DESIGN OF PHOTOVOLTAIC OFF GRID SYSTEM FOR SINGLE HOME BY USING OPTIMUM LCL FILTER

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
CANSU SOMTÜRK ÜRÜN

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA,2018

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Masters of Science in Electrical and Electronic Engineering

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

The demand of electrical power is rising day by day. Concurrently, traditional power resources are going down. Therefore, among increment of requests and generating a few alternative power sources must be utilized. Renewable sources look like up and coming solution. Photovoltaic power systems provide eco-friendly, clean and endless resources of power. The photovoltaic system is categorized into on grid and off grid systems. Photovoltaic array should connect with DC-DC converter to reach optimal voltage level for photovoltaic output. Thanks to DC-AC inverters, this optimal photovoltaic system output voltages can be transformed to AC system. A filter is needed to reduce harmonic output current and to impose back indication control of performance for both photovoltaic system types. Comparison among L, LC and LCL filters, LCL filters have better harmonic damping capableness. However, resonance peak in LCL filter can cause to become all system non-stable. For this reason, damping methods that can be passive or active way should be applied to the system and it provides to have better controlling in all system. There should be harmony among parameters such as inductors, capacitor and resistors and requirements like IEEE 519 standard to model optimal LCL filter. Thanks to optimization of LCL filter, system efficiency is increased. It reduces the power losses and cost. Most of the papers available in the literature contain just filter optimization. The contribution of this thesis is to apply this optimization into an off grid system.

In this thesis, off grid PV system which contains DC-DC boost converter, battery, single phase inverter, PWM inverter controller and optimal LCL filter by using passive damping method are designed and modelled in MATLAB Simulink software.

Keywords: Solar energy; boost converter; battery; inverter; LCL filter; IEEE 519 std

ÖZET

Enerji ihtiyacı her geçen gün artmaktadır. Aynı zamanda mevcut durumdaki güç kaynaklarında hızlıca bir azalma mevcuttur. Aradaki bu açığı kapatmak için ihtiyaçlardaki artışlarla alternatif güç kaynakları arasında bir bağlantı sağlanmalıdır. Yenilenebilir enerji kaynakları gelecek vaat eden bir çözüm olarak görülmektedir. Güneş enerji sistemleri sonsuz güç kaynağı, temiz ve çevre dostu gibi özelliklere sahiptir. Fotovoltaik sistemler şebeke bağlantılı ve şebeke bağlantısız olmak üzere 2 kategoride gösterilir. Fotovoltaik çıkış geriliminin optimal seviyeye ulaşması için DA-DA çeviriciler kullanılmaktadır. DA-AA eviriciler sayesinde de optimal olan fotovoltaik çıkış voltajı AA'a dönüştürülür. Her iki çeşit fotovoltaik sisteminde harmonik akımı düşürmek ve performansın geri bildirim kontrolünü uygulamak için filtre gereklidir. L, LC ve LCL filtreler arasındaki kıyaslama sonucu, LCL süzgeçler daha iyi harmonik düşme yeteneğine sahiptir. Ancak LCL filtresindeki rezonans tepesi tüm sistemin kararsız olmasına sebep olabilir. Bu sebepten dolayı, aktif veya pasif sönümlenme yöntemleri uygulanarak sistem daha iyi kontrole sahip olur. Kapasitör, direnç, indüktör gibi filtre parametreleri ile IEEE519 standartları arasında optimal LCL filtre elde edebilmek için uyum olmalıdır. LCL süzgecin optimizasyonu sayesinde sistemin dinamiği artar, kayıplar ve maliyet azalır. Literatürde yer alan makalelerin çoğu yalnızca süzgeç optimizasyonu üzerinedir. Bu çalışmanın özgünlüğü, süzgeç optimizasyonunun bir yenilenebilir enerji sistemine uygulanmış olmasıdır.

Bu tezde, DA-DA yükseltici çevirici, pil, tek fazlı evirici, PWM kontrol sistemi ve pasif sönümleme yöntemi kullanılarak şebekeden bağımsız sistem Matlab Simulink yazılımı kullanılarak tasarlanıp modellenmiştir.

Anahtar Kelimeler: Güneş enerjisi; yükseltici; batarya; evirici; LCL süzgeç; IEEE 519 standart

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LIST OF ABBREVIATIONS

a:	Ideal Diode constant
AC:	Alternating Current
C:	Capacitor
Cout(min):	Minimum output capacitor value of boost converter
Cwh:	Battery capacity
D:	Duty cycle
Dautonomous:	Day of Autonomous
DC:	Direct Current
DOD:	Depth of Discharge
ESR:	Equivalent Series Resistance
fres:	Resonance frequency
fsw:	Switching frequency
G:	Solar radiation on photovoltaic
Gn:	Nominal solar radiation
Isw:	Switching current
k:	Boltzman constant
L:	Inductor
Lg:	Grid side inductance
Li:	Inverter side inductance
n:	Efficiency
Pd:	Diode power
PV:	Photovoltaic
q:	Reactive power
Rd:	Damping resistor
S:	Switches
std:	Standards
T:	Temperature

THD: Total Harmonic Distortion

Vin: Input voltage

Vout: Output voltage

VSI: Voltage Source Inverter

Δ_L**:** Ripple current

CHAPTER 1
INTRODUCTION

1.1 Overview of the Thesis

Lately, power produced by pure, effective and peripherally friendly resources has been becoming one of main difficulty topic for researches. Incremental world power request, because of contemporary industrial community and expanding population, motivates many enterprises in power solution's choices for developing power productivity and energy quality problems (Vikas et al. (2013). The usage of solar power can be noted to become preliminary sources by reason of most of countries located around tropic or mild districts where solar irradiance intensity can arrive to 1000W/m. Basic system structure and control diagram are some of the benefits of off grid PV systems. But, for drawing maximal powers from photovoltaic modules and stock surplus power, battery units are needed for the system. The PV arrays generate just low quantity voltage and current. Therefore, for meeting huge load request single cells must be attached in modules then modules attached in arrays. Photovoltaic modules output tension can change according to insolation and region warmth (Haynes, 2013). Solar system can connect with utility network by step up(boost) converters for optimizing output of photovoltaic system (Mohan et al., 2003). Therefore, for connection system to the network PV arrays output tension must be stable and transformed to AC voltage coherent with network AC tension. Therefore, inverters can be used about power transformation from DC supply to AC output either off grid system or connected to network systems (Bratt, 2011).

The filter is necessary among voltage source inverter with network. Implementing back indication check of current performances and decreasing grid side current harmonics. Basic serial inductors may use, however harmonics attenuations aren't distinct. Additively, high tension drops are generated and needed inductor for the model is sizable.

Widely third order filter which is called LCL filter can be used instead of classic L type filters by reason of LCL filter smooths inverter's output current. LCL filter can succeed high attenuations. Also, it provides savings and reducement of all system parameter's size and weightiness (Jalili and Bernet, 2009).

LCL filter can be used at off grid system inverters with pulse width modulation (PWM) controller for minimizing the quantity of current defected embedded to the network (Akhter and Hoque, 2008). Great productivity may acquire between the range of power ratings furthest to megawatts by using small values of capacitor and inductors. Optimum LCL filter design permits usage of low switching frequency to come across harmonic restricts mentioned from standards like IEEE 519 std (Beres et al., 2016). But, beholding that there is no enough data convenient defining methodical modeling for LCL filter. For modeling efficient LCL filter it is needed to know suitable mathematical models for filter. In this thesis, design of LCL filter, modeling methods and passive damping ways are entirely mentioned (Pena-Alzola et al., 2013). The main purpose of this thesis is about modeling and analyzing of single phase off grid PV system with optimized LCL filter. Also, optimized and non-optimized LCL filter are compared. The recommended design and its control scheme are simulated in MATLAB Simulink software.

CHAPTER 2
STATE OF ART THE LITERATURE REVIEW ON LCL FILTER DESIGN

2.1 Introduction to LCL Filter Design

Various LCL filter model methods were shewed and mentioned in the litterateur. The purpose of the all works to implement productive adjustment on LCL filter variables considering to varied limitation. Between these limitations maximal filter capacity, depleted reactive powers, total harmonic distortion on network current, maximal current ripple's factor and resonance frequency are prominent (Park et al., 2017). But until now, some studies work on just providing LCL filter model for varied network situations characterized from big network impedance differentness (Pan et al., 2014). Actually, network impedance diversifies considerably in accordance with to the network form and situations like linking of parallel converters. In many situations by using passive and active damping method LCL filter's system are tried to be stable. Therefore, many works are related to apply better damping and modelling of LCL filter (Bres et al., 2015).

For model of passive damping, derivation of this method is really simple. Therefore, this method is interesting for various applications and interested topic for articles and books. In Jalili and Bernet (2009), the criterions of selecting passive damping method are progressed taking into the consideration of stability and power losses. In Asa and Bjc (2008), resistance's values are selected to become less than half of the capacitor impedance values at resonance frequency that cannot be available for various conditions. In Petterson et al. (2006), by using passive damping method parameter's values are selected by using trial error procedure considering bode diagram. In Liserre et al. (2005), two chosen damping formulas explained such as effective resonance and low pass damping that are suggested according to varied passive damping circuits diagrams. In Channegowda and John (2010), split capacitance passive damping was tested in different execution that can reach megawatts.

In Balasubramanian and John (2011), passive damping way of LCL filter that includes resistor, split capacitor and inductance is suggested depend on complicated link of inactive units. Active damping method is other damping method to direct stability of LCL filter at resonance frequency. Obtaining this method is really flexible and productive. There are several compensation ways of active method which argued in many books.

In Tang et al. (2012), generalized model of LCL filter of shunt active energy is conferred. Considering basic model characteristics involving chosen LCL variables, interacting among resonance damping harmonics and bandwidth model of this system. In Wang et al. (2010), active methods by using capacitor's current back indication are suggested and counselling for selecting resonant frequency of LCL filter. In Xin et al. (2016) offers excessively true model of LCL filter parameters depend on network impedance. In Wang et al. (2015), takes into consideration of multiplex network connected converter. The distribution of every converter for harmonic stability of energy model may be forecasted from Nyquist graphs. Several active ways may be discovered in Busada et al. (2015) and argued model about control perspective, omission internal damping features of LCL filter.

But, in respect to Parker et al. (2014), without using damping methods resonant frequency can be placed in stable region by using PI current control method. Consequently, by changing place of diversity of resonant frequency into the stable area, network current back indication is obtained more convenient.

Mohammed (2011) offered strong ad quick control strategy of load's tension adjustment in on grid inverter via LCL filter. The presented controller suggests conversely the efficient load tension adjustment, more properties such as efficient attenuation in dynamic, harmonic tension disorder and simple customizable control model free from strict system.

CHAPTER 3
PHOTOVOLTAIC POWER SYSTEMS

3.1 Solar Systems

Solar energy is used in the production of heat, light and electricity. Shortly,solar cells are made up of semiconductor cells, which convert solar energy into energy of electricity from sunlight. Under certain conditions, electric current is generated by the absorption of light (photons) over a semiconductor. In this way, systems that convert the solar energy to electricity are called photovoltaic or solar batteries. The surfaces can be square, rectangular, circular and their thicknesses of 0,2 or 0,4 mm with areas around 100m2. Depending on the structure of the solar battery, the solar energy can be converted electrical energy with efficiency of between 5 and 20 percentage (Haynes, 2013).

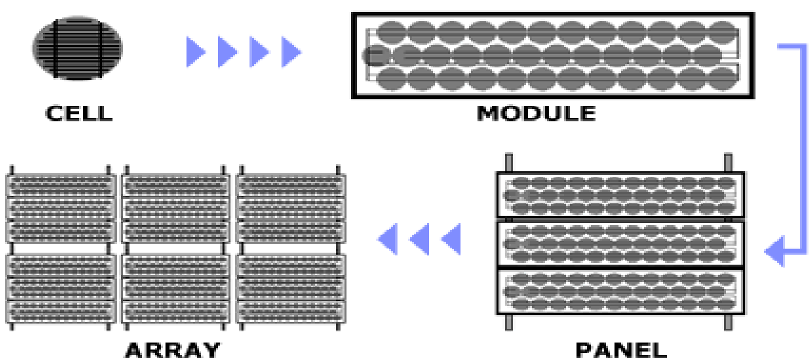

Figure 3.1: The types of solar cell (Haynes, 2013)

In order to increase the power output, a large number of solar panels are mounted on a surface in parallel or series to each other, this structure is called solar cell module or photovoltaic module.

Depending on the power demand, the modules can be connected in series or parallel to the each other. Thus, modules can provide to have power system which have a few watts till megawatts power (Bratt, 2011).

3.2 Working Principle of Photovoltaic Systems

The construction is consisting of a p and n joints similar to the diodes. Based on the principle of photoelectric effect, the electrons that detached by the photonpass through the joint and generate an electric current. In solar cell construction, inorganic semiconductor materials such as silicon (1.1ev) gallium arsenide (GaS-1.43eV) and cadmium telluride (CdTe) are used.N or p type dopants are required for semiconducting materials to be used as solar cells.Doping is achieved by the controlled addition of the desired additives into the pure semiconductor melt. The type of semiconductors which can be obtained n type orp type depends on the additive material. To obtain n type silicon from silicon which is used as the most common solar cell material, fostor is added from the 5th group elements. For this reason, the 5th group elements can be called donor or n type additive materials.

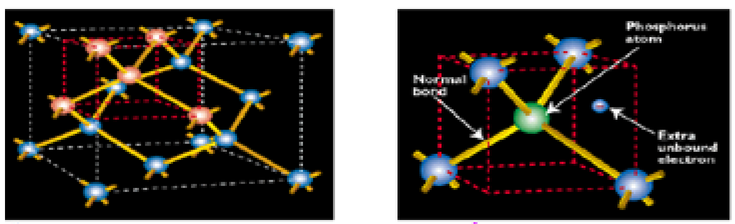

Figure 3.2: Silicon molecule vs. processed molecule (Quaschning, 2004)

In order to obtain P type silicon, elements such as aluminum, indium and boron are added from the third group. Electron deficiency occurs in the crystal. Therefore, these substances are called p type or receiving additive substances. Semiconductor joints are formed by the inclusion of the necessary additives in p or n type main materials. When the pn joint is formed, electrons with the majority carrier of type n form direct current to the p type. This event continues until load balancing occurs on both sides.

In order for the semiconductor joint to function as a solar cell, it needs to provide photovoltaic transformation in the joint region.This transformation takes place in 2 stages.

First, electrons are generated by dropping the light in the joint region. Secondly, they are separated from each other by the help of electric field in the region.Electron Hall pairs that separated from each other form a useful power output at the ends of the solar battery (Quaschning, 2004).

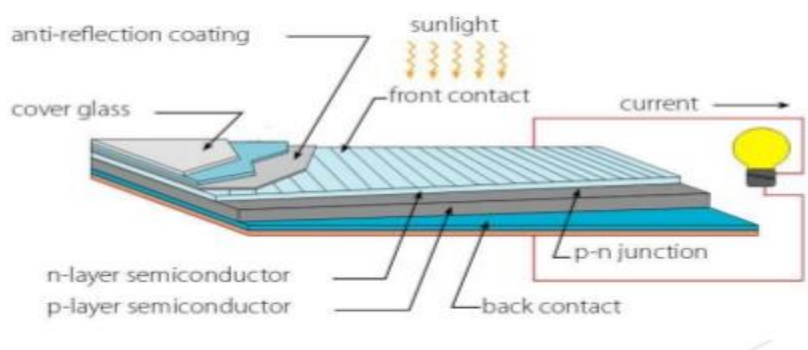

Figure 3.3: Photovoltaic cell structure (Quaschning, 2004)

3.3 Equivalent Circuit of Photovoltaic Cells

The PV cell produces a very low voltage at a high current density. Therefore, the PV element is a current source. The value of the Rs depends on the junction structure of the pn surface. Parallel resistance refers to the leakage current. In an ideal photovoltaic cell it is assumed that series resistance is zero 0 and parallel resistance is infinity. In a 1 inch high quality photovoltaic cell series resistance is around 0.05-0.10 Ω and parallel resistance is around 200-300 Ω. A small increase in series resistance reduces the output voltage by a significant amount. For this reason, the photovoltaic conversion efficiency is sensitive to the series resistance. When the load current is equal to zero, the cell opencircuit voltage is obtained. Typical electrical values at standard conditions, ie 1 kW / m^2 radiation and 25 ºC crystal temperature; short circuit current densityis 30.40mA / cm2 and open circuit voltage is 0,5, 0,6V (Green, 1982).

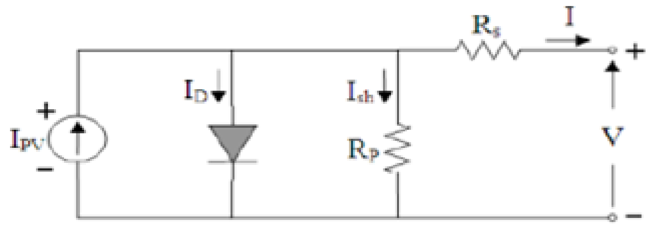

Figure 3.4: Electrical equivalent circuit of PV cell (Green, 1982)

In the equivalent circuit of the PV cell, there are series and parallel internal resistances. Accordingly, the output current of the PV cell can be expressed as in equation;

$$I = I_{pvcell} - I_o(\exp(V + R_s * I/V_t * a) - 1) \quad (3.1)$$

The light current produced by the photovoltaic cell is a linear relationship between I_{pvcell}, cell, solar radiation and temperature. This relation is given in Eq. 2. The ideal diode constant. The light current produced by the photovoltaic cell is a linear relationship between I_{pvcell}, cell, solar radiation and temperature. This relation is given in Equation.

$$I_{pvcell} = \left(I_{pv,n} + K_i * \Delta T\right) * G/G_n \quad (3.2)$$

Following equation is based on the temperature dependence of the diode's saturation current I_0 in the equivalent circuit.

$$I_o = \exp(I_{scn} + K_i * \Delta T/a * V_t) - 1 \quad (3.3)$$

The electricity generation of the solar battery is symbolized as a current source. The radiation falling on the cell is increasing in the waste electrical current. The solar cell is modeled with diodes because it is a semiconductor material.

The losses that occur during the conduction of the energy produced in the journaling to the poles are indicated by series resistance. This series resistance directly affects cell yield (Huang et al., 2001).

3.4 Characteristics of the Solar Battery

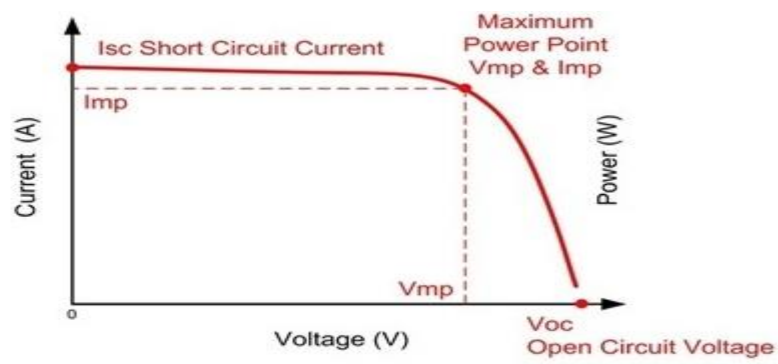

Figure 3.5: Load variation of I-V voltage characteristic of PV panel (Breeze, 2014)

As shown in Figure 3.5, when the current values drawn from the solar cell are low, the panel voltage is approximately constant and the voltage drops rapidly as the current approaches the short circuit current value. At the same time the elbow point at which the change speeds up is the point that the power to be taken from the panel reaches the highest value. This point is called the maximum power point and it is desirable to operate the system at this point so that the work can be highly efficient. Therefore, to take advantage of a PV cell panel installed and operated more efficiently, it is necessary to keep the output power of that panel at its maximum possible value. The maximum output power of the PV cell or panel varies depending on the incoming daylight level and operating temperature. The voltage current characteristic of the solar battery varies continuously depending on the severity of the sunlight, the angle and the ambient temperature. In this case, the maximum power point can be shifted right, left, up or down (Quaschning, 2006). Charts describing this situation are given in Figure 3.6 and Figure 3.7.

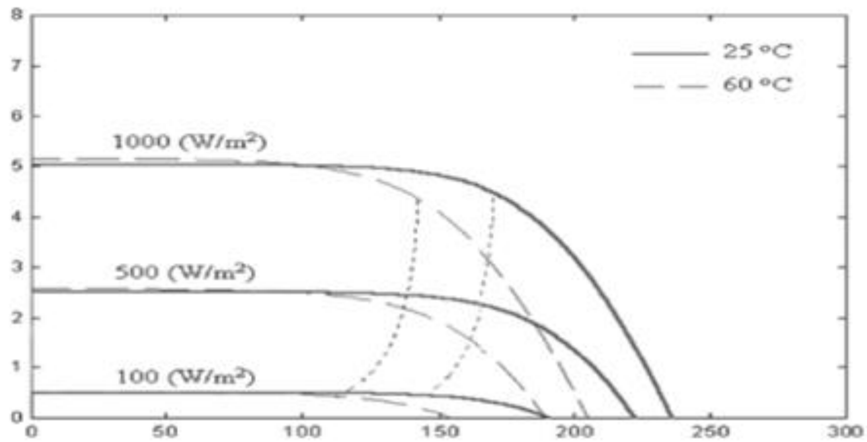

Figure 3.6: I-V characteristic of solar battery according to changing conditions (Breeze, 2014)

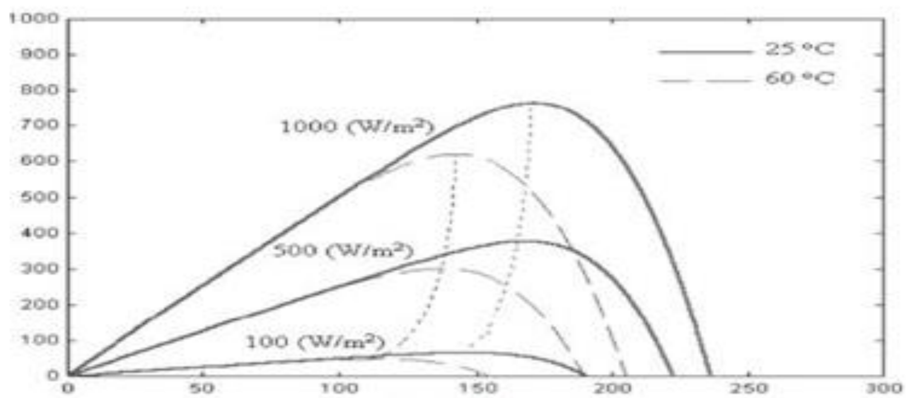

Figure 3.7: P-V characteristic of solar battery according to changing conditions (Green, 1982)

The process of changing the load to monitor the maximum power point is provided by DC-DC converter constructions. In DC-DC converters changing in the duty cycle values provides to have different output load. As a result of the variation of the occupancy rate, the voltage and current values of the solar system battery are measured. Also, the operating power point of solar battery is determined (Underland and Robinson, 2001).

3.5 Solar Battery Systems

Systems utilizing solar energy are examined in two groups. These are called fixed and mobile. A surface that follows the sun compared to a fixed surface receives an average of 43% more energy from sunlight. Solar powered systems that follow the sun are very important in solar energy system and water heating system. Also, it’s important to use this system that producing electricity with solar energy (Breeze, 2014). The applications of the solar cell system can be divided into two main groups;

- Grid connected solar systems
- Off grid solar cell systems

3.5.1 Grid connected solar battery systems

The first type system, basically needed electricity of residential unit can be met. The produced excess energy is sold to the electrical network. In case of the sufficient energy is not produced, the energy is purchased from the network. There is no need to store energy in such a system. Only required thing is that should be converted to AC and it’s compatible with network. The second type of grid-connected solar cell systems are large power generating centers that generate electricity by itself and sell it to the grid. The size of these varies from 600-700 kW to MW. The generated energy from these systems is relatively cheap because it removes storage costs (Kjaer, 2005).

3.5.2 Off grid solar battery systems

In these systems, a sufficient number of solar cell modules are used as the energy source. The battery is kept in the system for the time when sun is inadequate or for use especially during night. The solar cell modules generate electricity during a day and store it in the battery. The energy required for load is taken from the battery. In the applications where required compatible alternating current by adding inverter, the dc voltage in the battery is converted to 240V, 50Hz sinusoidal waves. In addition, various support electronic circuits can be added to the system according to the embodiment of the application (Ghafoor and Munir,2005).

3.6 The Advantages of Solar Energy

The world's largest energy source is the sun. Solar energy systems are a type of energy that is not consumed, which does not give harmful gases to the environment. The use of solar energy offers great advantages as it is an energy source that does not damage the environment. Also, it is uninhabitable and very cheap (Breeze, 2014). If we want to sort out the advantages of solar energy:

- First of all, the sun is a source of abundant and boundless energy.
- It is a clean energy type. It does not contain pollutants like smoke, gas, carbon monoxide, sulfur and radiation.
- Solar energy is suitable for local applications. Wherever energy is needed, it is possible to take advantage of solar energy almost everywhere. A lamp, a clock, a calculator or a lighthouse, a forest watchtower can be met at the energy needs of the place.
- It is far from economic depression because it is not dependent on outsiders.
- For many applications, no complicated technology is required. Operating costs are very low.

3.7 The Disadvantages of Solar Energy

In addition to its many advantages, there are some limitations due to usage of solar. These limitations are listed:

- If there is little solar radiation from the unit surface, a large surface is needed.
- Since solar radiation is not continuous, it requires storage. Storage possibilities are limited.
- In the winter months needed energy demand is more and the sun radiation is low.
- The system that makes use of solar radiation should not be overshadowed in order to keep the sun's light continuously (Huang et al., 2001).

3.8 Solar System Configurations

Photovoltaic strings provide DC tension and current in power application practices. Frequently, DC -DC converters can be used for stepping up low tension produced from solar panels.

Also, inverter can be used for utilized to transform up rating dc tension to AC tension to provide standard load. The photovoltaic string structure has an impact of power system modelling. In respect to what structures to select, mostly it based on residential ambience and price income. There are four main PV system structure. Two stage string inverter that is one of the system structure will explained following title (Rashid,2017).

3.8.1 Two stage string inverter

A two-level sequence inverter structure illustrates in Figure 3.8. This structure is well liked because of it has developed power ability, flexible modelling and modularity. All PV arrays involves low PV panels that enhance system durableness. The preliminary part is for amplifying less DC tension produced from PV strings to more DC level. The next step checks the energy transformation from DC to AC (Ghafoor and Munir, 2015).

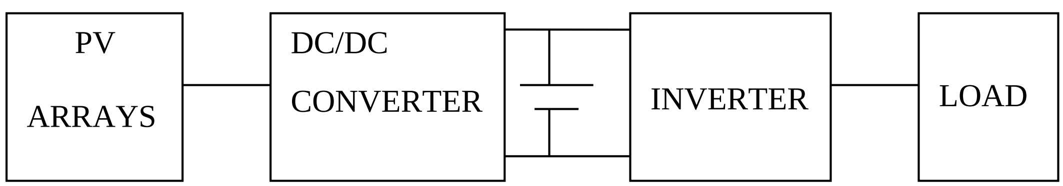

Figure 3.8: Configuration of two stage string inverter (Quaschning, 2006)

3.9 DC-DC Converters

DC-DC converters which find more applications in the days ahead continue to take a wide place in academic and practical work. A high efficiency is required with a uniform and regulated DC output voltage, which can be basically set within a wide range of these converters.

Also, DC-DC converters known as DC transformers, could be divided into two main groups. These are switched DC-DC converters and resonant DC-DC converters.

However, when it comes to DC-DC converters, it means more switched converters. In this case, resonant transformers can be regarded as a special (Underland and Robinson, 2001).

3.9.1 Switched DC-DC converters

Due to the fast switching response and high-power density, this converter industry is widely used. These converters can provide a uniform, regulated DC voltage that can be adjusted over a wide range. The basic DC-DC converters have been achieved by connecting three basic elements in different forms, consisting of a controlled semiconductor power element, a semiconductor power diode and a switching inductor. Controlled power element operated in full conduction or in full circulation in the circuit is called power switch or active element. The diode is a semiconductor passive power element. It is also assumed that the value of the inductance according to the operating frequency is sufficiently large so that the current flowing through the inductor is generally smooth and continuous. The operating principle of switched DC-DC converters is based on the energy transfer of the switched inductor. In these converters, either a power switch or a power diode transmission is in a switching period.

Generally, the energy injected into the inductor while the switch in conduction is transferred to the output when the diode is in conduction. A widely accepted classification of switched DC-DC converters classified in different forms like step up, step down, bidirectional converters ...etc (Rashid, 2017).

3.10 Basic Configuration of Boost Converter

The second type of topology is the most commonly used of switched power supplies. The degrading type consists of an inductor, a capacitor, a diode and a switching element as in inverters. The voltage applied to the input of the converter through the power supply brings the output to a higher voltage level with high efficiency.

Figure 3.9 shows the basic circuit of step up (boost) converter. When the key is passed to transmission, the source voltage completes the cycle through the coil and switch.

At this time, some energy is stored on the coil. Diode is in reverse polarity and supplies the output load to capacitor. The current of the capacitor is high.

When the switch is cut off, a voltage appears at the output as the sum of the source voltage and the voltage on the coil. In these circuits continuous current is drawn from the source.

When the switching element shown in Figure 3.9 is in transmission, the coil is directly connected to the ends of the rectifier source. Thus, output voltage is equal to input voltage. The switching element is in the cut and the diode is connected to the load when the conduction is passed. In this case, the voltage at the ends of the coil is equal subtraction of input and output voltage (Hauke,2009).

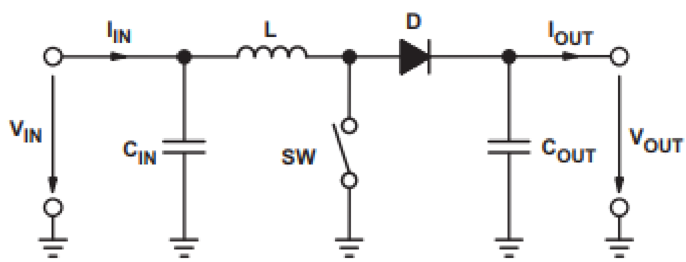

Figure 3.9: Basic boost converter configuration (Hauke,2009)

Required variables of the step up (boost) converter is the following three variables that can be required for determining this system are:

- Output tension Vout
- Maximal output current I out $_{max}$
- Created boost type converter is determining by using integrated power stage. It's essential the reason of a few variables for computing remove from datasheet. Assuming all variables are obtained, the determination of integrated circuit actualized.

Calculation of a maximal switching current is the primary stage for determining the duty cycle to minimal input tension. The minimal input tension is useable through pioneers for the maximal switching current (Rashid, 2017).

$$D = 1 - V_{IN(min)} * \eta / V_{OUT} \tag{3.4}$$

The productivity is considered for D determination, by reason of the converter must release besides power dissipated.

The computing provides more real D value than only equation absent productivity factor. Both a predicted factor, e.g. 70% (that is realistic for step up converter bad situation productivity), could be useable converter' datasheet. Subsequent to compute the maximal switching current is for making observation of ripple current. In DC-DC converter datasheet ordinarily significant inductor either inductor's variety can be called integrated circuits. Therefore, using the advised inductor values for computing ripple current value of inductor in the midst of the advised variety or considering that there is no information comes out, the computed in the inductor sampling (Caceres and Barbi, 1999).

$$\Delta I_L = V_{IN(min)} * D / f_s * L \tag{3.5}$$

At the moment, it must be specified supposing that chosen integrated circuit may release I_{MAXOUT} .

$$I_{MAXOUT} = \left(I_{LIM(min)} - \Delta I_L / 2\right) x (1 - D) \tag{3.6}$$

If the compute value to the $I_{MAXOUT}$for chosen integrated circuit is under the systems needed maximal output current, other integrated circuits via more switching current limitation get used. On condition that, maximal output current's computing value is less than required value, it can be potential to use chosen integrated circuit via more inductance. A superior inductance decreases ripple current, so it causes increment maximal output currents via chosen integrated circuits. Assuming that computing value is more than I_{MAXOUT} from of implementation, maximal switching current can be computed (Breeze, 2014).

$$I_{SW(max)} = \Delta I_L/2 + I_{OUT(max)}/1 - D \quad (3.7)$$

This formula shows peak value of switching current. Exterior diode and switches must resist. For determination of inductor, frequently, datasheet supplies varieties for advised inductor values. In the circumstances, it can be advised for selecting inductor around this ranges. More inductor value is provided by using $I_{MAXOUT}$the reason of decreasing ripple current.

Less values of inductor mean having a less solving size. Keep in mind that Imax is less than current rates in inductor shown in following equation, through changes value of current in inductance, given equation, through changes formula provides well prediction for obtaining true inductor value (Rashid, 2017).

$$L = V_{IN} * (V_{OUT} - V_{IN})/\Delta I_L * f_s * V_{OUT} \quad (3.8)$$

The ΔI_L couldn't be computed from first equation. The reason that inductor didn't recognized. A better prediction for ΔI_L should be around between 20 to 40 percentage.

$$\Delta I_L = (0.2 \text{ to } 0.4) x I_{OUT(max)} x V_{OUT}/V_{IN} \quad (3.9)$$

For selecting rectifier diode, decreasing loss, Schottky type diodes should be used. The advanced current grading required is correspond to I_{MAXOUT}.

$$I_F = I_{OUT(max)} \quad (3.10)$$

Schottky type diode has more maximum current ratings than mean ratings. For this reason, this is not matter for using more maximum current.

$$P_D = I_F x V_F \quad (3.11)$$

Determining value of output capacitor, the good implementation for using less ESR capacitors to minimize the ripple on the ΔI_L. If converters have exterior recompense, value of capacitor over suggested minimal in the datasheets may be used. However, recompense must be arranged for using output capacitance.

Inwardly, recompensed converters, the advised values of capacitor or inductor can be used. Exterior recompense, following formulas may be used to find C_{out} value (Jung et al., 2011).

$$C_{OUT(min)} = I_{OUT(max)} * D/f_s * \Delta V_{OUT} \quad (3.12)$$

The $\Delta V_{OUT(ESR)}$ causes to add farther ripple, explained with this formula.

$$\Delta V_{OUT(ESR)} = ESRx\left(I_{OUT(max)}/1 - D + \Delta I_L/2\right) \quad (3.13)$$

3.11 Battery for Off Grid Systems

Generally, batteries are an important part of the PV system because there is no temporal coherence between solar energy and energy use. With a battery placed between the voltage generating system and the consumer, the changes in solar energy, which are dependent on the meteorological conditions, the day / night differences, the seasons, can be prevented from being reflected to the consumer system. The batteries provide storage of electricity produced by using solar and wind energy. Electricity generated by solar or wind energy is stored in batteries for later use.

Batteries can be connected in series or parallel to reach the desired capacity and this capacity is adjusted to the desired autonomy time. There are many battery types according to different usage needs. The most advantageous batteries in solar and wind energy systems are full maintenance dry type batteries using special electrolytes. These batteries provide excellent performance over long discharges. It is tolerant to high temperature applications. It has a design that protects positive plates, thus prolonging cyclical life. The fact that it has a thicker plate that prevents rusting is also a feature that provides long life. It provides high performance due to low internal resistance. The battery can completely discharge the battery even if it is not fully charged (Hoppmann et al.,2014).

Storing capacity of battery's formula is denoted like;

$$Cwh = E \times (\text{Number of autonomous days})/(V_b \times DOD \times \eta) \quad (3.14)$$

where E is energy consumption, battery voltage is V_b, depth of discharge is DOD and η is the productivity of the battery.

Calculation of the number of batteries is given as

$$\text{Number of battery} = Cwh/Cwh1 \qquad (3.15)$$

where Cwh1 is the capacity of a single battery.

3.12 Single Phase Inverters

DC / AC conversion systems, in other words inverters, are devices that obtain a variable voltage waveform from the direct voltage. Also, this system can adjust the frequency and voltage independently from each other. The waveform and frequency that produced by the inverters depends on used the characteristics of the semiconductor element, the transmission and the insulation times. According to power and frequency as a semiconductor element; BJT, MOSFET, IGBT and fast SCR types can be used.

The output wave of idealized inverters is sinusoidal. However, in practice the waveforms of the inverters are not sinusoidal, so they contain harmonics. For low and medium power applications, square wave or square wave-like voltages are acceptable. For high power applications, sinusoidal waveforms with low distortion are desired. With high speed power semiconductor devices, the harmonic content of the output voltage can be significantly reduced. Inverters can find a wide range of applications in the industry. Examples include AA motor speed control, induction heating, uninterruptible power supplies. Here, the inverter input may be a battery system, PV module or other sources (Bauer, 2010).

Inverters; it is possible to distinguish two grubs as PWM (Pulse Width Modulation) inverters and Resonant inverters for driving signals. This work is based on PWM inverters. In PWM inverters, a reference signal is generated so that the inverter output can be determined. The frequency of the reference signal determines the inverter output frequency and the voltage peak value specifies the effective output voltage value. The number of pulses in per half cycle depends on the carrier frequency (usually triangle wave).

In these inverters the DC input voltage is fixed. The inverter controls the value and frequency of the AC output voltage (Hinga, 1994).

The method shown in Figure 3.10 is used in order to determine the synchronization moments of the semiconductor switching elements in PWM inverter and to provide synchronism.

A sinus reference signal, frequency and amplitude, that will determine the voltage and frequency of the inverter output is compared to a sinusoidally larger triangular wave. The overlap points of these two marks determine the timing of the triggering of the switching elements.

A pulse is initiated at the intersection of the sine wave with the negative slope of the triangular wave. The pulse is stopped at the intersection of the sine wave with the positive slope of the triangular wave. Throughout the entire pulse, the pulse duration varies approximately sinusoidally.

The amplitude of the reference sinusoid is reduced or raised to reduce or amplify the inverter output voltage. Changing the frequency is achieved by changing the frequency of the sinus sign (Akhter and Hoque, 2008).

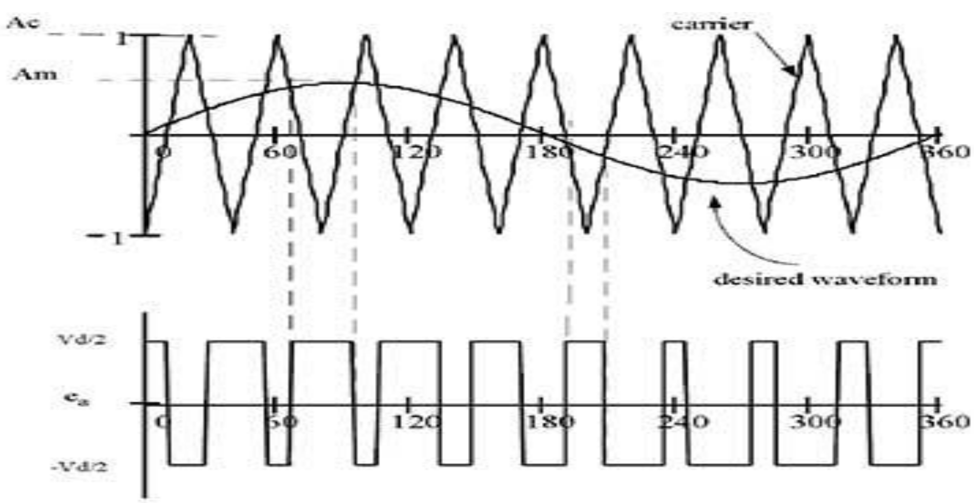

Figure 3.10: PWM inverter waveforms (Kjaer et al., 2005)

The shunt technique is used to control the inverter's variable voltage output. The square or step wave output voltages are repeated several times in each half-cycle, so that several pulses of equal amplitude are obtained. The amplitude of each pulse equals the amplitude of the input voltage of the inverter. Figure 3.11 shows the basic shape of PWM waves.

Pulse width T1 and zero duration T2 do not change over half a period. The amplitude of the output voltage can be controlled by changing the total duration of the transmission over the half period. This is achieved by keeping the pulse width constant and changing the pulse number or by changing the pulse width without changing the pulse number. As a result, inverter output voltage, switching is obtained by changing the rate at which the elements are in the conduction state. It is possible to study PWM inverters in two groups, half and full bridge. These two types of inverters are discussed below (Akhter and Hoque, 2008).

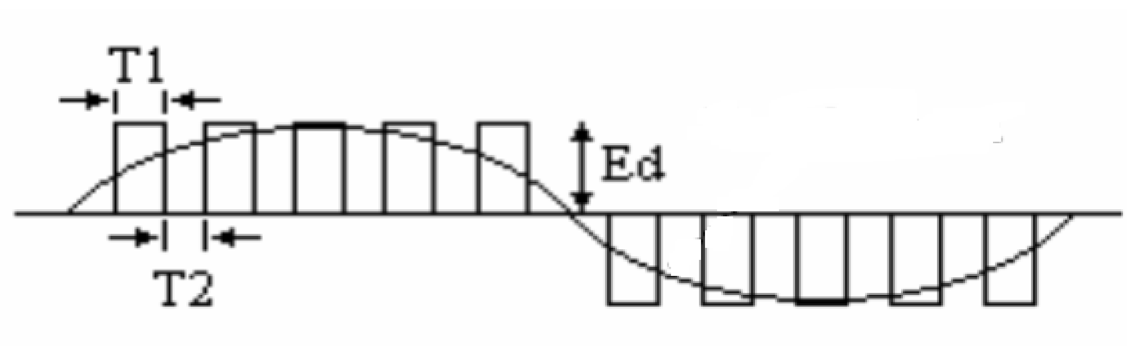

Figure 3.11: The basic shape of PWM waves (Akhter and Hoque, 2008)

3.12.1 Half bridge inverter

Each of them forms the neutral output of two capacitor inverters with a constant voltage value (Vi / 2). The C + and C- capacitors must be chosen at a high value in order for the harmonics to occur during operation of the inverter to be low-grade. As can be understood from the structure of the inverter, only one of the S + and S- switches in each switching period must be in the transmission state. According to this, in the inverter, there are 3 different switching states, 2 in which each switch is in separate transmission and the case in which both are in cut-off.

The uncertainty is that the switching element is selected by the carrier pulse width modulation technique to prevent shorting of the supply line in the third switching stage (Qin et al., 2002).

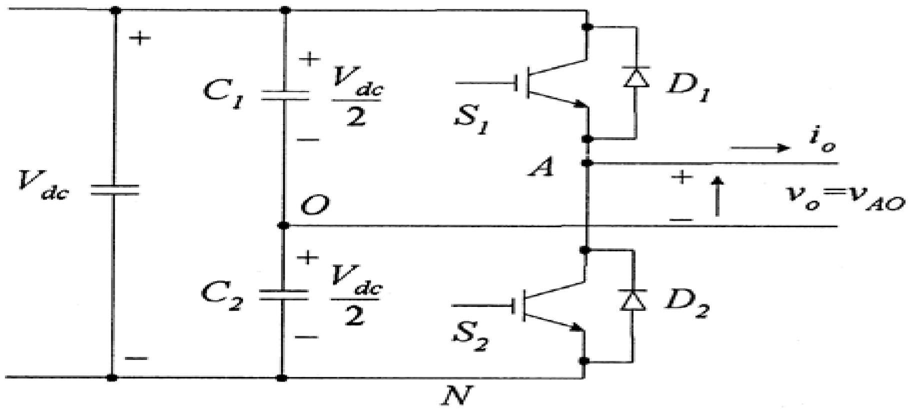

Figure 3.12: Single phase half wave bridge inverter (Qin et al., 2002)

3.12.2 Full wave bridge inverter

Full-wave bridge inverter is formed by two separate half-wave inverters. Half bridge topology is the basic topology used to generate two levels of output voltage. In this topology, it is necessary to have a mid-point voltage source. On the other hand, full-bridge topology is used to generate two-level and three-level output waveforms. The second switching line of the inverter determines the neutral point for the load. In this topology, also referred to as the H bridge, there are 5 states, 4 distinct and one indeterminate, to generate the output voltage.

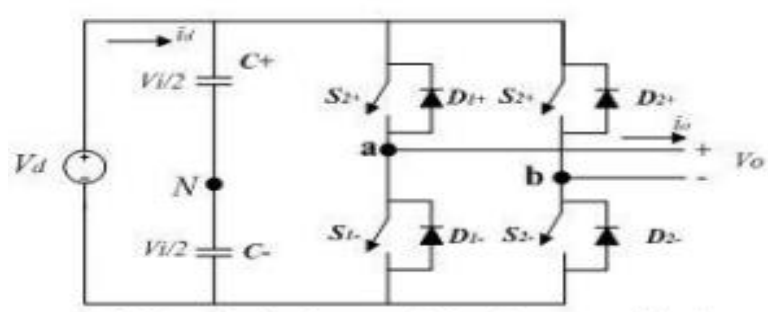

Figure 3.13: Single phase full wave bridge inverter (Bratt, 2011)

The indefinite state occurs at the time when all the switches are in the cut. Also, it is unpredictable which of the -V or + V potentials of the output voltage (Bratt, 2011).

3.13 Design of Off Grid System

3.13.1 PV module selection

According to refence home, daily requirement energy for single home is calculated. Table 3.1 shows the devices their power rate, working hours and daily energy requirement.

Table 3.1: Reference home daily required energy observation

Load Specification and Type	Qty	Power (W)	Working Hours	Total Daily Energy (Wh)
10 W energy saving light bulbs for around 6 hours a day	10	10	6	600
Refrigerator A+ for 24 hours	1	100	24	2400
TV for around 6 hours	1	70	6	420
Washes/Dishes Machine/Water pump	1	1200	2	3000
Computers for around 6 hours	1	75	6	450
Printer for around 2 hours	0	0	2	0
Microwave (800w) for around 1 hour	0	0	1	0
Air conditioner (1.5HP) (Optional)	1	1200	1	1200
Mobile Phone Charge	1	5	12	60
Fan (90 W) for 6 hours	0	0	0	0
Satellite Receiver (25 W)	1	25	6	150
DVD (25 W)	0	0	0	0
Electric kettle, Iron, Coffee Machine, Drill	1	1000	1	1000
Total		**3660**		**9280**

One PV cell is not powerful sufficient to produce complete size of system.

In various types which can be presented in books and articles, the parallel and serial joins of the cells or modules are connected among each other. Series connection raises cells or modules tension; in spite of that, the parallel combinations raise the current.

The array which is designed our system comprise of 12 strings of 3 series combination cells connected in parallel. The main variables are defined such as open circuit voltage, maximal system voltages and power rating.

The reference solar PV module is selected the model of SunPower SPR305 WHT-U, and the module characteristics are presented in Table 3.2.

Table 3.2: Reference PV module characteristics

DC Electrical Characteristics	
STC Power Rating	305W
PTC Power Rating	280.6W [1]
STC Power per unit of area	187.0W/m^2
Peak Efficiency	18.7 %
Power Tolerances	-5%/+5%
Number of Cells	96
Imp	5.58A
Vmp	54.7V
Isc	5.96A
Voc	64.2V
NOCT	45°C
Temp. Coefficient of Power	-0.38%/K
Temp. Coefficient of Voltage	-0,177V/K
Series Fuse Rating	15A
Maximum System Voltage	600V

Maximal tension, maximum current and STC power rating at standard test conditions which at temperature around 25 ° C and sun irradiance almost 1000W/m^2 are 54.7 V, 5.58 A and 305 Wp respectively. Finally, the maximum system voltage, that is variable for the serial combination of the PV cells is 600V.Determination of PV array output voltage, currents.

$$PV_{out} = 3 * 4 * 305$$

$$PV_{out} = 3.66 \text{ kW}$$

PV array mean voltage =164 V as expected from PV module specifications

$$PV_{avg,voltage} = N_{ser} * V_{mp} \tag{3.16}$$

$$PV_{avg,voltage} = 164 \text{ V}$$

PV array output current,

$$PV_{avg,current} = N_{paralel} * I_{mp} \tag{3.17}$$

$$PV_{avg,current} = 4 * 5.58$$

$$PV_{avg,current} = 22.32 \text{ A}$$

3.13.2 Boost converter calculation

Following equations helps to compute duty cycle.

$$D = 1 - V_i/V_{out} \tag{3.18}$$

$$D = 1 - 165/425$$

$$D = 0.61$$

$$T_{switching} = 1/f_{switching} \tag{3.19}$$

$$T_{switching} = 1/20x10^3$$

$$T_{switching} = 0.5 \text{ µs}$$

$$T_{on} = T_{switching} \times D \tag{3.20}$$

$$T_{on} = 0.5 \times 0.61$$

$$T_{on} = 31 \text{ µs}$$

$$T_{off} = T_{switching} \times (1 - D) \tag{3.21}$$

$$T_{off} = 0.5 \times (1 - 0.61)$$

$$T_{off} = 20\ \mu s$$

$$I_{Lavrg} = P_{out}/V_{in} \qquad (3.22)$$

$$I_{Lavrg} = 3660/165$$

$$I_{Lavrg} = 22.18\ A$$

$$\Delta_{iL} = 0.3 I_{Lavrg} \qquad (3.23)$$

$$\Delta_{iL} = 0.3 \times 22.18$$

$$\Delta_{iL} = 6.65\ A$$

Inductance selection,

$$V_{in} = L(d_i/d_t) \qquad (3.24)$$

$$L = V_{in}(d/\Delta_{iL}) \qquad (3.25)$$

$$L = V_{in}(T_{on}/\Delta_{iL}) \qquad (3.26)$$

$$L = 165\ (31 \times 10^{-6}/6.65)$$

$$L = 769\ \mu H$$

Capacitor selection,

$$C = I_{out}(T_{on}/\Delta V_{out}) \qquad (3.27)$$

$$\Delta V_{out} = 0.001\ V_{out} \qquad (3.28)$$

$$\Delta V_{out} = 0.001 \times 425$$

$$\Delta V_{out} = 425\ mV$$

$$I_{out} = P_{out}/V_{out} \tag{3.29}$$

$$I_{out} = 3660/425$$

$$I_{out} = 8.61\ \text{A}$$

$$C = 8.61\ (31\text{x}10^{-6}/425\text{x}10^{-3})$$

$$C = 628\ \mu\text{F}$$

3.13.3 About full bridge PWM inverter

Output of inverter is 340V_{rms}, and frequency is 50Hz. For computing input voltage of full bridge inverter, modulation index for PWM inverter is taken 0.8.

$$V_i = 340/0.8$$

$$V_i = 425V$$

3.13.4 Battery selection for off grid system

$$C_{wh} = E \times (\text{Number of autonomous days})/V_b \times DOD \times \eta \tag{3.30}$$

$$C_{wh} = 9700 \times 2/(425 \times 0.6 \times 0{,}85)$$

$$C_{wh} = 95Ah$$

CHAPTER 4
HARMONIC FILTERS

4.1 Output Filters for Voltage Source Inverters

In the output of voltage source inverters passive filters are used in different structures consisting of inductance (L) and capacitor (C) depending on the application area. These filters filter the voltage generated by the inverter to reduce the harmonic content [24]. The waveforms to be filtered may include low frequency, switching frequency, and high frequency harmonics. Each harmonic must be reduced adequately and appropriately. This filtering operation is performed with the aid of L, LC and LCL filters resulting from the use of L and C elements (Akagi,2005).

4.1.1 L type filter

L filter is widely used to filter the current at the inverter output. The reason is that the L filter can be controlled quite easily in the inverter. The L filter must have a high value to suppress the harmonics due to the attenuation gain of L filter is low. The voltage drop across the high value inductance increases the dynamic response time. If a normal valued L filter is used at the inverter output, the switching frequency of the inverter must be high, so that the harmonics can be suppressed as much as possible. The L filter has attenuation around 20dB/decade, so implementation of this kinds of filters are available with using more Fsw. Inductance provides to reduce dynamics of all practices (El-Habrouk et al.,2000).

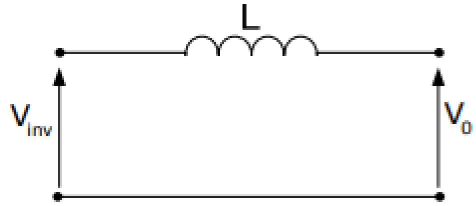

Figure 4.1: The basic configuration of L type filter (El-Habrouk et al.,2000)

4.1.2 LC filter

LC filters are called 2nd order filter. LC filters have good damping behaviors compared with first order filters. Basic structure of LC filter helps to model easily, also free of problems.LC filter's attenuation ensures around 12 decibels per octave. Since the L filter exhibits a low damping effect on the harmonic components of the switching frequency of the inverter, a parallel connected capacitor is used to increase this effect. Thus, the filter has a low impedance value against the switching frequency components. Figure 4.2 shows the resultant LC filter connected to the filter inductance parallel to the capacitor (Phipps, 1997).

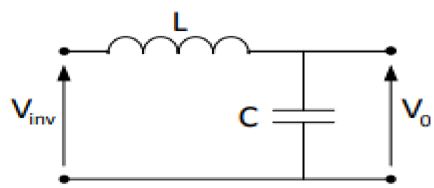

Figure 4.2: Structure of LC type filter (Phipps, 1997)

The main application area of this filter is executions where the output control variable is the voltage and the passive load or parallel AC source at the output. With LC filter, it is possible to reduce the losses and cost by keeping the capacitor value high and the inductance value low. However, the use of very high-value capacitors is avoided for reasons such as resonance problems and the formation of high reactive power in the fundamental frequency (Kim et al., 2000).

$$F(s) = 1/1 + sL_F + s^2 L_F C_F \qquad (4.1)$$

Self modelled of LC filter comes to agreement among inductance and capacitance values. Having a higher capacitance provides favorable effects on tension standards. Nevertheless, more values of filter's inductance can be necessary for succeeding requested filter cut off frequency. Connection of system via that type of filters for providing network, LC filter's Fres will consist of network impedance, so LC filter isn't available (Dahono et al.,2001).

4.1.3 LCL Filter

The LCL filter is a type of filter that has been widely used recently in voltage source inverters. The harmonic content will be reduced in the same way. The inductance value of the LCL filter is lower than the L filter inductance value. This feature makes filtration advantageous in terms of cost and dynamic response. In the LCL filter, since the high-frequency harmonics are filtered by the LC filter on the inverter side, the amount of fluctuation of the current on the output inductance on the load side is small. Thus, the output inductance can be kept low. At the same filter inductance value, the harmonic content obtained when using L filter with the lower switching frequency in the inverter using LCL filter is the same. This feature of the LCL filter increases even more when the use of low switching frequency is particularly important in large power systems where lower frequency and inductance can be used compared to the L filter for harmonic filtering in the same amount make this filter preferred in high power and low frequency applications. In addition to these advantageous features, there are also some problems caused by LCL filtration in the control of the system. Filter design is important because of factors such as resonance state, current ripple on inductances, total impedance of filter, suppression of current harmonics at switching frequency and reactive power generated by capacitor. Increasing the values of the inductances used in the filter leads to the increase of the tensions on the inductances (Liserre et al., 2005).

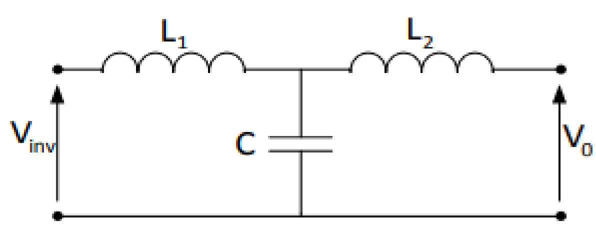

Figure 4.3: LCL filter (Liserre et al., 2005)

In this case, the DC bus voltage must be increased, which leads to an increase in switching losses. Since the capacitor value increases the reactive power factor, a capacitor should be chosen to keep it below the 5% reactive power limit.

The high capacitor value causes more reactive power to pass more current than the inductance and switches and reduce the system efficiency. The inductance value should be increased when the capacitor value is reduced. This increases the voltage on the inductance. In order to avoid the resonance problem that may occur in the filter, the resonance frequency range must be between 10 times the network frequency and half the switching frequency. Active and passive resonance damping methods are used to eliminate the resonance problem of the LCL filter. Because of the simplicity of application, passive damping method is used in industrial applications. Resonance is inhibited by an appropriately chosen resistance. However, an additional loss of resistance occurs and this method has a negative effect on the efficiency of the systems. Besides passive damping, there are active damping methods which are realized by changes made in the control algorithm but the control structure becomes more complicated. In order to ensure system stability in the LCL filter, only different inductances such as capacitor current, voltage, inverter, and load side inductance current must be added to the control loop as well as the inductance current. The control structure is therefore complicated (Beres et al., 2016).

4.2 Modelling of LCL filters

Test and prediction approachment for LCL filters via damping resistance shown at Figure 4.4. The simplification formulas for guessing variables of filter have laid down as condition in literatures. Similar approximation can be used for adjusting resistances, inductances and capacitance values. The basic purpose of LCL filters is for decreasing harmonics at output side, but in sufficient modelling can be reason raise of distortion. For this reason, LCL filter should be modelled properly and acceptably (Jalili and Bernet, 2009).

Whole parasitic resistors such as damping, grid and inverter side resistors can be ignored for present bad situation damping productivity of system. Network side current checked at below.

$$i_g(s)/v_i(s) = 1/s^3 L_i L_g C + s(L_i + L_g) \quad (4.2)$$

$$f_{res} = 1/2\pi\, x \sqrt{L_i + L_g/L_i L_g C_f} \quad (4.3)$$

Both using active or passive method to guarantee available process for voltage source inverters, it required to use resonant peak frequency. The reason that, LCL filter should have sufficient in switching frequency. Resonance frequency should be more than 10 times grid frequency and less than half of selected switching frequency (Pena-Alzola et al.,2013). Insertion of damping resistor remodels transfer function:

$$i_g(s)/v_i(s) = sR_dC + 1/s^3 L_i L_g C + s^2(L_i + L_g)R_dC + s(L_i + L_g) \quad (4.4)$$

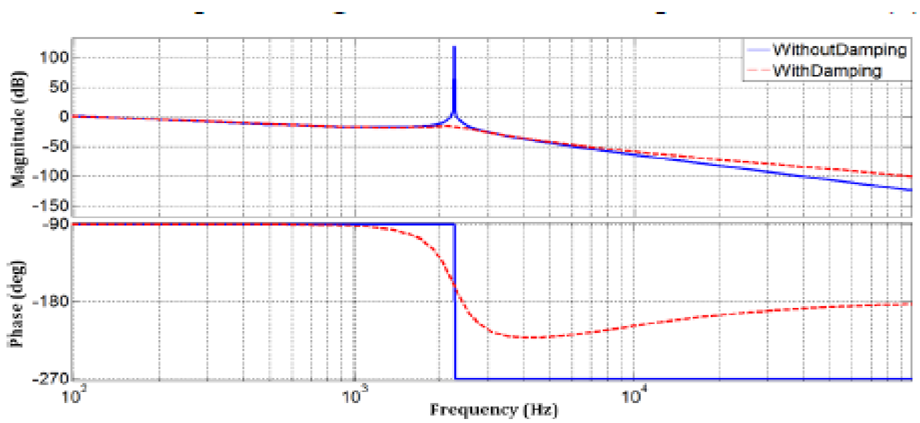

Figure 4.4: Bode diagram for LCL filters with and without damping (Pena-Alzola et al.,2013)

Therefore, filter parameters can be dedicated to based values percentage.

$$Z_b = U_n^2/S_n \quad (4.5)$$

$$C_b = 1/w_n x Z_b \quad (4.6)$$

The primary stage for computing LCL filter parameters is modelling of inverter side inductors that may restrict the Δ_{L-max} till maximum 10 percentage for nominal amplitude. This could be computed by following the formula:

$$L_i = U_{DC}/16 f_s x \Delta_{L-max} \quad (4.7)$$

Where is the 10 percentage of current ripple determined from Δ_{L-max}

$$\Delta_{L-max} = 0.01(P_n\sqrt{2}/U_n) \quad (4.8)$$

Modelling of capacitance of filter advances through maximum power factors variety admissible with network is 5%. For this reason, capacitance of filter could be computed like multiplying base capacitance.

$$C_f = 0.05C_b \quad (4.9)$$

The network side Lg value may compute like:

$$L_g = rxL_i \quad (4.10)$$

For decreasing oscillating and nonstable situation of LCL filter, damping resistor can be incorporated into the circuit with series between capacitance. Addition of resistance can call passive damping. It’s easy and confidential method. However, it causes increment in temperature lost and reduces productivity (Tang et al., 2016). Equation for damping resistor is shown at below.

$$R_{sd} = 1/w_{res}C_f \quad (4.11)$$

4.3. Optimal Modelling for LCL Filter

Comparison of L type filters, LCL filters are upward available to implementation of high energy and less switching frequency because of their good properties at high frequency. But, determining variables for LCL filter are complicated. Taking into the consideration expanding computation for less power energy resources and prices about filters along with power loss should be considered while model phase. Present model procedures of inverter output filters are unexciting for usages. That’s why nowadays optimization topics become popular in power system. Optimization ways for identifying active and passive damping are for resolving the system stability issue about resonance frequency (Langella et al., 2014).

Active damping modality depends upon identifying current of capacitance response that may efficaciously check current resonances out of variation LCL filter’s resonance frequency.

Passive damping method is based on addition to system damping resistance and changes in inductor value with changing the resonance frequency.

Passive damping method is selected to the system. Also, system is designed according to IEEE519 std for harmonic limitation (Duffey and Stratford, 1989).

4.3.1 Modelling stages of optimal LCL filter

Following steps need to be followed to model the optimal filter defined in this chapter:

1. Start with system parameters: the rated power P_r, dc link voltage V_{dc}, rated grid frequency f_g and switching frequency f_{sw}
2. Choose the damping methods (active via passive damping)
3. Adjust the ratio μ=1 ($\mu=L_i/L_g$)
4. Adjust the limitation on the reactive power compensation by the filter
5. Set the harmonic attenuations limits based on IEEE-519 std.
6. Determine the desired total inductance
7. Determine optimal capacitance
8. Determine the resonance frequency of the modelled LCL filter and apply condition $10f_g < f_{res} < 0.5f_{sw}$
9. Control the results

First step is about based system variables. According to the system power, network tension, dc link tension, network frequency and selected switching frequency should be stated. Next step is about choosing optimization method by the purpose of damping resonance peak value of LCL filters. Optimization methods are active via passive damping (Beres et al., 2016).

The rates among inductances that represented with μ should adjust 1. μ is the symbol of division about network side and grid side inductances. This rates that is Lg/Li influence whole LCL filter system attenuation. Additionally, this signified rate influences the differentness for resonance frequency by the time network inductance diversifies. Modified resonance frequency is shown following equation (Langella et al., 2014).

$$L_TC = (1+\mu)^2/4\pi^2 fres^2\mu \quad (4.12)$$

Taking the derivative accord to μ=0 provides L_tC is minimal with putting μ=1 and stable resonance frequency. That mean, if μ=1 is chosen, passive components have minimum capacity. It doesn't matter any value chosen for capacitor. Just adjusting μ=1 provides minimal total inductance(L_T). Minimal total inductance specifies having minimal tension decline, more dynamic reply and minimum power compensation. Additionally, equality between grid side and inverter side inductor can ensures economic advantages.

For passive damping method, per unit obtainment is regarded for consideration to generalize this model for large variety level.

Keep in mind that mostly inverter filter modelling in energy system, impedances can be taken in per unit (Channegowda and John., 2010). Now, initial formula becomes,

$$l_Tc = (1+\mu)^2 fbase^2/fres^2\mu \quad (4.13)$$

Low case letters for capacitance represent per unit value or parameters. Following equations help to determine this system.

$$l_T = 2\pi f_{base} L_T/Z_{base} \quad (4.14)$$

$$c = 2\pi f_{base} C Z_{base} \quad (4.15)$$

$$Z_{base} = V^2/P_{base} \quad (4.16)$$

$$P_{base} = P_{rated} \quad (4.17)$$

$$f_{base} = f_{grid} \quad (4.18)$$

l_TC is related to resonance frequency and ratio of inductance. In pursuant of IEEE519 std, this method is more feasible to notice LCL filter minimal passive parameters capacity.

Adjusting limitation at reactive power compensation from LCL filters. Lower case letter *q* represents per unit reactive power for inverters may conclude by,

$$q \approx l_T - c \quad (4.19)$$

Preventing increment ratio of full bridge inverter can be dropped at power factors because of reactive power. In theory filter reactive parameter must be zero, however in practice this assumption is not possible. Reactive parameters should outcome of high value of inductance that can abolish first profit bidden from less inductance filters when contrast via L type filters. To prevent minimal limitation in reactive power absent of overdrawing inverter inductance value should keep it lower and capacitance's value should be less.

Modelling method will compute primary restrict reactive inductance and capacitance. Minimum limitation can be provided by selecting q minimal value (Beres et al., 2016).

$$q_{min} = l_{t(max)} - c_{min} \quad (4.20)$$

$$(l_{T_{max}} - c_{min})l_{T_{max}} = (1 + \mu)^2 fbase^2 / fres^2 \mu \quad (4.21)$$

$$(l_{Tmax}^2 - q_{min})l_{Tmax} - k^2 \ [(1 + \mu)^2 fbase^2 / fsw^2 \mu] = 0 \quad (4.22)$$

k is equal fsw/fres which is the rate among switching and resonance frequency.

Calculate preferred value of total inductance. Calculate optimal capacitance value for filter (Park et al., 2015).

Compute modelled LCL filter's resonance frequency according to prevalent constraint. The condition is $10f$grid $< f$res $< 0.5f$sw. In order to avoid the resonance problem that may occur in the filter, the resonance frequency range must be between 10 times the network frequency and half the switching frequency (Tang et al., 2016).

4.3.2 Design sample for our system

Design codes are shown at Appendix part. The obtained results are explained next chapter. Inverter variables noted according to this model are itemized in Table 4.1.

Table 4.1: Optimal design parameters

Parameter	Value
Rated power (P_r)	4 kW
DC link voltage (V_{dc})	425 V
Grid voltage (V_{grms})	240 V
Grid frequency (f_g)	50 Hz
Switching frequency (f_{sw})	20 kHz

Passive damping method is chosed because of simplification for controllers execution.μ is adjusted 1. Benefits are explained above. According to IEEE519 std, limitation of reactive power compensation is taken 0.003. IEEE519 std limitations are listed in Table 4.2.

Table 4.2: IEEE519 standards and literature

Parameter	Value
μ (Li/Lg)	1
Minimum reactive power q_{min}	< 0.005 p.u.
$i_{g(pu)}$	0.003 p.u.
Total harmonic distortion (THD)	<5%

It shouldn't be forgotten that minimizing inductances are preferable topic because of reducing capacity. For our system minimal inductance (L_T=3mH) is calculated. Optimal capacitance values which suits to minimal total inductance is (C= 6.63μF).

Resonance frequency is chosen 2.3 kHz. Every system design has its own best crossover frequency after that frequency system start moving towards instability. That is why always frequency should be chosen in that range to remain its poles and zeros in stable area (0.5 kHz<f_{res}<10 kHz). All obtained outcomes of the chosen variables will be illustrated and defined in coming chapter.

CHAPTER 5
TEST AND SIMULATION OF THE DESIGNED SYSTEM

5.1 Design and Configuration of the Off Grid System in Matlab Simulink

All explained design of recommended single phase off grid PV power transformation system with LCL filter is performed in MATLAB Simulink software as illustrated in Figure 5.1.

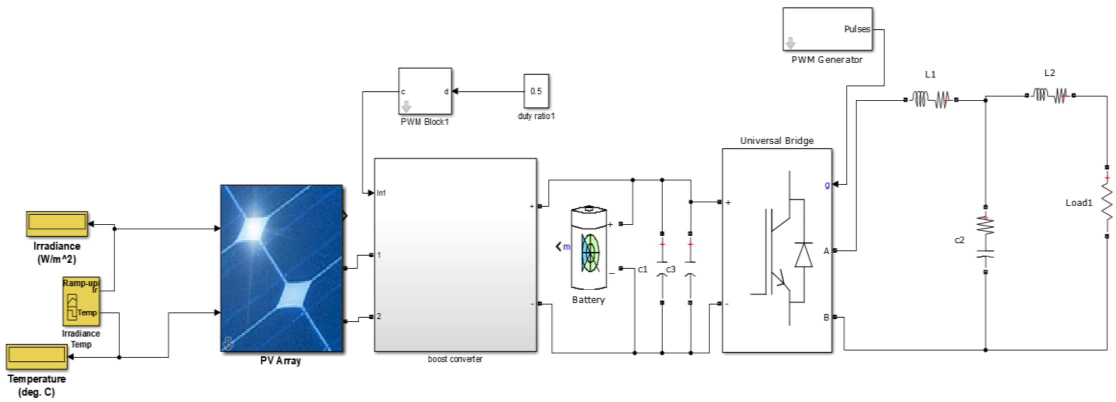

Figure 5.1: Configuration of the Off-Grid PV based power generation with using LCL filter

Figure 5.2 illustrates the output tension of PV as a 165V DC voltage for our system. The solar panel with 54.7V which is designed our system comprise of 12 strings of 3 series combination cells connected in parallel for 4kW system.

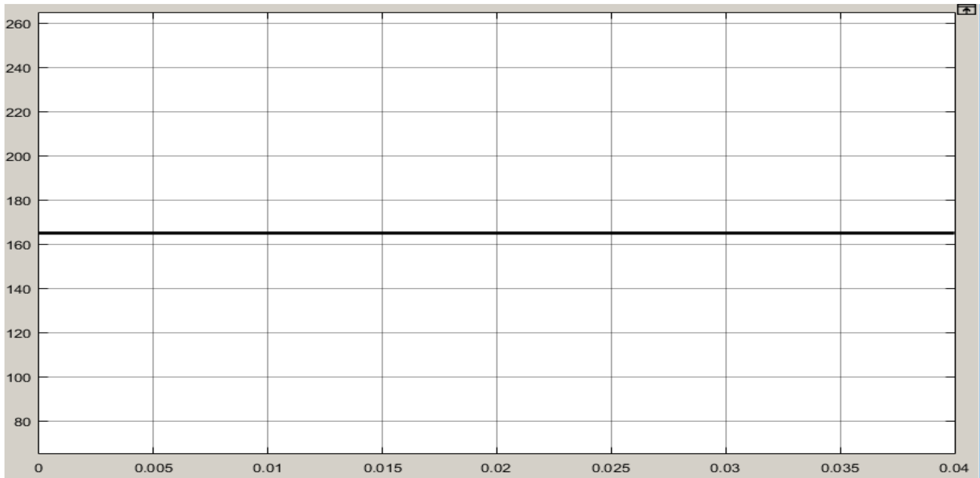

Figure 5.2: Output voltage of PV array

In design model, the purpose of using DC-DC boost type converter is to step up tension along battery changing. Boost converter increases the tension of PV arrays to covetable voltage for 425V. Figure 5.3 depicts the voltage which extracted from the output tension of PV system.

Figure 5.3: Boost converter output voltage waveform

Figure 5.4 depicts output tension of inverter before applying LCL filters in square curve. Hereby, tension of DC-DC converter 425V attached for inverter change to AC voltage.

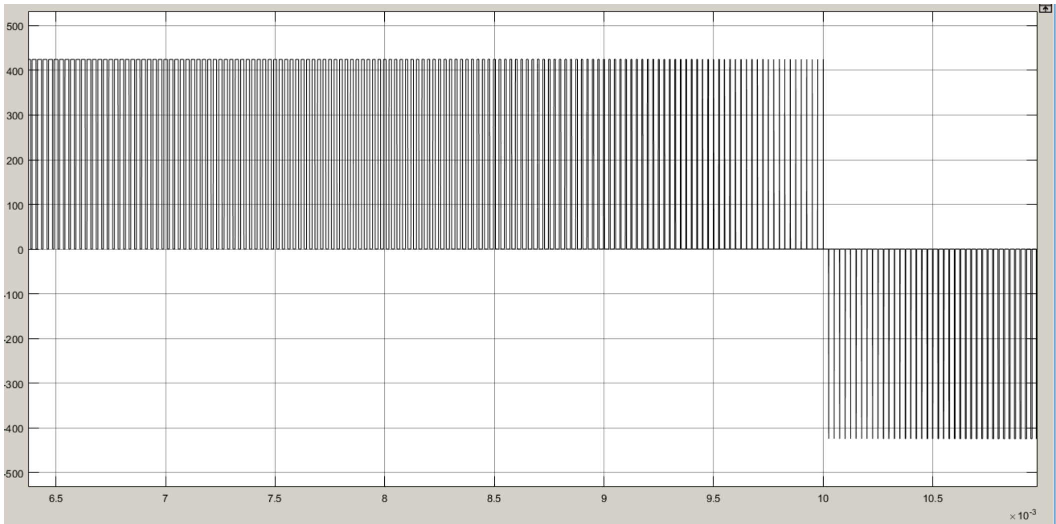

Figure 5.4: Single phase full bridge PWM inverter output voltage waveform

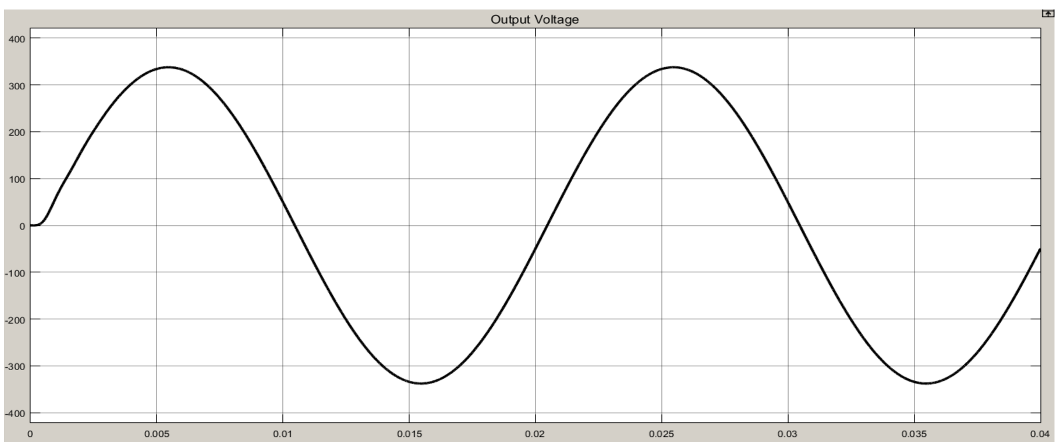

Figure 5.5: Output voltage configuration of system with LCL filter

5.2 LCL Filter without Optimization Method

At low and medium frequency interval, LCL filter's dynamic behavior alike other type of L filters. There is resonance peak at high frequency that can deflect network current critically. Many specialties should be noted in modelling LCL filter, like filter capacity, current ripple factors and reactive power requirements.

The necessity of reactive powers can be reason capacitor resonance interacting via network. Other reason can be that good switching frequency can be obtained with attenuation -60dB/decade. However, network side impedances echoed back to inverter side is mostly too low. Therefore, if resonance is exciting, oscillating may go on and it causes the system very weak. Impacts of resonance may be reason of nonstable current or tension around resonant frequency. In LCL filter bode diagram there is a peak around resonance frequency and phase frequency graph across 180^0degree. In consequence, the system is more vulnerable to disturbances and instability should be considered structure of efficient damping methods.

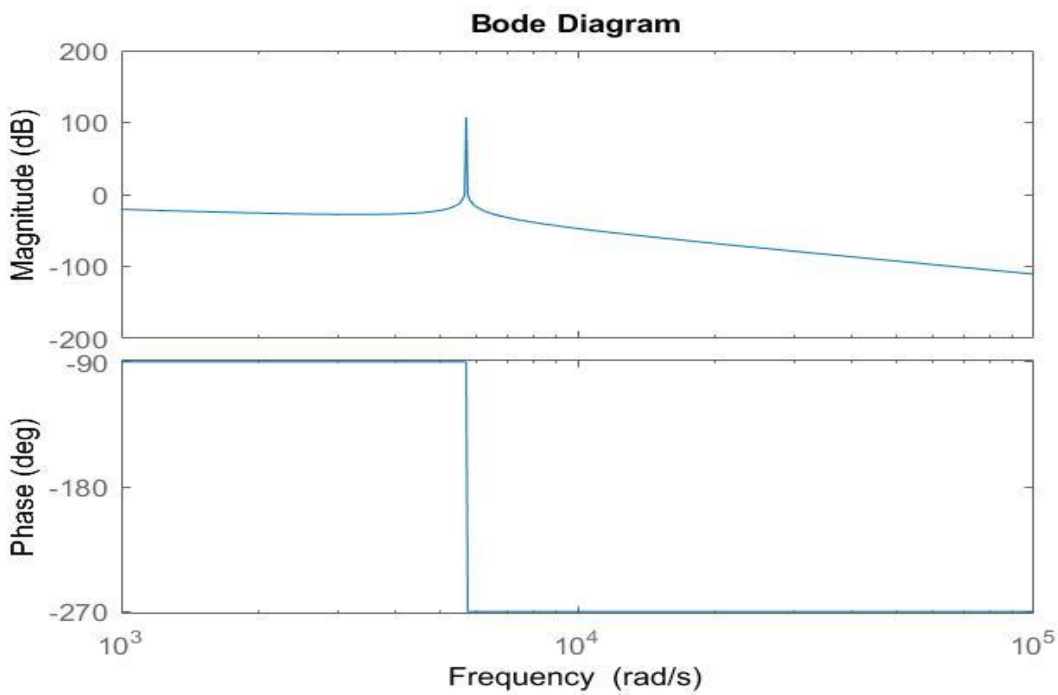

Figure 5.6: Bode plot of LCL filter without damping

Without optimization system codes and outcomes are in Appendix part. Table 5.1 shows obtained values of LCL filter design.

Table 5.1: LCL filter without optimization calculated parameters

Parameter	Value
Grid side inductance (L_g)	3.3 mH
Inverter side inductance (L_i)	5.6 mH
Inverter side, grid side and damping resistor (R_i, R_g, R_d)	0
Capacitance (C)	11μF
Resonance Frequency (f_{res})	4.132 kHz
Base impedance (Z_b)	14.4
Base capacitance (C_b)	0.22 μF
Maximum current ripple (Δ_{L-max})	235.7 mA
Ratio k (f_{sw}/f_{res})	4.63
Total harmonic distortion (THD)	2.2%

Following graphs which are Figure 5.7 and 5.8 are system output voltage and output current with LCL filter before optimization.

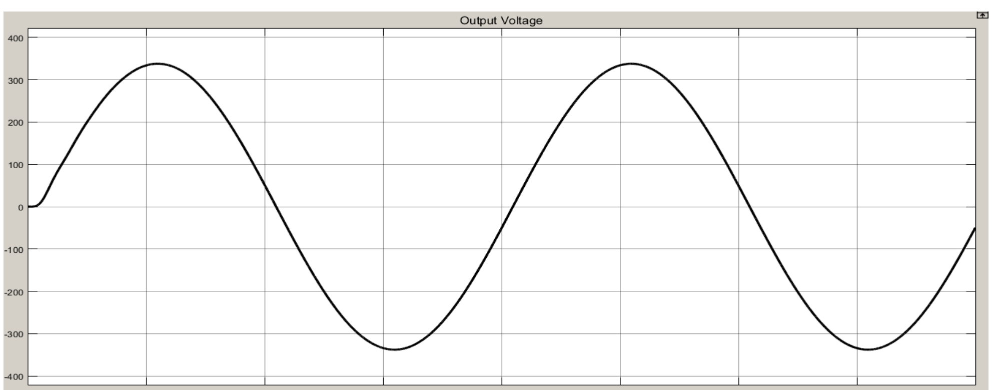

Figure 5.7: System output voltage with LCL filter before optimization

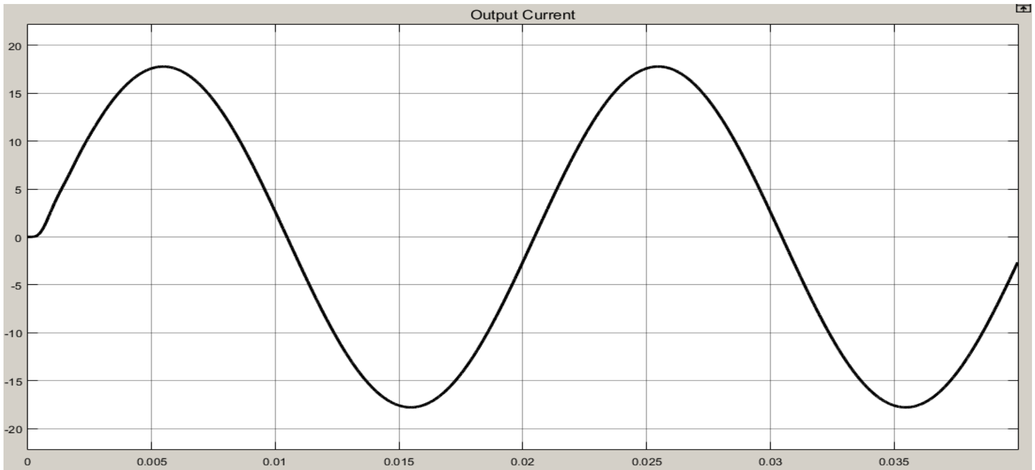

Figure 5.8: System output current with LCL filter before optimization

5.3 Optimal Design for LCL Filter

To protect working system of inverter, both active and passive damping method are needed for damping resonant peak at resonance frequency. Fort this reason, damping methods that can be passive or active should inserted system by resistances. Fort this study, passive damping method is chosen. According to passive damping procedure, addition of resistor provides to repress resonance peak. Basic solution can become supplementation of serial resistance coupled with capacitor to decrease Q factor that can think like capacitor current. Besides supplementation of serial damping resistance coupled with capacitor sifts gain spike, to make smooth all responses and rolls around -180^0 at high frequencies rather than -270^0. By using damping method 90^0 phase shift can be observed.

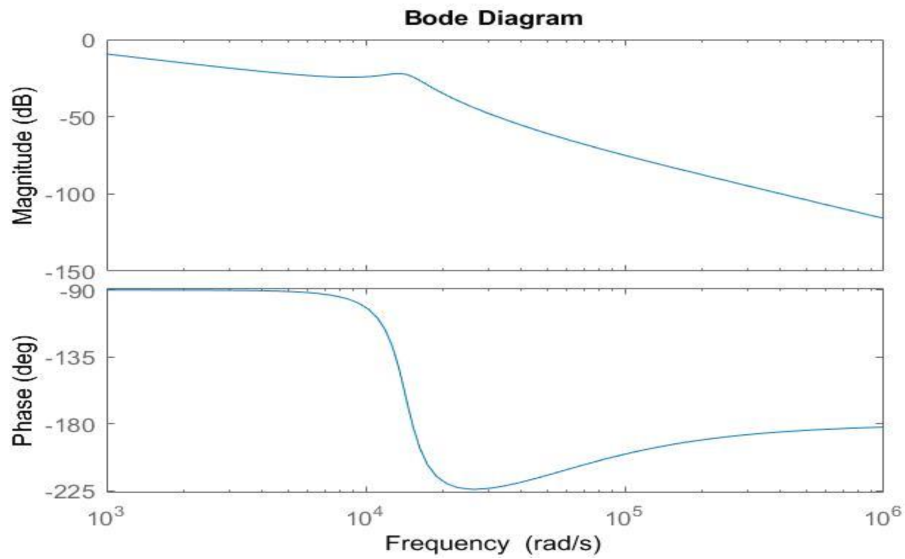

Figure 5.9: Bode plot of LCL-filter with damping

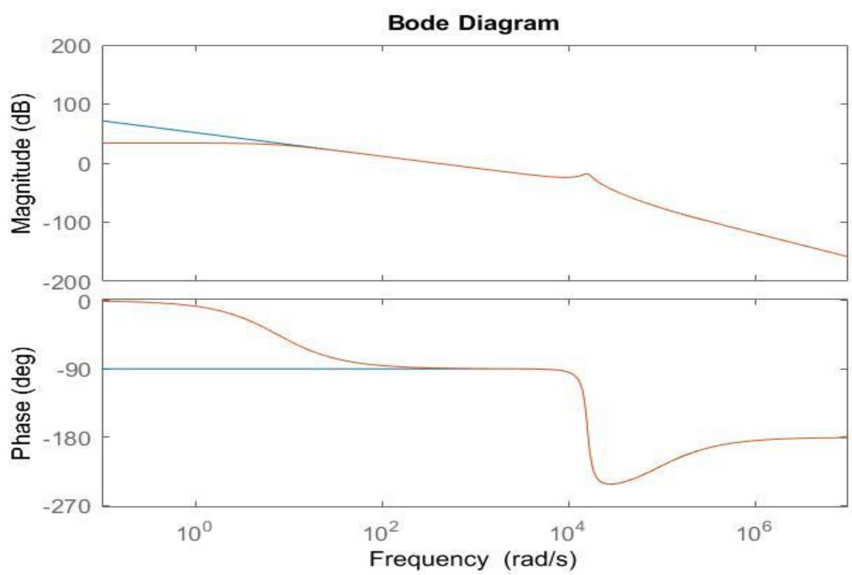

Figure 5.10: Bode diagram for LCL filter with stable and unstable system

With optimization system codes and outcomes are in Appendix part. Table 5.2 shows obtained values of LCL filter design.

Table 5.2: LCL filter with optimization calculated parameters

Parameter	Value
Grid side inductance (L_g)	1.5 mH
Inverter side inductance (L_i)	1.5 mH
Inverter side, grid side and damping resistor (R_i, R_g, R_d)	0.01, 0.01, 3.52
Capacitance (C)	6.63 µF
Resonance Frequency (f_{res})	2.3 kHz
Base impedance (Z_b)	14.4
Base capacitance (C_b)	0.22 µF
Maximum current ripple (Δ_{L-max})	235 mA
Ratio k (f_{sw}/f_{res})	8.81
Total harmonic distortion (THD)	1.95%

Following graphs which are Figure 5.11 and 5.12 are system output voltage and output current.

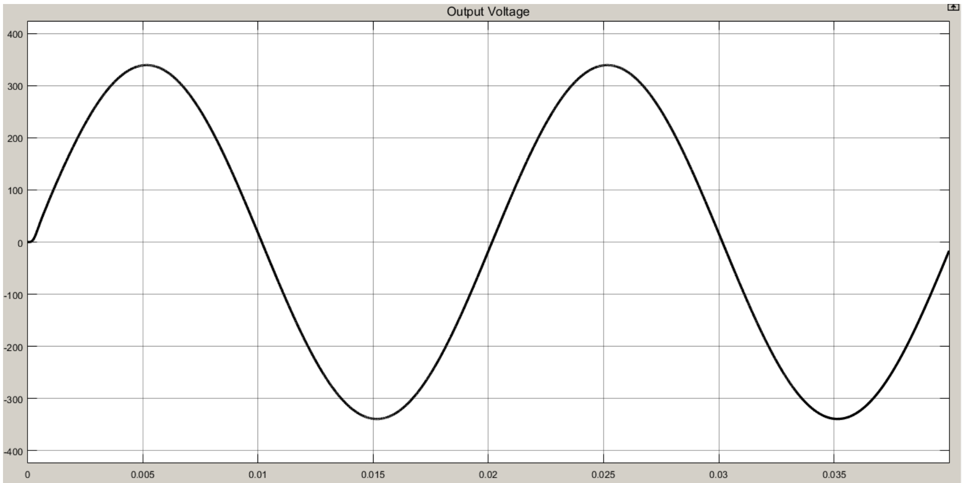

Figure 5.11: System output voltage

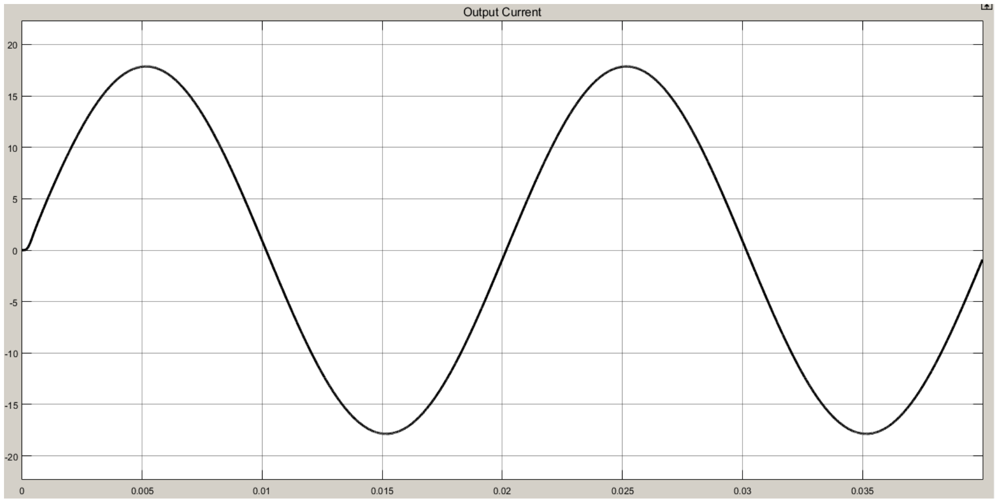

Figure 5.12: System output current

According to with and without optimization methods study, the system parameters can be compared. Table 5.3 shows the comparison of LCL filter based on without optimization parameter values and proposed optimal value. Suggested modeling method compared with first proposed design is accomplished of decreasing filter capacitor, inductance values and THD values by taking into account of requirements.

Table 5.3: The comparison of LCL filter based on without optimization via proposed optimal values

Parameter	Without optimization value	Proposed optimal value
Inverter side inductance (Li)	3.3 mH	1.5 mH
Grid side inductance (Lg)	5.56 mH	1.5 mH
Capacitance (C)	11 μF	6.63 μF
Resonance frequency (fres)	3.31 kHz	2.3 kHz
Total Harmonic Distortion (THD)	2.2%	1.95%

CHAPTER 6
CONCLUSION

In this thesis, an off grid photovoltaic power transformation by using optimized LCL filter is presented for single home. The photovoltaic system is generally connected with dc system. And AC load is attached with dc bus thanks to inverter. Additionally, for off grid photovoltaic system battery is needed to charge or discharge of the system. Preliminary, the importance of this topic is mentioned. Also, components and their working structures which are required to obtain off grid PV system are explained step by step. According to daily energy requirement of reference single home, the proposed system consists of boost converter, battery, single phase pulse width modulation-based inverter and LCL filter. At the end of the first section, system is designed out of LCL filter.

Following part is based on inverter filters. Inverter filter's types, their properties and influences on the system are discussed. In proposed model, LCL filter is selected because of features such as attenuation, effectiveness...etc. Today, it's not enough to model standard system. The key point is to design optimum and best system. Consideringly, optimum LCL filter is designed according to requirements like IEEE519 standards. Reactive power compensation, damping methods, total harmonic distortion requirements, limit of network side and inverter side inductances and dc bus suitability are the main required to consider topics for modelling optimal LCL filter. MATLAB code for standard and optimized LCL filter calculation is shown in Appendix. Optimized parameters for LCL filter obtained from MATLAB code which is at appendix part 2. Optimum LCL filter provides to system stable and having better dynamic. Also, cost and the power losses of filter reduced. This method is the newest idea for off grid application and brings many advantages. Therefore, this work contributes to science.

In test and simulation part, all graphs which outcome of the system are illustrated step by step. Apparently, computed parameters and simulation’s results are accorded. All obtained graphs are explained in simulation section.

Both model with and without optimization works are shown. As a result, suggested modeling method compared with first proposed design is accomplished of decreasing 50% of filter capacitor, inductance values and THD values by taking into account of requirements.

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APPENDICES

APPENDIX 1

LCL FILTER CALCULATION CODE

```
% System parameters
close all;
clear all;
fsw = 20000; %Switching frequency: 20000 Hz
Pn = 4000; %Inverter power: 4000 W
Vdc=425; %DC link voltage
Vg=240; %rms
Ts=1/20000;
wg=2*pi*50;
wsw=2*pi*fsw;
Zb = (Vg^2)/Pn;
Cb = 1/(wg*Zb);
delI_max = 0.01*((Pn*sqrt(2))/Vg)
Li = Vdc/(16*fsw*delI_max) %Inverter side inductance
u=0.6; %Li/Lg ratio
Lg=u*Li %Grid side inductance
%Calculation of wres, resonance frequency of the filter
wres = sqrt((Li+Lg)/(Li*Lg*Cf));
fres=wres/(2*pi)
x=0.05; %Damping capacitor multiplying factors
Cf = x*Cb  %Filter capacitor
b2=1;
a1=Li*Lg*Cf;
a2=0;
a3=(Li+Lg);
```

```
Planttf=tf([0 0 0 b2],[a1 a2 a3 0])
opts = bodeoptions('cstprefs');
opts.PhaseVisible = 'off';
opts.FreqUnits = 'Hz';
bode(Planttf)
plant_rddc=c2d(Planttf, 0.0001);
```

APPENDIX 2

LCL FILTER OPTIMIZATION CODE

```
close all;
clear all;
fsw = 20000; %Switching frequency:20000 Hz
Pn = 4000; % Inverter power:4000 W
Vdc=425; %DC link voltage
Vg=240;%rms
fg = 50;
ri=10e-03; % resistance of inverter side inductor while practical implimentation copper wire have some resistance
rg=10e-03; % resistance of grid side inductor while practical implimentation copper wire have some resistance
Ts=1/fsw;
wg=2*pi*50;
wsw=2*pi*fsw;
Zb = (Vg^2)/Pn ;
Cb = 1/(wg*Zb);
delI_max = 0.01*((Pn*sqrt(2))/Vg);
Li = Vdc/(16*fsw*delI_max);
u=1; %Li/Lg ratio
Lg=u*Li;
x=0.05; % damping cap multiplying factors
Cf = x*Cb
c = 2*pi*fg*Cf*Zb;
fres = 2310;
LT = (1+u)^2/(4*(pi^2)*(fres^2)*Cf)
lt = 2*pi*fg*LT/Zb ; % Per unit optimized total inductance
```

```
L1= LT/2
L2 = L1
Fres = sqrt(fg^2*(1+u)^2/(lt*c*u))
%Wres = sqrt((L1+L2)/(L1*L2*c));
Wres = 2*pi*Fres;

%Damping resistance
rd = 1/(3*Wres*Cf)
b0=1+L2*Cf;
b1= Cf*(rd+rg);
a1=L1*L2*Cf;
a2=(Cf*L1*(ri+rd)+L1*Cf*(rg+rd));
a3 = (Cf*rg*(ri+rd)+Cf*ri*rd+L1+L2);
a4=ri+rg;
plant_2=tf([0 0 b1 b0],[a1 a2 a3 a4]);
Planttf=tf([0 0 Cf*rd 1],[L1*L2*Cf (L1+L2)*rd*Cf L1+L2 0]);
opts = bodeoptions('cstprefs');
opts.PhaseVisible = 'off';
opts.FreqUnits = 'Hz';
bode(Planttf)
plant_rddc=c2d(Planttf, 0.0001);
```

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