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Research Article

Design of an LLCL type filter for stand-alone PV systems' harmonics

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Abstract: This paper is regarding the design, modeling and simulation for reducing harmonics with passive LLCL filter in off-grid solar system. It is desired that current and voltage waveforms are to be in the sinusoidal form during energy generation from stand-alone solar systems. This condition can be provided by the most important one of the main factors which to determine the quality of electrical energy. Due to the harmonics produced by the non-linear loads, the waveform of the current and voltage is distorted from the sinusoidal form. The passive LLCL filter is designed and analyzed for mitigation of the total harmonic distortion for current (THD_I) in the proposed off-grid PV system. The passive LLCL filter is practically installed between solar inverter and non-linear load. Simulation results are in a good compliance with the theoretical analysis. This study describes a design methodology of a LLCL filter for off-grid power system with a comprehensive study of how to mitigate the harmonics in off-grid solar system. The using of a LLCL filter mitigates the THD_I that injected by a six pulse rectifier which is used as a non-linear load. The simulation result shows that the reduction of THD_I from 89.89% to 3.257%. This paper attempts to show that the using of LLCL filter with a stand-alone solar system can highly improve the power quality of the system.

Keywords: *PV module model, Passive LLCL harmonic filter, Total harmonic distortion (THD), Off-grid PV system, Harmonic mitigation*

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Nomenclature	
T	Temperature
G	Irradiance
PV	Photovoltaic
Voc	Open circuit voltage
Isc	Short circuit current
THD	Total harmonics distortion
THD_I	Total harmonics distortion for current
PWM	Pulse-width Modulation
LLCL Filter	Inductance-Inductance-Capacitor-Inductance Filter

1. INTRODUCTION

Photovoltaic (PV) cells are systems that convert solar energy directly into electrical energy without the need for any moving mechanism without polluting the environment, polluting the environment. PV system is safe and clean sources, and the use of these systems is increasing day by day. PV systems can be divided into two main field; off-grid or stand-alone applications and on-grid or grid-connected applications. Stand-alone systems can be used to provide energy for remote loads where the electric grid cannot access.

Design of an LLCL type filter for stand-alone PV systems' harmonics have been studied widely in the literatures. In [1] an efficient procedure was studied to design passive LCL-filters for active power filters. Thus, it was studied on the hybrid filters. However, our study is only on the mitigation of harmonics by LLCL filter in stand- alone PV system.

In [2] analytical solutions were investigated for LLCC filters connected in parallel resonant converters. In [3,4] elimination of harmonic components was studied by passive filter in electrical facilities, whereas in [5] harmonics elimination was investigated in grid-tie inverter. However, in some previous studies which were discussed about the design of an LLCL type filter for stand-alone PV systems' harmonics. In [6] optimum design of passive harmonic filter was studied by using game theory concepts. The authors concluded that choosing filter with using game theory concepts more important than other selections method.

Stand-alone PV systems are used in some power applications such as an electrical grid where is not existing, water pumps, communication stations, traffic signs, etc. [7,8]. The output voltage and current of solar inverter generally contain a lot of harmonic components as a result from the switching signals. Besides choosing a higher switching frequency to reduce the harmonic, the high frequency harmonic contents can be filtered by using active or passive filters. Principle scheme of a stand-alone PV system is as shown in Fig. 1.

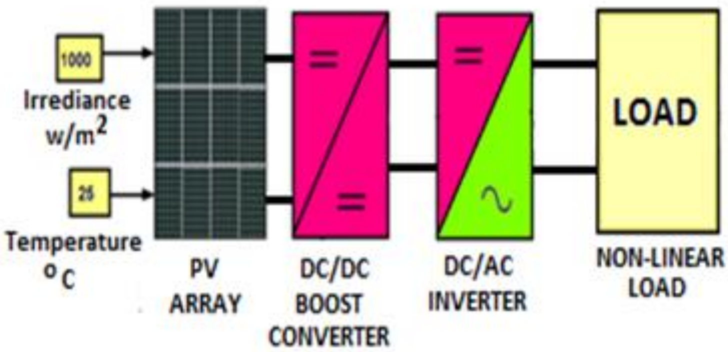

Figure 1. Principle scheme of stand-alone PV system (unfiltered)

The current and voltage waveforms away from the sinus form are distorted because the electrical loads do not have a non-linear characteristic. These results cause power quality problems due to harmonic components. Harmonic components cause many problems in power systems. They also have negative effects on photovoltaic sources and converters. Therefore, they should be mitigated. Converters are source of harmonics because of their switching elements, which have non-linear characteristics.

It is highly preferred to use passive filters to reduce harmonic components that occur in the solar PV system. Passive filters are used to reduce the input current of the total harmonic distortion (THD_I) of an uncontrolled rectifier. According to these results, the designed passive filters have a simple structure and control is not too complicated provides significant advantages and are not complicated to control, which provides significant advantages. Passive filters are placed between source and load. Thus, they are designed to destroy components outside the basic component.

The use of passive filters in off-grid systems have many advantages such as including its small size, low cost and high performance. These filters are used for mitigation of harmonics occurred by both PWM inverters and low rated irradiation. They are also used to reduce harmonic components and improve the power quality in off-grid power systems. Passive filters must be used to keep the harmonic components at the limits specified in the standard.

The use of passive filters has many advantages, such as increasing the lifetime of the off-grid PV system, increasing in energy quality and improvement of the power factor value. The passive filters also reduce the value of harmonic components caused by six-pulse power converters, and solar inverter. Therefore, THD_I value drops significantly in the system.

On the other side the active harmonic filters have some disadvantages compare to passive filters such as they are complicated from technical wise, using of active filters are sophisticated in both electronics and software. Therefore, their maintenance is difficult and also manufacturer is being contacted usually for solution in any failure. In addition, active harmonic filters are always more expensive than passive harmonic filters.

Two types of filters are used in off-grid systems for harmonic mitigation, and can be classified into two main categories, passive and active filters. The active filters are much more complex, require active switches, and control algorithm. In recent years, LLCL filter has been widely used in renewable energy sources.

This energy is stored in the battery pack via the solar charge controller and is ready for use during day or night hours [3,9]. By adding a solar inverter to the system, the devices working with the mains voltage is fed. Panel slopes and orientations should be selected according to the season in which the energy will be consumed. The Principle scheme of stand-alone PV system is given in Fig.2.

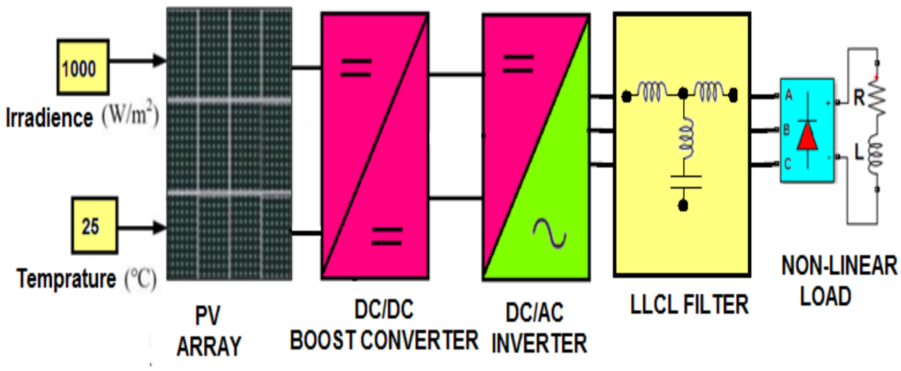

Figure 2. Principle scheme of stand-alone PV system (filtered)

All panels connecting to a charge controller should be on the same slope and orientation. The size of the PV array should be selected by some parameters such as seasonal variation of solar irradiation, cell temperature, the daily energy usage, battery efficiency, etc. [10,11]. The two main basic variables that can be set to the input of PV simulation system. These variables are the solar irradiation level W/m^2 and the module's temperature ºC.

Mitigation of harmonics will be achieved for the irradiation value 880 W/m^2 and the temperature is 20 ºC. The harmonics that occur in the stand-alone system change depending on the radiation and the temperature [1,12]. This change has a nonlinear character, and the PV panels produce direct current electrical energy proportional to the temperatures and irradiance intensity.

In this paper, a six-pulse rectifier, which is used as a non-linear load, causes quite high value of THD_I in the stand-alone PV system. Therefore, passive LLCL filter is the most frequently used method for mitigation of THD_I in off-grid solar system. In this article, LLCL filter is designed and modeled for reduction of harmonics in stand-alone PV system. The proposed standalone PV system in this paper is formed as follows, a DC/DC boost converter, a solar inverter, an uncontrolled six pulse rectifier, a passive LLCL filter and an inductive R-L load.

According to the results obtained, harmonic problems still exist in the off-grid system that feeds a non-linear load and these problems should be solved. In this study, it was observed that this problem was mitigated and harmonics were cleaned significantly with LLCL type filter.

2. POWER SYSTEM HARMONICS IN OFF-GRID PV SYSTEM

The development of power electronics has led to an increase in harmonics in power system. The most important reason for the deterioration of the voltage waveform, the correlation between the terminal voltage and current with non-linear loads are non-sinusoidal sources. Even if nonlinear loads are low powering solar system, they distort sinusoidal current and voltage waveforms. Harmonics causing serious pollution problem in power system, and they also reduce the quality the energy give to the consumer. In addition, they cause transformer losses, line losses and resonance problems [2,13].

The six pulse converters, which used in off-grid PV system is the great harmonic source. Nonlinear loads create voltage and current harmonics, and these harmonics cause many problems. Six pulse rectifiers is used in off-grid PV system as a load [14]. The odd harmonics have greater impacts on power quality than even harmonics as they have higher magnitude. Harmonics generated by the converters may be formulated depending on the number of pulses of the converter. The harmonics produced by converters is calculated as:

$$h = kp \pm 1 \qquad (1)$$

Where, h is the harmonic component, k is positive integer number and p is number of the pulse converter. The odd-numbered harmonics are present in the six-pulse converter; but triple harmonics are not present in this converter. For example, 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc., are present as active in the six pulse uncontrolled rectifier. These harmonic components are as shown in the eq. [2].

$$\begin{aligned} i(\omega t) = {} & 14.88 Sin(\omega t - 0.159) + 2.98 Sin(5\omega t + 178.4) + 2.121 Sin(7\omega t - 179.2) \\ & + 1.348 Sin(11\omega t - 0.8763) + 1.14 Sin(13\omega t - 0.4928) + 0.8717 Sin(17\omega t \\ & + 178.7) \end{aligned} \qquad (2)$$

These harmonic components waveform is as illustrated in Fig.3.

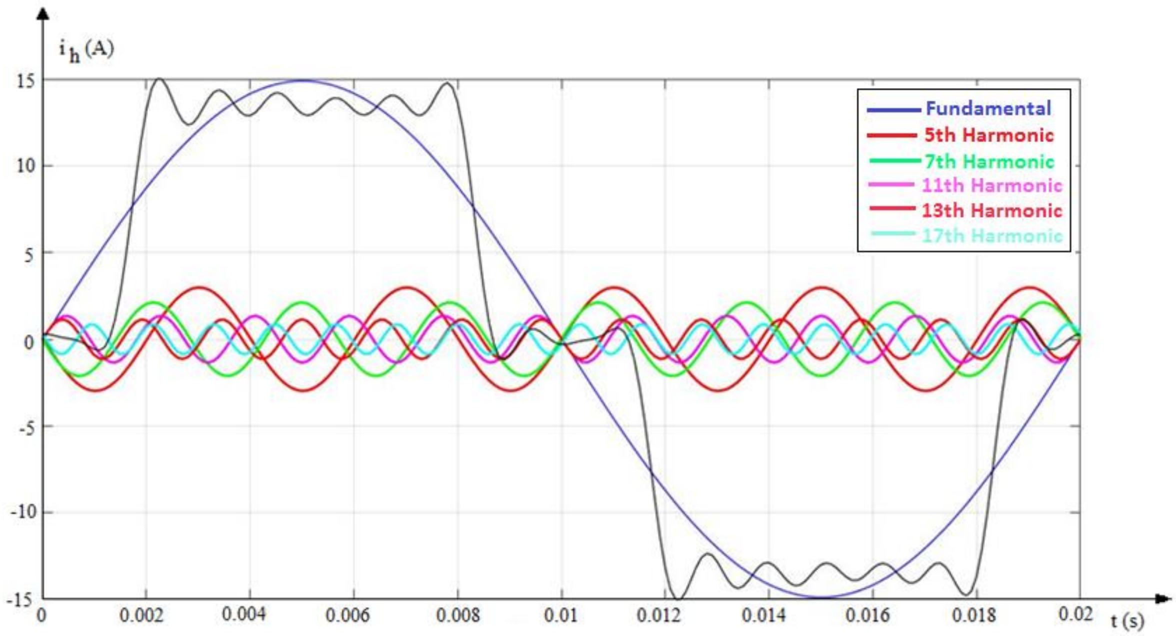

Figure 3. Six-pulse rectifier input current harmonics waveform

Current and voltage that is in the sinusoidal waveform distorted by non-linear, loads that even if they are in small power. Harmonic components cause the following damages in the PV system such as; Increased losses of elements in the off-grid PV system. Disruption of the dielectric insulation of elements in the power system, increase in voltage drop in off-grid PV system and inconstant voltage level, incorrect measurements on measurement systems, disorders in control circuits.

Resonance with harmonics component, Incorrect opening in protection relays, Incorrect operation of microprocessors and data loss, Noise in communication devices, change of power factor, Overheating and power loss of power system equipment such as cables, AC/DC converters, inverter, six pulse rectifier and inductive R-L load, shortened life span of off-grid system devices such as cables, DC/DC boost converter, and inverter, false trigger switching elements such as Insulated-Gate Bipolar Transistor (IGBT), Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Bipolar Junction Transistor (BJT) and etc., errors measurements voltage, current and power in off-grid PV system.

Harmonics must be continuously monitored for power quality. THD_I or total harmonic distortion for current is a common measurement of the level of harmonic distortion present in electrical power system [4,5]. In order to be able to measure the energy quality and classify the distortions, it is necessary to define the total harmonic distortion. The THD_I term expresses as effective value of the all harmonics, divide by the effective value of its fundamental of current. We can determine the level of damage harmonics giving to the network by the THD coefficient. The distortion as a percentage of total harmonic distortion for current is defined as follow:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{3}$$

Where, I_n effective current of the nth harmonic, I_1 is the effective of the current of the fundamental frequency. The high THD have negative effects on power system such as equipment overheating, motor vibration, neutral overloading and low power factor. THD_I or total harmonic distortion for current is a common measurement of the level of harmonic distortion present in power system. If the harmonics components are equal to the “0”, total harmonic distortion will be equal to the “0” where, In, is the effective voltage of nth harmonic and n=1 is voltage of the fundamental frequency [6, 15]. The analytical solutions and simulation program applications have been observed that fit harmonics occur in the electrical grid system, any or both of these sources of non-sinusoidal nonlinear elements in general.

There are many damages is given by harmonics to off-grid PV system such as excessive current in neutral wire, overheating of the DC/DC boost converter, microprocessor problem and unexplained inverter crash. The presence of harmonic currents and voltages of the power system means that the degradation of sinusoidal waves. Deteriorated waves called non-sinusoidal waves [16]. Voltage and current waveform distortion due to harmonics can lead to the power system and electrical consumer either damaged or out of order.

Some non-linear loads cause harmonics in off-grid solar system such as switched power supplies, control circuits, battery chargers, solar inverters, DC/DC converter, DC/AC rectifier, PV systems. Although capacitors themselves do not produce harmonics, they are one of the elements most affected by harmonics. The harmonic effect is usually observed in parallel-connected capacitor groups.

There are two commonly used methods for destroying harmonics. One of these measures taken during the design phase of the power system, the other circuit elements such as L, C, and L are added to circuit. In order to mitigate the harmonics, these elements are called "harmonic filter" which enables to mitigate the harmonic components that are formed by the nonlinear elements which are present in the circuit. Over voltages and currents that occur as a result of the resonance phenomenon generated by the harmonics.

Harmonics cause additional heat losses in the off-grid energy system. This additional loss reduces the efficiency of the system. It is impossible to destroy the harmonics. Measures will be taken to minimize harmonics. For example, rectifiers can be selected with 12 pulses instead of 6 pulses. These measures are not enough to filter absolutely necessary.

The general purpose of the harmonic filter to reduce the effects of current and voltage in the designated frequency. In parallel with the developments in the power electronics, many nonlinear loads are connected to the power system. It may be possible to filter harmonics with passive filters consisting of L, R, C elements.

3. ANALYSIS AND DESIGN OF LLCL PASSIVE FILTERS

Working of electricity systems smoothly and safety depends on the foundation of quantities such as current and voltage which are sinusoidal and 50 Hz frequency However, these foundation quantities lose their sinusoidal characteristics because of many reasons, and unwanted harmonics occur in the system. The DC / DC boost converter, DC/AC inverter and six-pulse uncontrolled converter are harmonics sources which use in the off-grid PV system.

This study focuses on the design and analysis of LLCL passive filters for improvement power quality in off-grid PV systems. In the last decade, owing to the quick growth of renewable energy in the world, the LLCL filter has been used extensively for various applications in renewable energy sources. Harmonic currents generated by power electronic based devices such as thyristor, diode, MOSFET and IGBT these elements cause critical power quality problems in the PV systems.

Having more THD during low solar irradiation might force PV system operators to either use bigger and more expensive filters or even disconnecting the PV system from the grid to avoid paying the high THD levels penalty specified by the utility operator. As a result, the use of these nonlinear elements increases the effectiveness of the harmonics in the system. In addition, rectifiers, inverters, DC/DC converter are the most significant harmonic sources in off-grid power system. This problem occurs around resonance frequency Fig.4. Shows the frequency response of LLCL filter.

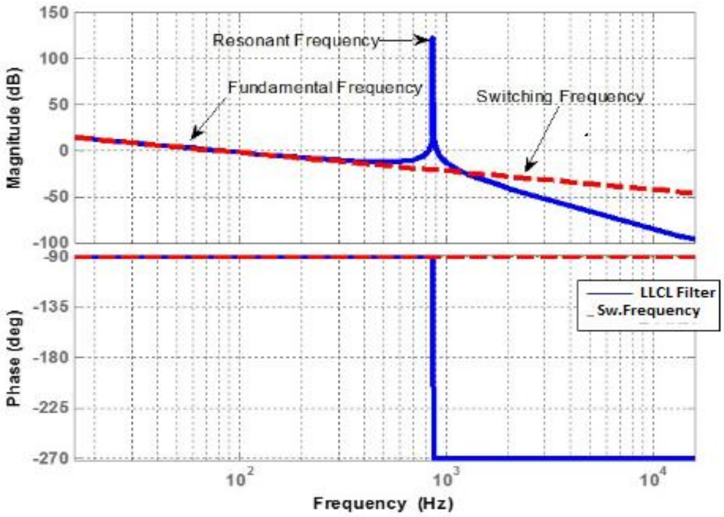

Figure 4. Frequency response of LLCL filter

The harmonic filters are designed so that the current or voltages at one or more frequencies to reduce or mitigate the effect of the harmonic level. Generally, designs are made for the most effective harmonic components. In fact, the reason for using filters is both technical and economical. It is aimed to mitigate the technical and economical disadvantages resulting from the harmful effects of the harmonics with the filters.

Passive LLCL filter is circuits consisting of capacitor C_f, inductance L_1, inductance L_2 and inductance L_f elements, which is placed between the solar inverter and load. Thus, they are designed to mitigate harmonics components outside the fundamental frequency. A passive LLCL filter has a lot of advantages over an active filter such as guaranteed stability, no power consumption, inexpensive, and conventional. Input voltage of solar inverter is given in Fig. 5.

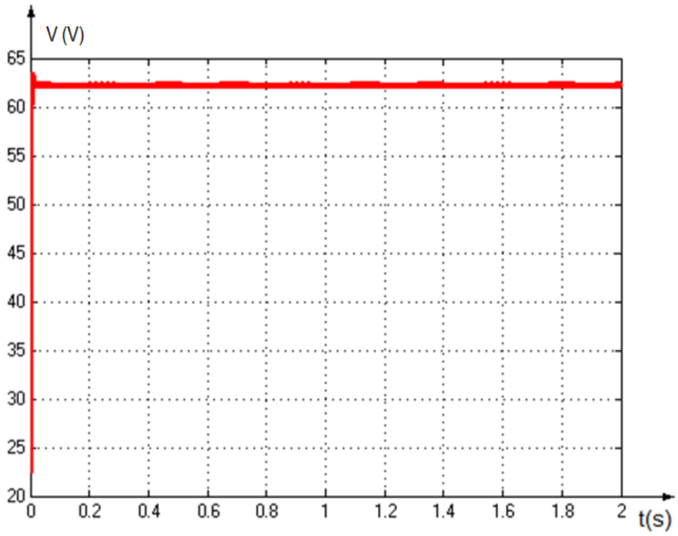

Figure 5. Input voltage of solar inverter

Passive LLCL-filter is usually used on the load side of renewable energy sources, such as wind energy, PV energy etc. These devices improve and ensure the overall quality energy produced by off-grid PV system. Schematic diagram of the LLCL filter is as illustrated in Fig.6.

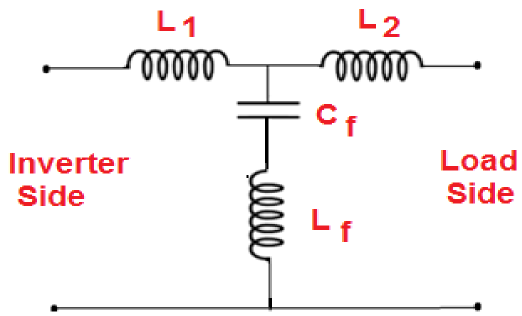

Figure 6. Schematic diagram of LLCL filter

Passive LLCL filter is used to reduce harmonics and improvement power quality in off-grid power system. This filtering is based on the principle of mitigating harmonic components in the network by adjusting the L-C passive elements. The structure of these filters being simple, low prices, high efficiency and being able to meet basic frequency reactive power needs at the same time the ones of this filters advantages. LLCL filter is become popular in the renewable energy industry nowadays, but it can only be used in systems with fixed nonlinear loads.

A passive LLCL harmonic filter should be designed correctly for stand-alone PV system. A passive LLCL filter can be designed for purposes such as harmonic current spectrum of harmonic generating nonlinear loads, the value of the total harmonic distortion allowed in the solar system, reactive power value required in solar system, level of harmonics caused by other sources, the other loads in the network and the equivalent circuit of the solar system impedance change for effective harmonics, working values of the filtration (frequency, temperature, voltage).

The value of a filter is the fundamental frequency of this filter is defined as the reactive power that it provides. This is equal to the value of the fundamental reactive power provided by the capacitors. The filter should be positioned nearest to the harmonic load.

The resonance event is one of the harmonic components or close to these harmonic components the values of the harmonic current and voltage values reach very large levels Therefore, by adjusting the filter resonant frequency is shifted. It provides an efficient way to improve the quality of power fed from off-grid PV system to the inductive R-L load. As shown in Fig. 6, the LLCL filter circuit consists of on the inverter side inductance L_1, on the load side inductance L_2 and a capacitor C_f the LLCL filter transfer function is as given below.

$$G(j\omega) = \frac{L_f C_f s^2 + 1}{\left[L_1 L_2 C_f + (L_1 + L_2) C_f\right] s^3 + (L_1 + L_2) s} \tag{4}$$

The resonant frequency of the LLCL filter should be chosen in the range given below. When selected in this range, no resonance occurs in the off-grid solar system.

$$10\,\omega_0 \leq \omega_{res} \leq (\omega_{switch}/2) \tag{5}$$

Where w_0 is the utility frequency rad/s, W_{res} is the resonant frequency rad/s and W_{switch} is the switching frequency rad/s. The resonant frequency of LLCL filter at the switching frequency is defined as:

$$f_{res} = \frac{1}{2\pi * \sqrt{\left(\frac{L_1 L_2}{L_1 + L_2} + L_f\right) C_f}} \tag{6}$$

If we choose C_f large value, we can mitigate more harmonic, but it results in higher reactive power and increased demand of current from L_1thereby decreasing the efficiency of the overall filter system. Reactive power absorbed by capacitor is defined as:

$$Q_c = \frac{3V_{rated}^2}{X_c} = \frac{3V_{rated}^2}{\frac{1}{\omega\, c}} = 3(2\pi f)C_f V_{rated}^2 \le \alpha P_{rated} \tag{7}$$

Where Qc is reactive power absorbed by capacitor. V_{rated} is effective value of phase voltage. α is reactive power absorption rate. It is generally chosen as given below.

$$\alpha < 5\% \tag{8}$$

LLCL filter is occurred three inductors and one capacitor. The capacitor shunt element in the design will further attenuate the switching frequency. The C_f value for the LLCL filter is chosen by determining the reactive power absorbed by the filter at rated conditions [7]. Eq. [9] determines the selection of C_f value for the LLCL filter.

$$C_f = \frac{\alpha P_{rated}}{3(2\pi f)V_{rated}^2} \tag{9}$$

The inductors in the LLCL filter are designed by determining the current ripple. Selection of small values of ripple current decreases the switching losses. However, the size of the inductor increases. The value of L_1 in LLCL filter is defined as

$$L_1 = \frac{N_{in}}{8hf_{res}} \tag{10}$$

Where V_{in} is the input voltage of the inverter, h is the amount of ripple current which should be 5% of rated current. The value of $L_2$is defined as

$$L_1 = aL_2 \tag{11}$$

Where,$a$is the inductance ratio factor. For low and medium power applications, this coefficient is chosen to be greater than 1. Passive LLCL filters are placed between the source and the load and they are designed to destroy components outside the basic component. These filters have risks such as serial and parallel resonance, the filtering frequency is fixed, and being large volumes disadvantages of these filters.

$$L_f = \frac{1}{C_f\, \omega_{s\omega}^{\;2}} \tag{12}$$

Harmonics are undesirable magnitudes in the network because they affect all system elements. Therefore, it is electrical network. Band pass and high-pass filters are frequently used.

4. MITIGATION OF HARMONICS USING PASSIVE LLCL FILTER

The irradiation and temperature are taken as 880 W/m^2 and 20 ºC in stand-alone PV system. The Point of Common Coupling (PCC) will be the focus of analysis which THD_I is limited less than 5%. It is clear that the THD_I of the current of inverter is 89.89 %. Higher order harmonics can affect whole of the system.

These effects reduce the performance of the power system and other equipment. Simulation model of the proposed system is simulated in a software program as shown in Fig. 7. Simulation program was used to analyze performance of the designed passive LLCL filter in stand-alone PV system. The model of stand-alone PV system (unfiltered) is also given in Fig.7.

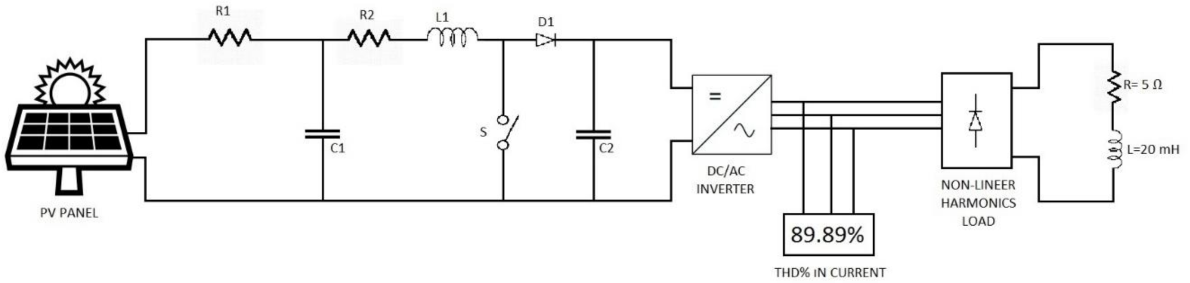

Figure 7. Model off-grid PV system (unfiltered)

A Simulation program was used to analyze performance of the designed passive LLCL filters. Harmonics which are produced by non-linear loads must not resonate the PV system. Resonance conditions should be calculated separately for each harmonic component. If harmonics are injected into a power system from harmonic sources, they affect the PV system in such a way that it will resonate with any component. The output voltage waveform of stand-alone system is given in Fig.8.

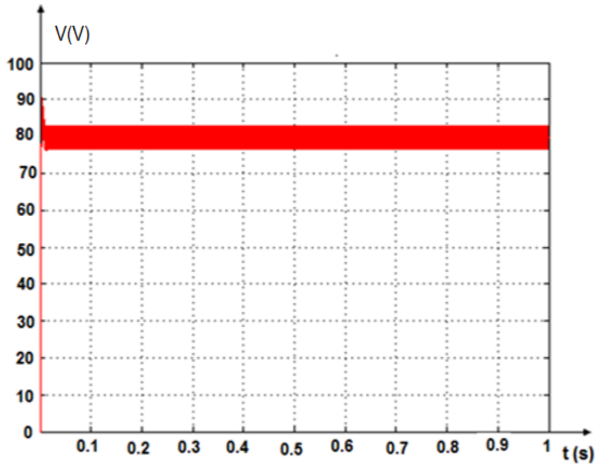

Figure 8. The output voltage waveform of Stand-alone System

Passive LLCL filters are generally used in power systems. The reason for this is that the cost is lower than the active filter and easy to use. The dominant harmonics are detected in the power system and the passive LLCL filter is designed accordingly. While harmonic compensation is made with passive LLCL filter, and the reactive power compensation is also performed.

System structure and working modes are analyzed in detail firstly, and then THD_I belongs to the power system analysis based on the simulation program. The results clearly show that the passive LLCL filter can reduce harmonics at various frequencies as compared to active filter. The inverter output currents waveform for unfiltered condition is shown in Fig.9.

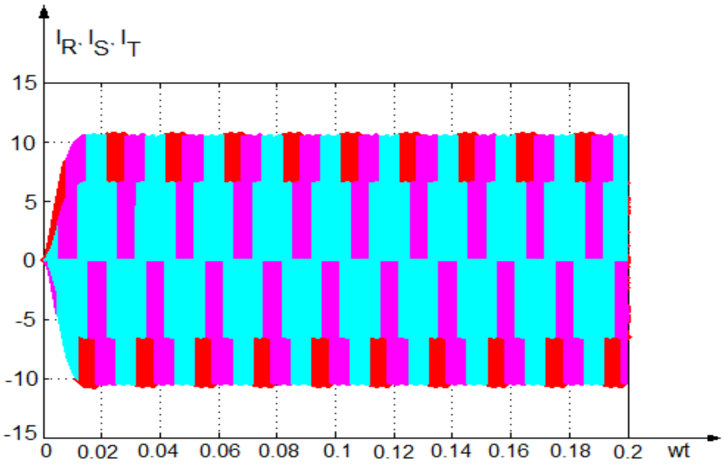

Figure 9. Inverter output currents waveform (without filter)

Harmonics have two effects on stand-alone PV systems, technical and economical. Technical problems affect the delivery of quality electricity to the load. Economic problems affect optimal work. Fig. 10, shows the schematic diagram of the power system after filtering. In this system, LLCL filter is used to mitigate all of the harmonics. In this paper, stand-alone PV power system has been simulated with and without passive filters in the Simulation software program. Parameter values of the LLCL filter values obtained from Eqs. [9,10] are given in Table 1.

Table 1. Designing parameters of LLCL filter

Parameters of LLCL filter	Values
Cf	115.55 µF
L1	258.19 mH
L2	314.55 mH
Lf	140.4 µF

Higher order harmonics can affect the whole stand-alone system. These effects reduce the performance of the power system and other equipment. There are odd and even harmonics in off-grid PV systems. THD values vary with high and low radiation values. It has been observed that THD value increases at low radiation. The simulation results show that the odd harmonics components are contributed to more harmonics as compared to even harmonics. It also shows that THD_I value has come down to 3.257 %.

Passive LLCL filter is placed between solar inverter and the load. They are designed to destroy components outside the basic component. These filters have risks such as serial and parallel resonance, the filtering frequency is fixed, and being large volumes disadvantages of these filters. Harmonics are undesirable magnitudes in the network because they affect all system elements.

The increase of power electronic elements and various nonlinear elements every day causes the increase of the non-sinusoidal size circulating in the energy system. Therefore, it is necessary to establish filter circuits to mitigate harmonics. For this reason, filters are installed in renewable energy sources. Band pass and high-pass filters are frequently used. Model stand-alone PV system with filter is given in Fig.10.

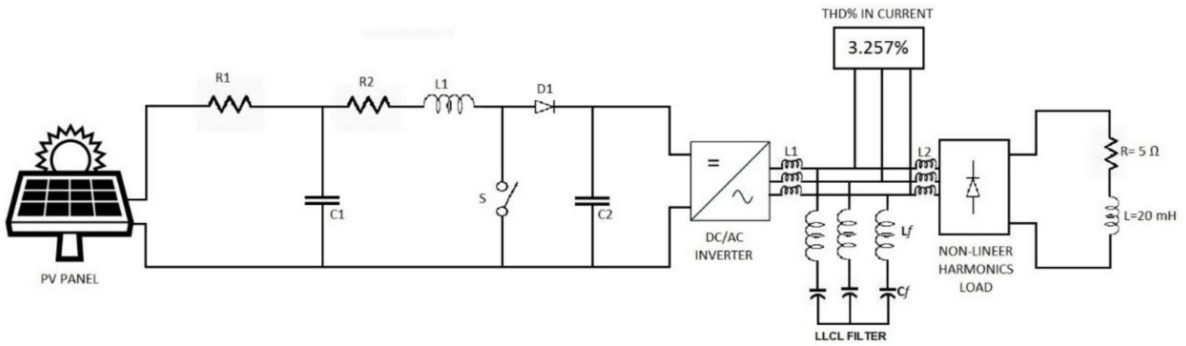

Figure 10. Off-grid PV system model with LLCL filter

This paper presents the passive LLCL filter application is to mitigate harmonics and improve the power quality of the off-grid PV system. Simulations are performed to see what affects the harmonics on the system waveform and what kind of problems will be solved. Thus, we have used passive LLCL filter to mitigate harmonics in PV system. LLCL filter is especially popular in the renewable systems. This filter has many advantages like small losses, small size and weight. The output voltage of DC/DC boost converter waveform is as shown in Fig. 11.

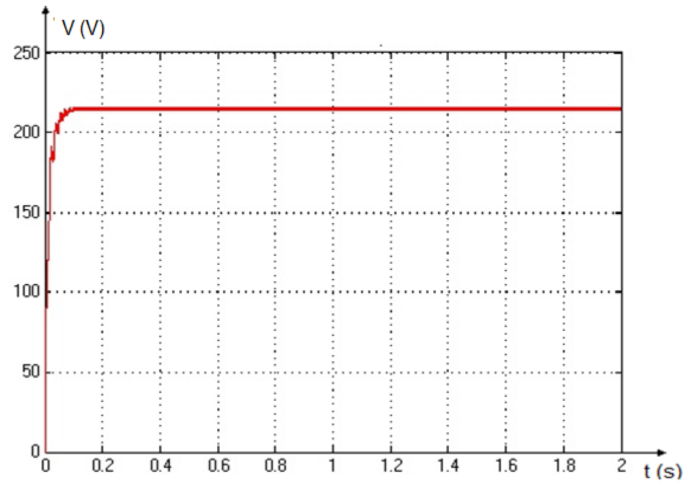

Figure 11. Output voltage of DC/DC boost converter

Harmonics cause additional losses in energy cable, motors, capacitors and transformers. In some cases, harmonics cause the power system components to breakdown or be disabled. They will also increase the probability of occurrence of resonance, and over-currents and voltages that may occur as a result of resonance will cause great damage to the operating elements. The THD_I has been successfully decreased from 89.89 % to 3.257 % for the used non-linear load system, which fulfills the recommended (IEEE-519).

LLCL filter has been commonly used to limit the flow of harmonic currents in stand-alone PV system. They are usually custom designed for the application. However, their performance is limited to a few harmonics and they can introduce resonance in the stand-alone system. The idea of using passive LLCL filter is to compensate for current and voltage harmonics in off-grid PV system. The passive LLCL filter plays rather an important role in reducing system harmonics for better quality energy, but the main drawback of the LLCL filter is a stability problem.

Working of electricity systems smoothly and safety depends on the foundation of quantity effects such as current and voltage, which are sinusoidal and 50 Hz frequency. However, these foundation quantities lose their sinusoidal characteristics because of many reasons, and unwanted harmonics occur in the system. These harmonics which are occurred on the current and voltage waves can damage electricity installation and consumers depended on them.

The most common ways to reduce them in order to take precautions such as larger neutral conductor section, using of K-factor transformers, using passive LCL filters, with some transformer connections some harmonics can be eliminated. For example, delta-star transformer connection eliminates 5th and 7th harmonics, delta-star transformer connection eliminates 3rd harmonic, 5th harmonic is destroyed by transformer with delta-zigzag connection, using a passive filter to neutralize triple harmonics in the neutral conductor, using high- pulse converters.

There are many serious effects of harmonics in the power system such as distortions of voltage waveform, decrease system efficiency and increase losses in the system. One of the most important harmonic components in energy systems is single and three phase converters. Harmonics should be drawn below the values stated in standards.

Non-linear elements cause serious harmonic pollution in stand-alone PV system and decrease the quality of energy given to load. Mitigation of harmonics and improvement of the power quality is essential this work. Harmonic filters cause temperature increase in the panel. Therefore, care should be taken to ensure that the panels provide adequate airflow. As a result of LLCL passive filter application the system was cleaned from harmonics and the THD_I value fell below 5%. As the system losses decreased, efficiency increased. It is clear that the THD_I has drawn to 3.257 %. PV system model with LLCL filter the output currents of solar inverter waveform is as shown in Fig. 12.

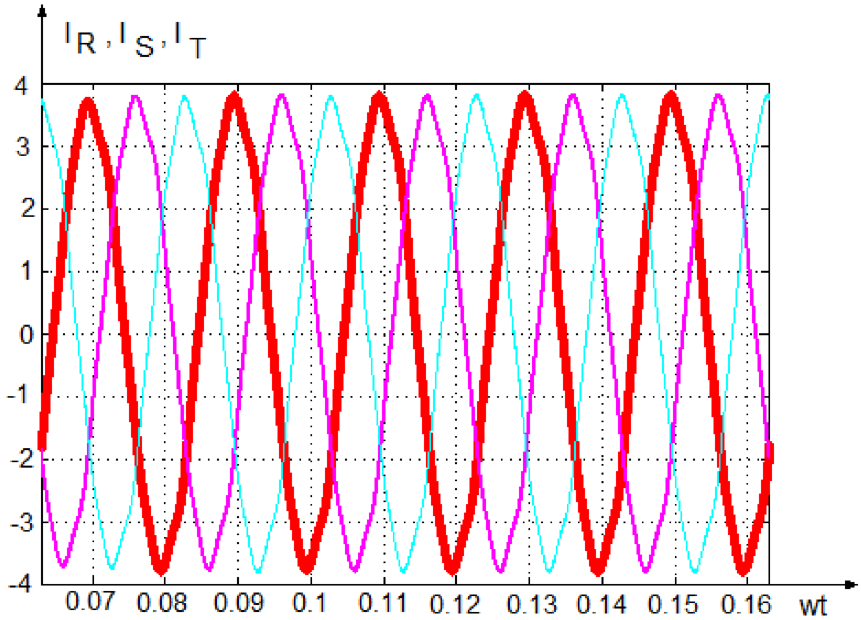

Figure 12. Output currents of solar inverter (after filtering)

The development in renewable energy over time has increased the demand for LLCL filters, which are an efficient and economical way of ensuring and improving the quality of power fed from the stand-alone PV system to load. Traditionally passive LLCL filters are used to mitigate line current harmonics. However, in practice, these passive filters have some disadvantages such as serial and parallel resonance.

One of the biggest harmful effects of harmonics is resonance effect, and the resonance occurs if the inductive reactance is equal to the capacitive reactance. As the frequency increases in the power systems, the inductive reactance increases, the capacitive reactance decreases. In the case of resonance, current and voltages are generated in the circuit at the excessive level.

5. RESULTS AND DISCUSSION

The power system consists of PV array, DC/DC boost converter, DC/AC solar inverter, passive LLCL filter, six pulse uncontrolled rectifier and inductive R-L loads. The design of passive LLCL filters to mitigate harmonic distortion caused by nonlinear loads in off-grid PV system. Mitigation of harmonics is so important for the power quality of stand-alone PV system. Passive LLCL filter is an effective filter to suppress high-level frequency components that are generated by PWM converter and non-linear loads.

The LLCL passive filter has the risk of resonance with the 5., 7., and 11., harmonic components in the PV system. The risk can be reduced partially by connecting a series resistor in the LLCL passive filter. It is convenient to use an LLCL passive filter in the Stand-alone PV systems. In addition, it is much more economical comparing to active filters.

There are some disadvantages for LLCL passive filters such as their sizes are big and they cannot fulfill the requirements in case of load changes then the parameters (L-C-L) should be changed based on the load. The aim is to mitigate such these negative effects for researchers who study in passive filters will be achievement.

In order to provide a constant output voltage for the six-pulse uncontrolled rectifier, a band-pass LLCL circuit has been applied. Especially in rectifier circuit applications, the LLCL filter gives better results. As a result of using the passive LLCL filter in the stand- alone PV system, THD_I reduced from 89.89 % to 3.257 %. These values correspond to the values expressed by the standards.

LLCL filters have some problems such as stability and resonance. It should be concentrated especially on these problems in order to get desirable results for the future.

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