IMPROVING THE ENERGY CONVERSION STABILITY OF HYBRID SOLAR PHOTOVOLTAIC / WIND TURBINE RENEWABLE ENERGY SYSTEMS

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ABSTRACT

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Berk Aşçıoğlu

M.Sc., Electrical & Electronics Engineering

Supervisor: Asst. Prof. Dr. Canraş Batunlu

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In the last few years, renewable energy sources such as wind turbines, photovoltaics, hydropower stations etc. have become widespread because of raising energy needs of the world. Since the fossil fuel consumption excessively has increased, lack of energy has caused the renewable energy requirement. Furthermore, renewable energy has an important role because of the economic and environmental worries. In other words, industrial and inhabitant needs by provided the traditional energy is no longer a successful way due to the high cost and peripheral concern. Besides renewable energy sources, during the recent years, the power electronic technology has grown rapidly because of improvement of semiconductor devices switching quickly, real time computers implementing advanced and complex algorithms. These improvements also have led to the development of the lower cost converters which can be used to make the connection between renewable energy sources and electric power system grids. This thesis will investigate the issues when connecting renewable energy sources to the electric power system grids and try to solve these issues by analyzing the effects of filter techniques, new switching methods and converter designs. In this thesis conventional techniques will be examined by a broad research and new methods will be proposed in order

to make the solutions of power quality issues easier. Also, due to the insufficient renewable energy that is caused by uncertain behaviors of renewable sources, important electrical and electronic components will be examined. Finally, there will be some case analysis and comparisons of different connection types to explain how the system can be optimized in term of harmonic distortion. Compared to the 2 level inverters, 3 level inverters 10 % better energy yield in the current waveform, and with the battery usage, both systems have 2 % of increased energy efficiency.

Keywords: Renewable energy systems, wind, photovoltaic, electric power system grid, electrical and electronic components, connection types, case analysis

ÖZ

Son birkaç yılda, rüzgar türbinleri, güneş pilleri, hidro güç istasyonları gibi yenilenebilir enerji kaynaklarının kullanımı, dünyanın genel enerji ihtiyaçları nedeniyle yaygınlaştı. Fosil yakıt tüketiminin aşırı şekilde artması nedeniyle, bu enerji eksikliği yenilenebilir enerjiye ihtiyacı gerektirdi. Buna ek olarak, yenilenebilir enerji, ekonomik ve çevresel endişeler dolasıyla önemli bir role sahip. Diğer bir deyişle, yüksek maliyet ve çevresel kirlilik nedeniyle, yerleşik halkın ve sanayinin ihtiyacını karşılayan eski enerji elde etme teknikleri artık iyi bir yol olarak gözükmüyor. Yenilenebilir enerjinin yanında, güç elektroniği teknolojisi de hızlı tepki veren yarı iletken cihazların ve ileri seviyede uygulama ve algoritma yapılabilen gerçek zamanlı bilgisayarların gelişimiyle hızlı bir şekilde büyüyor. Bu gelişmeler ayrıca yenilenebilir enerji kaynaklarının elektrik güç sistem şebekelerine bağlanmasında kullanılan düşük maliyetli dönüştürücülerin de geliştirilmesine yardımcı oluyor. Bu tezde, yenilenebilir enerji kaynaklarının elektrik güç sistem şebekelerine bağlanmasındaki durumlar incelenerek ve filtreleme tekniklerinin etkileri, yeni anahtarlama yöntemleri ve dönüştürücü dizaynları analiz edilerek ortaya çıkan sorunlara çözümler incelenecek. Ayrıca, yenilenebilir enerji kaynaklarının belirsiz davranışları nedeniyle zaman zaman yetersiz kalmasından dolayı kullanılan elektrik ve elektronik cihazları incelenecek. Son olarak, sistemiz optimize edebilmek için gerekli olan farklı bağlantı çeşitlerinin karşılaştırılması ve durum analizi harmonik bozuklukların optimizasyonu için yapılacak.

Anahtar Kelimeler: Yenilenebilir enerji kaynakları, rüzgar, güneş, elektrik güç sistem şebekeleri, elektrik ve elektronik cihazlar, bağlantı çeşitleri, durum analizi

DEDICATION

I dedicate this thesis to my supportive family, friends and supervisor.

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ABBREVIATION

AC	Alternating current
ADC	Analog to Digital Converter
BDFIG	Brushless Doubly Fed Induction Generator
BDFRG	Brushless Doubly Fed Reluctance Generator
CPV	Concentrated Photovoltaic
CO_2	Carbon dioxide
DC	Direct current
DFIG	Doubly Fed Induction Generator
EMF	Electromotive Force
IGBT	Insulated gate bipolar transistor
kW	kilowatt
MPPT	Maximum power point tracking
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
PV	Photovoltaic
RMS	Root Mean Square
SCIG	Squirrel Cage Induction Generator
THD	Total harmonic distortion

VAR	Volt-Ampere Reactive

CHAPTER 1

INTRODUCTION

1.1 Background

Studies in recent years showed that the raising fossil fuel consumption has created a resurrection of relevance in using renewable energy alternatives to meet the increasing energy needs of the world (Youm, 2000; Horst & Hovorka, 2009) It is clear that fossil fuels produced %81 of energy of the world. Actually, fossil fuels produce energy which has a big environmental effect causing the global warming, so this was a big problem. In addition to the global warming, high sea level is raising the carbon dioxide concentration and other greenhouse gases like methane, ozone, water vapor etc. The electricity sector is the biggest sector to be a source for the emissions of CO_2 and it will increase constantly in times to come. In brief, fossil fuel usage has increased, so carbon dioxide usage has commenced the global warming (Hall, Mynick & Williams, 1991).

There are five main renewable energy sources as it can be seen at the right side of the fig. 1. These are biomass having three subparts which are biomass waste, biofuels and wood, geothermal, solar, wind and hydroelectric.

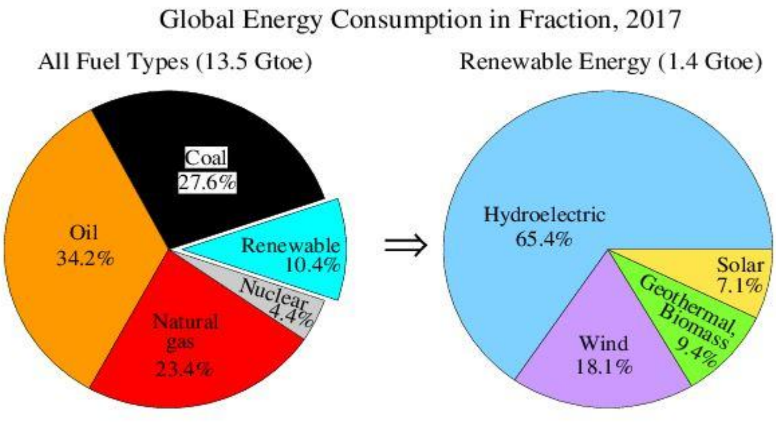

Figure 1: Energy consumption by sources (Alrikabi, 2018)

Wind energy creates the kinetic energy by using the wind turbines, and it converts the kinetic energy to the generator torque. After that, electricity is created thanks to the generator and this maintains the power system grid. Solar energy also can have an effect on the electric power system grid by changing the frequency response and the voltage.

Renewable energy technologies can be considered as pure sources of energy by using the resources from the nature. Thus, it has some advantages in terms of sustainability and environment. It reduces the emissions of greenhouse gases and the air pollution. It also conserves the native forests and minimize wasting (Sims,2003).

In brief, researchers from different countries and governments may work together to provide the world more efficient renewable energy sources and improve the technologies of renewable energy sources. Also, renewable energy can be used on the international trade.

1.2 Electricity Generation

In this section, electricity generation from wind energy, solar energy and wind & solar hybrid system will be examined separately.

1.2.1 Electricity Generation from Wind Energy

Wind's kinetic energy is converted into the rotational mechanical energy by the wind turbines, and then, this mechanical energy is converted into the electricity by a generator (Ahmed & Jiang, 2018). Wind turbines generally have 3 blades to collect the wind energy. These blades are called a rotor, which is connected to a long tower. It is important to use a long tower because of stronger winds higher from the ground. Wind energy is another form of solar energy because it comes from the pressure and temperature changes in atmosphere, so this causes the air to move around the earth surface. The wind is captured by a wind turbine, so it provides the rotor spin and the energy is produced. In brief, the power is converted into electricity. Conversion of power into electricity is provided by magnets that moves past stationary wire coils. This type of coils of wire is called a stator. Hence, AC electricity is generally produced, and then, it is converted to DC electricity. This electricity provides the batteries to be charged or it can be used for feeding into a grid inverter.

A wind turbine usability depends on the wind resource amount in the areas, and these areas are generally the coast or farms. Before installing a wind turbine, the average speed of wind should be found, and generally it should be higher than 5 m/s. Modern wind turbines can be categorized as vertical axis and horizontal axis design (Dang,2009).

1.2.2 Electricity Generation from Solar Energy

The sunlight energy is converted into electricity by a solar cell, which is a semiconductor device. It is also called Photovoltaic Cell (PV cell), because this conversion is affected by photovoltaics. Current and voltage are produced when the sunlight comes through PV cells. The power amount produced by a PV cell depends on the sunlight coming through it. In other words, it depends on weather conditions as in fig. 2. In addition to this, there are some other parameters like the cell area, intensity and falling angle of the sunlight. In order to get more power, the cell area and the intensity of the sunlight should be larger. Also, the optimal power is obtained when the sunlight is perpendicular to the PV cell. (Singh, Kumar & Vijay, 2014)

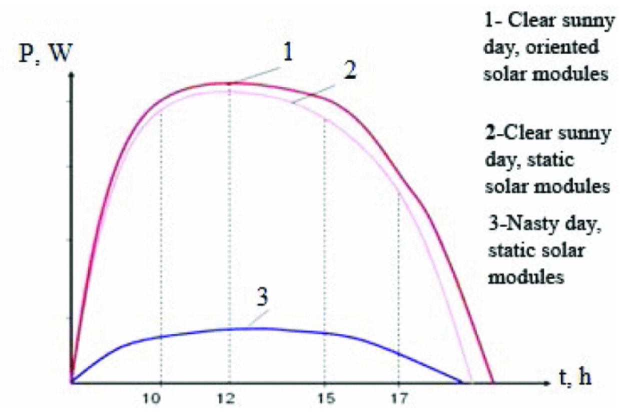

Figure 2 : Dependence of output on solar power station on weather conditions (Moltov, Vaskov & Tyagunov, 2018)

PV cells are refined with boron and phosphorous in order to create a silicon wafer, which is a semiconductor material. After that, silicon wafers are lined together to form the PV cells. There are two terminals (negative and positive terminals) in PV cells in order to get the current from them. Generally, a PV cell comprises of PN junction at the middle, front contact at the top and back contact at the bottom (Jones, Coutu & Lake, 2016). As it is known, the sunlight has collections of photons, and every photon includes a certain energy amount. PV cells need to absorb these photons to produce the electricity. The band gap energy and photon energy are two important factors while the photons are absorbed. Because of absorption of the photons, electron-hole pairs are formed at the junction, and then, they are separated when the load-cell connection is provided. After the separation, holes go to the positive terminal and electrons go to the negative terminal, and finally, electric potential is produced between these terminals, and the voltage is obtained. Thanks to this, the current flows through the inverter and loads. In case of having more photons, the current value of PV cell increases, but it can convert a certain amount of energy into the electricity. The reason of this situation is different photon wavelengths of the sunlight. All photons cannot enter to the cell and they reflect to back. (Bell, He, Xiong & Eggleton, 2016)

There are some technologies which are applied to the PV cells in order to increase the efficiency of conversion to about % 50, but this requires higher costs. The best way is to connect some PV cells in series and the remaining cells in parallel, higher electric potential difference can be obtained. Connecting the PV cells creates "PV modules" and connecting the PV modules creates "PV array" which can generate higher power. (Killam & Bowden, 2017)

1.2.3 Electricity Generation from Wind & Solar Hybrid System

A hybrid energy system is installed because of uncertain and unbalance energy resources. The wind-solar PV hybrid energy system makes the condition easier where wind and solar have seasonal shifts (Vasant & Pawar, 2017). For example; there is no sunlight for the whole day and the weather is not windy for the whole day. Thus, it will not be good to use only one source. In order to increase our power source reliability, using a hybrid system which is a combination of solar and wind power and storing the energy in a battery will be a better option. As our load can still use the stored energy in battery, there is no need for sun and wind all the time. There are two important factors to build a hybrid system which are the highest reliability and the efficiency, so this makes the hybrid systems more useful (Ravikumar & Vannila, 2017). An example of basic solar & wind hybrid system can be seen in fig. 3.

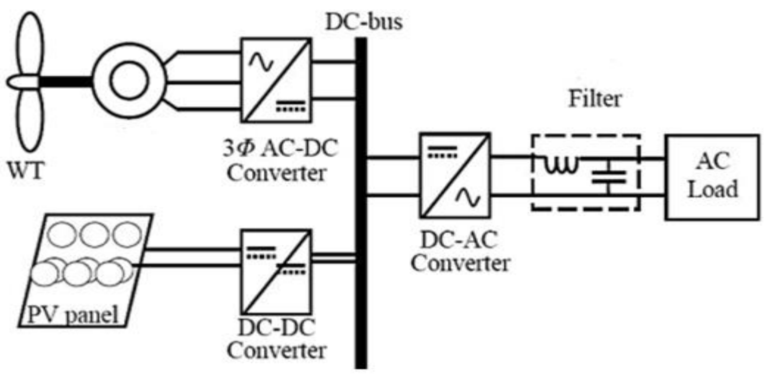

Figure 3: A basic solar/wind hybrid energy system

1.3 Power Quality Issues

There are some power quality issues such as harmonics and voltage – frequency fluctuations. Harmonics can be classified as voltage and currents with their frequencies which includes the multiple of integers of fundamental electric power frequency. Electrical devices such as motors and generators generate harmonics and this can result in a lot of problems about power quality (Kavitha & Subramanian, 2017). Generally, grid connected inverters with high and low level harmonic currents can result in harmonic problems. Whereas the most used inverters cannot support the harmonics which is necessary for the grid connection, voltage sources can support this. On the other hand, they have higher cost but some compensators can be used in order to make cheaper.

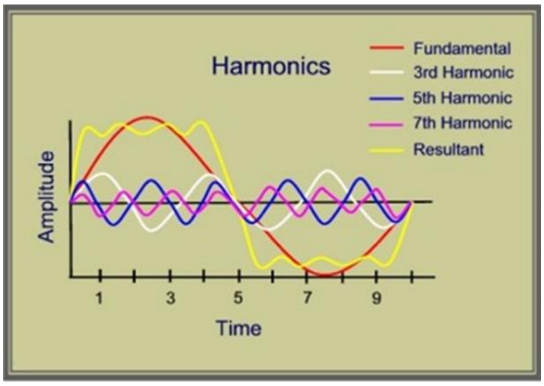

Figure 4: Effect of Harmonics

In addition to these, when there is not enough sunlight to meet the losses of switches, there cannot be harmonics for the PV array inverters. When the number of harmonics increase, there will be more distortion and this affect the power quality. Also, due to the insufficient power factors, regulating the voltage is hard and power losses raise. In order to make the power factor correction, power factor should be fixed or adjusted automatically (Singh, Khadkikar, Chadra & Varma, 2011).

While providing the power factor correction, the size of inverter should be larger and the injection of reactive power should be done. When this kind of reactive power compensation is successful for the control of voltage on most of the systems, compensation of VAR is not sufficient because of the more resistivity, and injection of the active power has more efficiency in order to regulate the voltage. Also, there might be a limitation for the utilization control to inject the imaginary power (Xu, Chen, Liu, Tian & Yan, 2018; Vatu, Ceaki Mancasi, Porumb & Seritan, 2015).

Because of the different amplitudes of the voltages of the phases, voltage balance cannot be provided for the three phase systems and the phase systems which has phase differences close to 120^o. For the case of single phase, this concept might result in some networks which are not balanced and this can damage the voltage control, generators, transformers, motors, some electronic applications, so the accretive system sizes need to be equal as far as possible (Oramas-Piero, Vega Fuentes & Deniz, 2018)

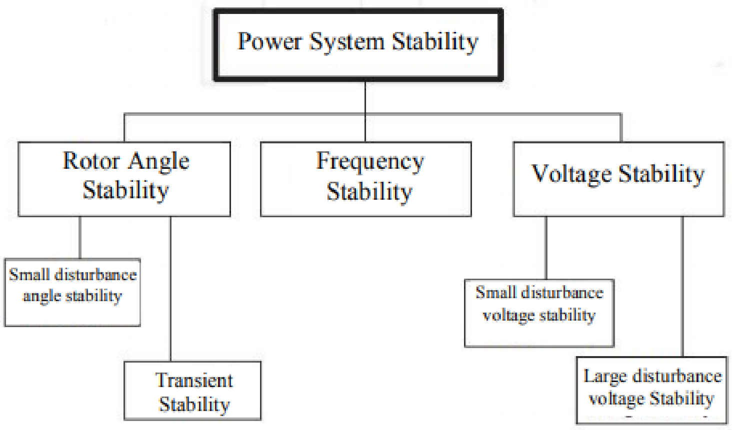

Figure 5: Classification of Power System Stability (Kumar, Pandey & Sinha, 2016)

According to fig. 4, the power system stability can be categorized as: rotor angle stability; frequency stability; and voltage stability. Therefore, different viewpoints are seen concerning the stability issues increasing different kinds of the stability problems which includes these stabilities.

Rotor angle stability provides the system maintenance of equilibrium between mechanical torque and electromagnetic torque of the generators in the system. Instability that might result occurs in the form of raising angular swings of some generators that lead to their loss of synchronism with other generators (Kumar, Pandey & Sinha, 2016). Voltage stability provides the power system a maintenance of its steady voltage at all buses of the system under the operating conditions, and after exposing a disturbance (Jirjees, Al-Nimma & Al-Hafidh, 2018).

Furthermore, voltage should be a little bit larger than the nominal voltage in order to decrease the losses at the transmission lines. Thus, voltage regulator can be used to meet the drop at the voltages and maintain the transmission line voltage in range which is designed.

Also, some nontechnical issues of the grid connected renewable energy sources particularly wind and solar PV are as below:

- Deficiency of technical talented man power
- Less transmission line availability to accommodate the renewable energy sources.
- Renewable energy source technologies are excluded from the competition by giving them priority to dispatch discouraging the setting of the new power plant for the reserve purpose. (Kumar, Pandey & Sinha, 2016)

1.4 Problem Statement

This thesis is motivated by the need to optimize the unbalanced situation between renewable energy sources and the electricity grid because of power quality. In fact, this situation needs to be optimized with some new technologies of the electrical system components such as converters, filters, maximum power point controllers and batteries. A grid connected model with renewable energy sources can be created with most of these system components, but the important point is efficiency here under varying weather conditions. Thus, right decisions should be made while choosing the types of these components in order to make the system efficient and improve the energy conversion stability by a hybrid controlling algorithm.

1.5 Thesis Organization

This thesis is addressing the improvements of power quality of grid connected hybrid solar and wind systems. Generally, there is an unbalanced situation between renewable energy sources and electricity grids. This situation needs to be optimized with some new technologies of electrical system components such as converters, filters, maximum power point controllers and batteries. The literature review of this thesis is done according to the basic components of grid connected hybrid solar and wind systems and presented in Chapter 2. In Methodology part, presented in Chapter 3, first, grid connected wind turbine system and grid connected PV system are set up separately, and then an overall system is set up. MATLAB is used to make these setups. For grid connected wind turbine and PV systems, different wind speed and irradiance levels are experimented by using MATLAB. Also, different converter, filter, maximum power point tracking controller and battery types are experimented with their different inputs in order to get different outputs and simulations. In Chapter 4, case analysis and comparison of these types are made to optimize the system and get the best performance and cost efficiency. Finally, in Chapter 5, conclusion and future work are presented.

Chapter 2

Literature Review

2.1 Types of Wind Turbine Generators

Wind power is converted into the electricity by wind turbines. In other words, mechanical power is converted into the electric power by the generator of the turbine. The efficiency of energy production depends the velocity of the wind. Wind turbine generators can be categorized as in table 1.

Table 1: Types of Wind Turbine Generators

Full Scale Wind Turbine Generators	**Half Scale Wind Turbine Generators**
Squirrel Cage Induction Generator	Doubly Fed Induction Generator
Permanent Magnet Synchronous Generator	Brushless Doubly Fed Induction Generator
Wound Rotor Synchronous Generator	Brushless Doubly Fed Reluctance Generator

2.1.1 Squirrel - Cage Induction Generators

SCIG (Squirrel-Cage Induction Generator) is directly connected to the step-up transformer, and its speed is constant towards electric grid frequency. It is also called Type 1 Wind Turbine Generator. The active power can be generated by this item if the shaft of turbine rotates quicker than the electric gird frequency, and this frequency develops a negative. Change in electrical output is controlled by the kinetic inertia with drive when there are some sudden changes in wind speed. These generators are generally work at almost a rated speed, because of machine slip. This slip causes a deviation at the electrical output. SCIG's consume the reactive energy because of the massive currents and excitation (Bierhoff & Rhinow, 2015). An example of SCIG is as in fig. 6.

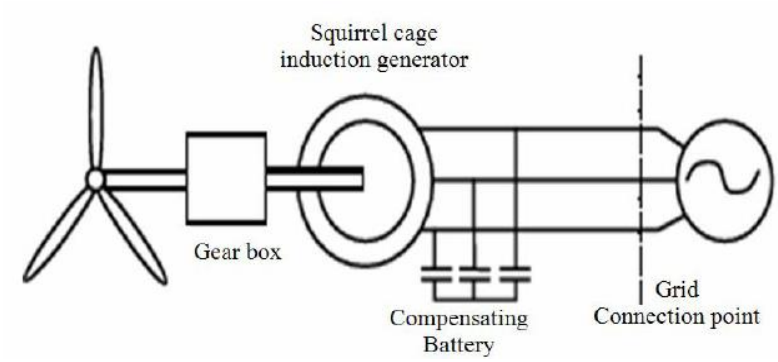

Figure 6: Squirrel Cage Induction Generator (Djemai & Bouktir, 2008)

2.1.2 Permanent Magnet Synchronous Generators

This type of wind turbine generators, which can be also called type 4, provides a more flexibility in process and design due to full scaled characterization. (Das, Zhang & Pota, 2016). Permanent magnet is used to crate magnetic fields, whereas electromagnets are used by other generators to generate magnetic fields, so permanent magnet generators does not require a coil. These types have brushes and slip rings instead of DC voltage supplies, they feed rotor winding's direct current. The rotation speed of this type is generally optimal. However, its voltage regulation can not be easily provided due to flux problems which can not be controlled. A good example of PMSG is as in fig. 7.

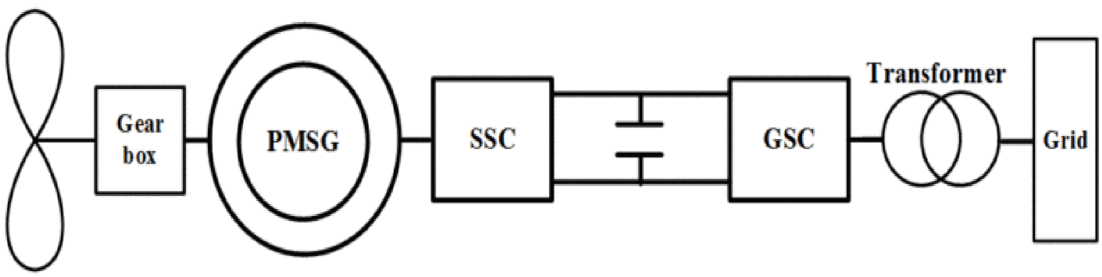

Figure 7: Permanent Magnet Synchronous Generator (Duong, Le, Grimaccia, Leva, Mussetta & Zich, 2014)

2.1.3 Wound Rotor Synchronous Generators

This type of generators as in fig. 8 is directly connected to the step-up transformer like SCIG's, and it is also called Type 2 Turbine. However, they also include a variable resistor in the actual rotor signal (Abdel-Wahab, Abdo & Hanafy, 2016). This can be provided by adding some resistors and external power electronic components to the rotor having slip rings. In addition to this, these resistors and components can be added in the rotor without the slip rings. These resistors control the rotor voltage and maintain the power. When the generator rotates faster, the pace can be controlled easily, and the best energy output can be obtained for the actual turbines. This is the main advantage of using wound rotor induction motor.

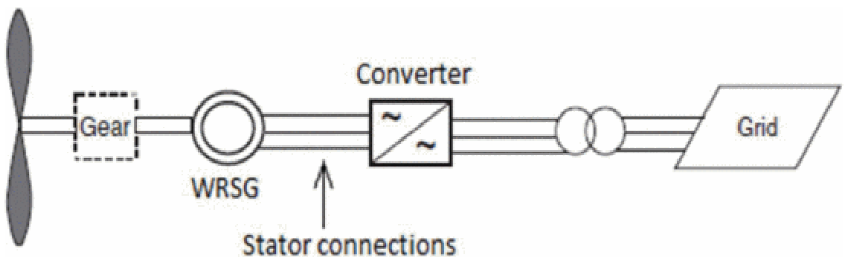

Figure 8: Wound Rotor Synchronous Generator (Das, Zhang & Pota, 2016)

2.1.4 Doubly Fed Induction Generators

DFIG (Doubly Fed Induction Generator), which is also called Type 3 Turbine, is an upgraded version of Type 2 Turbines. The extra rotor excitation is supplied via slip happens to be by a latest regulated, voltage resource converter, which in turn adjust the windmill currents' magnitude and phase. This rotor-side converter is connected back-to-rear with a grid side converter, that exchanges power immediately with the grid. A small volume of power is injected into the rotor circuit to make a large difference in the control of power in the stator circuit. This is a major advantage in the DFIG, and it can be a good option compared to other wind turbine generators at low wind velocities (Autkar & Dhamse, 2018). An example of DFIG is as in fig. 9.

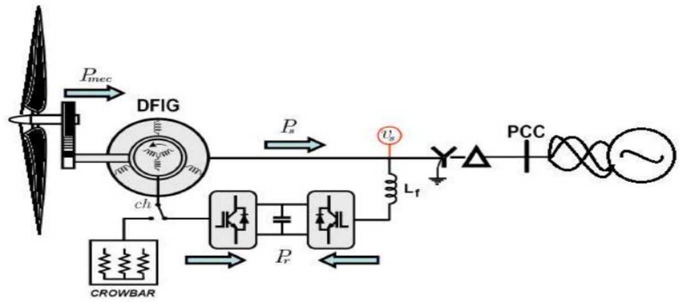

Figure 9: Doubly Fed Induction Generator (Patel & Bhuria, 2018)

2.1.5 Brushless Doubly Fed Induction Generator

BDFIG (Brushless doubly fed induction generator) is a type of doubly fed induction machine, and it is known as a generator that needs a converter having low power rating. This type of generators has lower cost and high reliability because they do not have brushes and slip rings (Wang, Lin & Wang, 2017). BDFIG's can be used in the standalone systems under a lot of different conditions like small hydropower stations and offshore wind farms because of their low maintaining cost and high reliability. This type is a formation of three phase control winding and power winding. Control winding is created with a different frequency and voltage power converter whereas power winding is used as a power generator which provides the connection with the load. For the coupling, rotor winding is used instead of stator winding (Lu, Chen, Sun, Zou & Kang, 2015). A conceptional diagram of BDFIG is as in fig. 6.

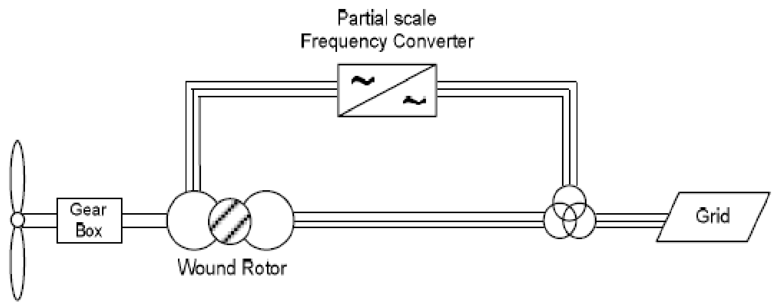

Figure 10: Conceptional diagram of BDFIG (Kim & Lu, 2010)

2.1.6 Brushless Doubly Fed Reluctance Generator

BDFRG (Brushless doubly fed reluctance generator) provides higher torque and power and lower power loss compared to induction and synchronous wind turbine generators (Singh & Niwas, 2016). All the permanent and windings are in the stator instead of the rotor in these generators (Ademi & Jovanovic, 2014). Probability of making mistakes of this type is lower because it does not have slip rings and brushes. This type of generators has two windings in their stators which are control windings and power windings. Reliability and robustness are better compared to other generators because rotor winding is used as control winding in the stator, so slip rings and brushes are ignored. However, there can be some technical issues at the controllers of power converters which can damage the power flow and power factor through the control and power windings (Zhang, Wang, Jia & Ma, 2014). A conceptional diagram of BDFRG is as in fig. 6.

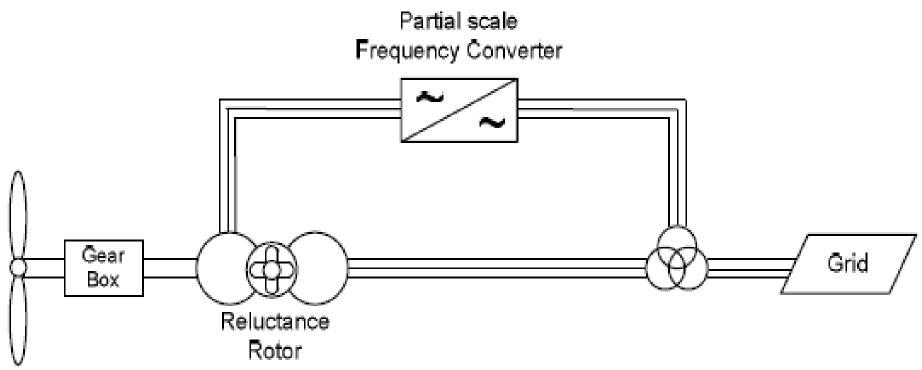

Figure 11: Conceptional diagram of BDFRG (Kim & Lu, 2010)

2.2 Types of PV Panels

PV panels can be categorized as 1st, 2nd and 3rd generation PV panels. According to their generations, 4 different PV panel types as in table 2 will be examined in this section.

Table 2: PV Panel Types

Generation Type	**PV Panel Type**
1st Generation	Monocrystalline PV Panels
1st Generation	Polycrystalline PV Panels
2nd Generation	Thin – Film PV Panels
3rd Generation	Concentrated PV Panels

2.2.1 Monocrystalline PV Panels

Most important feature of this type is its purity. Thanks to its purity, monocrystalline solar panels are one of the high efficient solar panels, and its efficiency percentage can exceed 20. This type can be realized from their certain edges on a dark base as in figure 12

Figure 12: View of a monocrystalline PV panel (Verma & Singhal, 2015)

This type of PV panels provides high powers at its output and does not require too much space, but they are longer than the other types. Because of their length, they also have higher cost than the other types. High temperature does not affect monocrystalline PV panels too much whereas they have a bigger effect on polycrystalline PV panels.

2.2.2 Polycrystalline PV Panels

This type of PV panels comprise of squares which have different tones of blue as in figure 13, they are formed by melting silicon. Thanks to this, polycrystalline PV panels have lower cost and quicker process than monocrystalline PV panels.

Even though their lower cost, polycrystalline PV panels have lower efficiency rate which can decrease to below 15. Because of high temperature effect, they are also short-lived compared to monocrystalline PV panels. However, there is not a big difference between monocrystalline and polycrystalline PV panels, and the user decision can change condition to condition which are generally efficiency and cost.

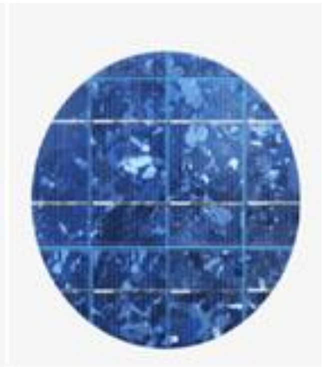

Figure 13: View of a polycrystalline PV panel (Verma & Singhal, 2015)

2.2.3 Thin – Film PV Panels

Thin-film solar panels can be formed by putting one or more PV material (copper, silicon etc.) on a basement layer as in figure 14. It is very uncomplicated to manufacture these PV panels, and they do not require too many pieces while producing them. This also makes thin – film PV panels cheaper. Hence, this type of PV panels can be a good option to use because of their low cost.

Figure 14: View of a thin – film PV panel (Verma & Singhal, 2015)

Another advantage of thin – film PV panels is their flexibility, because it is important to use a panel type for different applications, and these types are not also affected by high temperatures. However, they are short – lived compared to monocrystalline and polycrystalline PV panels, and this seems as a disadvantage of this type.

2.2.4 Concentrated PV Cells

CPV's is the best choice if the high efficiency is needed to produce electrical energy. Their efficiency rate can reach to above 40%. Thus, this type of PV panels offers higher performance than other PV panel types. However, they should be placed properly in order to catch the sunlight and get high efficiency rates. Solar trackers can be used to achieve this issue. (Albarbar & Batunlu, 2018).

2.3 Converters

2.3.1 Rectifiers

Rectifiers are used to convert the AC power to the DC power, and this conversion is called rectification. This is the most known diode application. Rectifiers include a semiconductor diode which allows unidirectional electron flow. For example, half wave rectifier is the simplest version of rectifiers. Half of an AC waveform allowed to go through to the load. However, this rectification is insufficient for most of the applications because of the harmonics and filtering them is too difficult. In order to get both sine wave half cycles, full wave rectifiers which have transformers on their centers are used. Single and three phase full bridge rectifiers will be discussed in this section. (Zailan et. al., 2016)

2.3.1.1 Single Phase Full Bridge Rectifiers

This type of rectifiers has four diodes, and two of them are reverse biased whereas the other two are forward biased. Thanks to this, two diodes can be used in the conduction path, but this causes voltage amplitude difference between input and output voltage because of the voltage drops of two diodes. If the circuit in figure is considered without capacitor, during the positive side of the input voltage, D2 and D3 are reverse biased whereas D1 and D4 are forward biased, so the current goes through the resistor from D1 and then flows to D4. During the negative side of the input voltage, D1 and D4 are reverse biased whereas D2 and D3 are forward biased, so the current goes through the resistor from D2 and then flows to D3 (Lv, Zhang &Dai, 2015). For both, a positive output peaks are produced by input waveforms, and the load current always flows in the same direction through the load. It can be said that the voltage and current are unidirectional at the load. These rectifiers can also have a capacitor to be filtered as in the fig. 15.

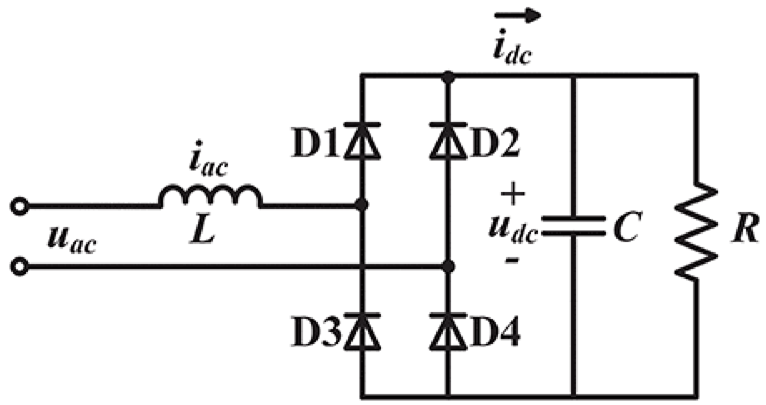

Figure 15: Single Phase Full Bridge Rectifier (Lv, Zhang &Dai, 2015)

2.3.1.2 Three Phase Full Bridge Rectifiers

A three-phase full bridge rectifier as in fig. 16. has six thyristors, and it can be derived from two half wave rectifier circuits. This type of rectifiers has lower output ripple compared to the half wave rectifiers.

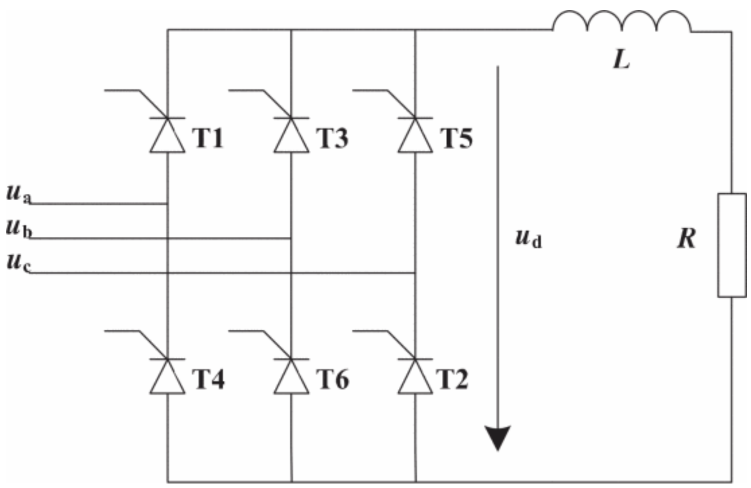

Figure 16: Three Phase Full Bridge Rectifier (Song, Kang, Xu & Zhang, 2018)

A pair of thyristors are connected between each phase as it can be seen above. For every pair, one of the thyristors supplies the positive side of the load whereas the other one supplies the negative side of the load. Thyristors 1,2,3 and 4 create a bridge rectifier between A and B phases, thyristors 3,4,5 and 6 create a bridge rectifier between B and C phases, thyristors 1,2,5 and 6 create a bridge rectifier between A and C phases. The positive rail is fed from thyristors

1,3 and 5 whereas the negative rail is fed from thyristors 2,4 and 6 (Song, Kang, Xu & Zhang, 2018).

2.3.2 Inverters

At the essential output frequency and voltage, DC power is converted to AC power. DC power is provided by a fuel cell. Inverters can be categorized as current source and voltage source inverters. DC source at voltage source inverters has too small resistance whereas DC source at current source has very high impedance. Three phase two level and three phase three level inverters will be handled in this section.

2.3.2.1 Three Phase Two Level Inverters

For three phase two level inverters, the procedure is as explained in next section, but there are some differences in terms of efficiency, cost etc. For example, waveforms are produced by pulse width modulation, and this causes a distortion of the current and voltage in 2 level inverters, and there is a poor total harmonic distortion. The load rectifier losses play a big part in the entire system efficiency.

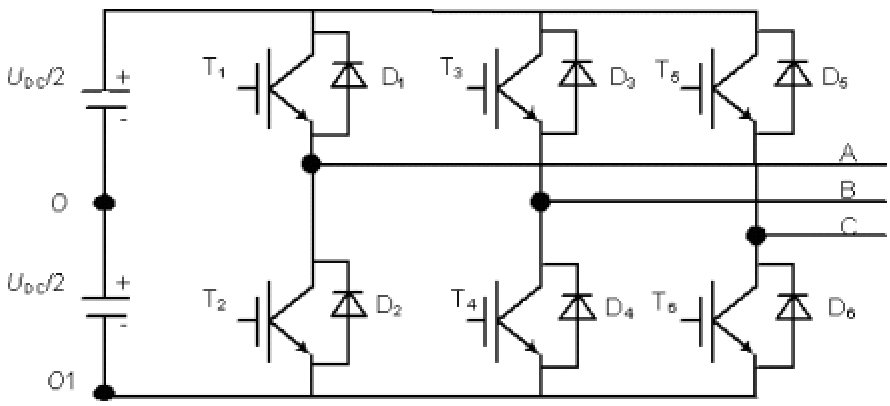

Figure 17: Three Phase Two Level Inverter (Chen, 2011)

Also, a harmonic analysis of the capacitor current should be made to make an accurate approximation, and in order to do this, Fuchs and Bierhoff used geometric wall model for this analysis (Bierhoff & Fuchs, 2008). An example of 3 phase 2 level inverter is seen in fig. 17.

2.3.2.2 Three Phase Three Level Inverters

Three phase three level inverter is a well-known inverter type which can be widely used in power electronic applications. Neutral clamped can be a good example for three level inverter type. All of three phases of this inverter use a common direct current bus, and this inverter has two series connected capacitors. DC bus voltage is divided into 3 levels by the DC link capacitors. These voltage levels can be seen at each phase's output by switching of semiconductor devices. The point which is between the capacitors is called the neutral point. Each phase has two switch pairs and two diodes for this inverter type. The outer ones are the main switches, and they can be used to operate for PWM whereas the inner ones are the auxiliary switches which connects the neutral point to the outputs. However, based on the condition, different three level inverter typess can be used. For example, fig. 18 shows an example of three phase three level inverter structure with nine switches.

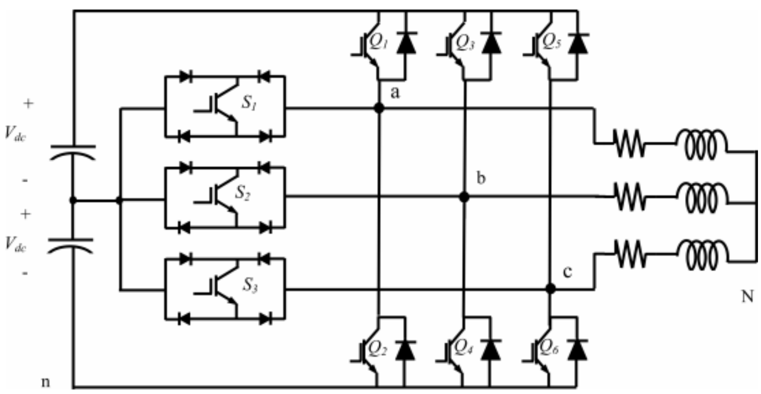

Figure 18: Three Phase Three Level Structure with Nine Switches (Ahmed & Mekhilef, 2008)

2.3.3 Choppers

DC – DC converters are used to regulate and control the output power of fuel cell system. For a DC system, voltage regulation is provided by these converters based on the applications. They are required high power conversion efficiency, high density, small size, light weight, low cost, decreased ripple current and low electromagnetic interference. These converters also categorized as non-isolated and isolated because of electrical relationship between the output and input. Boost converters, buck converters, fly back converters and forward converters will be examined in this section.

2.3.3.1 Boost Converters

For this converter as in fig. 19, a high frequency square wave is applied in the second transistor whereas the first transistor is ON. During the ON state, the second transistor is conducted and the input current comes from the inductor to the second transistor. Because of the potential ground for the anode, the second diode cannot conduct. When the capacitor is charged, this applies load to the whole circuit during the ON state and some oscillator cycles can be obtained. During this period, the capacitor discharges some ripple frequency of output voltage. Hence, the potential difference can be obtained by the summation of VS and VL.

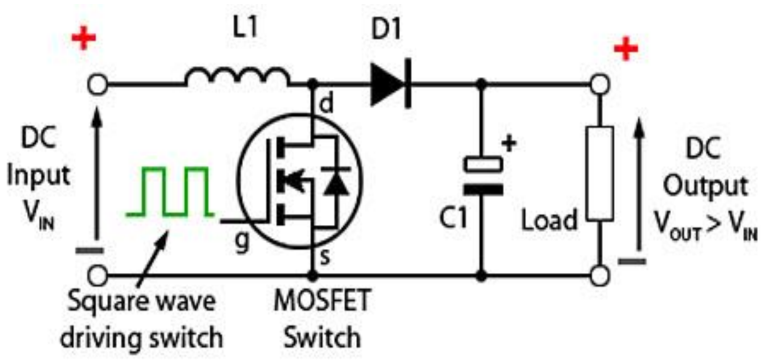

Figure 19*: A Boost Converter (Lander, 1993)*

During the OFF state, the capacitor is discharged and the inductor is charged. Depending on the current change rate of the second transistor, a back EMF. is produced by the inductor. This reverses the voltage polarity across the inductor. Finally, the output voltage is found as equal to the input voltage or it can be higher a little bit.

2.3.3.2 Buck Converters

For a buck converter as in fig. 20, first transistor is ON and the second transistor is OFF because of the high frequency square wave. If the first transistor gate terminal is higher than the magnetic field current that charges the capacitor, the load is supplied. Because of the positive voltage of cathode, the diode, which is a Schottky diode, is OFF.

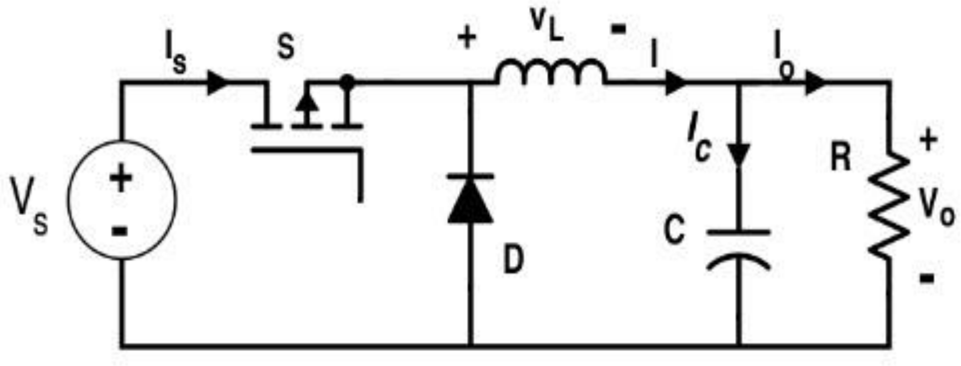

Figure 20: A Buck Converter (Lander, 1993)

The initial current source is the inductor for this circuit. The flow of the current is in the buck operation when the first transistor is OFF. The back emf. is produced by the collapsed inductor and the flow of the current is provided in the load and the diodes. Thanks to the current, inductor discharge reduces. During the ON state, the current goes to the load, and keeps the output voltage during the OFF state. Hence, this makes the output voltage closer to the Vs value.

2.3.3.3 Fly Back Converters

A fly back converter is an isolated converter based on the buck – boost converter, and it is used in low power levels. The isolation is provided by a high frequency transformer, and this transformer also stores the energy. During the ON condition of T1 in the circuit in fig. 21, the current flow starts in the transformer's primary coil. Diode D1 is reverse biased by the secondary voltage of the transformer during the conduction of T1. Hence, the capacitor C1 supplies the current to the load. Low switching losses are produced in this topology because of one commutating switch at high frequency

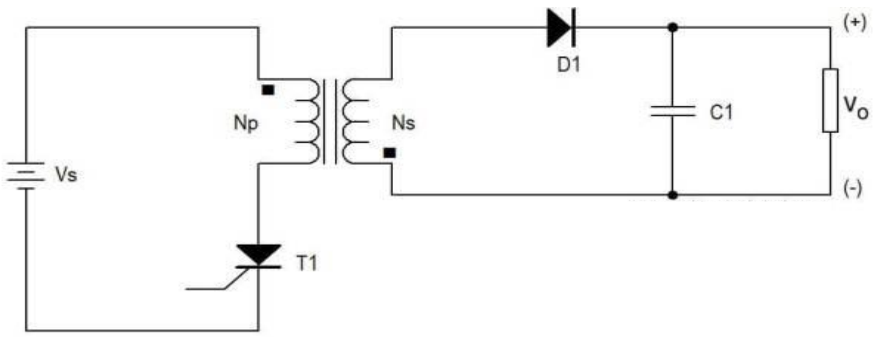

Figure 21: A Fly Back Converter

During the OFF condition of T1 in the circuit, the polarity of secondary voltage of the transformer is inverted. Because of this inversion, diode D1 is forward biased and it starts the conduction. Hence, the energy is supplied to the load and the capacitor by the secondary coil pf the transformer.

2.3.3.4 Forward Converters

A forward converter as in fig. 22 is a switching circuit transferring energy like a fly back converter, but this energy transfer occurs during the OFF state unlike the fly back converter. During the conduction phase of the transistor, the transformer passes the energy directly.

During the ON state of the transistor switch, the current flow is provided in the primary side of the transformer, and this causes the current flow in the secondary side. This current flows through the output filter, the output voltage is obtained. During the OFF state of the transistor switch, the action will be reversed by the voltage of the transformer, and this will increase the cathode voltage of the D_{TR} until the ON state of the transistor switch.

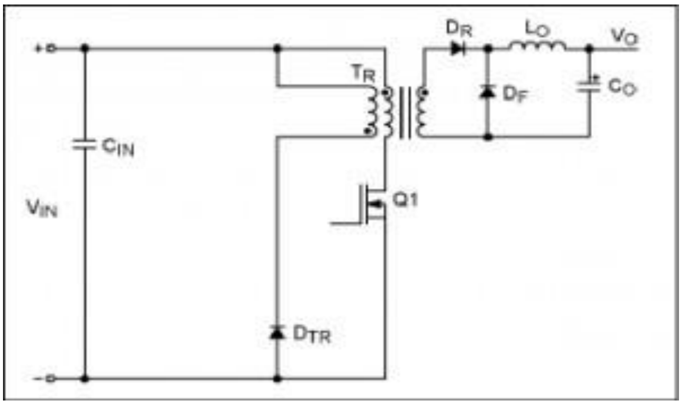

Figure 22: A Forward Converter

This type of converters requires a bigger transformer, an active snubber and higher losses during the conduction. However, it can be set up easily and its operation is more understandable.

2.4 Filters

Filters can be used to pass certain frequencies when other frequencies are eliminated. For example, undesired high frequencies can be eliminated to decrease ripples on a power source. There are a lot of applications to use filters such as radio communications, audio networks and ADC's. Filter can be categorized as active, passive and hybrid.

2.4.1 Active Filters

Active filters can be defined as an analog circuit which uses a transistor or an operational amplifier that includes capacitors and resistors to filter at low frequencies. Voltage and current harmonics can be eliminated, and reactive powers can be compensated to get higher power quality in a system. Thanks to a shunt active filter, current harmonics can be eliminated by using a power converter having a switching mode. This is an important advantage of active filters over passive filters. Shunt active filters perform parallel with a nonlinear load, and their power converters provide a current to compensate harmonic coming from the nonlinear load. Figure shows the interaction between a three-phase supply system and shunt active filter. (Ahmed, Reddy & Bhakre, 2018)

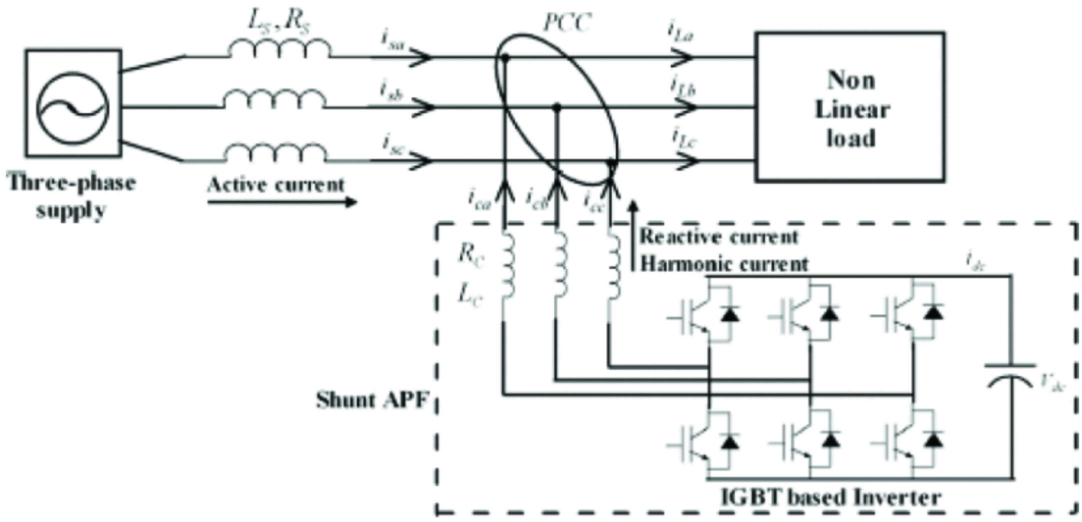

Figure 23: A basic scheme of three phase supply and shunt active filter (Ahmed, Reddy & Bhakre, 2018)

Shunt active filters may not be appropriate for larger systems, and series active filters may be needed. These filters can also be used to decrease harmonics by performing as a voltage regulator. Active filter can be used to compensate the flickers and correct the power factor. Cost can be considered as a disadvantage of active filters compared to passive filters, but in recent years, cost difference between active and passive filters has decreased due to suitable price of insulated gate bipolar transistors and digital signal processors (Motta & Faundes, 2016)

2.4.2 Passive Filters

Passive filters are another important form of filtering that does not use a power source and depends on passive capacitors, inductors and resistors, so these filters consume the signal energy and there is no power gain whereas active filters need an external power source and have a power gain. Passive filters can be categorized as low pass and high pass filters. High pass filters can be set up with an inductor in parallel with or an inductor in series with a resistor whereas low pass filters can be set up with resistor in parallel with a capacitor or in series with an inductor, so high frequencies pass while low ones are eliminated. According to the needs, high pass filters may be first order, second order, third order or C type as can be seen in figure. (Ji, Zeng, Liu, Luo & Zhang, 2012)

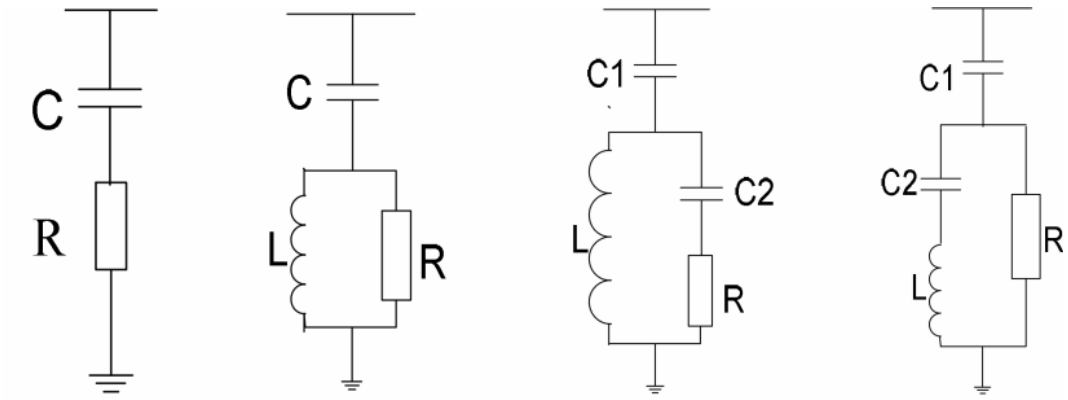

Figure 24: Topology of high pass filters (Ji, Zeng, Liu, Luo & Zhang, 2012)

The biggest advantage of these filters can be considered as the cost. However, spending more time, being careful in complex design studies, overload risk and limitation in high frequency reductions are the drawbacks of passive filters (Motta & Faundes, 2016).

2.4.3 Hybrid Filters

A hybrid filter is a combination of a number of active filters and/or passive filters. The active filters provide high harmonic's mitigation while the passive filters provide basic filtering operation at the dominant harmonics. In other words, hybrid filters are a common path that tries to take advantages of active and passive filters and reduce their disadvantages (Kedra, 2014). There can be different combinations such as a shunt passive filter with an active filter, a shunt passive filter in series with an active filter and a shunt passive filter in series an active power filter. Figure shows an example schematic of hybrid filters which includes a shunt active filter and a passive filter. Active filters may be more efficient but hybrid filters have lower costs than active filters. (Schwanz, Bollen & Larsson, 2016)

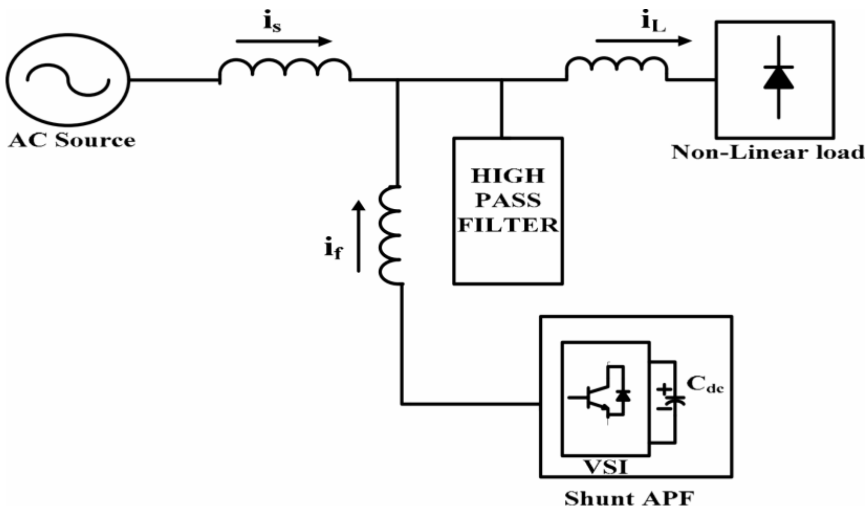

Figure 25: Schematic diagram of a hybrid filter (Kumar & Bhat, 2016)

2.5 Maximum Power Point Tracking (MPPT) Controllers

A maximum power point tracker, or MPPT is a DC – DC power converter which converts higher voltage outputs from wind turbine generators or PV panels to the lower voltages that the utility grids or battery banks need. This tracker or converter is used to get maximum power from the power supply (Krishanan, Joseph, Kumar & Kumar, 2013) There are many

MPPT techniques, but four main techniques which are incremental conductance, perturb and observe, neural networks and fuzzy logic are handled.

2.5.1 Incremental Conductance

For the incremental conductance technique, two current and voltage sensors are used to measure the sensibility of the PV array output voltage and current. The voltage of array terminal depends on the maximum power point voltage. Power curve of the array behaves according to the equations on the graph in figure. Also, slope of the array is zero at the maximum power point as it can be seen in the graph. Left side of the graph shows the incremental conductance whereas right side of the graph shows the instantaneous conductance. The operation of PV array will be at MPP, if the negative output conductance is equal to the change ratio of output conductance. PWM control signal of DC-DC boost converter is regulated by the maximum power point tracking if the condition of $(\partial I/\partial V) + (I/V) = 0$ is obtained. This method has disadvantages which are the irradiation changes and the steady state condition of the oscillations. (Chung, Daniyal, Sulaiman & Bakar, 2016)

2.5.2 Perturb & Observe

Perturb and Observe technique is one of the most used maximum power point tracking techniques. The cost needed to apply this method is less because there is only one voltage sensor is used. This method includes two perturbations which are in the DC link operating voltage and the duty cycle. DC link voltage is modified by perturbing the power converter duty cycle. (Nigam & Gupta, 2016) In order to make decision of the next perturbation, the last increment sign and the last perturbation sign are needed. If the power increases, the perturbation is needed to be in the same direction. However, if there is a decrement, the next perturbation is needed to be in the opposite direction. The operation continues until the maximum power point is obtained. This algorithm comes closer to the maximum power point, but it cannot stop on this point. In order to prevent from this situation, a suitable error limit may be set up. However, this limit also cannot overcome the sudden changes the level of the irradiation, and the steady state condition of the voltage and current oscillations creates a problem. (Raiker, 2017)

2.5.3 Neural Networks

Neural network is another popular technique to implement the maximum power point tracking. It has an input, hidden and output layer. The number nodes depend on the user in each layer and they are variable. The input ones may be an irradiance, temperature or some parameters like open circuit voltage and short circuit current of a PV array. The output ones may be a signal like a duty cycle signal which drives the power converter to close or operate at the maximum power point. At the hidden layers, there are some algorithms and these algorithms determine the distance between the MPP and operating point. This type of control techniques needs to be trained for the PV arrays which are used in order to determine the accurate maximum power point, because these arrays have different specifications and they do not remain same. (Xu & Root, 2017)

2.6 Batteries

For a grid connected renewable source system, one of the sources like wind may suddenly drop because of uncertain weather conditions. Therefore, this will instantly decrease the amount of energy generated, and most of the traditional grids cannot compensate. However, this increase and decrease levels in energy behaviors can be reduced by batteries, and the energy can be stored by using them as stabilizers. This provides the system enough time to compensate. In other words, when the amount of the produced energy is more than the demanding one, the battery systems can store it for using later in the case of less wind speed or solar irradiance level. Important battery types which can be used in grid connected types are lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion and lithium polymer. According to these battery types, most effective ones are the types lithium-ion and lithium polymer, but they have higher cost than the others (J. Haase et al., 2017). In addition to these, comparison of different electrochemical storage technologies can be seen in table 3.

Table 3: Overview of Electrochemical Storage Technologies (Bragard, Soltau, Thomas & Doncker, 2010)

Technology	Efficiency	Typical usage / Remark
Lead Acid	75-85 %	backup systems, inexpensive
Nickel Cadmium	60-70 %	longer lifetime
Sodium Sulphur (NaS)	86-89 %	stationary, high temperature
Zebra (NaNiCl)	90 %	delivery cars, high temperaure
Lithium Ion	90-95 %	cars, PV systems, expensive
Redox Flow	70-80 %	power and energy scaling

2.7 Old Studies

Al Badwawi et. Al. (2015) published a paper about the advantages hybrid solar – wind systems on standalone systems. It was stated that the impact of the variable nature of solar and wind resources can be partially resolved and the overall system becomes more reliable and economical to run. They determined that integration of renewable energy generation with battery storage and generator back-up systems is becoming a cost-effective solution for stand-alone type. It was also stated that high system efficiency along with high reliability and least cost can be provided with an overall system. Furthermore, voltage and frequency fluctuation, and harmonics can be resolved to a large extent by having advanced fast response control

Hangaragi et al. (2016) published a paper about a hybrid model with Solar and wind power generation system. A battery bank was used as a backup source for voltage stabilization. In their work, a variable speed doubly fed wind turbine was used. However, they used two level inverter. Therefore, with a three-level inverter their results could be improved.

Shen et. Al. (2014) published a paper which was focused on the configuration of wind turbine and solar panel and MPPT control methods. The perturb and observe MPPT controller was utilized in both wind power and solar power, which demonstrated a stable and effective tracking performance under the variation of wind speed and solar illumination. A control strategy was proposed to generate the maximum power from these renewable energy sources and battery while connected to a common coupling point.

Vasant et. Al. (2017) published a paper about solar & wind hybrid systems. The generation of electric power from hybrid system is cost effective and efficient. The constant voltage controller was used. The use of this algorithm will make it flexible by giving stable voltage and power. They did not use a battery bank, so it could be used to make it useful for voltage and power stabilization.

Nayak et. Al. (2016) proposed a hybrid model with wind and solar system. Permanent magnet synchronous generator was used and it was stated that this generator has the high productivity and unwavering quality, since there is no requirement for outside excitation littler in size and simple to control. Incremental conductance MPPT controller was also used and they indicated that this controller is easy to use and simple in operation and required less hardware as compare to other. However, they used an active filter between the load and inverter, and this may be improved with a hybrid filter.

Liu et. Al. (2017) proposed a hybrid model with a large scale solar and wind system by adding a damping controller in the rotor side of DFIG for large-scale wind/solar hybrid system is proposed. They stated that this control scheme improves the system transient voltage stability dynamically. Also, the degree of voltage oscillation can be reduced in large-scale wind/solar hybrid system. The large-scale wind/solar hybrid system has higher reliability compared with wind power generation alone and solar power generation alone.

Nagwanshi et. Al. (2017) proposed a hybrid model solar and wind system. In the first part of their work, battery storage system is not connected in the system and in the second part battery circuit is introduced in the system. After connecting the battery, they realized that load disturbance distorts the voltage at dc link, this distortion is handled by battery discharging, and voltage is maintained constant with little fluctuations involved which can be ignored.

Chapter 3

METHODOLOGY

Solar & wind hybrid model is designed based on fig. 26. All sub-models will be shown and explained in this section.

Figure 26: Flowchart of Modelling

3.1 Solar Panel Modelling

Before setting up a grid connected hybrid model, a solar panel was set up by using MATLAB Simulink. This solar panel model has some sub-systems; 2 separate Power Plant and block parameters such as diode, gain, rate, mean, multiplier, voltage measurement, irradiance and scope as it can be seen in fig. 27.

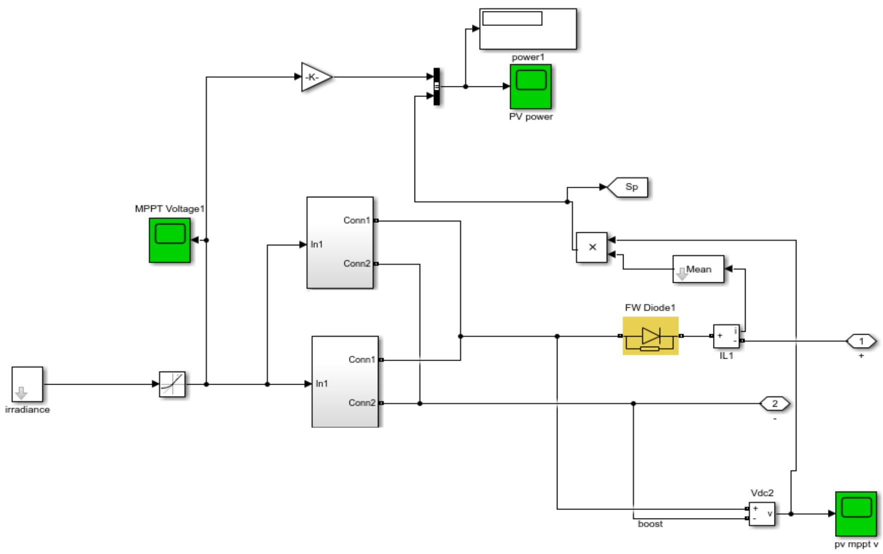

Figure 27: Structure of Solar Panel Model

According to the solar panel model, a P-V graph was obtained as in fig. 28.

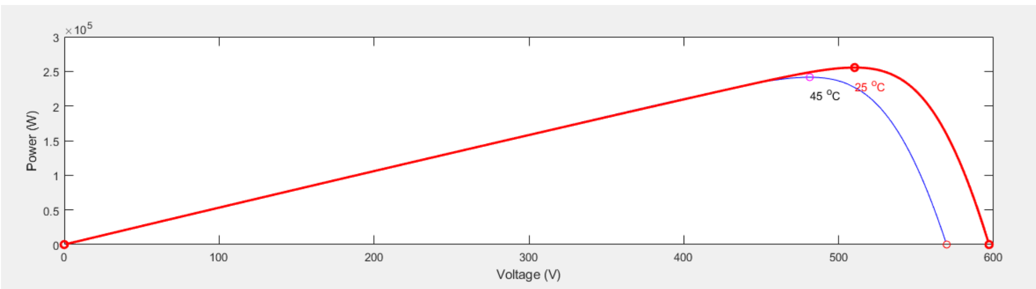

Figure 28*: P-V Characteristic of Solar Panel Model*

3.1.1 Irradiance

After setting up the solar panel model, a rate limiter with irradiance input as in fig. 29 was used to see how the system reacts.

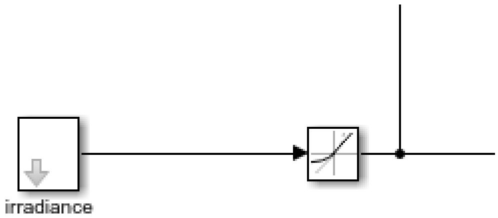

Figure 29: Irradiance Input

Irradiance constant was adjusted to 1000 W/m^2 while irradiance was adjusted as in fig. 30.

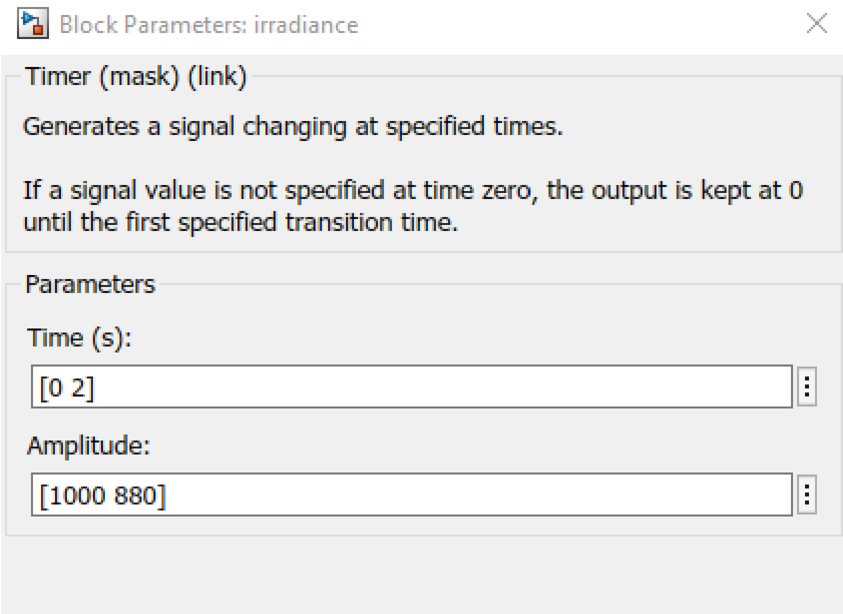

Figure 30: Irradiance Block Parameters

Finally, change in irradiance after 2 seconds was realized as in fig. 31 and it decreased to 880 W/m^2.

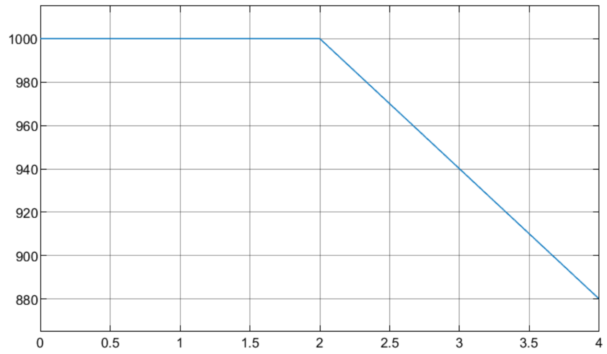

Figure 31: Change in Irradiance

3.2 Wind Turbine Modelling

After setting a solar panel model, a wind turbine model was set up in order to create a hybrid model. PMSG was used to take advantages of it, and the wind turbine model has some other sub-systems which are pitch angle controller, diode rectifier, voltage measurement, current measurement, gain, scope, multiplier, inductor, discrete RMS, timer and bus selector as in fig. 32. PMSG has 3 phases and sinusoidal back EMF waveform. Wind turbine has 12 m/s base wind speed, base rotational speed is 1 in terms of pu.

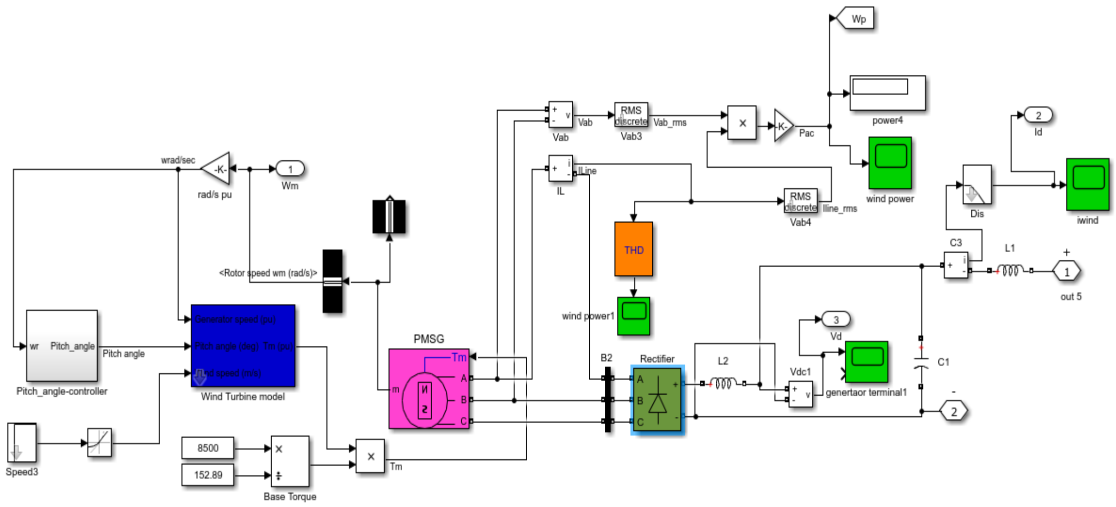

Figure 32: Wind Turbine Model

According to the wind turbine model, turbine speed vs turbine output power graph as in fig. 33.

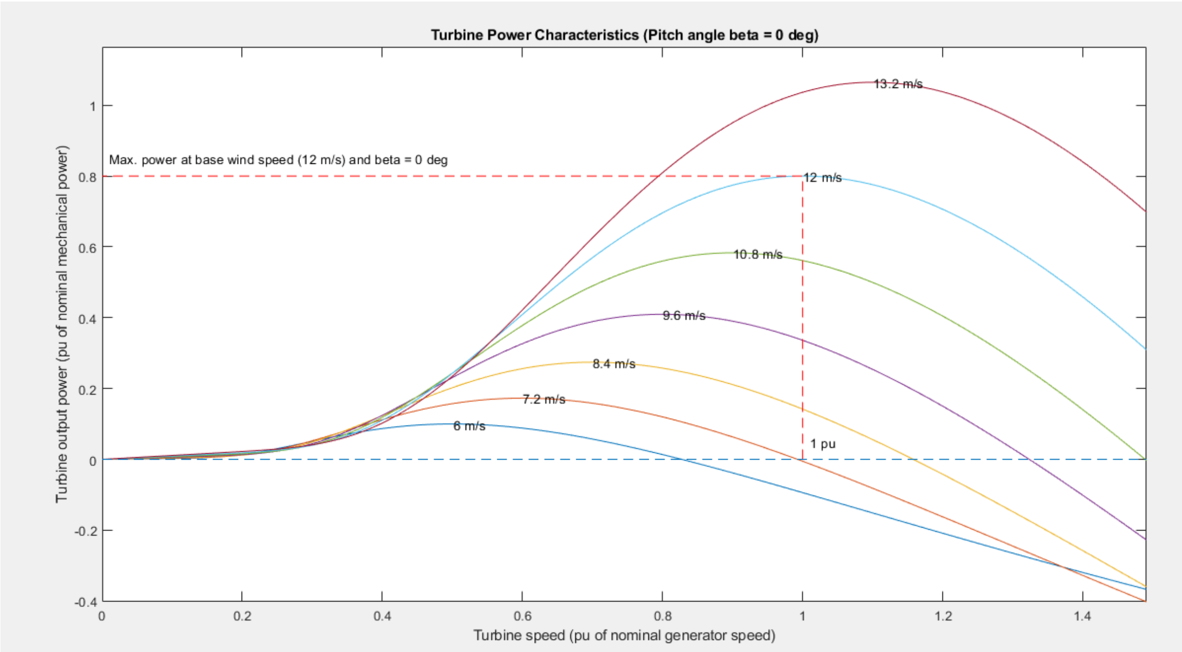

Figure 33: Turbine Speed vs Turbine Output Power Characteristics

A speed input with a rate limiter was used to see how the system reacts as in the solar panel model, and wind speed was adjusted as in fig. 34

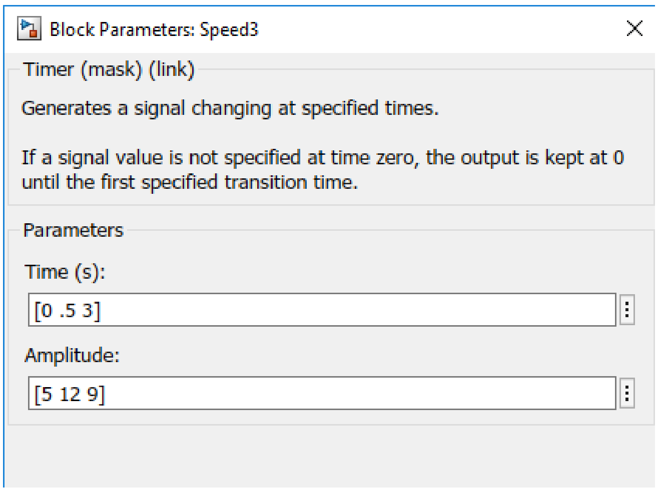

Figure 34: Wind Speed Block Parameters

Finally, change in wind speed after 2 seconds was realized as in fig. 35. First, it started to increase to 12 m/s, and then, it stayed constant until 3rd second, and it decreased to 9 m/s after 3rd second.

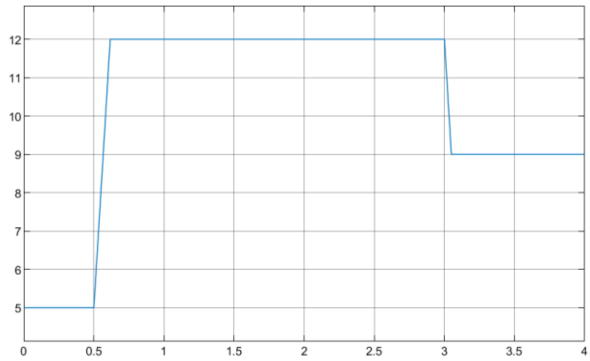

Figure 35: Change in Wind Speed

3.3 Filter Modelling

3.3.1 Passive Filter

Passive filter was set up with L and C branches as in fig. 36.

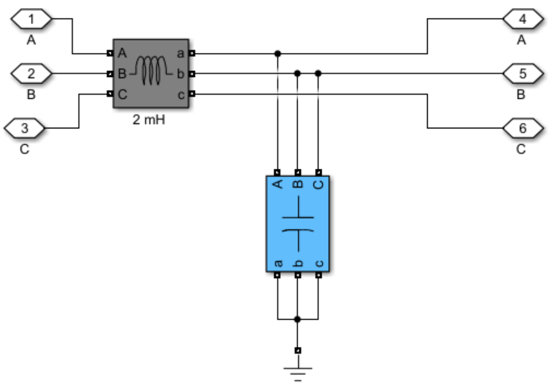

Figure 36*: Passive Filter*

For the passive filters, capacitors and inductors can be included in diode rectifiers in order to get better current waveforms from the grid. Thus, harmonics can be reduced easily. In addition, power factors can be more acceptable values. Using capacitance and inductance together result in a decrease in the peak to peak ripple in the rectified output voltage. There can be additional losses because of inductor, but diode conduction losses reduce. According to fig. 37, thanks to capacitor and inductor, current waveform becomes more square-wave.

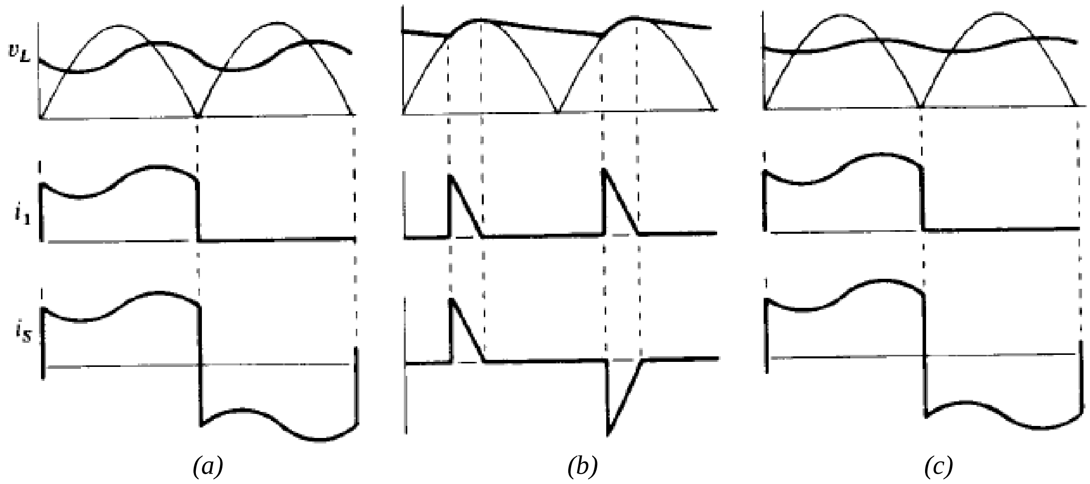

Figure 37: Rectifier output filtering (a) Inductor-only Filter (b) Capacitor-only Filter (c) Inductor-Capacitor Filter (Lander, 1993)

The ratio output of the output voltage of passive filter can be found by using the following formula;

$$\frac{\frac{1}{\omega C}}{\omega L-\frac{1}{\omega C}} = \frac{1}{\omega^2 LC-1} \tag{1}$$

Where C = Capacitor, L = Inductor, and ω = angular frequency.

Also, the ripple factor of load voltage can be calculated using the following formula;

$$\text{Ripple } Factor = \frac{({V_{rms}}^2 - {V_{mean}}^2)^{1/2}}{V_{mean}} \tag{2}$$

Where V_{rms} = Total rms values of alternating components and V_{mean} = Mean value.

3.3.2 Active Filter

Active filter was set up with pulse generator, instantaneous power, PI control, compensating current, coupling inductor and its inverter as in fig. 37.

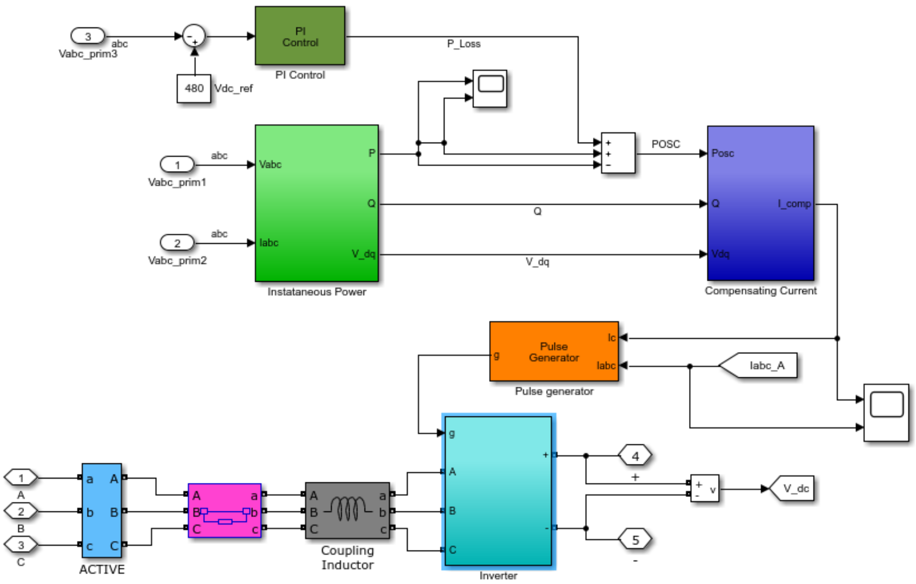

Figure 38: Active Filter

Fig. 39 shows what an active filter does. i_S is the sinusoidal current for the ideal situation and i_R is a quasi-squarewave current while supplying the power. Active filter neutralizes harmonic rectifier components and all reactive powers, and it does not absorb any power.

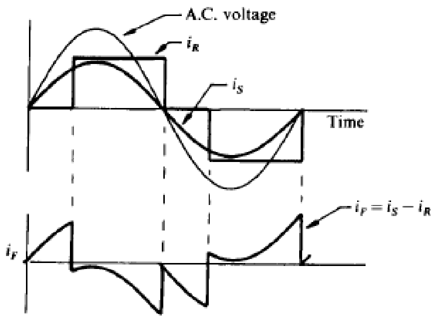

Figure 39: Active Filter Effect (Lander, 1993)

3.3.3 Hybrid Filter

Hybrid filter is a combination of active and passive filters, and they were shown in previous sections. However, how they were connected can be seen in fig. 40.

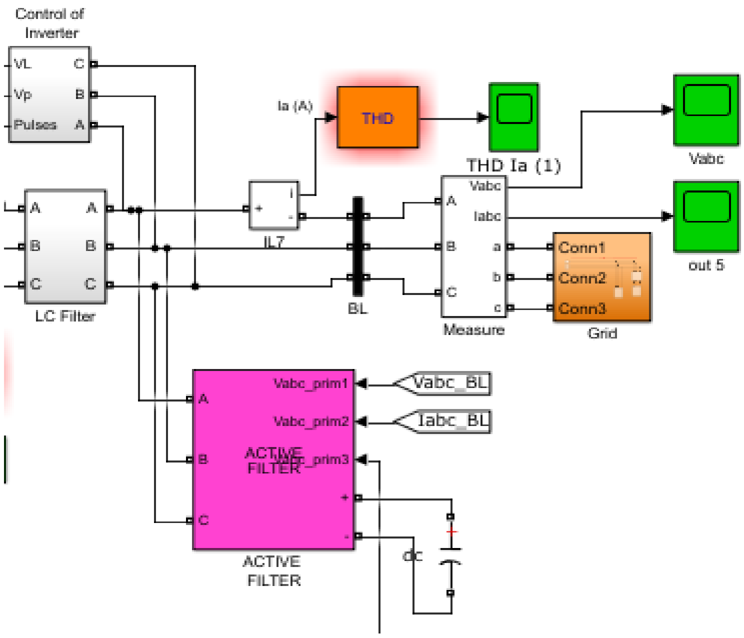

Figure 40: Connection between Active and Passive Filter

3.3.4 Proposed Controlled Hybrid Filter

Controlled hybrid filter was set up as a hybrid filter with its control components as in fig. 41. It includes some memory block parameters, gates and switches for all phases to adjust timing in order to control which filter works. During change in wind speed and irradiance, active filter works whereas passive filter works when wind speed and irradiance stay constant. Also, display block parameters were used to prove this as in fig. 41. When there is change in wind speed, display connected to wind shows “1” whereas when there is change in irradiance, display connected to light shows “1”.

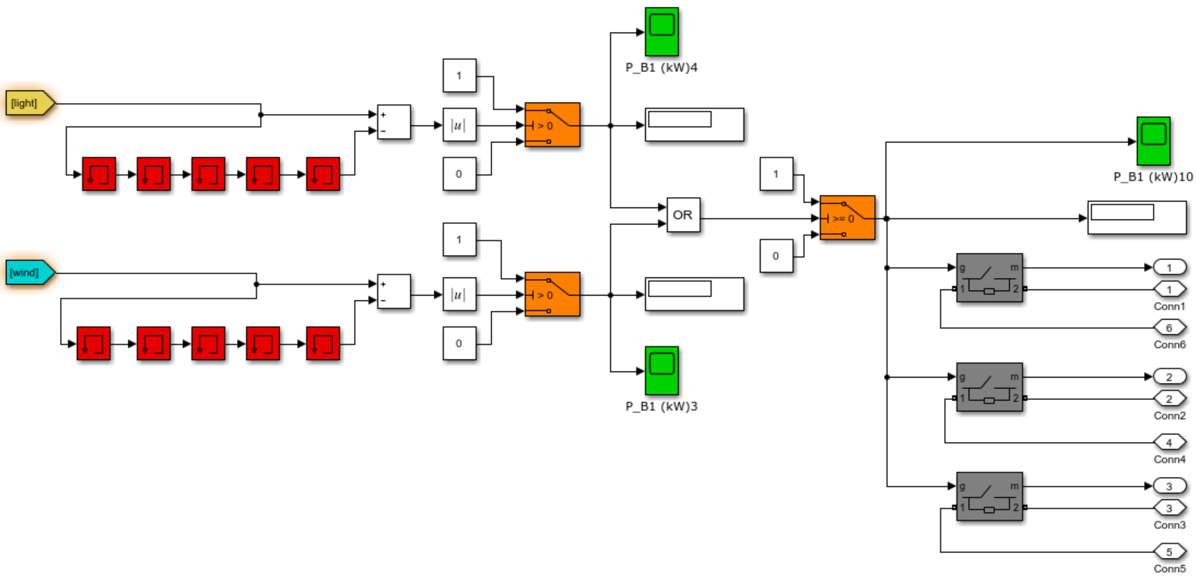

Figure 41: Proposed Controlled Hybrid Filter

3.4 Converter Modelling

3.4.1 Boost Converter DC/DC Regulator

Boost converter was modelled as in fig. 42. It includes some important block parameters which are PI controller, transfer function, timer, duty cycle, capacitor, inductor and resistor.

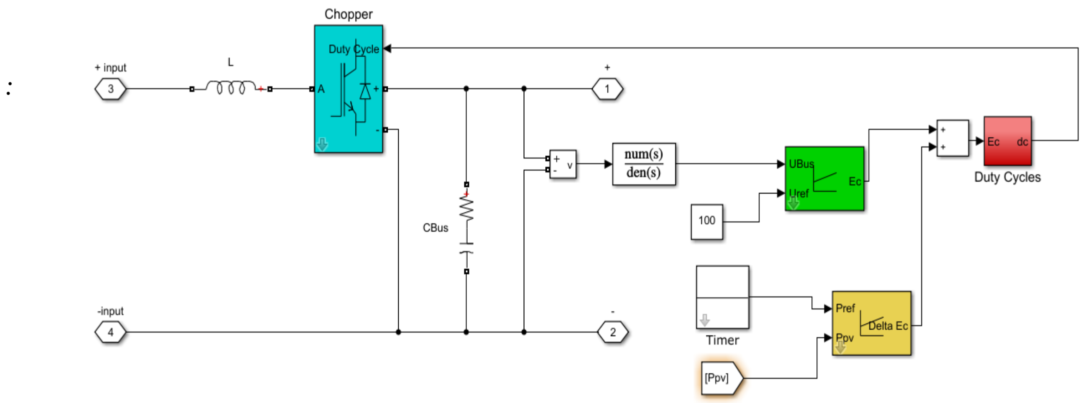

Figure 42: Boost Converter

The output voltage of boost converter can be obtained at desired level by adjusting time sequence calculated by using following formulas and fig. 43;

$$T_{ON} + T_{OFF} = T_P = \frac{1}{f} \tag{3}$$

$$T_{ON} = DT_P, \qquad T_{OFF} = (1 - D)T_P \tag{4}$$

Where f = switching frequency, T = switching period and D = duty cycle

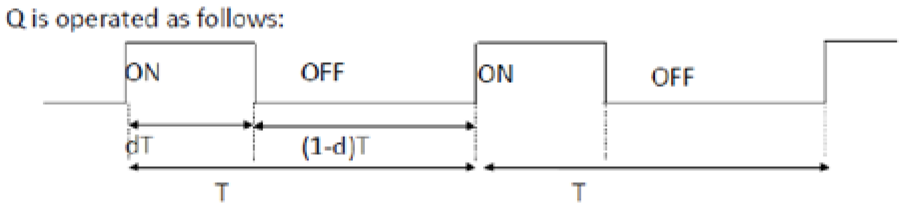

Figure 43: Switching Time Sequence of Boost Converter

3.4.2 Two Level DC/AC Inverter

2-L inverter was used directly from the library browser of MATLAB. It was placed as in fig 44.

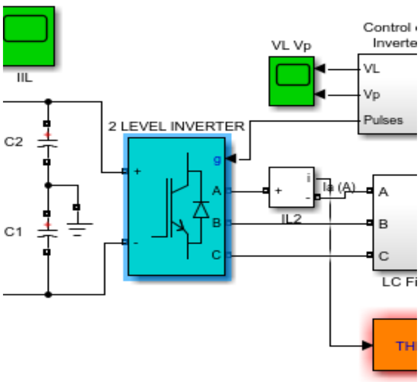

Figure 44: 2-L Inverter

Mostly 2-L inverters are used to produce AC voltage from DC voltage. Actually, they produce two different voltages for the output. If the input voltage is V_d, output voltages becomes $+V_d/2$ and $-V_d/2$ based on the switching off devices as in fig. 45.

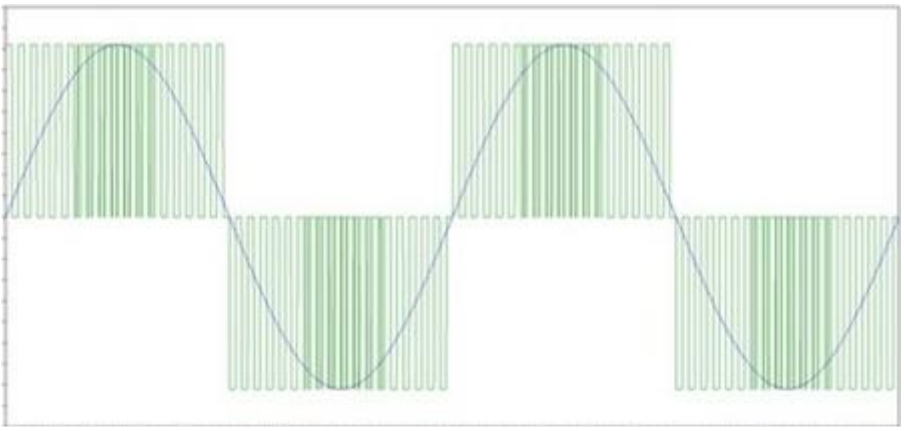

Figure 45: 2-L Inverter Output Voltage

3.4.3 Three Level DC/AC Inverter

3-L inverter was also used directly from the library browser of MATLAB. It was placed as in fig. 46.

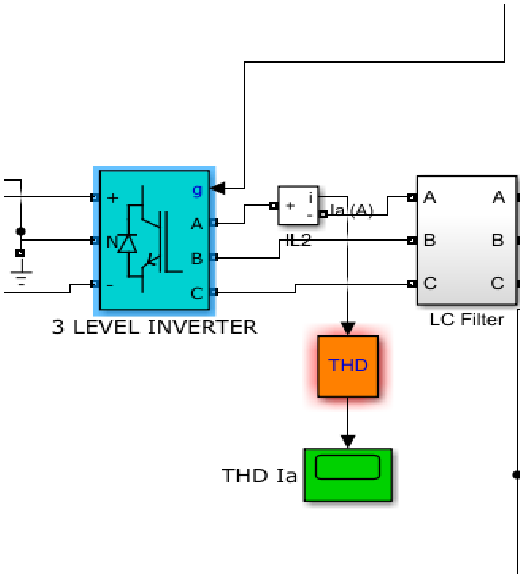

Figure 46: 3-L Inverter

In order to get a smoother stepped output voltage and current waveforms, more than two levels are combined together and lower harmonic distortions can be obtained. If the level number increases, waveforms become more sinusoidal as in fig. 47.

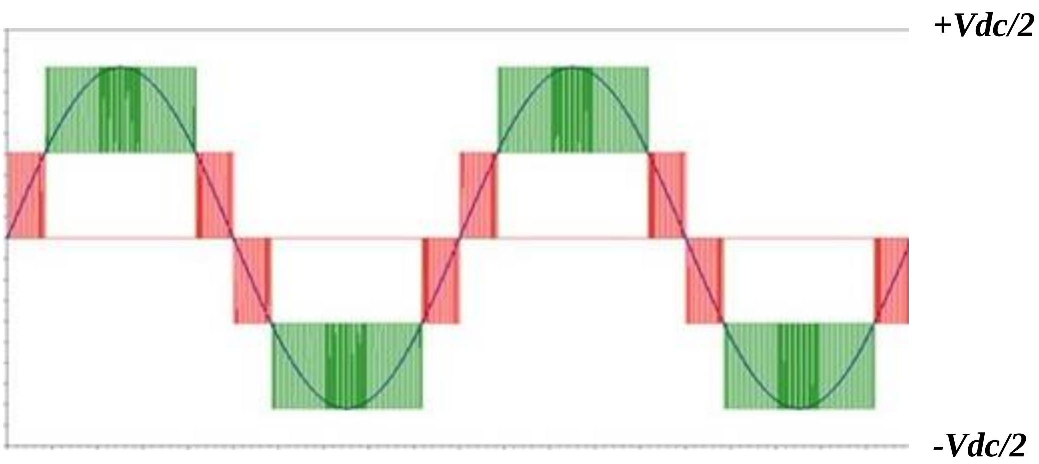

Figure 47: 3-L Inverter Output Voltage

3.5 Battery System Modelling

Battery was set up with a battery controller as in fig. 48. Two IGBTs and two diodes were used with a DC-DC converter. Lithium-ion battery type was used thanks to its high efficiency.

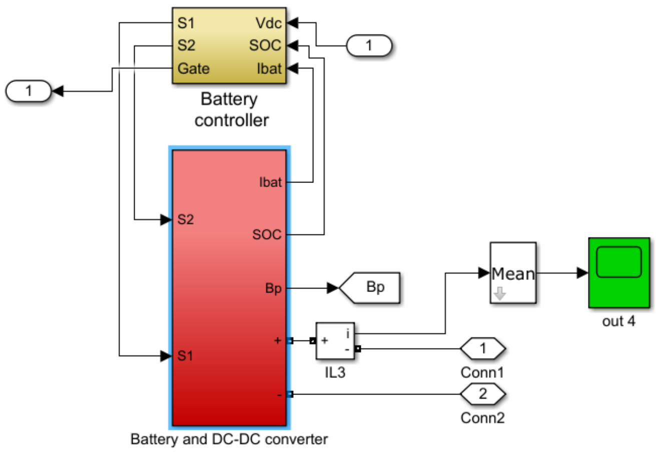

Figure 48: Battery System Model

3.6 Grid Modelling

Grid was designed with a three-phase circuit breaker and two loads which are three-phase parallel RLC as in fig. 49. Load 1 has 10 kW while Load 2 has 4 kW in order to get better result.

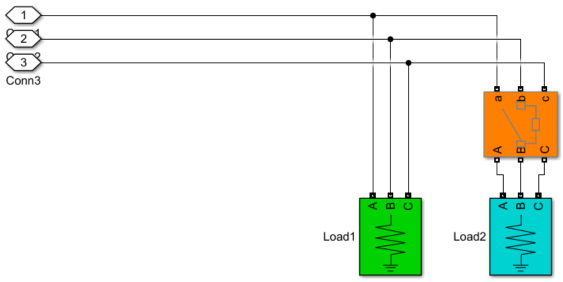

Figure 49: Grid Model

3.7 Whole Design of Solar/Wind Hybrid Model

According to the sub-models, Solar/Wind hybrid model was set up with a battery, 3-L inverter, controlled hybrid filter, converters and grid as in fig. 50. THD's were used to show the harmonics.

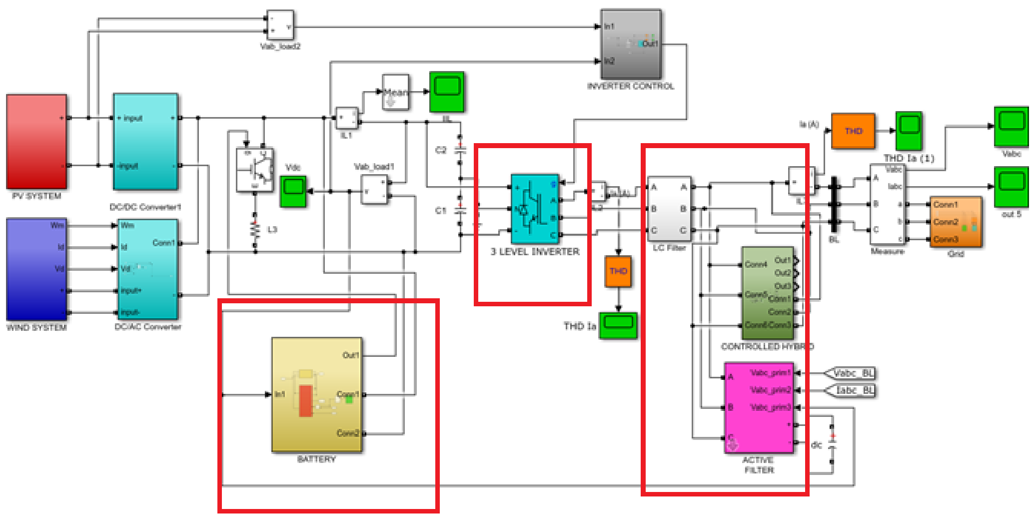

Figure 50: Solar/Wind Hybrid Model

However, 15 different cases were set up and examined to analyze and compare battery, rate, filter and inverter types. These cases are as following;

- Case 1: Solar Panel + Wind Turbine + 2-L Inverter + Passive Filter
- Case 2: Solar Panel + Wind Turbine + 2-L Inverter + Active Filter
- Case 3: Solar Panel + Wind Turbine + 2-L Inverter + Controlled Hybrid Filter
- Case 4: Solar Panel + Wind Turbine + 2-L Inverter + Passive Filter + Battery
- Case 5: Solar Panel + Wind Turbine + 2-L Inverter + Active Filter + Battery
- Case 6: Solar Panel + Wind Turbine + 2-L Inverter + Controlled Hybrid Filter + Battery
- Case 7: Solar Panel + Wind Turbine + 3-L Inverter + Passive Filter + Battery
- Case 8: Solar Panel + Wind Turbine + 3-L Inverter + Active Filter + Battery
- Case 9: Solar Panel + Wind Turbine + 3-L Inverter + Controlled Hybrid Filter + Battery
- Case 10: Solar Panel + Wind Turbine + 3-L Inverter + Passive Filter
- Case 11: Solar Panel + Wind Turbine + 3-L Inverter + Active Filter
- Case 12: Solar Panel + Wind Turbine + 3-L Inverter + Controlled Hybrid Filter
- Case 13: Solar Panel + Wind Turbine + 2-L Inverter + Active + Passive Filter + Battery
- Case 14: Solar Panel + Wind Turbine + 3-L Inverter + Controlled Hybrid Filter + Battery w/o Rate
- Case 15: Solar Panel + Wind Turbine + 2-L Inverter + Active + Passive Filter + Battery + Rate

According to these cases, line voltage, line current, average harmonics, instantaneous harmonics and DC link voltage outputs are represented in appendix section.

Chapter 4

Results and Discussion

4.1 Definition of Inputs

4.1.1 Irradiance

In order to test the irradiance level changes on filter, a dynamic weather condition was modelled. It begins at highest level and drops gradually to 880 W/m^2 at around 4th second as in fig. 51.

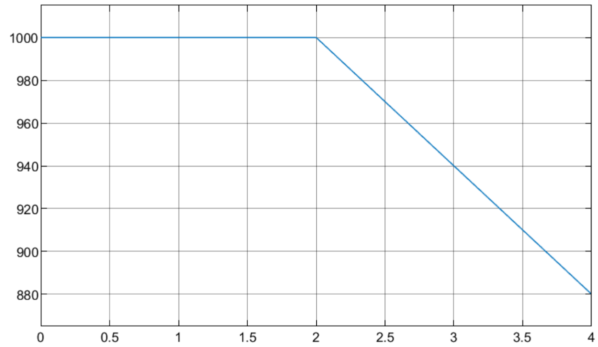

Figure 51: Change in Irradiance Level

4.1.2 Wind Speed

Wind speed change was also modelled. First, it started to increase to 12 m/s, and then, it stayed constant until 3rd second, and it decreased to 9 m/s after 3rd second as in fig.52.

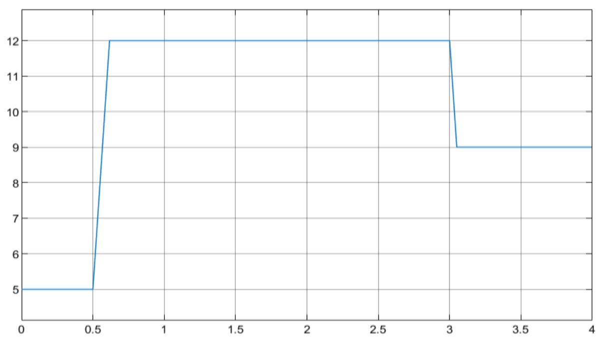

Figure 52*: Change in Wind Speed*

4.2 Analysis and Comparison of Cases

4.2.1 Effect of Battery

If cases 1,2,3,10,11,12 and cases 4,5,6,7,8,9 are considered separately, batteries are good barriers for clamped line voltage and current waveforms as it can be easily realized in cases 4,5,6,7,8,9. The differences can be depicted in Figures 53 and 54.

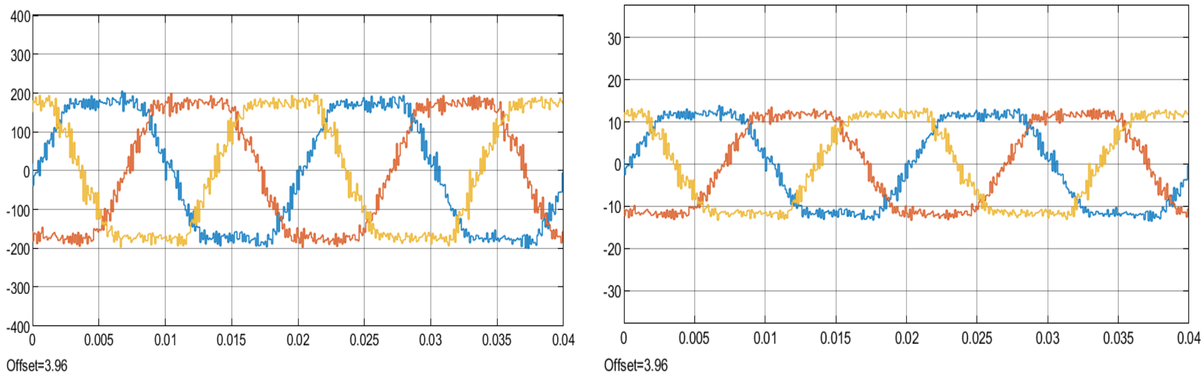

Figure 53: Line Voltage - Current Waveforms of Hybrid Solar/ Wind with 2-L Inverter w/o Battery (Active Filter)

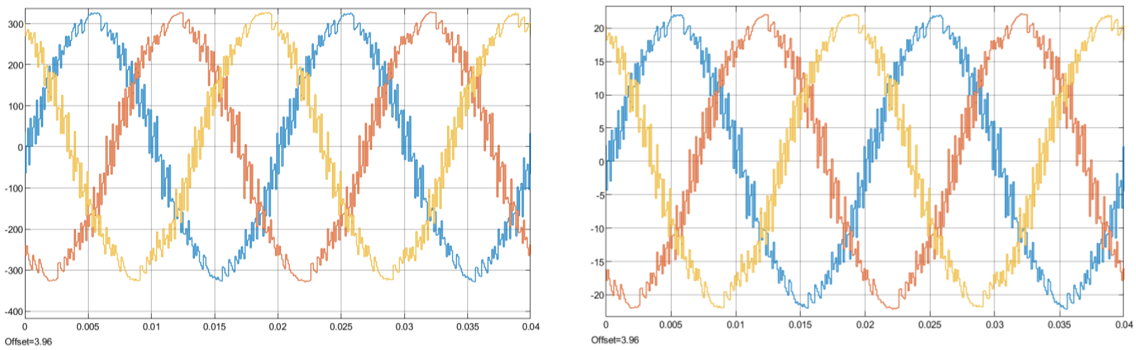

Figure 54: Line Voltage - Current Waveforms of Hybrid Solar/ Wind with 2-L Inverter with Battery (Active Filter)

When the wind speed suddenly decreases, generated energy amount will also decrease instantly. Hence, if this happens quickly, the balancing systems in the grid can be unable to compensate. However, increase and decrease of power outputs can be dampened by the battery, which can be used as a stabilizer. In fact, batteries store the energy and this helps saving the energy efficiency. Finally, this gives the balancing systems enough time to compensate accordingly. For instance, in the cases 1,2,3 there is not any batteries, so around 200 V decrease from 640 V to 440 V DC link voltage is obtained compared to the cases 4,5,6 where there is battery. In addition, not only storing but also stabilizing of the battery system helps during the drastic weather change conditions. For instance, in the cases 10,11,12 there is no battery used and the peak voltage reaches around 700 V before it stabilizes down to 640 V. This does not occur in the cases 7,8,9 because of the battery usage. Furthermore, at around 2nd second of the simulation time, slide decrements occur due to the irradiance level change but it is quickly recovered by the battery control unit.

4.2.2 Effect of 2-L and 3-L Inverter Usage

If cases 1,2,3,4,5,6 and cases 7,8,9,10,11,12 are considered separately, it can be seen that the line voltage and current waveforms are distorted and the THD of the voltage and current are poor in cases 1,2,3,4,5,6. However, in cases 7,8,9,10,11,12, line voltage and current are much more sinusoidal and the THD is better. The difference between the current and voltage waveforms are given in Figures 55 and 56.

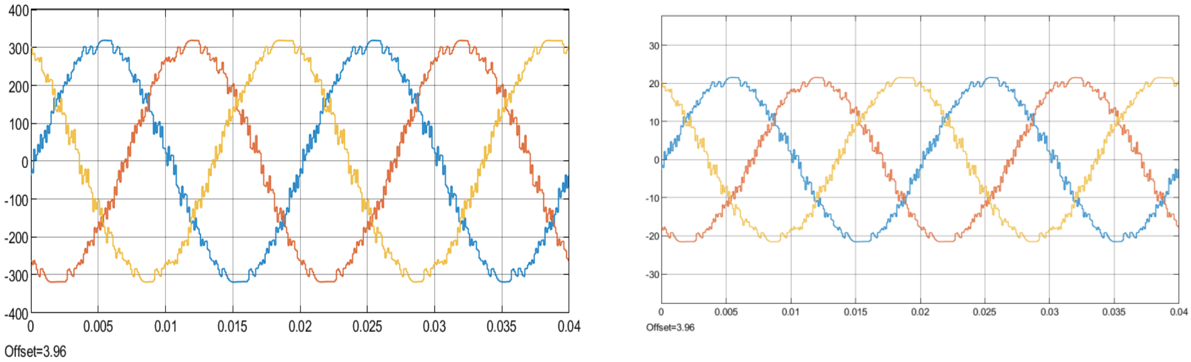

Figure 55: Line Voltage – Current Waveforms of Hybrid Solar/ Wind with 2-L Inverter with Battery (Passive Filter)

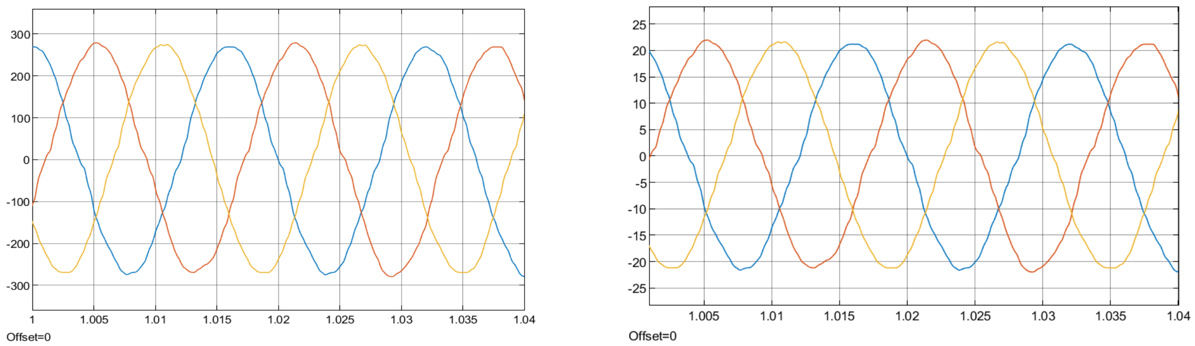

Figure 56: Line Voltage – Current Waveforms of Hybrid Solar/ Wind with 3-L Inverter with Battery (Passive Filter)

In 2-level inverter the efficiency of the whole system is dominated by the rectifier losses in light loads. In 3-level inverter the efficiency at full load is better than in 2-level inverter. This means better energy capture of the system. Better efficiency at rated power means also smaller heat sink and better reliability. Efficiency of the 3-level inverter at small power is also improved.

Sinewave view of 3-level inverters help decrease the size of an LC filter used to smooth the output waveform into a sine wave. Furthermore, since the output voltage swing of a 3-level inverter is half that of a 2-level inverter per switching action, the 3-level inverter has less switching loss. Therefore, 3-level inverters are suitable for decreasing the size and improving the energy efficiency. Compared to the 2-level inverters at all cases, 3 –level inverters caused 1% less total harmonic distortion. The differences can be seen in Figures 57 and 58.

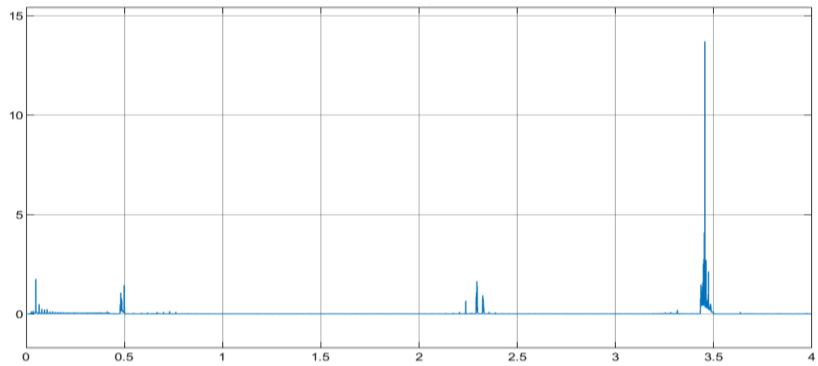

Figure 57: Instantaneous Harmonics of Hybrid Solar/ Wind with 2-L Inverter with Battery (Passive Filter)

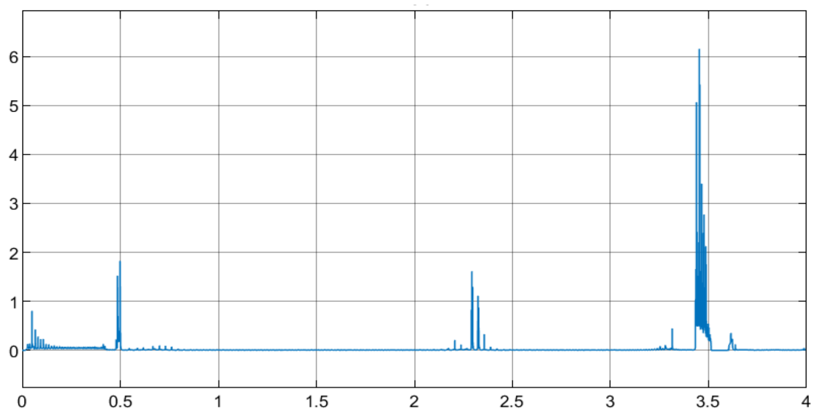

Figure 58: Instantaneous Harmonics of Hybrid Solar/ Wind with 3-L Inverter with Battery (Passive Filter)

4.2.3 Effect of Filters

If cases 1,4,7,10 are considered where there is passive filter usage, during constant irradiance and wind speed, better harmonic distortion percentage can be obtained compared to the cases 2,5,8,11 where active filter is used. However, during the weather condition changes, active filter used cases showed better performances in terms of harmonic distortion. This can be explained as dynamic structure of the active filter where the duty cycle is adjusted from the controller advances during the weather conditions changes. In the case 13, active and passive filters used at all times in order to test the suitability of the hybrid system without the proposed control method. Not much difference is estimated compared to the passive filter usages for the average harmonic distortion with 2.2 %. Therefore, the effect of the active filter is eliminated in this usage. Hence, with the proposed algorithm at section 3.3.4, the passive filter is activated in constant weather conditions only and active filter is activated at varying weather conditions. This method helps the overall system to be subjected 2 % of the average harmonic distortion which can be seen in case 6. The related Figures 59 and 60 are shown below.

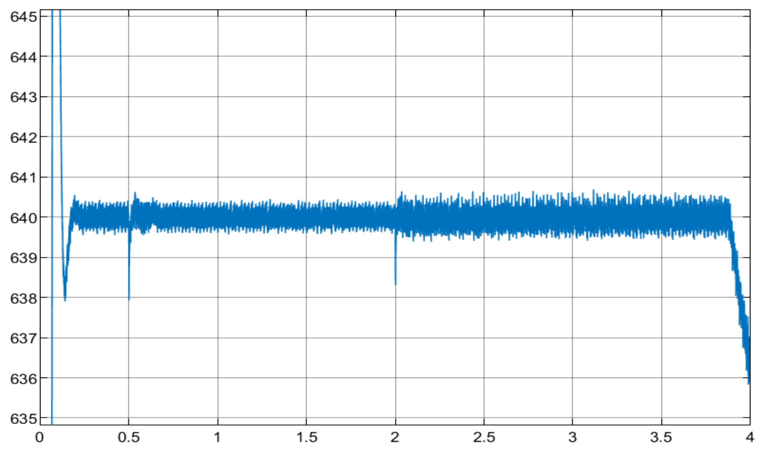

Figure 59: Instantaneous Harmonics of Hybrid Solar/ Wind with 3-L Inverter with Battery (Passive Filter)

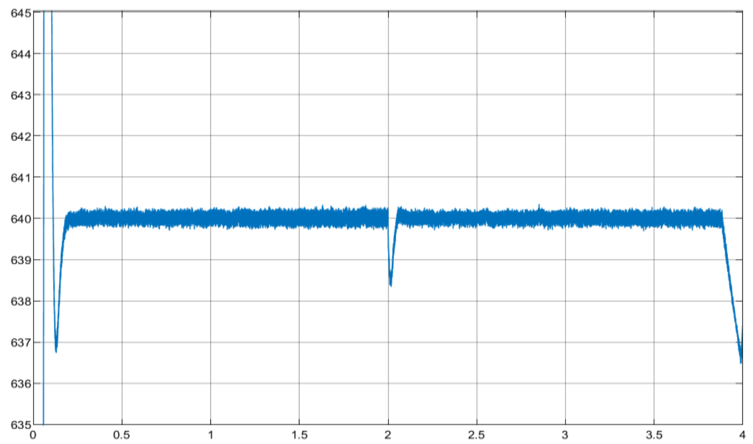

Figure 60: Instantaneous Harmonics of Hybrid Solar/ Wind with 3-L Inverter with Battery (Active Filter)

4.2.4 Effect of Realistic Timing Approach of Wind Speed and Irradiance Changes

Neither wind speed nor solar irradiance change, suddenly. Therefore, a rate limiter block is used in the input block as discussed earlier. In case 9, the highest instantaneous harmonic distortion is 5 % where the rate block is used for more realistic approach. However, in case 14, this block is deactivated and 6.5% the highest instantaneous harmonic distortion occurred. The latter seems to be 1.5% higher as a very sudden change is applied to the system. These two cases are generated on purpose in order to test the stability of the system during rough weather changes. It can be commented that, even in a unrealistic case, the system response and occurred highest instantaneous harmonic distortion is still in acceptable level. In Figures 61 and 62 the differences are shown.

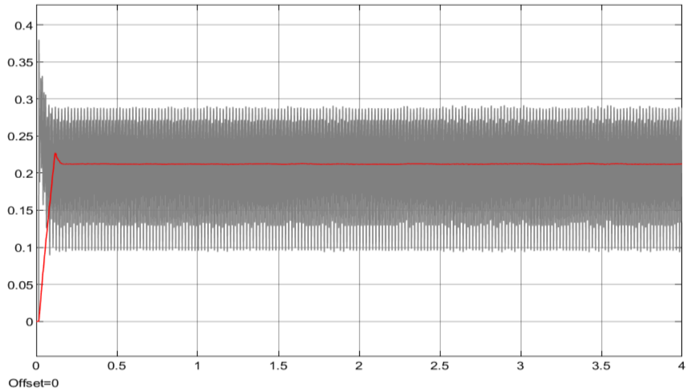

Figure 61: Average Harmonics of Hybrid Solar/ Wind with 2-L Inverter w/o Rate Limiter Block (Hybrid Filter)

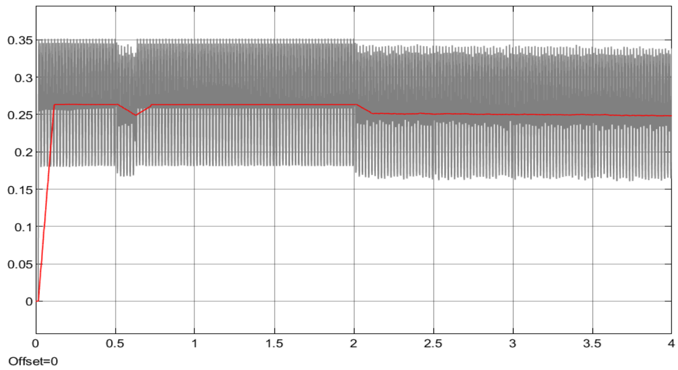

Figure 62: Average Harmonics Hybrid Solar/ Wind with 2-L Inverter with Rate Limiter Block (Hybrid Filter)

4.3. General Summary of Case Studies

Table 4: Numerical Comparison of Case Studies

Type of Inverter	**Battery Usage**	**Rate Limiter**	**Filter Type**	**Case Number**	*Line Voltage*	*Line Current*	*Average Harmonics*	*DC Link Voltage*	*Highest Instantaneous Harmonics*
2 LEVEL	W/O Battery	W/O Rate	PF	1	210 V	15 A	2.7%	450 V	14%
			AF	2	185 V	12 A	2.6%	410 V	11.5%
		Rate	HF	3	200 V	13 A	2.5%	440 V	17%
	With Battery	W/O Rate	PF	4	310 V	21 A	2.2%	640 V	14%
			AF	5	310 V	22 A	2.3%	640 V	11.5%
		Rate	HF	6	310 V	22 A	2%	640 V	6.3%
3 LEVEL	With Battery	W/O Rate	PF	7	280 V	22 A	1.3 %	640 V	6.1 %
			AF	8	280 V	22 A	1.6%	640 V	2.6 %
		Rate	HF	9	280 V	22 A	1.2%	640 V	5%
	W/O Battery	W/O Rate	PF	10	280 V	22 A	1.4%	640 V	10.5%
			AF	11	265 V	20 A	1.6%	640 V	2.5%
		Rate	HF	12	280 V	22 A	1.3%	640 V	7%
2 LEVEL	With Battery	W/O Rate	PF+AF	13	310 V	22 A	2.2%	640 V	4.6%
3 LEVEL	With Battery	W/O Rate	HF	14	280 V	22 A	1.3%	640 V	6.5 %
2 LEVEL	With Battery	Rate	PF+AF	15	310 V	22 A	2.2%	640 V	4.4%

All the related results, obtained in the case analysis, can be found in the Appendix section accordingly. The most considerable differences are among in the average harmonic distortion and line current amplitudes. The highest harmonic distortion occurs when two level system is used without any battery and highest current peak is seen in passive filter usage. Dynamic characteristics of the active filter is quite effective during weather condition changes and passive filters work efficiently during static weather conditions.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In recent years, a lot of works on power quality have been done and will continue to raise as the issue of power quality in power generation never ends. On the other hand, a lot of researchers stated many solutions for standalone solar and wind models, hybrid models, inverter types, filter types, controller types, battery usage and its types. Furthermore, different hybrid techniques were presented increasingly on renewable energy and filtering techniques. However, researchers studied on certain parameters and did not think about a lot of cases and parameters together. This research method and targets present a wider knowledge on which wind turbine, PV panel, which battery, which filter, which converter, which inverter and which controller engineers and academicians choose while creating a new model.

Energy needs around the world is growing rapidly, but important thing is energy wastage rather than its production. System components such as multilevel inverters, hybrid filters, concentrating PV panels, lithium ion batteries can prevent from energy wastage, but the ways how their costs can be lower should be found.

5.2 Future work

It is needed that all of these should be done experimentally. It would be more effective if the necessary wind turbines and PV panels were suitable to be use. Also, it would be better if a grid or micro grid prototypes were used. As it is known, components which are needed to increase energy efficiency and get better performance have generally high costs. However, a cost analysis was not created in this thesis, there should be a work on this in the future.

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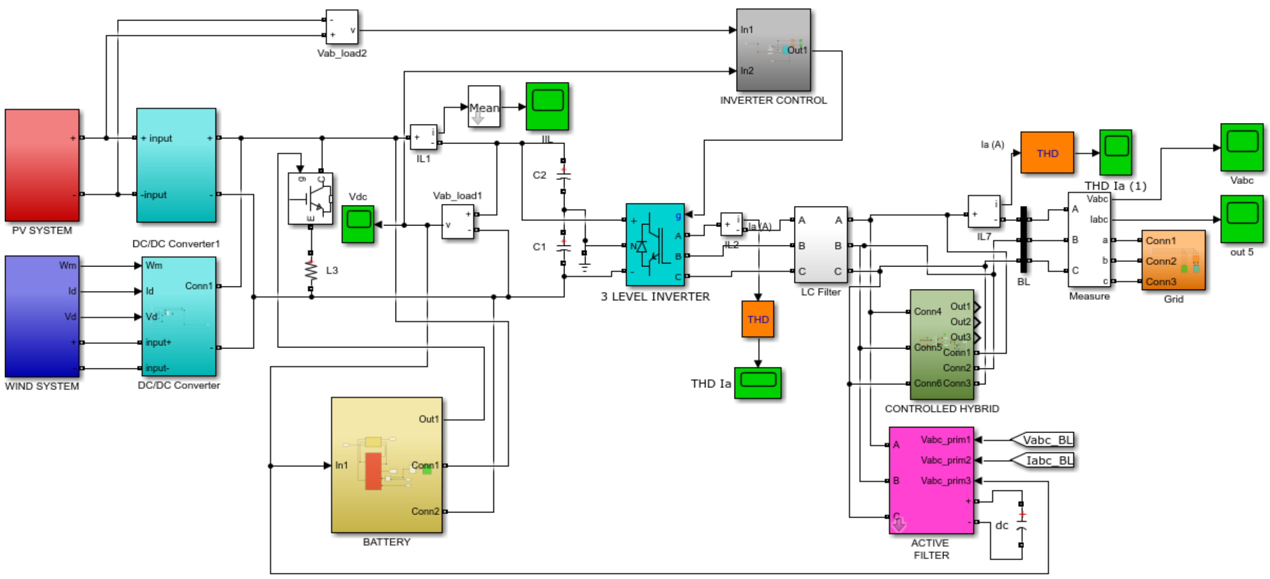
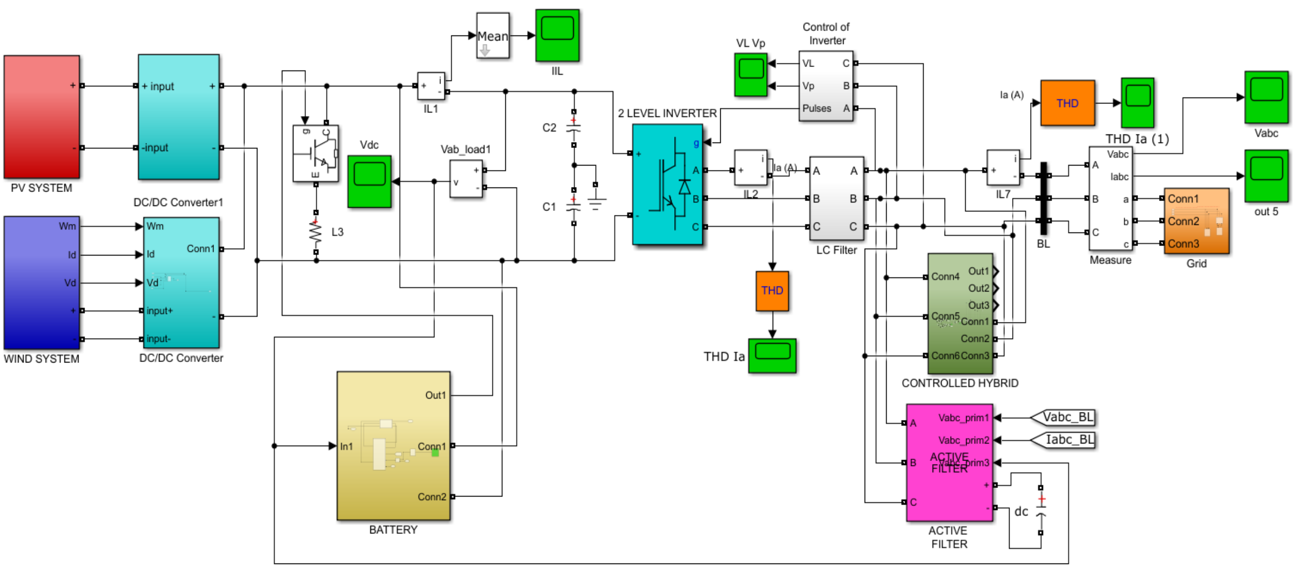
APPENDIX

Hybrid Solar and Wind System with 3 Level Inverter + Battery

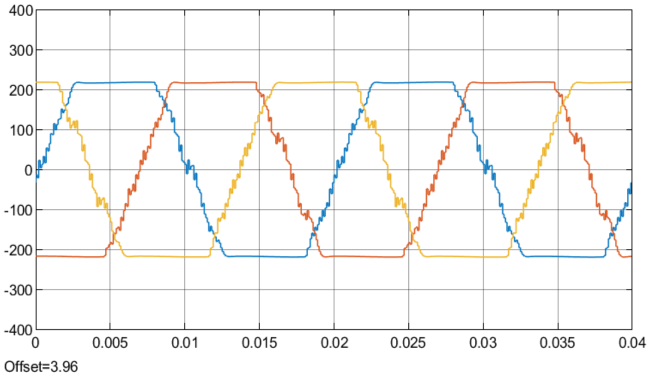


Hybrid Solar and Wind System with 2 Level Inverter + Battery



Case Studies

CASE 1 – Hybrid Solar/ Wind with 2-L Inverter w/o Battery (Passive Filter)



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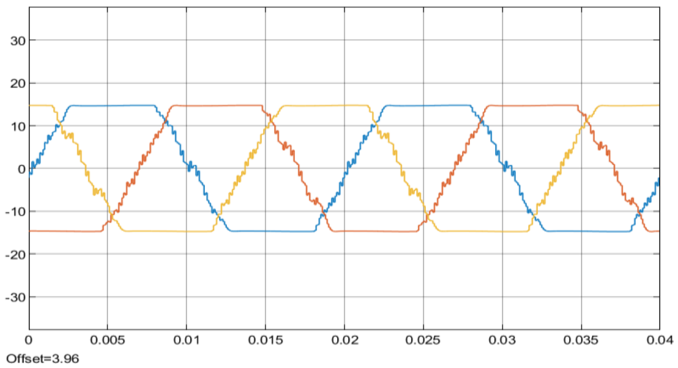

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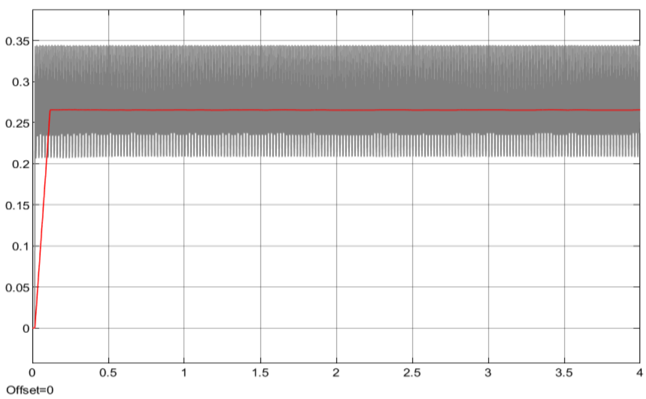

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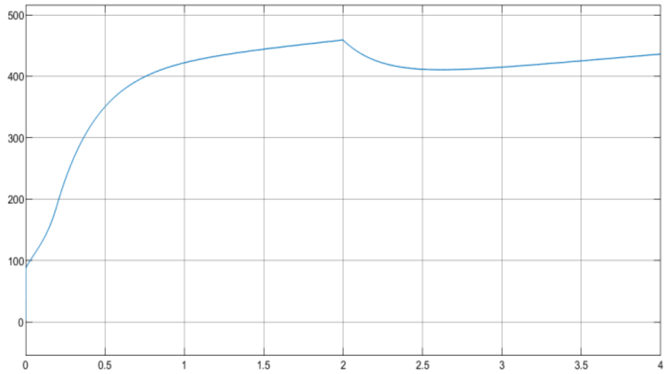

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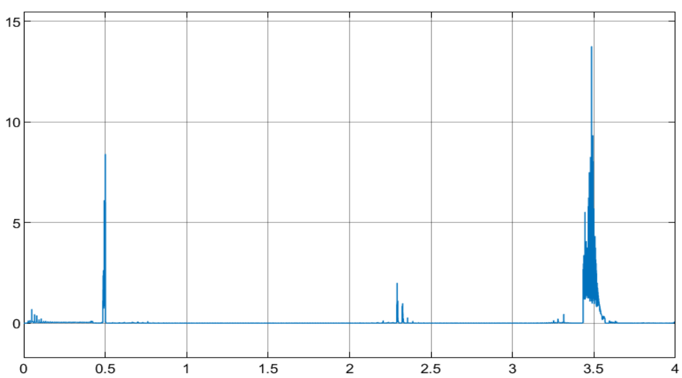
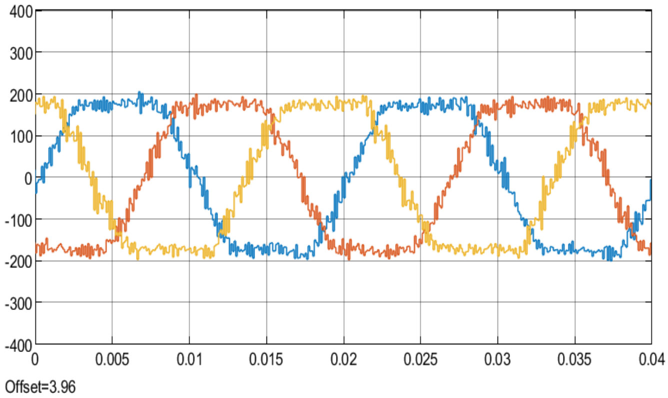


(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 1

CASE 2 – Hybrid Solar/ Wind with 2-L Inverter w/o Battery (Active Filter)



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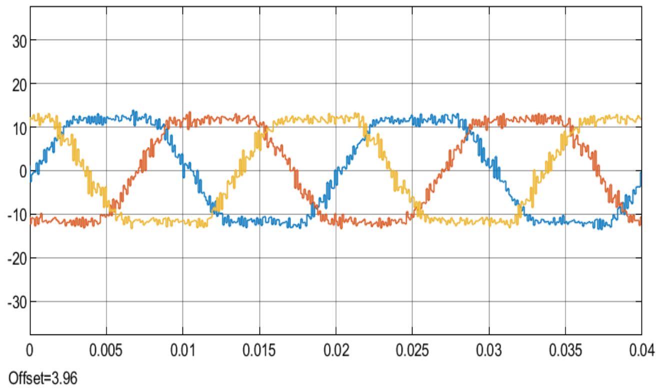

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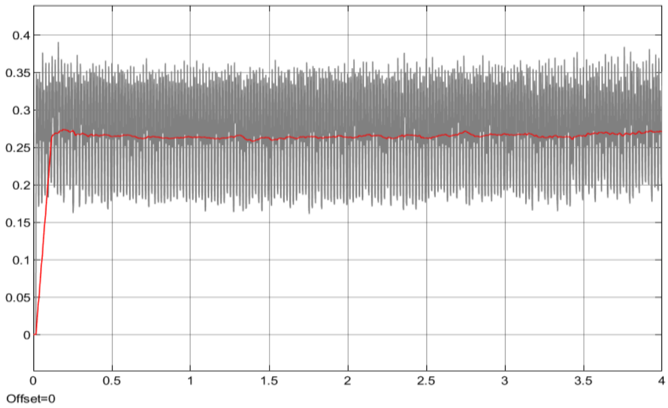

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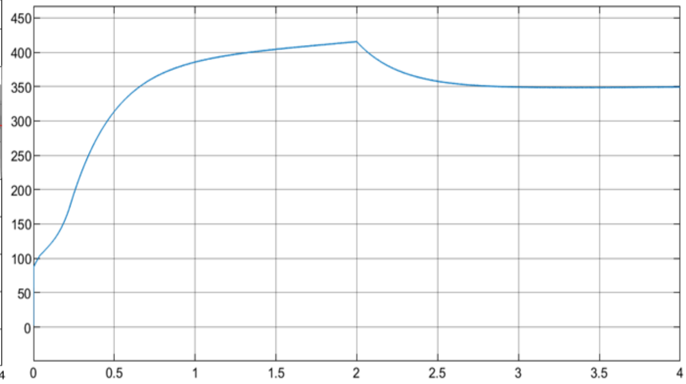

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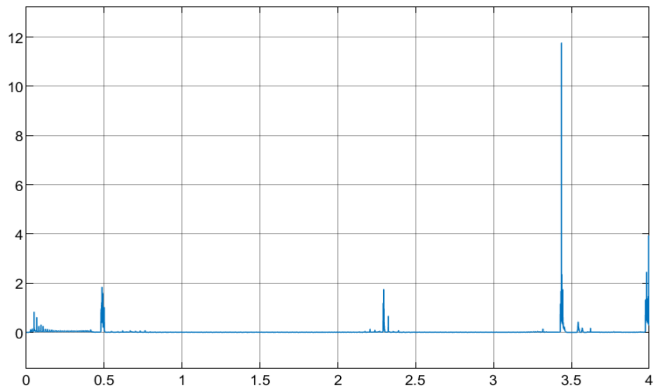
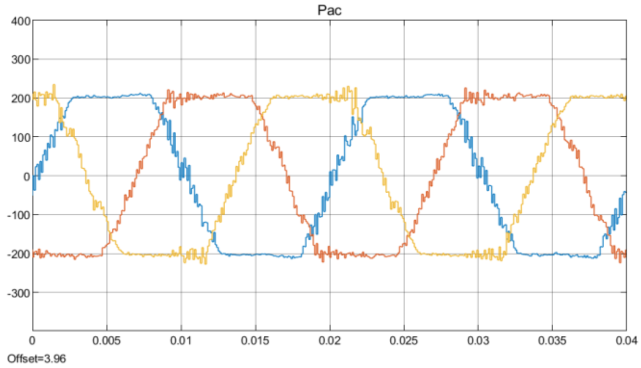
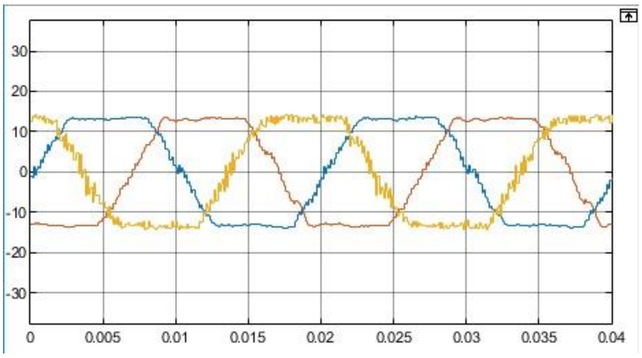


(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 2

CASE 3 – Hybrid Solar/ Wind with 2-L Inverter w/o Battery (Hybrid Filter)





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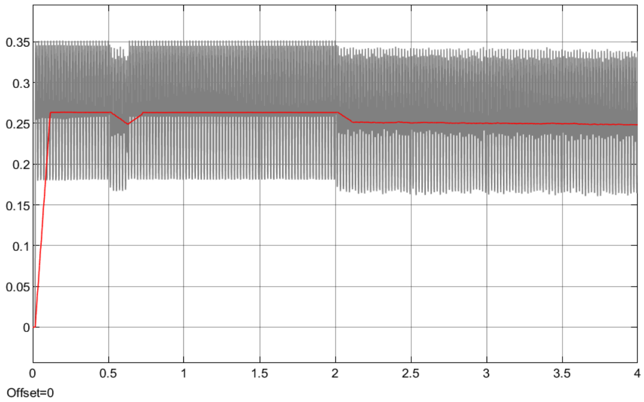

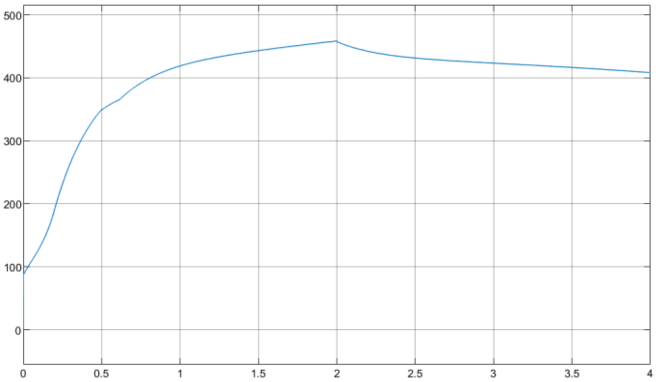

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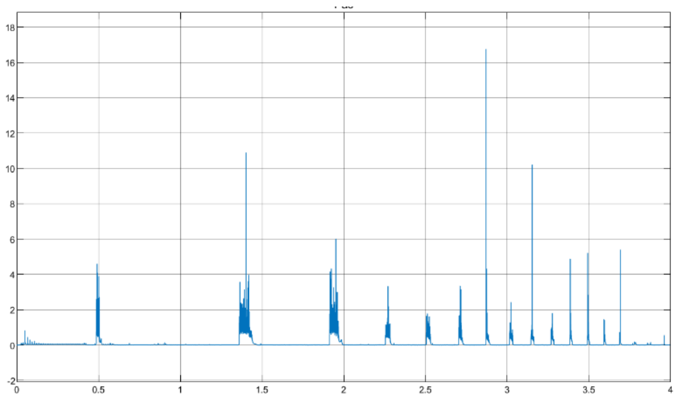

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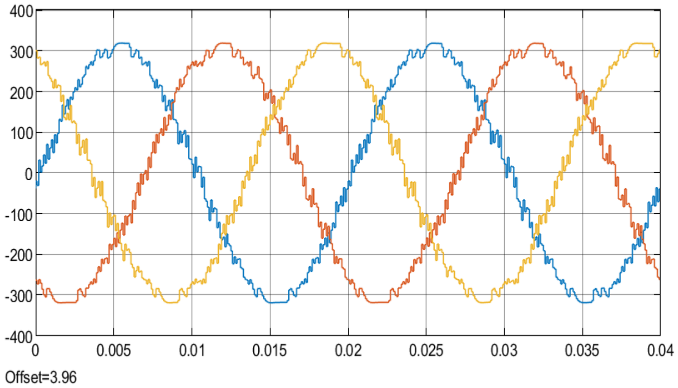
(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 3

CASE 4 – Hybrid Solar/ Wind with 2-L Inverter with Battery (Passive Filter)



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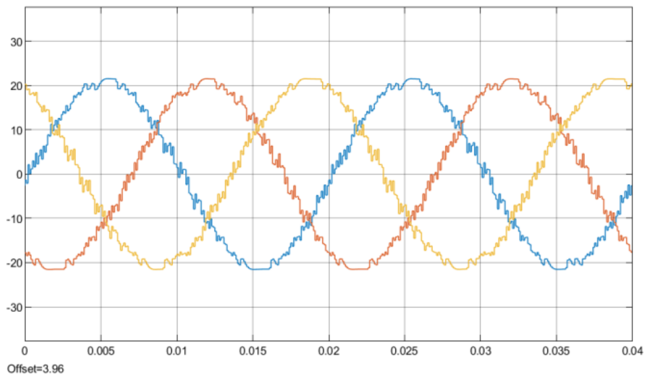

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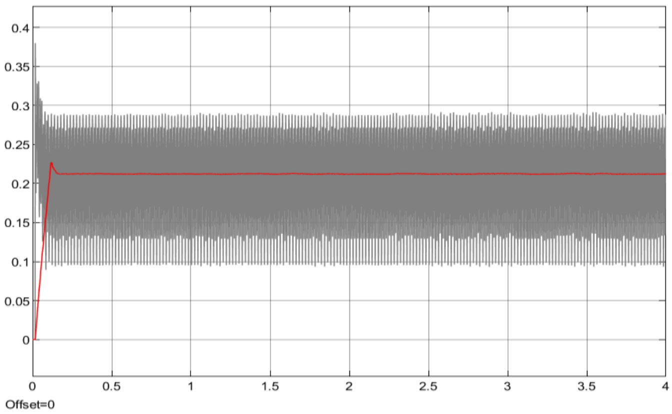

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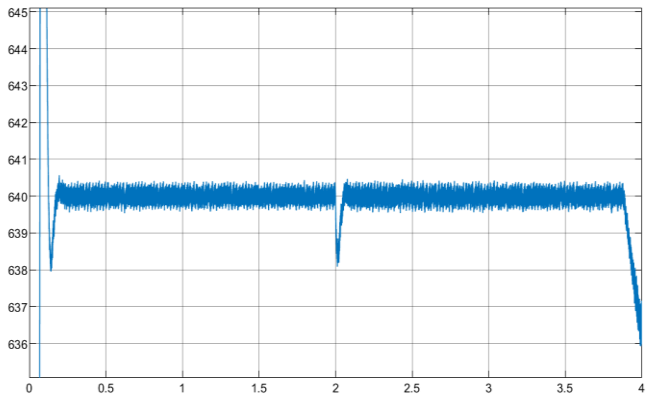

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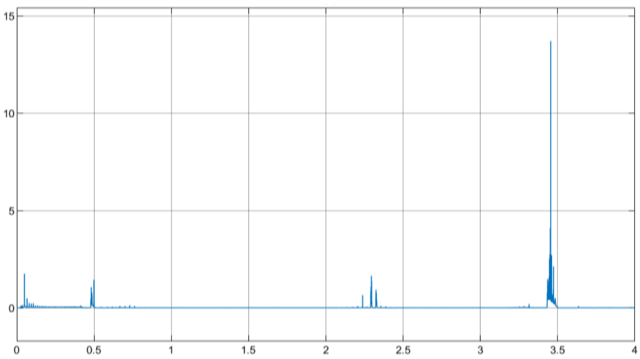

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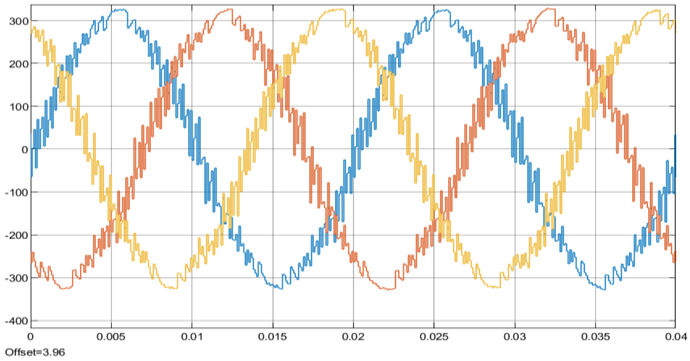
(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 4

CASE 5 – Hybrid Solar/ Wind with 2-L Inverter with Battery (Active Filter)



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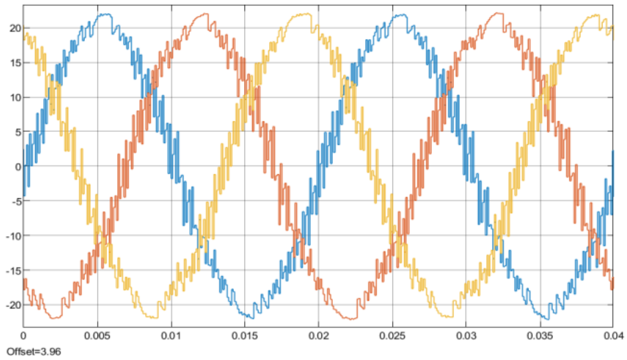

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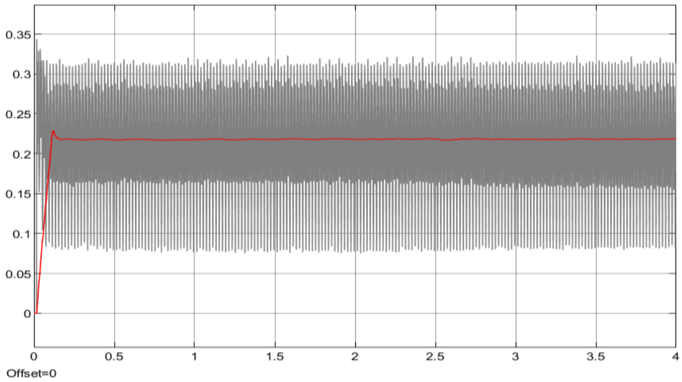

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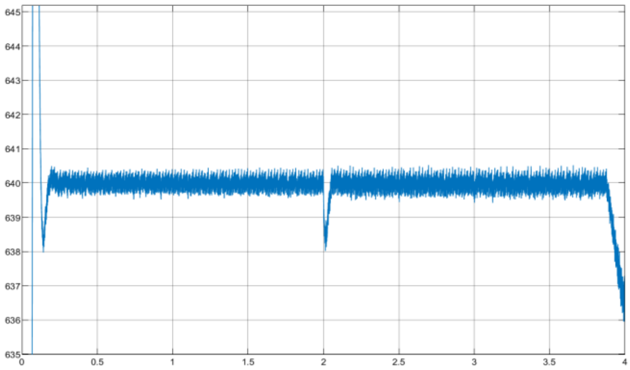

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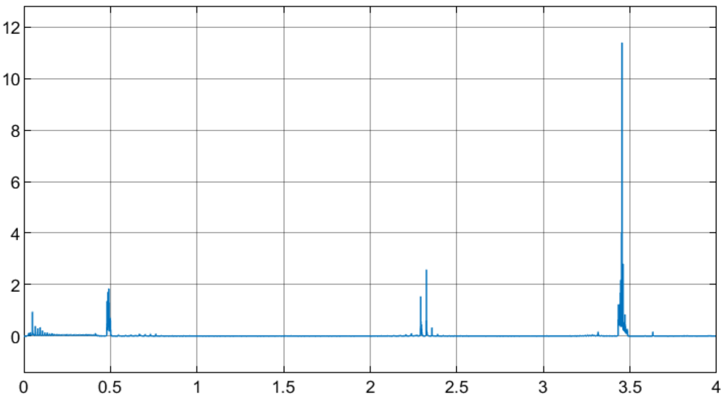

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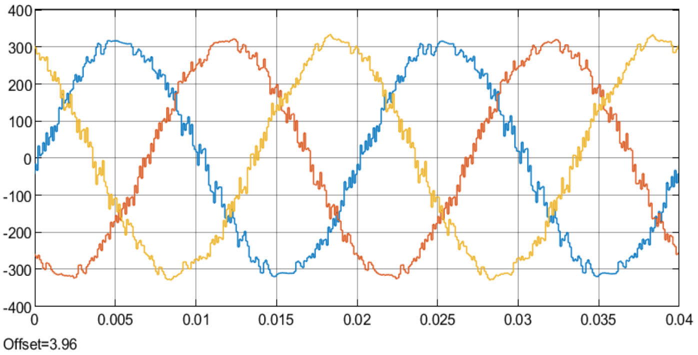
CASE 6 – Hybrid Solar/ Wind with 2-L Inverter with Battery (Hybrid Filter)



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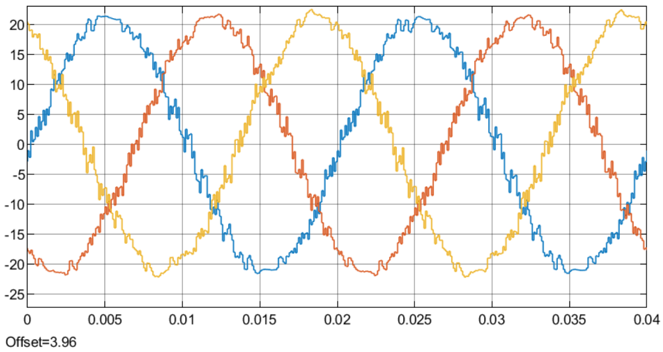

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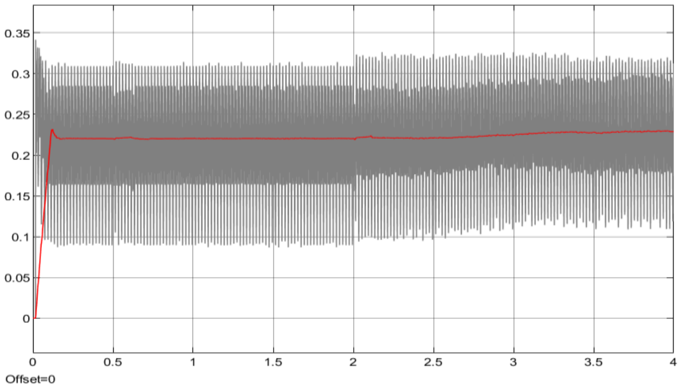

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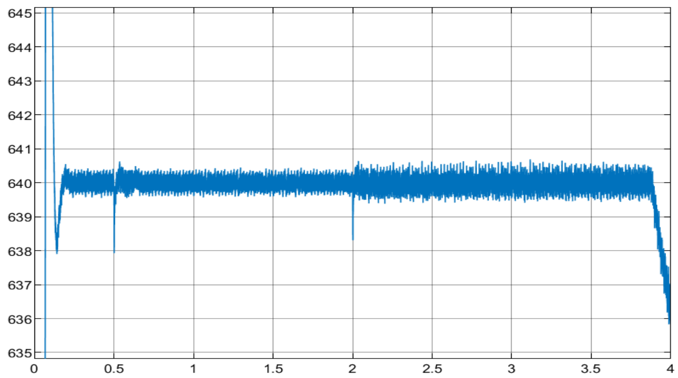

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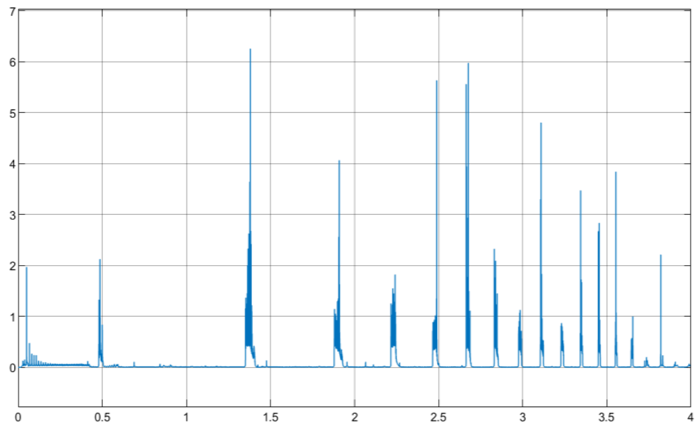

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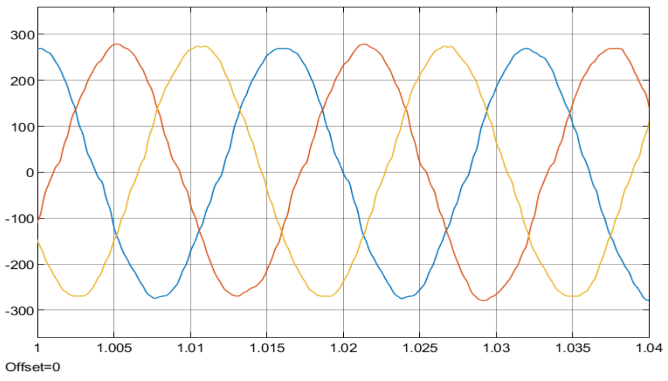
CASE 7 – Hybrid Solar/ Wind with 3-L Inverter with Battery (Passive Filter)



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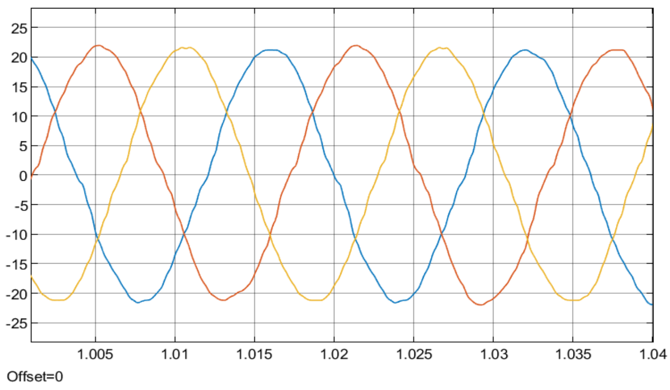

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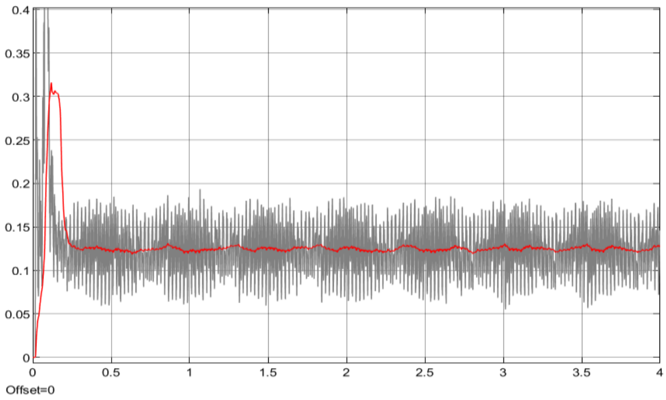

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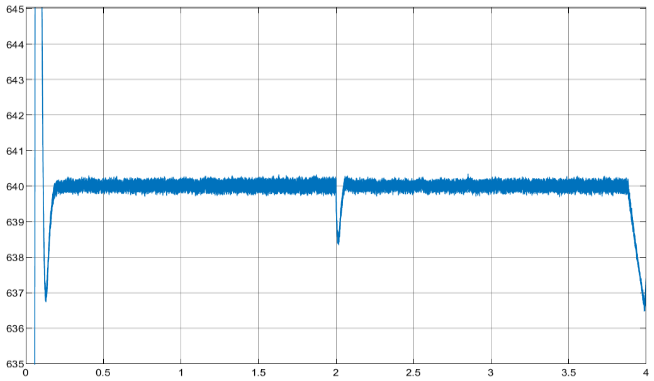

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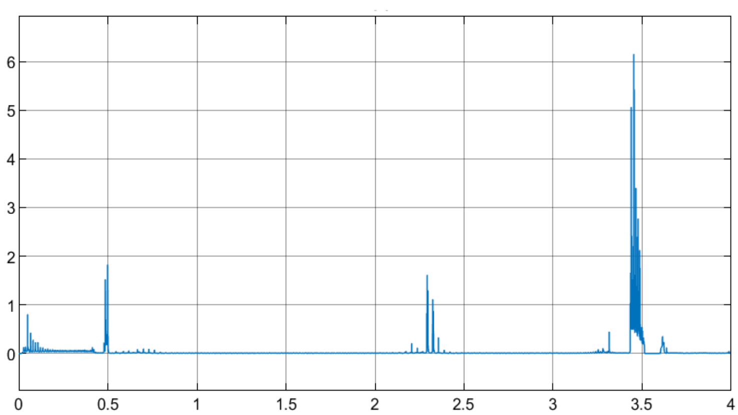

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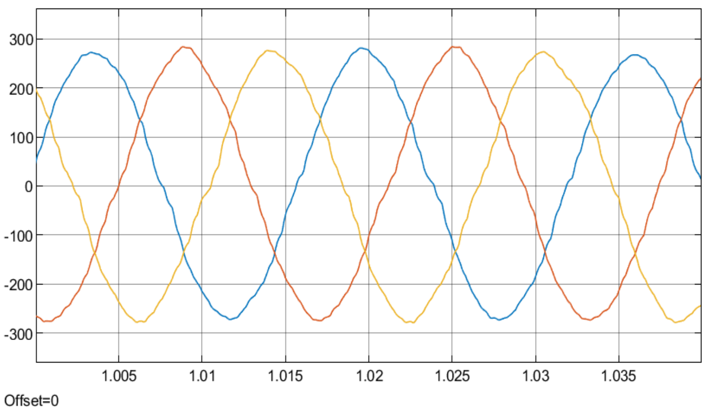
CASE 8 – Hybrid Solar/ Wind with 3-L Inverter with Battery (Active Filter)



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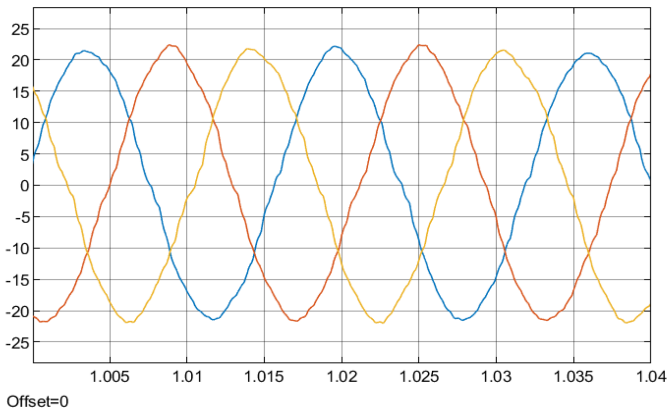

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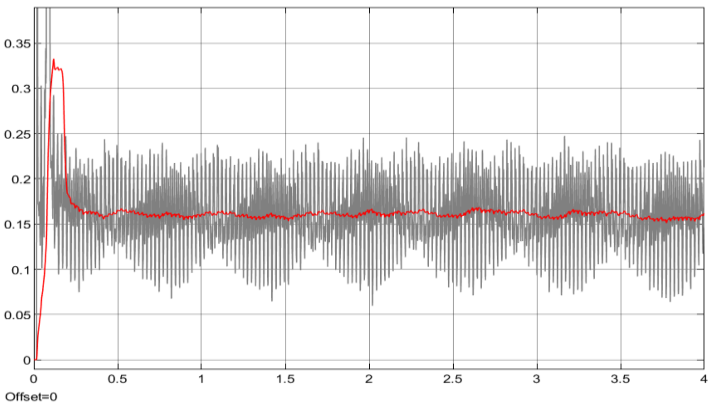

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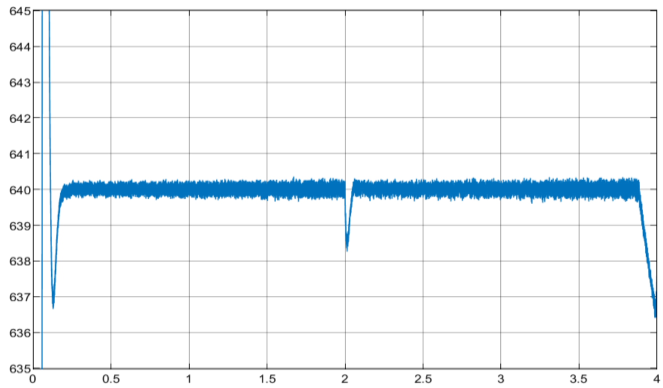
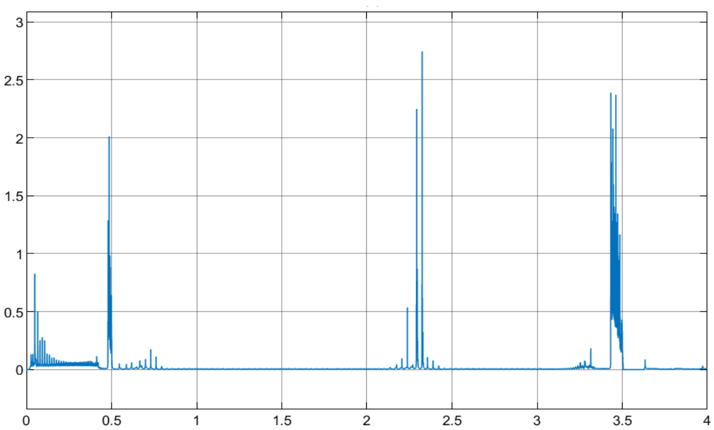


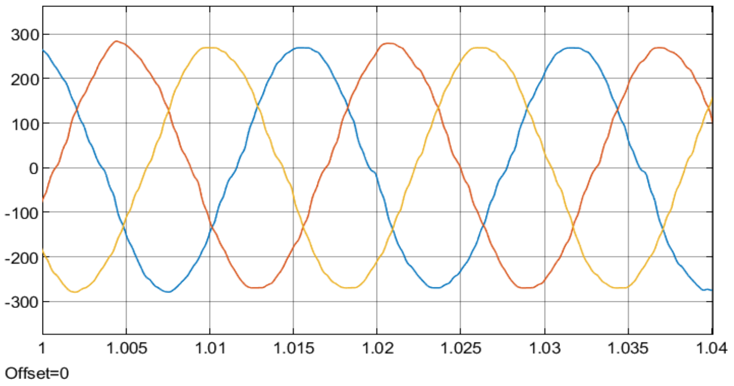
(d)



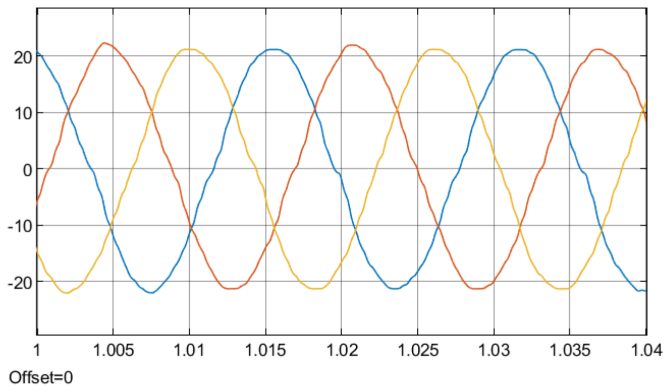
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 8

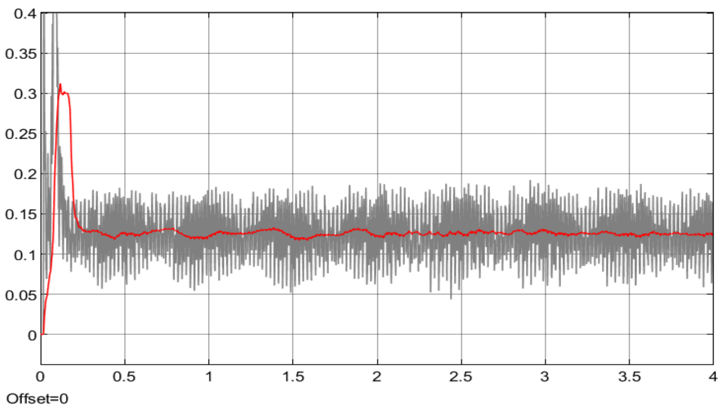
CASE 9 – Hybrid Solar/ Wind with 3-L Inverter with Battery (Hybrid Filter)



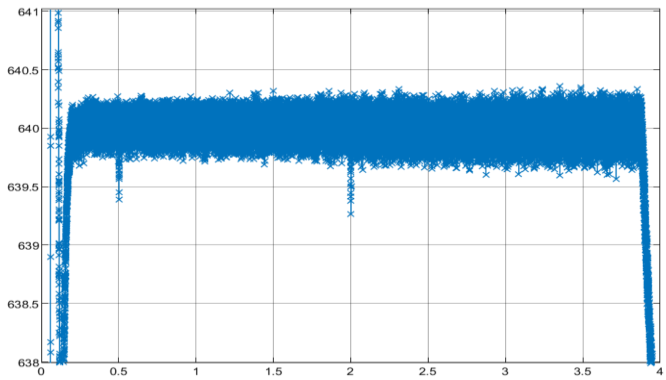
(a)



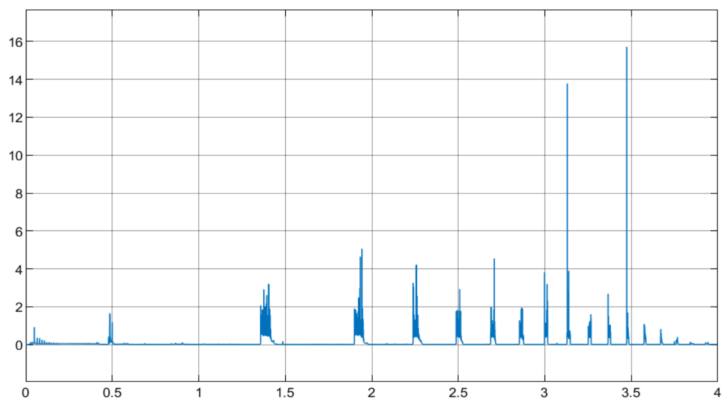
(b)



(c)



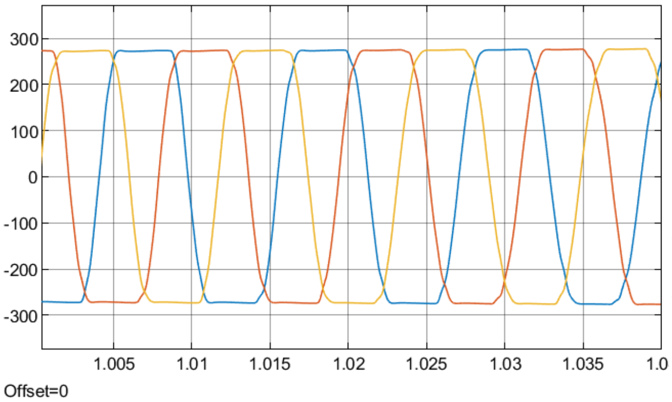
(d)



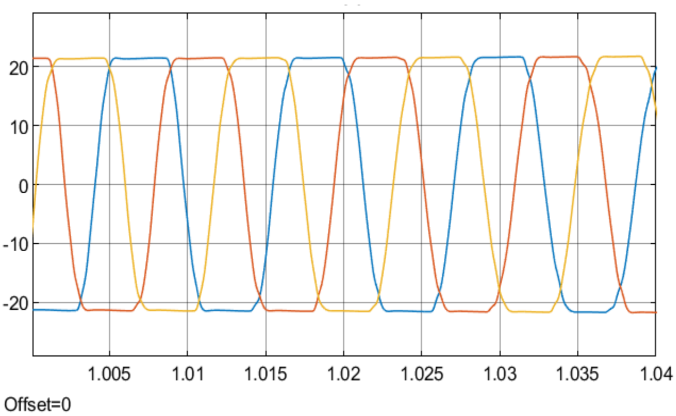
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 9

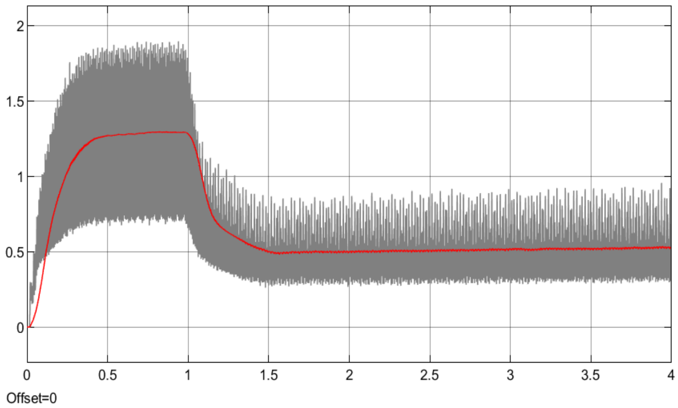
CASE 10 – Hybrid Solar/ Wind with 3-L Inverter w/o Battery (Passive Filter)



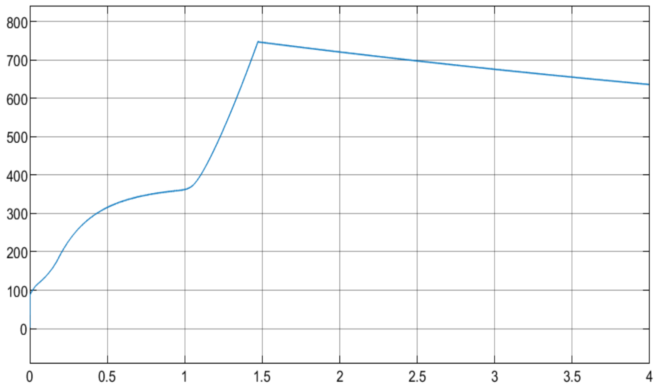
(a)



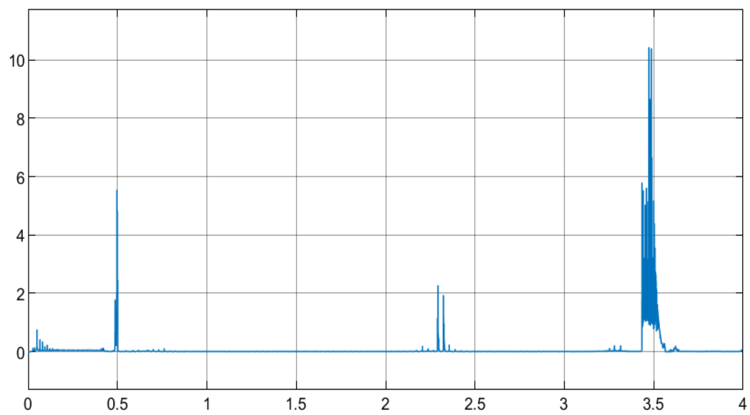
(b)



(c)



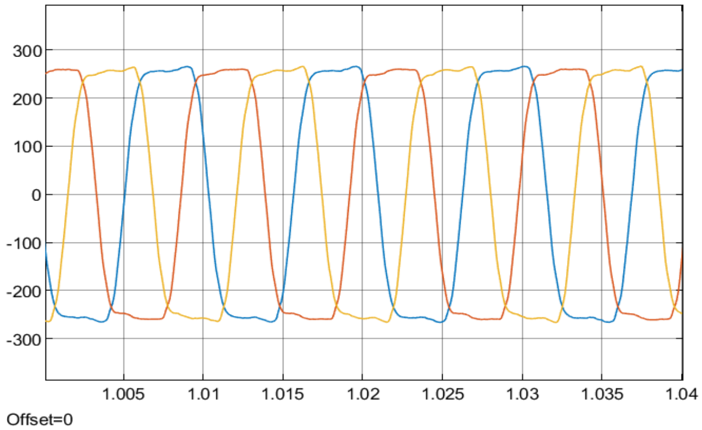
(d)



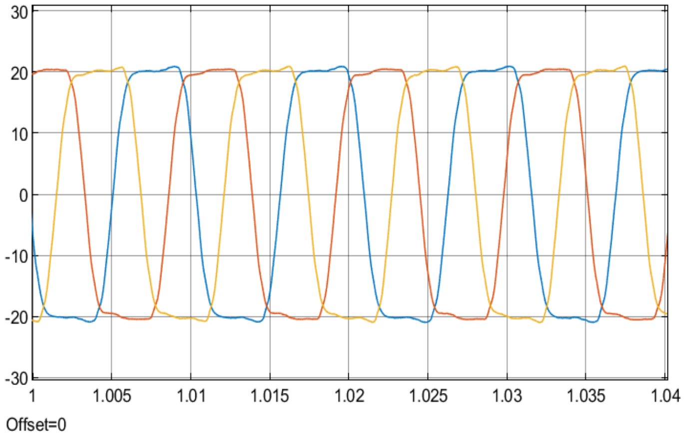
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 10

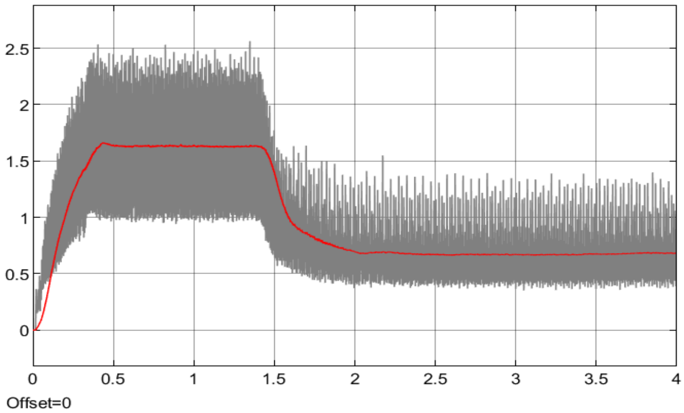
CASE 11 – Hybrid Solar/ Wind with 3-L Inverter w/o Battery (Active Filter)



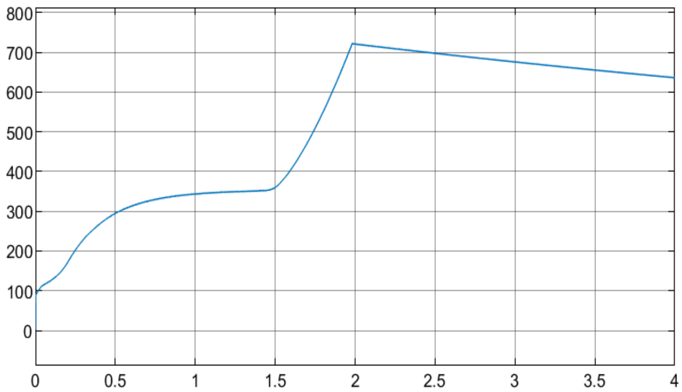
(a)



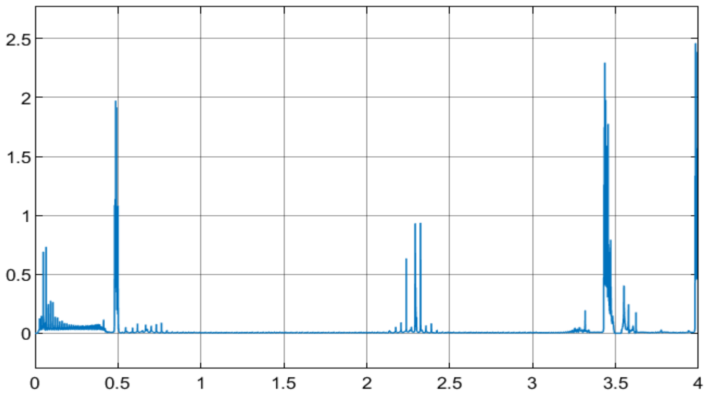
(b)



(c)



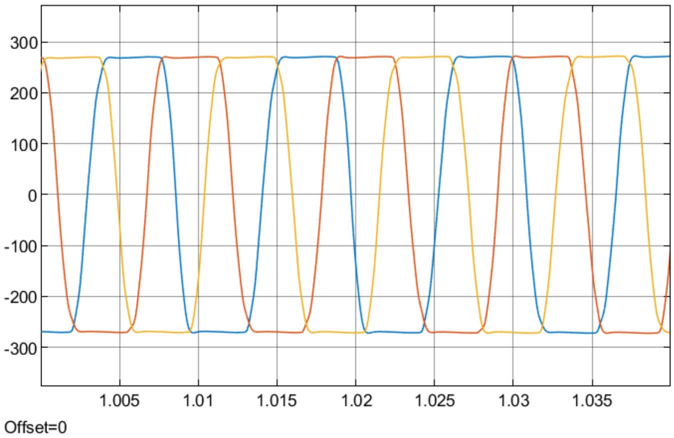
(d)



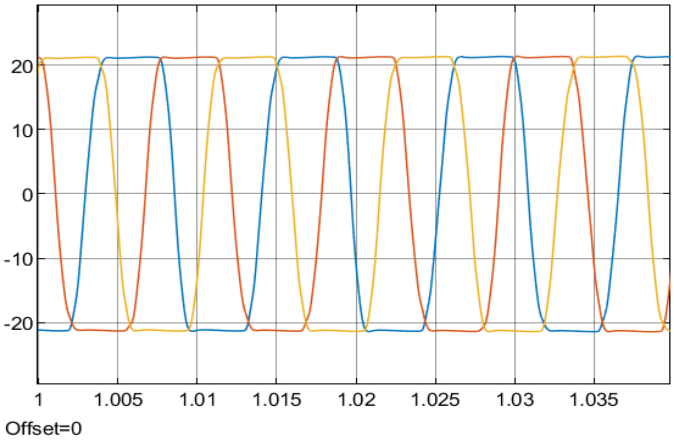
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 11

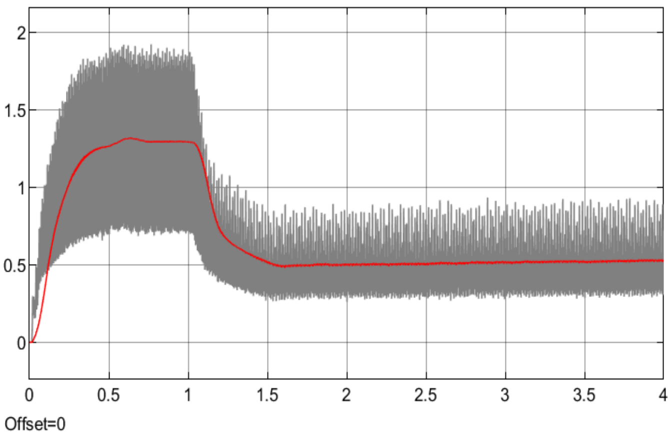
CASE 12 – Hybrid Solar/ Wind with 3-L Inverter w/o Battery (Hybrid Filter)



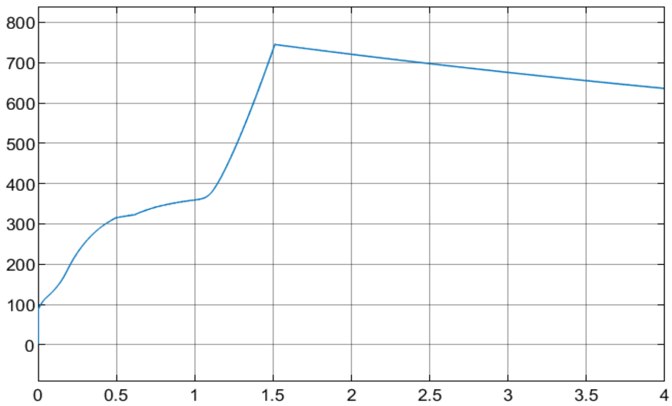
(a)



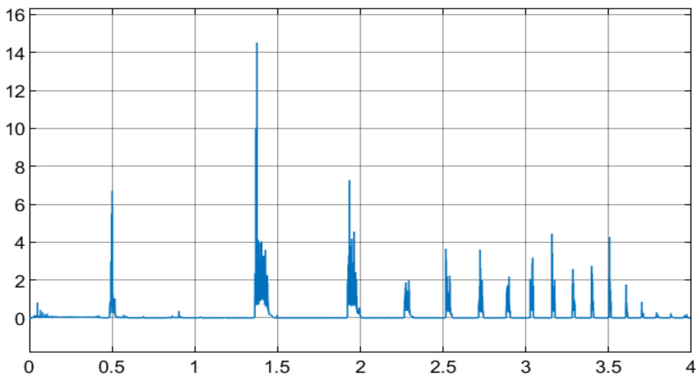
(b)



(c)



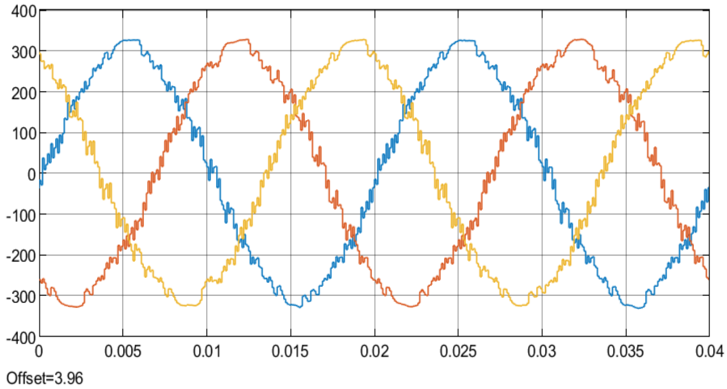
(d)



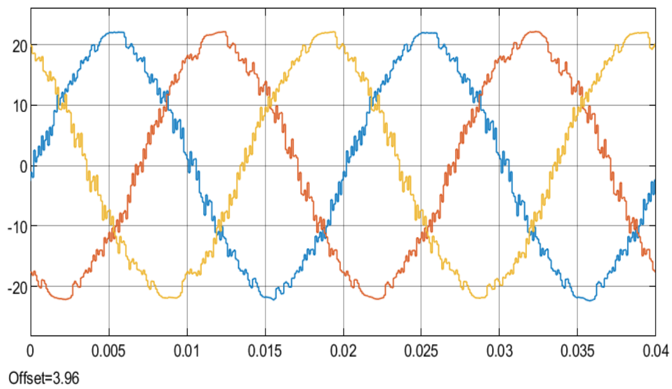
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 12

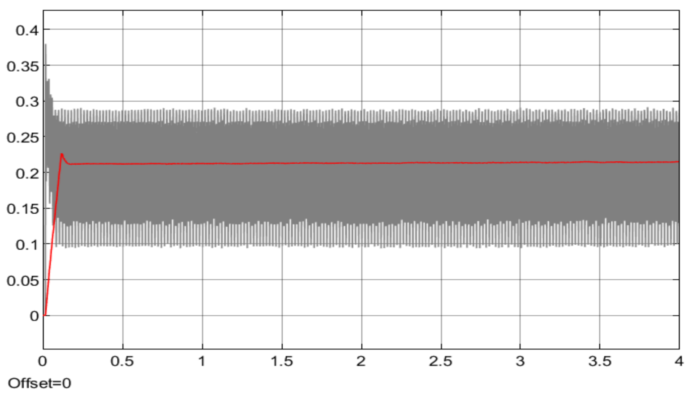
CASE 13 – Hybrid Solar/ Wind with 2-L Inverter with Battery (Active + Passive Filter)



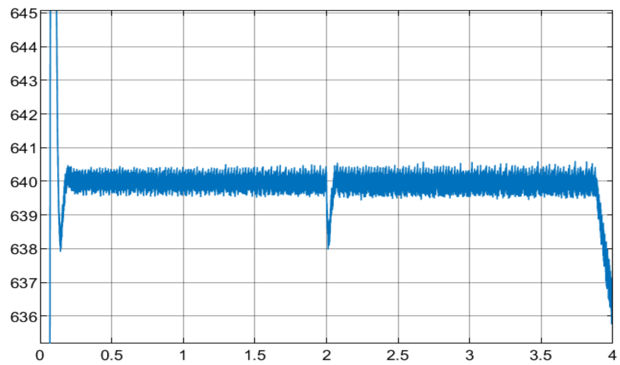
(a)



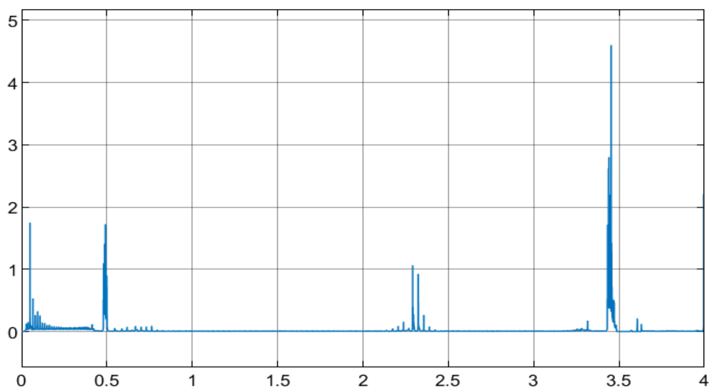
(b)



(c)



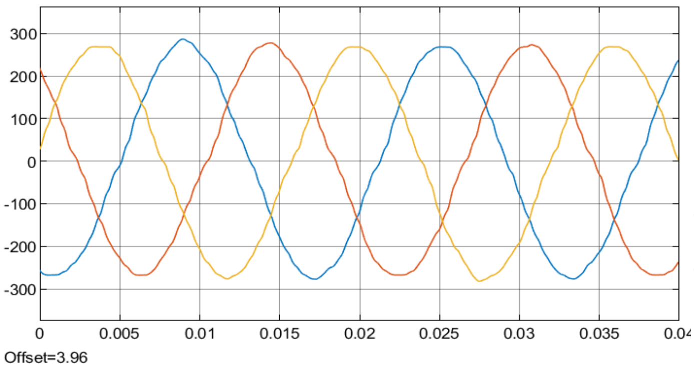
(d)



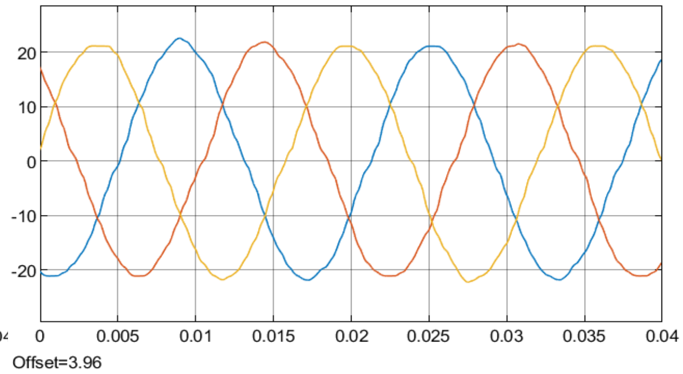
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 13

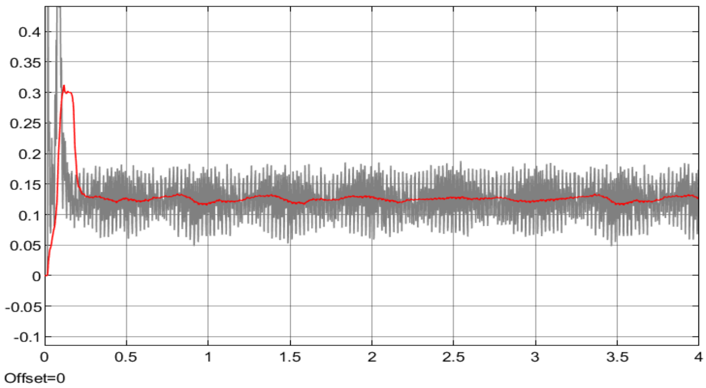
CASE 14 – Hybrid Solar/ Wind with 3-L Inverter with Battery w/o Rate (Hybrid Filter)



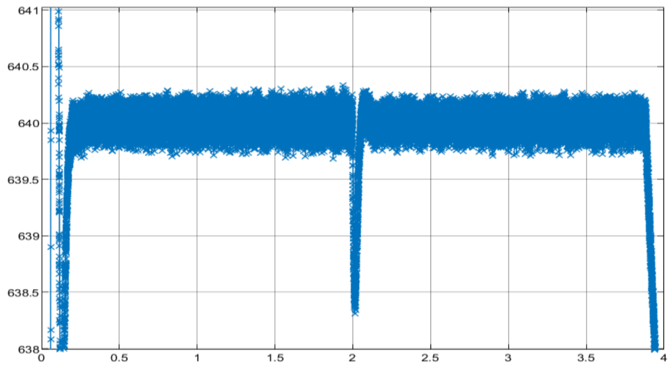
(a)



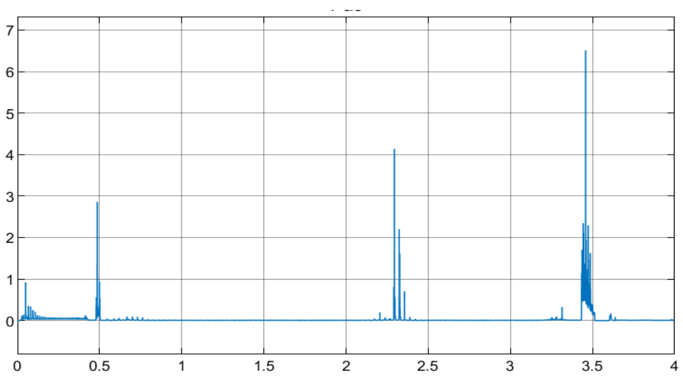
(b)



(c)



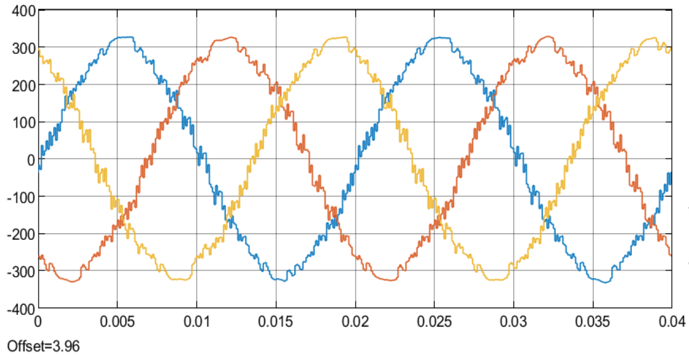
(d)



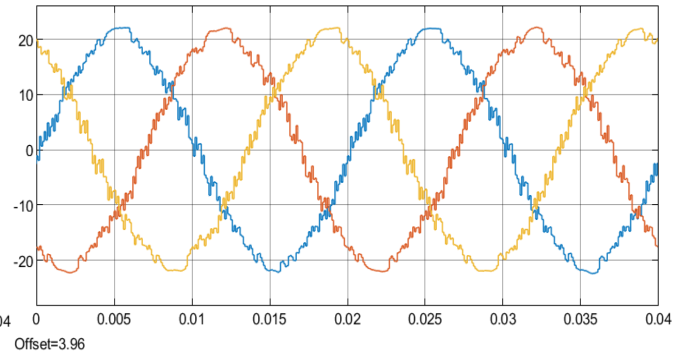
(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 14

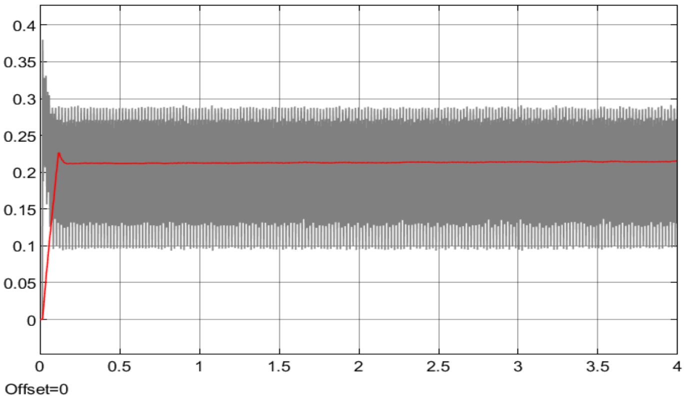
CASE 15 – Hybrid Solar/ Wind with 2-L Inverter with Battery & Rate (Active + Passive Filter)



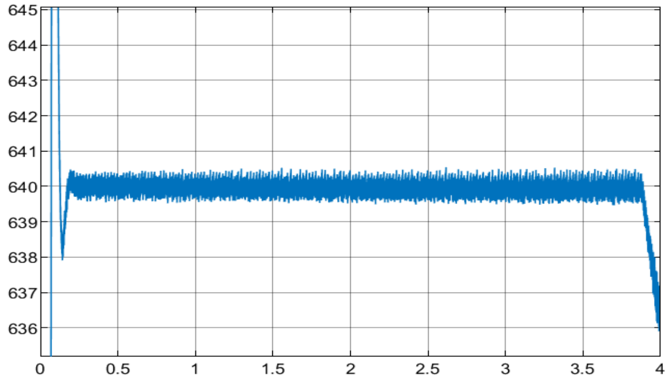
(a)



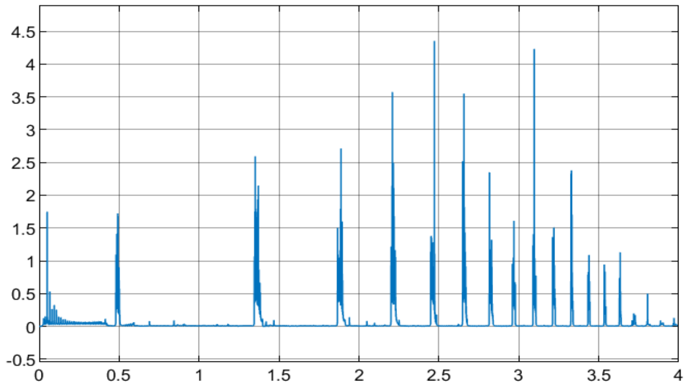
(b)



(c)



(d)



(e)

(a) Line Voltage (b) Line Current (c) Average Harmonics (d) DC Link Voltage (e)Instantaneous Harmonics for Case 15