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Mitigation Harmonic with LCL Passive Filter in off-Grid PV System

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ABSTRACT

The increased use of power electronic based devices and the nonlinear characteristics of circuit elements used in these devices have led to the formation of harmonic components in power systems. The stable and safe working of power systems depends on the foundation of quantities such as voltage and current, which are sinusoidal and at 50 Hz frequency. However, these foundation quantities lose their sinusoidal characteristics because of many reasons and unwanted harmonic components occur in the off-grid power system. It is highly preferred to use passive LCL filter to reduce the harmonic components that occur in the solar system. The proposed power system is a combination of solar panels, a DC/DC boost converters, solar inverters, six-pulse rectifiers, passive LCL filters and R-L inductive loads. A six-pulse uncontrolled rectifier produces 5th, 7th, 11th, 13th, 17th, 19th, etc. Harmonic components. A passive LCL filter is used to reduce the input current of the total harmonic distortion (THDI) of an uncontrolled rectifier. According to these results, the designed passive LCL filters have a simple structure and control is not too complicated provides significant advantages and are not complicated to control, which provides significant advantages. Modelling of off-grid PV power system and simulation was performed with Matlab/Simulink. Simulation results showed that the THDI value reduced from 91.53 % to 2.927%. As a result, LCL filter improves both the system efficiency and reliability of stand-alone PV power systems

1. Introduction

The global energy sector is mainly dependent on fossil fuels, which have detrimental effects on the environment and clean-air goals. Over the past few decades, the demand for solar energy has increased considerably due to concerns over the environment. In addition toot her factors, such as energy security, global warming, technological improvements and the need for reducing costs, photovoltaic (PV) systems are considered an alternative source of energy especially considering that these systems are clean and environment friendly. PV sources have been used in a lot of places lately as they bring the benefits to air pollution. In recent years, the demand for solar energy sources has started to depend on factors, such as increasing efficiency of solar cells, developments in production technology of cells, etc.

The main reason for the formation of harmonics is nonlinear circuit elements used in electric circuits. These elements cause disorders in the sinusoidal form of current and voltage signals. Non-linear waveforms contain harmonic components. These harmonic components occur in integer multiples of the main components. Harmonic distortion is generally caused by a non-linear elements in electrical solar power systems. Harmonic currents generated by power electronic elements, such as thyristors, diodes; metal-oxide-semiconductor field-effect transistors (MOSFET), IGBT cause a decrease in the power quality of stand-alone PV systems. As a result, the use of these non-linear elements increases the effectiveness of the harmonics in the system. In addition, rectifiers, inverters and DC/DC boost converters are the most significant harmonic sources in off-grid power system. The use of LCL filters in off-grid systems has many advantages, including its small size; low cost and high performance filter to use for off-grid PWM inverters. Due to the stability problems of this filter a damping resistor can be added to LCL filters [1-2]. However, the resistor has power loss in off-grid PV power system. The principle diagram of a stand-alone PV power system is given in Figure 1.

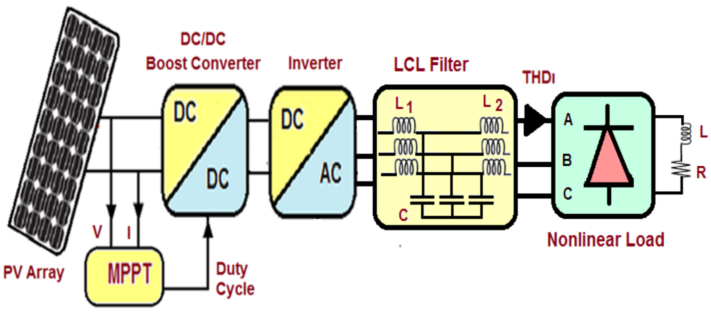

Figure1. Schematic representation of an off-grid power system

In off-grid PV systems, there are problems related to power quality. Among these problems harmonics is found to be the most important issue for stand-alone PV systems or off-grid PV systems. Output power generated by PV modules is influenced by the temperature of the solar cells, intensity of solar cell radiation and so forth. The typical module is made up of around 36 or 72 PV cells in series.

PV systems employ a frequent electrical energy storage algorithm so that the stored electrical energy is held for later use. The largely common storage contraption comprises of batteries in order to employ more striking mechanisms for storage. Maximum power point (MPP) occurs from a few hyperbolic curves, The (I-V) factor and the point is defined as IV=constant. The hyperbolic point is in the relationship of the two opposite curves intersecting the tangent point that gives maximum power for the cell on the (I-V) factor. The MPP can be found by differentiating the cell power equation and setting the result equal to zero. This is known as the MPP, and corresponds to the knee of the curve.

An insulated gate bipolar transistor (IGBT) is used to switch an element into a solar inverter. This element has non-linear characteristics. Therefore; the inverter produces harmonic components in PV systems. 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 non-linear loads are low powering solar systems, they distort sinusoidal current and voltage waveforms. Harmonics cause serious pollution problems in power systems and reduce the quality of solar energy provided to the consumer. In addition they cause transformer losses, line losses and resonance problems.

2. Materials and Methods

This article presented the design implementation and simulation results of an off-grid PV system, a six pulse rectifier, an inductive R-L load and a passive LCL filter. The six pulse converters which are used in off-grid PV systems are the great harmonic source. Voltage and current harmonics are created by non-linear loads, and these harmonics cause many problems. Six pulse rectifiers are used in off-grid PV systems as a load. The odd harmonics have greater impact 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:

$$h = kp \pm 1$$

(1) (1)

Where h is the harmonic order, k is any positive integer, and p is the pulse-number. A six-pulse rectifier produces harmonic components, such as 5th, 7th, 13th, 17th, 19th, 23th, 25th, etc. Harmonic components are generated by six pulse rectifier as given in Equation (2).

$$i(\omega t) = 14.88Sin(\omega t - 0.159) + 2.981Sin(5\omega t + 178.4) + 2.121Sin(7\omega t - 179.2) + 1.348Sin(11\omega t - 0.8763) + 1.145Sin(13\omega t - 0.4928) + 0.8717Sin(17\omega t + 178.7) + 0.7848Sin(19\omega + 178.8) \quad (2)$$

A result of changing spectrum Equation (2) is as shown in Figure 2.

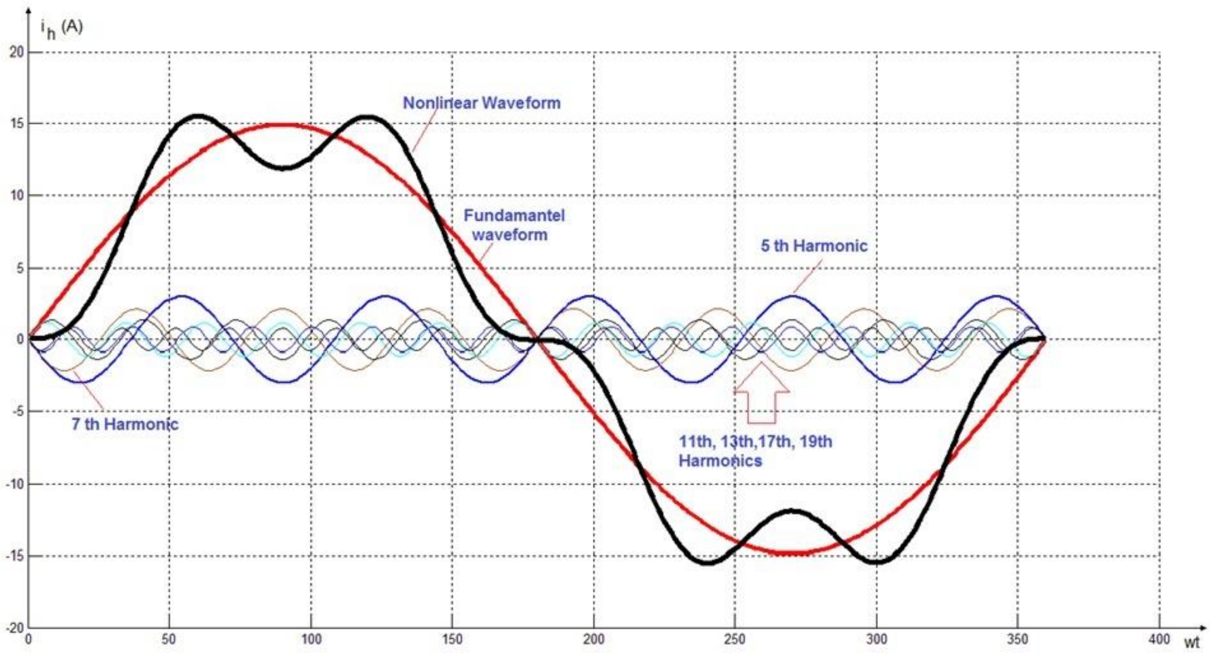

Figure 2. Six-pulse rectifier input current harmonics waveform

Even if non-linear loads are low, they cause distortion of sinusoidal waveform current and/or voltage. Harmonics in the power system will cause the following damage:

- 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 the off-grid PV system,
- Incorrect measurements on induction type meters.
- Disorders in control circuits,
- Incorrect opening in protection relays,
- Incorrect operation of microprocessors and data loss,
- Noise in communication devices,
- Change of power factor,
- Overheating of power system equipment such as cables, AC/DC converters, inverters, six pulse rectifiers and inductive R-L loads,
- Shortened life span of off-grid system devices such as cables, DC/DC boost converters and inverters.
- False triggers switching elements, such as IGBT, MOSFET, gate turn-off thyristor (GTO) and thyristor.
- Errors measurements voltage, current and power in off-grid PV systems.

THD_I is an important aspect in off-grid solar systems and should be kept as low as possible. It is a common measurement of the level of harmonic distortion present in solar systems. THD_I is defined as a ratio of the harmonic components to the fundamental component and expressed as a percent of the fundamental component [3]. The distortion as a percentage of total harmonic distortion for current is defined as follows:

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

Where I_n is the RMS current of the nth harmoniccomponent, I_1 is the effectivecurrent of the fundamental component.The high THD_I have negative effects such as equipment overheating, motor vibration, neutral overloading and low power factor on power systems. THD_I is a common measurement of the level of harmonic distortion present in off-grid PV systems. Harmonics can cause on off-grid PV systems many damages, such as excessive current in neutral wire, overheating of the DC/DC boost converter, microprocessor problems and unexplained inverter crashes [4]. Deteriorated waves are called non-sinusoidal waves. Voltage and current waveform distortion due to harmonics can lead the power system and electrical consumers to either become damaged or become out of order. Some non-linear loads causing harmonics are listed below:

- Uninterruptible power supplies (UPS),
- Switched power supplies,
- Control circuits,
- Frequency converters,
- Battery chargers,
- StaticVAR compensators,
- Variable frequency motor drives,
- Direct current converters,
- Inverters,
- Electric transport systems,
- DC/DC converter,
- Rectifier,
- Photovoltaic systems,
- Induction furnaces.

Reducing the efficiency of non-linear loads and reducing harmonic distortion are very important in terms of the quality of the energy. LCL filters are circuits consisting of capacitor (C), inductance (L) and in some cases resistance (R) elements which is placed between solarinverter and load. Thus, they are designed to eliminate harmonic components outside the fundamental frequency [5-6]. A passive LCL filter has a lot of advantages over an active filter such as guaranteed stability, no power consumption and being inexpensive and conventional. The passive LCL filter plays rather an important role in reducing system harmonics for better off-grid PV quality energy [9-10].

LCL filters are harmonic filters usually used on the load side of renewable energy sources, like wind energy and PV power systems [7-8]. These devices improve and ensure the overall power quality of the produced energy from off-grid PV system. The LCL principle diagram of the LCL filter is shown in Figure 3.

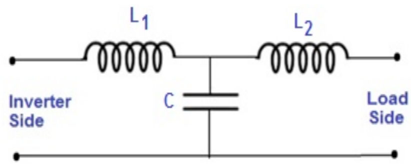

Figure 3. LCL filter modelling

An LCL filter is used to interconnect a solar inverter to the load so as to filter the harmonic components produced by the solar inverter. A passive LCL filter is used to reduce harmonics and improve the power quality in off-grid power systems. This filtering is based on the principle of eliminating harmonic components in the load side by adjusting the L-C passive elements. The LCL filter must be used to keep the harmonic components at The LCL filter must be used to keep the harmonic components at the limits specified in the standard. The Transfer function of LCL filter is defined as:

$$G(j\omega) = \frac{1 + Z_{load} j\omega C}{L_1 L_2 C (j\omega)^3 + (L_1 + L_2) Z_{loud} c (j\omega)^2 + (L_1 + L_2) j\omega} \tag{4}$$

Where Z_{load} is the impedance of the load connected to the off-grid PV system. The frequency of resonance must be in the following range fort to avoid resonance problems.

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

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 LCL filter is defined as:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \tag{6}$$

Reactive power absorbed by capacitor is defined as:

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

The value of the capacitor used in the LCL filter is

$$C = \frac{\alpha P_{rated}}{3(2\pi f)V_{rated}^2} \tag{8}$$

A third-order LCL filter has smaller size in applications. However, resonance frequency is still a problem of this filter. When low value filter inductance is used at the inverter output the THD_I value increases at low switching frequency. The value of L_1 is chosen using Equation (9).

$$L_1 = \frac{V_{in}}{8\lambda f_{res}} \tag{9}$$

Where V_{in} is the input voltage of the inverter, λ is the ripple current which should be 5% of the rated current. The value of L_2 is chosen so that $L_1 = aL_2$, where a is the inductance ratio factor. It is chosen to be greater than 1. This paper describes a design methodology of an LCL passive filter for load inters connectedsolar inverters along with a comprehensive study of how to mitigateharmonic components.

Passive LCL filters are placed between the source and the load and theyare designed to destroy components outside the basic component. These filters have risks, such as serial and parallel resonance. Resonance conditions must be calculated separately for each harmonic components Against this risk can be taken precautions by using passive damping methods [19,20]. Harmonics are undesirable magnitudes in the network because they affect all system elements.

Therefore, it is absolutely necessary to establish filter circuits to eliminate harmonics. For this, filters are installed in the electrical network. Band pass and high-pass filters are frequently used.Resonance occurs in the circuit by equalizing the capacitive and inductive impedances in the system. As a result, ohmic character is not fully effective in the power system. It is clear that the THD_I of the current of output inverter is 91.53 %.

Simulations are performed to see what affects the harmonics on the system waveform and what kind of problems will be solved. Thus, in this study a passive LCL filter was used to mitigate the harmonics in power systems [10-11]. Higher order harmonics can affect the whole system. These effects reduce the performance of the power system and other equipment. A simulation model of the proposed system is as shown in Figure 4.

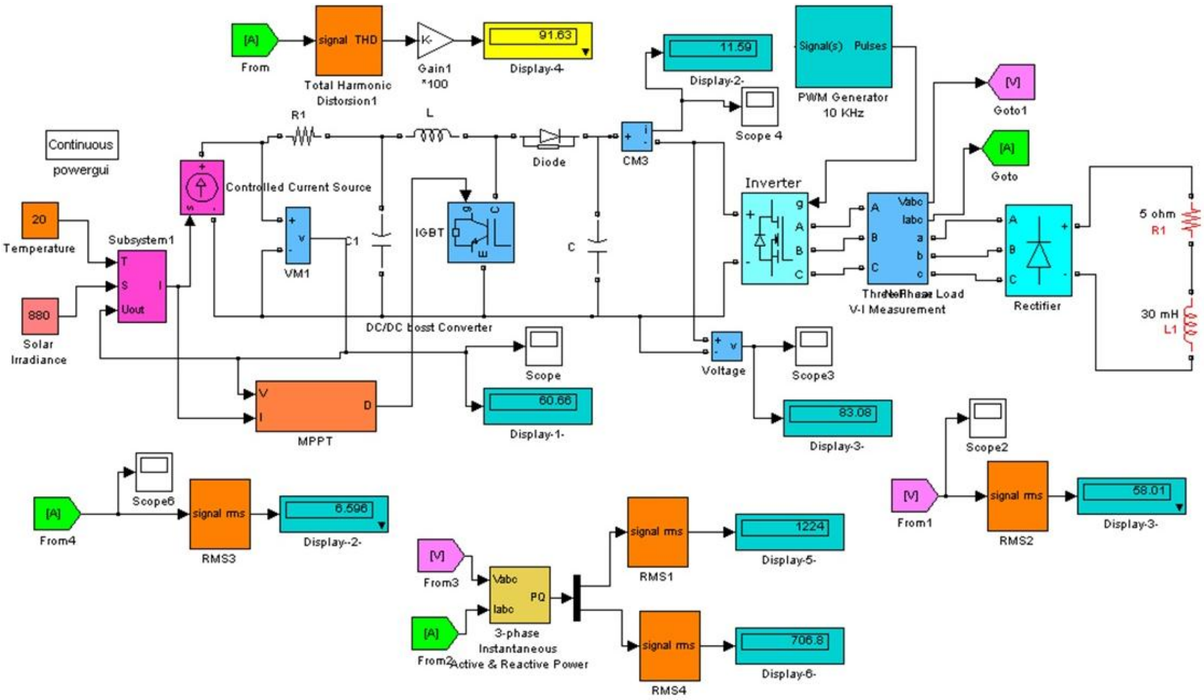

Figure 4. Model off-grid PV system (unfiltered)

As shown in Figure 4, total harmonic distortion is measured as 91.53 %. The six pulse rectifier used as a load in the off-grid PV system is a harmonic source.The six pulse rectifier output voltage waveform is as shown in Figure 5.

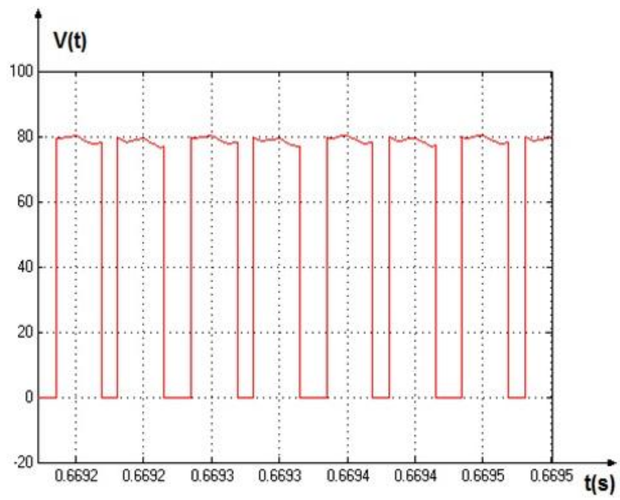

Figure 5. Six pulse rectifier output voltage

Matlab/Simulink program was used to analyze the performance of the designed passive LCL filters. Harmonics produced by non-linear loads must not resonate with the power system. The resonance conditions must be calculated separately for each harmonic component [12-13]. If harmonics are injected into a power system from harmonic sources, they affect the network in such a way that it will resonate with any component.

3. Findings

Simulation of the PV system has been performed in Matlab/Simulink, and parameters used in simulation are given in Table 1. The parameter values of the LCL filter values obtained from Equation (8) and Equation (9) are given in Table 1.

Table1. Parameter values of the LCL filter

Parameters of LCL filter	Values
C	15.45 μF
L_1	11.83 mH
L_2	0.237 mH

Even if non-linear loads are at low power, they distort sinusoidal current and voltage waveforms in off-grid power systems. There are odd and even harmonics in off-grid PV systems. The simulation results show that the odd harmonic components contribute more to harmonics as compared to even harmonics. The results also showed that the THD_I value came down to 6.778 %. As a result, it has been observed that the LCL filter provides a high performance, taking into account some risky points.

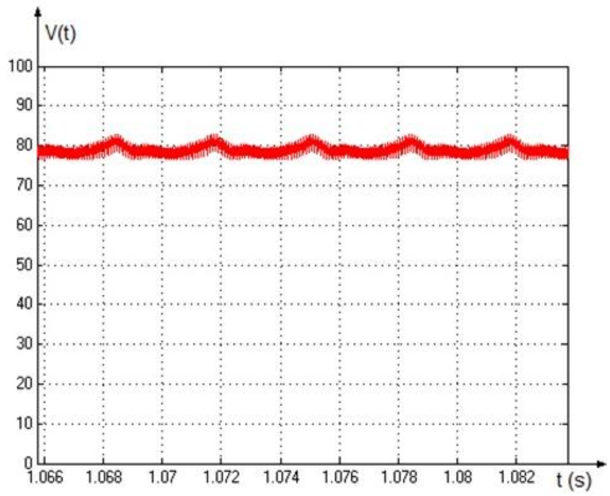

Figure 6. Inverter input voltage waveform

Passive LCL filters are generally used in power systems. The reason for this is that the cost is lower than the active filter and that they are easy to use. The dominant harmonics are detected in the power system and the passive LCL filter is designed accordingly. While harmonic compensation is made with passive LCL filter, power quality in stand-alone system also improved. System structure and working modes were analyzed in detail firstly, and then THD_I belong to the power system analysis based on the simulation program. The results clearly show that the passive LCL filter can reduce harmonics at various frequencies [14-15]. The inverter output current waveform is as shown in Figure 7.

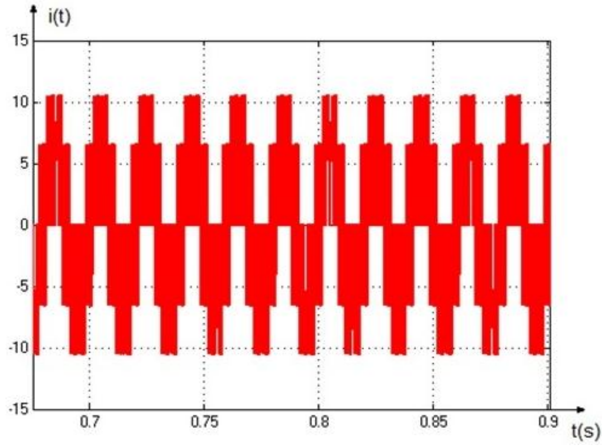

Figure 7. Inverter output current waveform (without filter)

In this system, LCL filter is used to eliminate low order harmonics, and improves off-grid PV power system efficiency. The structure of these filters being simple, low in cost, highly efficient and able to meet basic frequency reactive power needs at the same time are many of their advantages. In this paper, the power system was simulated with and without passive LCL filter in the Matlab/simulink software program. The schematic diagram of the stand-alone PV power system after filtering is shown in Figure 8.

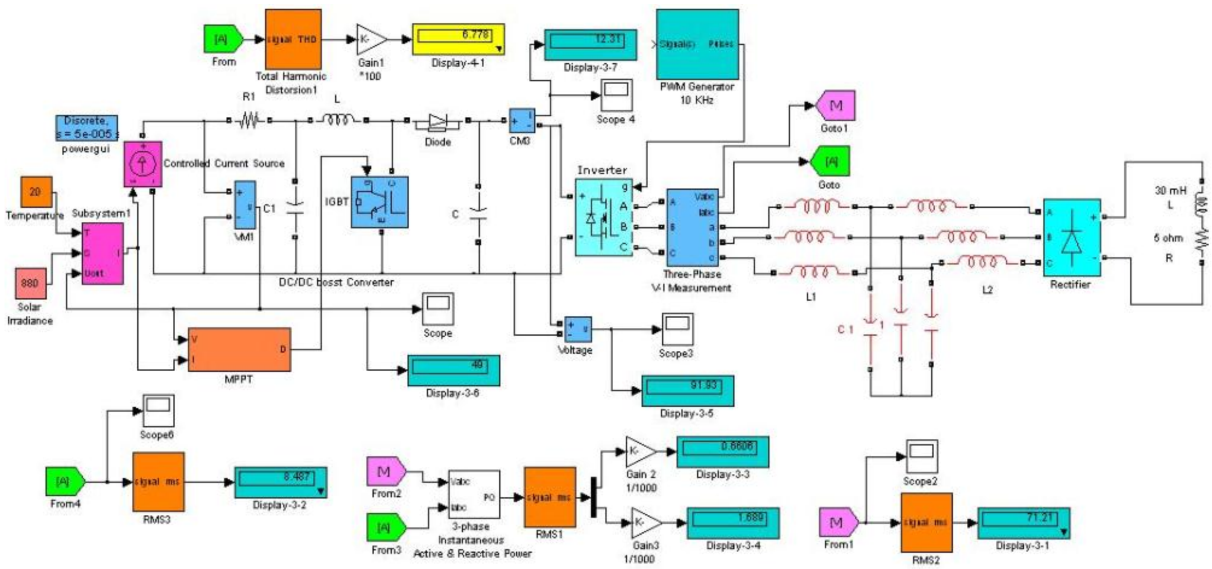

Figure 8. Off-grid PV system model with LCL filter

The change of the inverter output current waveform is given in Figure 8. It is clear that the THD_I of the current is 6.778 %. When the LCL passive filter is used to reduce the switching ripple injected by solar inverter. Reducing the efficiency of non-linear loads and eliminating harmonic distortion is very important in terms of the quality solar energy. Non-linear elements cause serious harmonic pollution in off-grid PV systems and decrease the quality of energy provided to consumers. Harmonics should be drawn below the values stated in standards. The mitigation of harmonic components and improvement of the solar system power quality is essentials of this work. When a large number of non-linear loads connected to the power systems are taken into consideration, it is inevitable that the additional losses and THD values reach power quality also improved high values. The results show that the harmonics distortion generated by PV inverter is reduced by using LCL passive filter. Changing THD_I dependent on temperature irradiance are given in Table 2.

Table2. The value of THD_I depends on temperature & irradiance

Temperature (^OC)	Irradiance (w/m^2)	Total Harmonic Distortion for Current (THD_I)
15	1050	6,780
12	950	6,620
35	1200	7,24
20	880	6,77
22	1150	7,012
10	960	6,797
25	1000	7,083
20	1200	7,250
10	900	6,74

This paper presents the passive LCL filter application to mitigate harmonics and improve the power quality of the off-grid PV system. The THD_I has been successfully decreased from 91.53 to 6.778%. for the used non-linear load system, which fulfils there commended by standard for current. In this study, LCL filter design and performance analysis were performed. As a result, it has been observed that the LCL filter provides a high performance.

There are many serious effects of harmonics on the power systems, such as distortions of voltage waveform, decreases in system efficiency and increases in losses in the system. One of the most important harmonic components in energy systems is single and three phase converters. There are various precautions to reduce them. These precautions are as follows:

- Larger neutral conductor section,
- Use of K-factor transformers,
- Using passive LCL filters,
- Using high-pulse converters.

As a result of LCL passive filter application the system was cleaned from harmonics and the THD_I value fell below 5%. As system losses decreased, efficiency increased. Solar inverter output current waveform is shown in Figure 9.

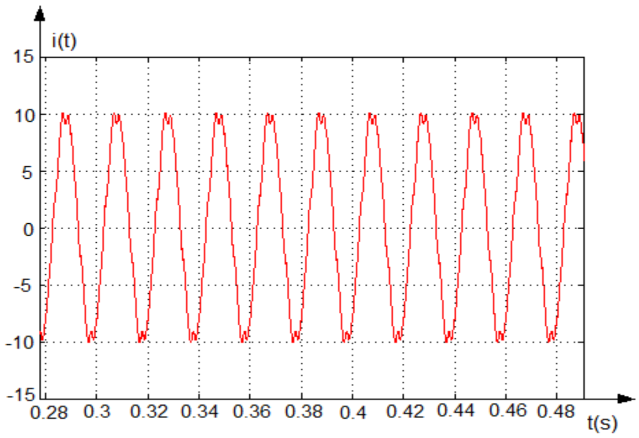

Figure 9. Inverter output current waveform (with filter)

LCL filters are used to reduce input current harmonic components of controlled and uncontrolled rectifiers, where total harmonic distortion exceed given in standards. LCL filters have some disadvantages, such as current ripple on inductances, the total impedance of the filter, reactive power generated by the capacitor, the resonance state of the LCL filter and has a third order transfer function.

4. Results and Discussion

The use of LCL filters have many advantages, such as the increase in the lifetime of the off-grid PV system, the increase in energy quality and the improvement of the power factor value. LCL filter also reduces the value of the 5th and 7th harmonic components caused by six-pulse power converters, so THD_I value in the system also drops.

LCL passive filter is usually used to interconnect between solar inverter and non-linear load so as to filter the harmonic components produced by solar inverter and non-linear load. As a result LCL filter has been observed to suppress inverter side switching and non-linear load harmonics.

The THD_I value was measured as 91.53 % in the off-grid PV system. After using passive LCL filter, the THD_I value was measured as 6.778%.These values correspond to the values expressed by the standard (IEEE STD 519) .

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