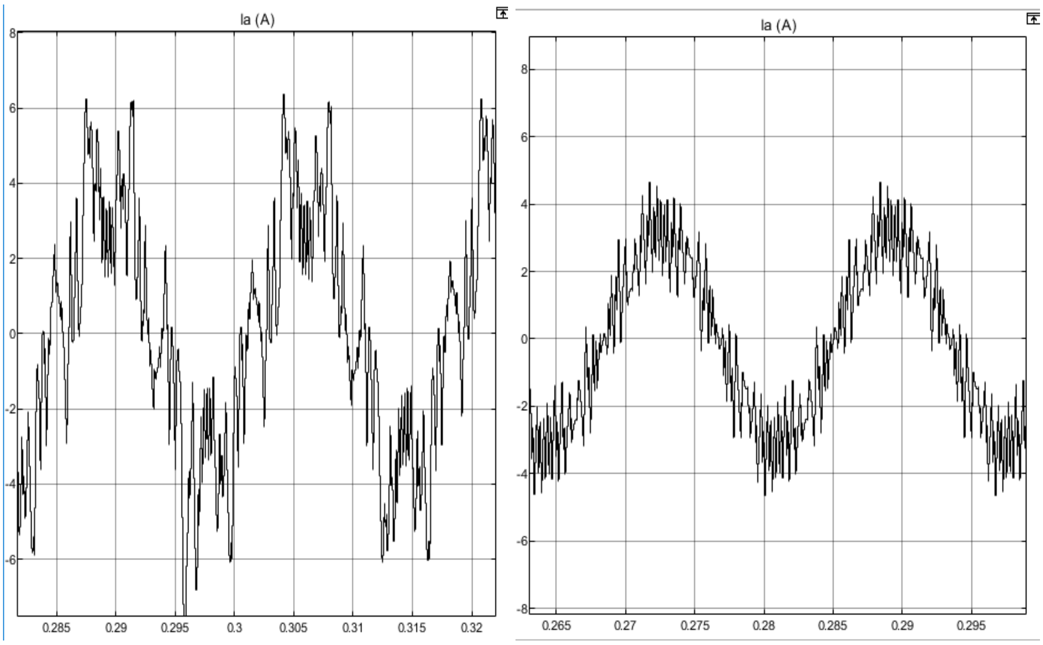
Two-level three-level

Figure 33: With Passive filter scenario



Two-level Three-level

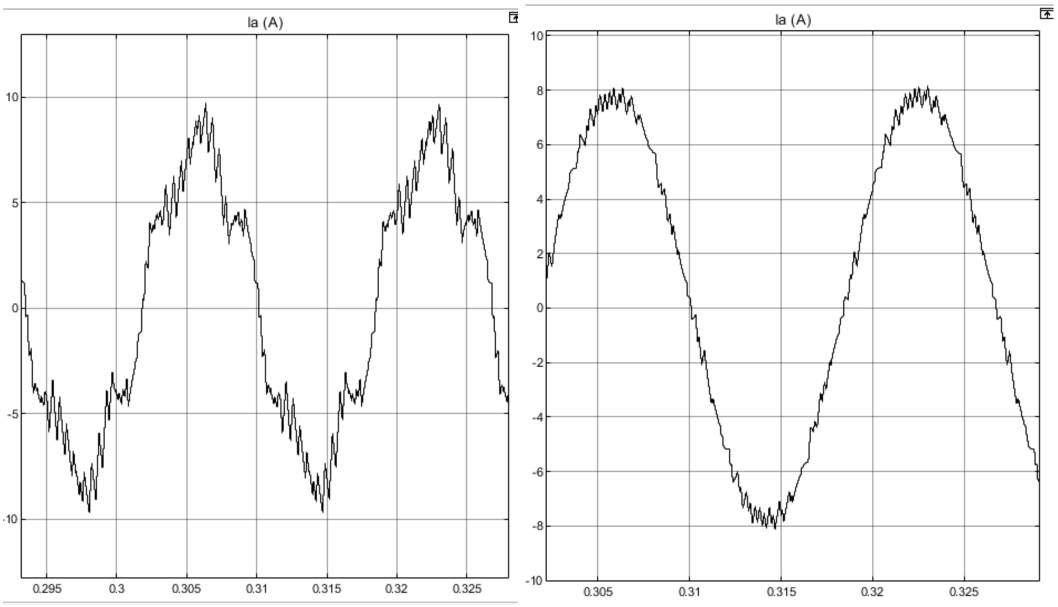
Figure 34: Active filter without RL scenario



Two-level Three-level

Figure 35: Active and passive filter without RLscenerio

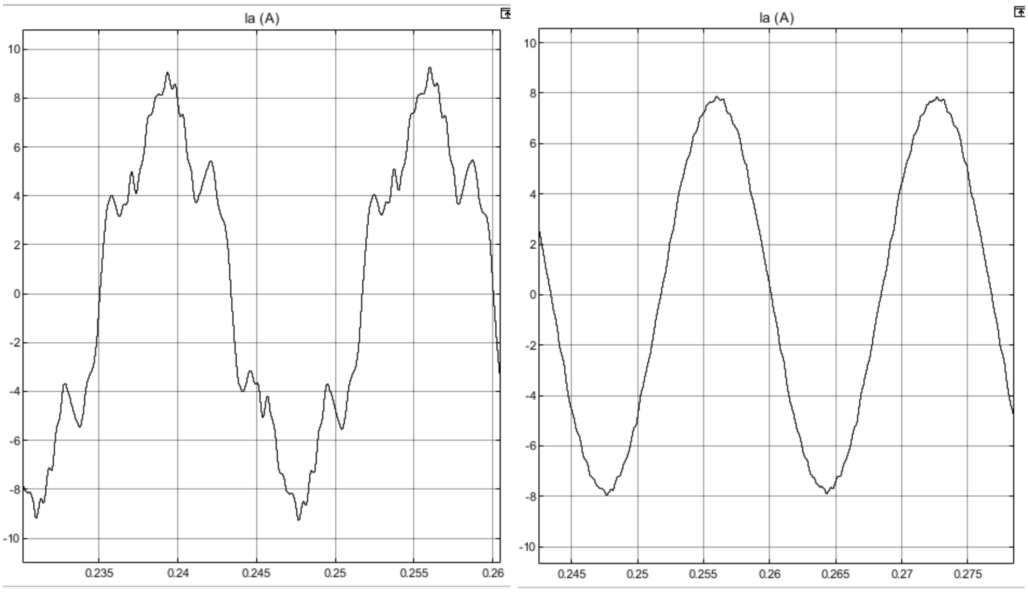
The next result shows the addition of RL together with an active filter in Figure 36 and the implementation of RL together with active and passive filter shown in Figure 37 as well.



Two-level

Three-level

Figure 36: Active and passive filter without RLscenario

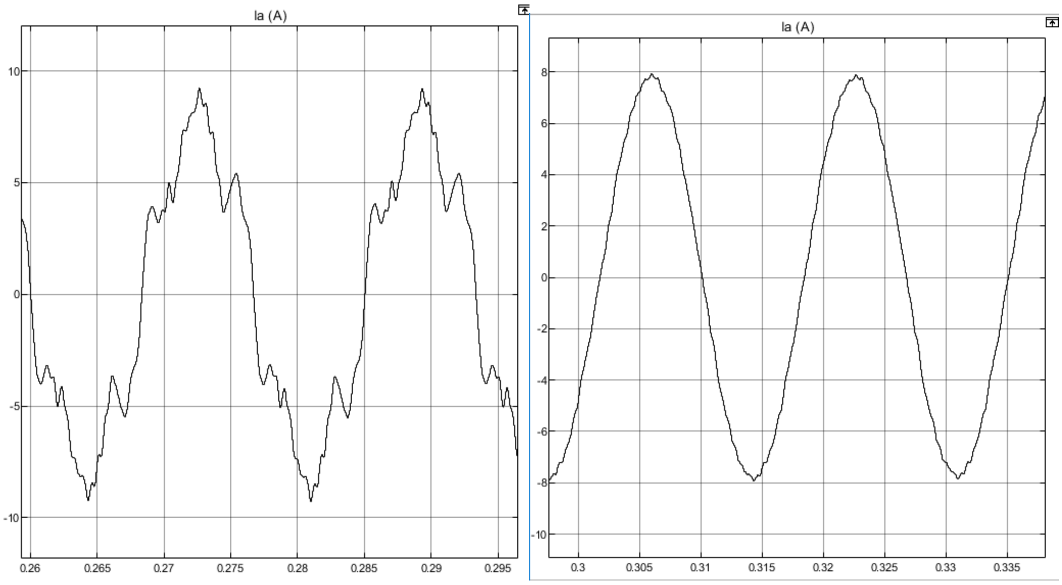


Two-level

Three-level

Figure 37: Active and passive filter with RL scenario(Hybrid)

The finally, a control was applied to the hybrid filtering technique to allow the active filter to operate and at a lower irradiance; the hybrid strategy will be employed. This combination waveform pattern is shown in Figure 38.



Two-level Three-level

Figure 38: RL, Active with controlling of the passive filter scenario

4.5 Power Losses comparison

Power efficiency is always the important factor in any power delivery system, in a system utilizing two-level inverter; its output voltage is produced from two voltage level while for the system using three-level more voltage level is applied thereby more efficient energy delivery, lesser THD, and lesser switching losses. Power loss in two-level inverter compared to three-level inverter can be as high as over forty percent (>40%) (Ikonen et al., 2005).

Power loss in two-level and three-level inverters can be calculated using Eq. (13), using the unit losses as tabulated in Table 5 (Ikonen et al., 2005).

$$P_{loss} = 3 \times p_{con.} + 3 \times P_{cp} + P_{SW} \tag{13}$$

Where P_{loss} = Total power loss, $P_{con.}$ = conduction losses, P_{dclink} = DC link Power losses, and P_{sw} = Switching power losses

Table 5: Per unit losses

CONFIGURATION	I_{crms} (A)	I_{cdrms} (A)	(A)	ESR (mΩ)	Loss/unit(W)	Total Loss(W)
2-LEVEL	31,6	26,9	41,5	65	112	670
3-LEVEL	73,2	62,3	96,1	14	129	520

For two-level given conduction losses of 260W and switching losses of 186W each switch,

Total power loss = 3 × 260 + 3 × (2 × 186) + 670 = 3 (260 + 2×186) + 670 = **2566W**

For three-level given conduction losses of 352W and switching losses of 66W for both switches,

Total power loss = 3 × 352 + 3 × (2 × 33) + 520 = 3 (352 + 2×33) + 520 = **1774W**

To have fully efficient power generation it is very important to minimize losses, such as conduction as well as switching losses(Sanjeev & Jain, 2013).

The two-level inverter for a unit compared with the three-level inverter has about 27% in term of cost, which is mainly as a result of use of diode in three-level inverter topology. The cheaper cost of two-level inverter when measured together with there efficiency and compared with the three-level inverter, the three-level inverter bettered the two-level with over 20% in just one year with an energy rate of 12cent.

The price for a two-level inverter was calculated as **741 usd**, based on major components of IGBT and DC-link while for three-level was **1014 usd**, similarly based on IGBT, Diodes and DC-link.

Total Cost of two-level for one year

Energy losses = 2566 W × 12 cents = 30.792cents per kWh

For one year = 30.792 × 8760 = 2698.08 usd

Overall cost for one year = 741 + 2698 = **3439 usd**

Total Cost of three-level for one year

Energy losses = 1774 W × 12 cents = 21.288cents per kWh

For one year = 21.288 × 8760 = 1864.83 usd

Overall cost for one year = 1014 + 1864 = **2878 usd**

Therefore, the three-level topology in term of cost after just one year is cheaper than the two-level topology.

– 2878 = 560 usd (approximately 20%)

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The number of literature work on power quality is numerous and will continue to increase as the issue of power quality in power generation is very important. Similarly, significant number of researchers presented lots of solution for mitigating current and voltage harmonics, ranging from filtering, either using passive, active or hybrid filters. Also, pulse width modulation techniques were presented with increasing emphases on controlling strategy. However, literature studied during this research work did not look at the situation in PV power generation from the advent of poor or severe weather resulting in lowered irradiance. This research targets this area and most of all to present a broader knowledge in one entity, to provide reasons for METU campus to look into advancing from two-level inverter used in its power plant to a three-level.

The general need for energy is growing rapidly, it is similarly important to look into energy wastage rather than its creation. If two-level inverters caused a significant power loss of over forty percent, avoiding this wastage is same as generating the power loss. Finally, the three-level inverter topology become cheaper after just a year, which shows how effective and significant energy can be managed using the three-level topology.

5.2 Future work

This study will be more effective if its experimented, thus there is the need to have a prototype model of a grid or a microgrid in this great institution to fasten the growth in renewable research and development. Most importantly, as the school moves graciously in having a wind turbine it will be meaningful to have a microgrid as well.

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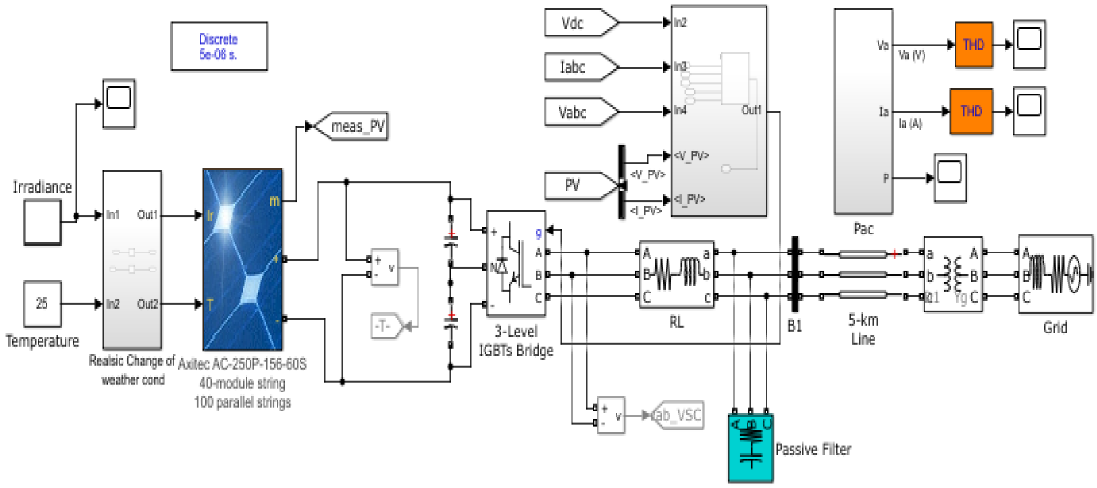
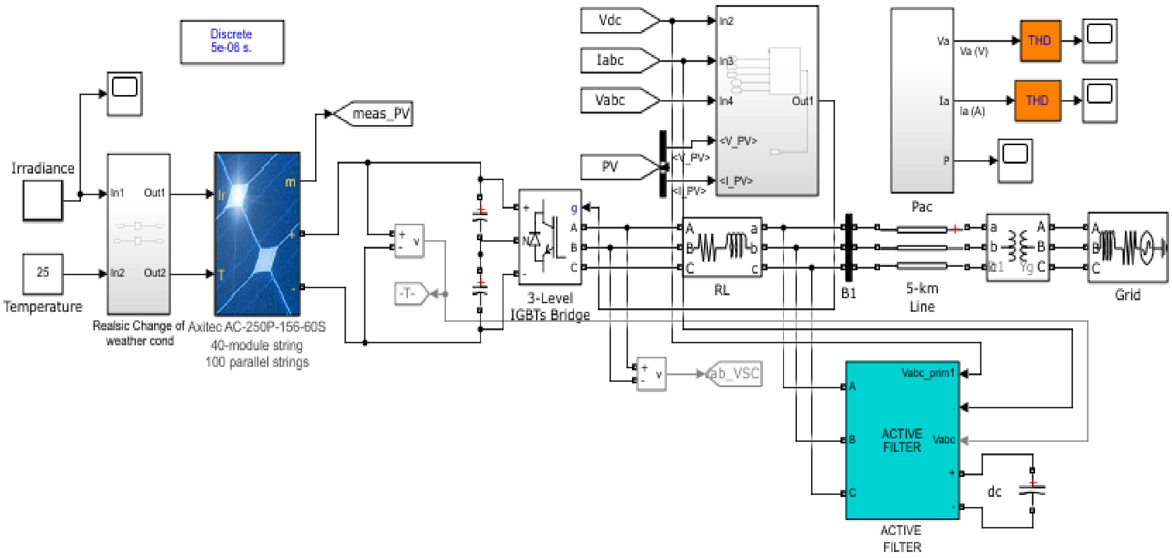
APPENDIX I

Passive filtering



APPENDIX II

Active filtering



APPENDIX III

Hybrid filtering