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ORIGINAL ARTICLE

Harmonics Mitigation of Stand-Alone Photovoltaic System Using LC Passive Filter

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Abstract
This article investigates modeling and simulation of the off-grid photovoltaic (PV) system, and elimination of harmonic components using an LC passive filter. Pulse width modulation (PWM) inverter is used to convert the direct current to alternating current. It is very important in terms of energy quality that the inverter output current total harmonic distortion (THD_I) is below the value given by standards. Harmonic components have negatively effect on off-grid PV power system. THD_I should be kept below a certain level in order to prevent damage to the equipment in the off-grid system and to ensure a higher quality energy flow to reduce the total harmonic distortion (THD) of the solar inverter output current; LC passive filter must be connected to the output of the PWM inverter. There are many types of passive filters for solar inverters. One of the most widely used filter types is the LC filter. LC filters are used in off-grid systems. LC filter is smaller in size and lower cost than other filters. But it is more complicated to determine the parameters of the LC filter. Therefore, in order for the system to remain in a steady state, the parameters must be accurately calculated and analyzed. In this study, the output power of the solar inverter, switching frequency, bus voltage etc. values were determined and LC filter parameters were calculated. Since high inductance values are used in LC filters, the voltage drop increases in these filters. To reduce the voltage drop, the DC bus voltage must be increased, which increases the switching losses. LC filter is connected between the inverter and the nonlinear load to filter the harmonic components produced by the DC/DC boost converter, DC/AC inverter and non-linear load. Matlab/Simulink program was used in Simulation and analysis of off-grid solar system. Solar inverter output current THD was measured as 91.55%. After the LC filter is connected to the system, this value has dropped to 2.62%.

Keywords Six-pulse rectifier · Total harmonic distortion for current · Passive LC filter · Off-grid photovoltaic system

1 Introduction

We need to turn to renewable energy sources so as to meet the energy needs of future generations and to minimize the damage to the environment. Photovoltaic (PV) energy is very economical in terms of usage and installation and has no harm to the environment. However, its efficiency in terms of energy production is low and it does not have a regular production. In other words, its production can rise and fall. PV energy is converted into electrical energy by PV panels. PV energy, which is among the renewable energy sources, can be obtained without any harm to the environment. This type of energy, which was much more costly in the past, is now increasing rapidly thanks to more affordable costs.

Non-linear elements such as power electronic converters, speed control drivers, arc furnaces, voltage regulators, uninterruptible power supply generate harmonic components, and they are injected harmonics into power system.

Owing to the nonlinear elements in the power system and the events cause, they can deviate from the exact sinusoidal wave form. Deviation from full sinusoidal wave form is often expressed by the appearance of components called harmonics. One of the most important harmonic components in energy systems is single and three phase line commutated converters.

The PWM inverter output current THD total value can be reduced using the LC passive filter. Passive filters are frequently used in solar systems to reduce the amplitude of harmonic components and improve power quality. These filters have many advantages such as high efficiency, low

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cost, high durability and simple structure. In addition, these filters are preferred to compensate for the reactive power of the system. The principle scheme of the off-grid PV system is as shown in Fig. 1.

The off-grid power system consists of PV panel, DC/DC boost converter, DC/AC PWM inverter, six pulsed uncontrolled rectifier inductive R-L loads and passive LC filter. Off-grid power system is modelled by using Matlab/Simulink which shows the effectiveness of passive filter. Power electronic equipment such as DC/AC PWM inverters, DC/DC buck-boost converter operate according to the switching principle. These switching strategies cause significant harmonic components and negatively affect on quality of the off-grid PV system. In this article, it is proposed to use an LC filter to suppress harmonic components at the output of the PWM inverters and to obtain output current in sinusoidal form in off-grid solar system [1, 2].

LC passive filters, the most commonly used filters in order to compensate harmonic component. There are many types' passive filter such as single tuned, double-tuned and band-pass. Theoretically LC passive filters eliminate harmonics by showing zero impedance at the selected frequency [4, 5]. 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 LC passive filter to mitigate harmonic component in power system [3–6]. High THD value can affect the whole system. These effects reduce the performance of the power system and other equipment.

2 Effects of Harmonic Components in Stand-Alone PV System

Harmonic components are produced by devices using power electronic components such as thyristors, diodes, Metal Oxide Semi-conductor Field Effect Transistor (MOSFET), Insulated Gate Bipolar Transistor (IGBT) in their circuits. Harmonic components cause serious power quality problems in off-grid solar systems.

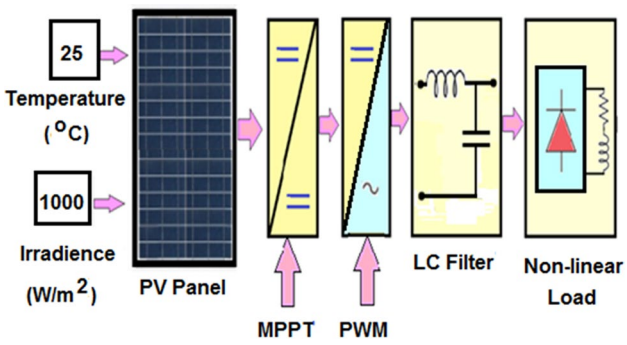

Fig. 1 Schematic Representation of stand-alone power system

Non-linear elements cause severe harmonic pollution in solar power systems and negatively affect the quality of energy produced. DC/DC Buck-boost converter, DC/AC PWM inverter and used in solar systems are harmonic sources. Because characteristics of the switching elements used in these are non-linear characteristic. In solar systems, passive filters are widely used to eliminate harmonic components created by non-linear loads and converters. Harmonics generated by the converters may be formulated depending on the number of pulses of the converter. Non-linear elements cause severe harmonic pollution in solar power systems and negatively affect the quality of energy produced. DC/DC Buck-boost converter, PWM inverter and used in solar systems are harmonic sources. Because characteristics of the switching elements used in these are non-linear characteristic.

In solar systems, passive filters are widely used to eliminate harmonic components created by non-linear loads and converters. 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:

$$h = np \pm 1 \tag{1}$$

where h orders of harmonics, n an integer, p number of pulses. The six pulse converters which used in power system is the great harmonic source. The harmonics components in the solar system are created by nonlinear loads and these harmonics cause many problems. Harmonics components cause increased energy losses in solar system and decrease the quality of the produced energy. Six pulse rectifiers are usually used in industrial plants. The following relationship exists between the fundamental components current (I_1) and the harmonic component current (I_n).

$$\frac{I_n}{I_1} = \frac{I}{n} \tag{2}$$

The odd harmonics have greater impacts on power quality than even harmonics as they have higher magnitude. Non-linear elements cause distortion of the sinusoidal waveform even if they have low power. Harmonics components or low THD in the power system will cause the following damage in off-grid power system:

- Increased losses of elements in the power system,
- Disruption of the dielectric insulation of elements in the power system,
- Increase in voltage drop
- 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 and inductive R-L load.
- Shortened life span of power system devices such as cables, rectifier, and transformer.
- False triggers switching elements such as thyristors, igbt and mosfet.
- Errors measurements voltage, current and power in power system.
- The THD_I term expresses as effective value of the all harmonics, divide by the effective value of its fundamental of current.

Non-linear current wave is defined as:

$$\begin{aligned} i(\omega t) = {} & 5.19\sin(\omega t - 0.16) + 2.11(5\omega t + 180) \\ & 1.11\sin(7\omega t - 171) + 0.99\sin(11\omega t - 0.19) \\ & + 0.55\sin(13\omega t - 0.5) + 0.11\sin(17\omega t + 176) \end{aligned} \quad (3)$$

The graphic of the nonlinear current wave is shown in Fig. 2.

Non-linear elements cause distortion of the sinusoidal waveform even if they have low power. Harmonics components or low THD in the power system will cause the following damage in off-grid power system:

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- False triggers switching elements such as thyristors, igbt and mosfet.
- Errors measurements voltage, current and power in power system.

The THD_I term expresses as the ratio of effective value of the all harmonics to the effective value of its fundamental of current. We can determine the level of damage harmonics giving to the network by the THD coefficient. Total harmonic distortion for current is defined as:

$$THD_I = \frac{\sqrt{\left(I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2\right)}}{I_1} * 100\% \quad (4)$$

where In is Root mean square (RMS) current of the nth harmonic and n = 1 is the fundamental frequency. I_1 is the.

effective current at the fundamental frequency, If the sum of harmonic components is equal to "0", the THD will be equal to "0". The high THD have negative effects on power system such as equipment overheating, motor vibration, neutral overloading and low power factor.

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 nonlinear loads are non sinusoidal sources. Even if nonlinear loads are low powering solar system, they distort sinusoidal

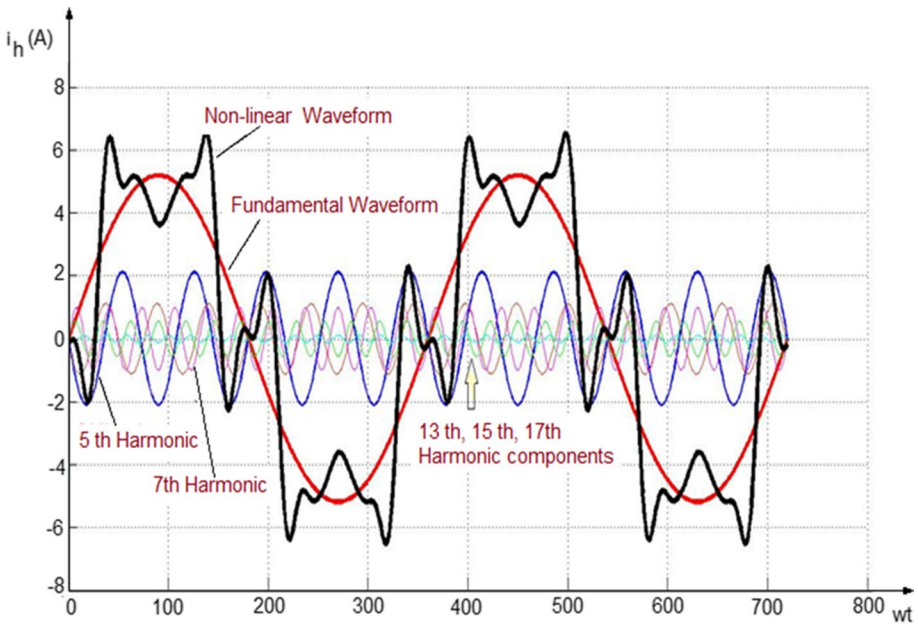

Fig. 2 Six-pulse uncontrolled rectifier input current harmonic spectrum

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.

3 Passive LC Filter Topologıes

Passive filters are classified as serial passive filters and parallel (shunt) passive filters. Parallel passive filters are the most generally used filter structures to compensate harmonics. There are many types of passive filters, such as single tuning, dual tuning, and band passing. Theoretically passive filter showing zero impedance at tuned frequency and eliminates harmonics. Passive filters are placed between the source and the load. They are designed to destroy components outside the basic component. In [7–9], are mentioned in the topology of passive filters. However, it does not describe a large scale passive LC filter..

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 [10–14]. Passive filters are generally tuned to a harmonic order, and they exhibit low impedance to the harmonic order to set, and eliminating harmonics. Filters which set of frequency theoretically displaying zero impedance and eliminates harmonics stability analysis as a decoupling network is used.

The increasing use of power electronics based devices has led to an increase in non-sinusoidal current and voltage magnitudes in off-grid energy systems [11, 12]. 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. Structures of LC passive filter are shown in Fig. 3.

The LC filter is connected to the inverter output to reduce the THD value. Passive filter circuits consisting capacitor (C), inductance (L) and in some cases resistance (R) elements which are placed between the source and load. Thus, they are designed to eliminate components outside the fundamental

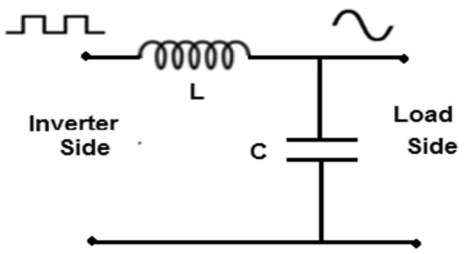

Fig. 3 Schematic diagram of passive LC filter

frequency. A passive filter has a lot of advantages over an active filter such as guaranteed stability, no power consumption, inexpensive, and conventional. LC filter is a crucial part in designing the PWM inverter [15–17].

Passive LC filter is used to reduce THD_I and improvement power quality in off-grid power system. This filtering is based on the principle of eliminating harmonic components in the network by adjusting the L-C passive elements [6, 13, 14]. The structure of LC filter being simple, low prices, high efficiency and being able to meet basic frequency reactive. To avoid resonance problems in the LC filter, the filter's resonance frequency must be more than 10 times the value of the mains frequency and less than half the switching frequency. Therefore, the resonance frequency should be within the range given by Eq. (5) below:

$$10f_o \leq f_{res} \leq \frac{f_{sw}}{2} \tag{5}$$

where f_0 is the utility frequency, f_{sw} is the switching frequency and f_{res} witch is the resonant frequency. The resonant frequency of LC filter at the switching frequency is defined as:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{6}$$

As a result of selecting high capacity value, it provides filtering of high order harmonic components. However, a large selection of C causes an increase in the current passing through L, which causes a decrease in filter efficiency. In case of small selection of the capacity value, L should be chosen larger. This causes the filter size to increase. Reactive power absorbed by capacitor is defined as:

$$Q_C = \frac{3V_{rated}^2}{\frac{1}{\omega c}} = 3(2\pi f)CV_{rated}^2 \leq \alpha P \tag{7}$$

where Q_c is reactive power absorbed by capacitor. V_{rated} is effective value of phase voltage. α is reactive power absorption rate. It is usually chosen below 5%. C value is chosen according to the reactive power absorbed by the filter. capacitor value from Eq. (7) is defined as:

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

found as. High capacitance capacitor is used to prevent high inrush currents at fundamental frequency. The value of the L inductor is designed by determining the current ripple.The value of L is chosen using Eq. (9).

$$L = \frac{v_{dc}}{8\Delta I_{ripple} f_{res}} \tag{9}$$

where Vdc is the input voltage value of the inverter, ΔI the ripple rate is chosen as 5% of the rated current, fres is the resonant frequency of the LC filter [17]. Passive LC filters are placed between the PWM inverter and the load. It is designed to destroy harmonic components outside the basic component [16–18]. The proposed system is simulated in Matlab/Simulink software program as shown in Fig. 4.

The DC/DC boost converter used in Fig. 6 consists of C1, C2, L1, R1, R2 parameters. The values of these parameters, C1 = C2 = 2mH, L = 0.011 H and resistance values were found as R1 = 0.99 Ω, R2 = 0.88 Ω. DC/ DC boost converters are widely used in photovoltaic power systems.

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. Therefore, it is absolutely necessary to establish filter circuits to eliminate harmonics. For this, filters are installed in the electrical network. Harmonics components amplitudes should be reduced below the limit values specified in the standards. LC passive filter has the following disadvantages:

- It is very sensitive to changes in the value of elements over time.
- Single tuned filters can be used only for nonlinear load systems with fixed power.
- When the inductive loads in the system are removed. In this case, excessive compensation may occur.
- The filter characteristic is influenced by the source impedance.
- The filter can be overloaded when the harmonic current components increase.

Thanks to the LC filter connected to the output of the PWM inverter, a sinusoidal current is obtained. The passive LC filter plays quite an important role in reducing system harmonic components for better quality energy.

Passive filters are used to reduce harmonics components and improvement power factor in electrical networks. This filtering is based on the principle of eliminating harmonic components in the network by adjusting the LC passive elements [19, 20]. 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.

PWM inverter output current THD was measured as 91, 55%. This value is quite high. It should be reduced by using a passive LC filter. High THD values affect the entire system, reducing the quality of energy transferred to the load. These effects reduce the performance of the power system and other equipment. LC filter is harmonic filter usually used on the load side of stand-alone energy sources. This filter improve and ensure the overall power quality of the system. The filtering of the solar inverters' switching frequency is crucial for an optimized system configuration and the fulfillment of standards. Before filtering the inverter output current waveform is as shown in Fig. 5.

Using an LC low-pass filter will prevent the voltage drop in the output voltage. Matlab/Simulink program was used to analyses performance of the designed passive LC filters. Harmonics produced by nonlinear loads must not resonate with the power system. Resonance conditions must be calculated separately for each harmonic component. If harmonics are injected into a power system from harmonic sources, they affect the network in such a way that it will In this model, the LC filter parameters are designed using a Matlab/ Simulink model.

The THD value of the current transferred to the load in the solar inverter must comply with international standards. In order to transfer the current to the network in compliance

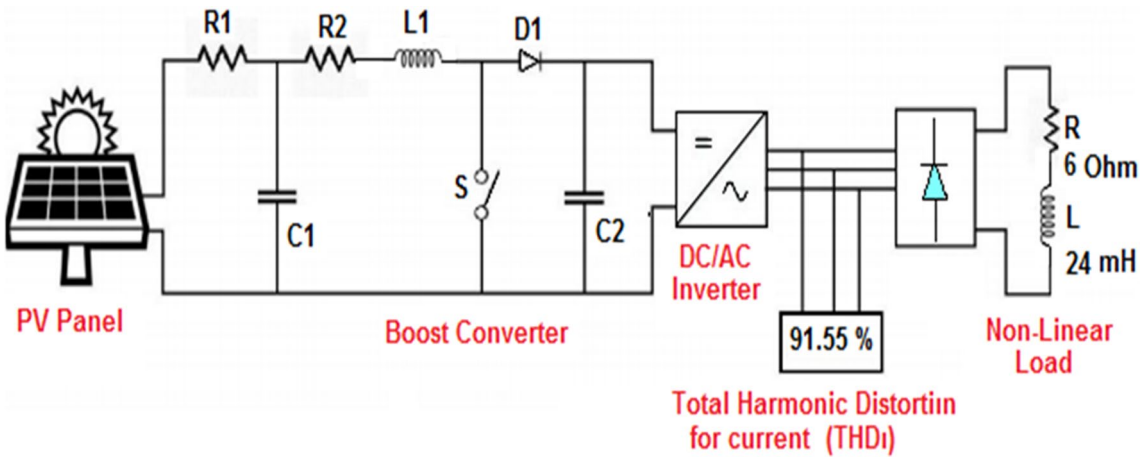

Fig. 4 Model of stand–alone PV system (without filter)

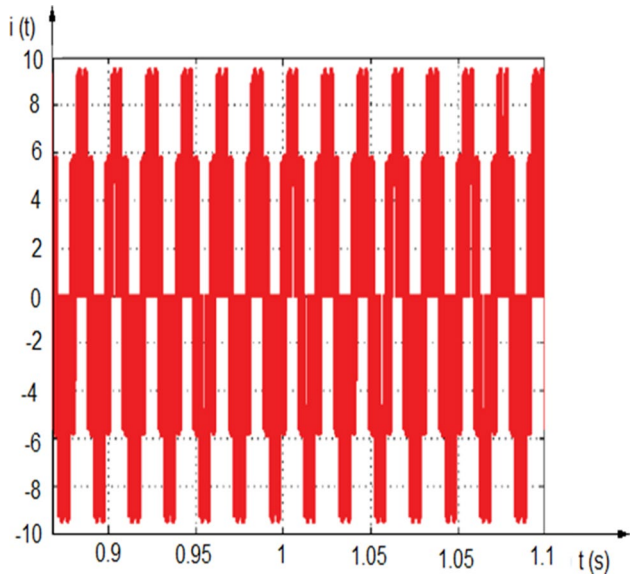

Fig. 5 Output current of PMW inverter (without filter)

Table 1 Designing parameters of LC filter

Parameters of LC filter	Values
L	11.19 µF
C	82.99 mH

with these standards, a filter must be used at the output of the inverter.

There are many filtering methods for grid interactive inverters. The most widely used filter type is LC filter. LC filter is smaller in size and cost less than other filters. However, determining the parameters of the LC filter is more complicated. Therefore, in order for the system to remain in steady state, parameters must be calculated and analyzed correctly [21].

LC filters generally have a widespread use in off-grid photovoltaic systems. In this context, LC filters are not designed as grid-connected. Parameter values of the LC filter values obtained from Eqs. (8) and (9) are given in Table 1.

The occurrence of this phenomenon causes a maximum flow of current through the system. The aim of harmonic filters is to reduce the negative effects of harmonics and to improve the power factor in system. The proposed off-grid power system is designed in Matlab/Simulink program. The main purpose of LC filter is to eliminate of the unwanted harmonic component which are results of high switching frequency of the mosfet transistors. Figure 6 shows the schematic diagram of the power system after filtering.

4 Elimination of Harmonics by Using LC Passive Filter

Matlab/Simulink program was used to analyse performance of LC passive filter. Harmonic component produced by non-linear loads must not resonate with the power system. Resonance conditions must be calculated separately for each harmonic component. The dominant harmonics are detected in the power system and the passive LC filter is designed accordingly. While harmonic compensation is made with passive LC filter, and the reactive power compensation is also performed.

System structure and working modes are analysed in detail firstly, and then THD_I belong to the power system analysis based on the Matlab/simulation program. The results clearly show that the passive LC filter can reduce harmonic component at various frequencies as compared to active filter. In this paper, off-grid PVpower system is

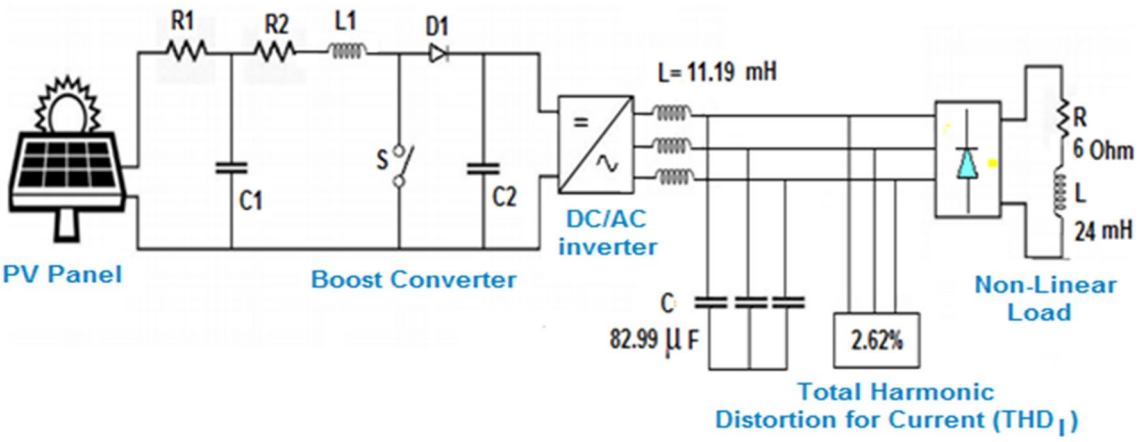

Fig. 6 Power system model with LC passive filters

simulated with and without LC passive filters in the Matlab/simulink software program.

Harmonic components have two effects on energy systems, technical and economical. Technical problems are problems that affect the delivery of quality electricity to consumers. Economic problems are problems that affect optimal work. Reducing the efficiency of non-linear loads, eliminating harmonic distortion is very important in terms of the quality energy. The proposed off-grid power system is designed in Matlab/Simulink program. The main purpose of LC filter is to eliminate of the unwanted harmonic component which are results of high switching frequency of the mosfet transistors.

The LC filter parameters calculated using the script give very good performance. There are odd and even harmonics in off-grid PV systems. 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 2.62%.

In this article, the LC passive filter is used to reduce the inverter output current THD_I value in the off-grid PV system. As losses decrease in the solar system, the efficiency of the system increases. Harmonic components are pollution in off-grid PV systems. As the use of DC/DC and/or DC/AC converters increases day by day, this pollution rate is constantly increasing. The PWM inverter output current change is as shown in Fig. 7.

Non-linear elements cause serious harmonic pollution in off-grid solar systems and decrease quality of energy transferred to consumers or load. There are many serious effects of harmonic components in the off-grid power system such as distortions of voltage and current 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. Resonance occurs in the circuit by equalizing the capacitive and inductive impedances in the system. The connection diagram of the LC filter is as shown in Fig. 8.

The transfer function of the circuit in Fig. 3 as following,

$$G(s) = \frac{U_{load}}{U_{inv}} = \frac{1}{LCs^2 + 1} \tag{10}$$

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G=tf ([1], [928.66 0 1]);
bode (G).
grid on.
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Bode diagram of the LC filter is given in Fig. 9.

Passive 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 filter is designed accordingly. While harmonic compensation is made with passive filters, and the reactive power compensation is also performed. System structure and working modes are analysed in detail

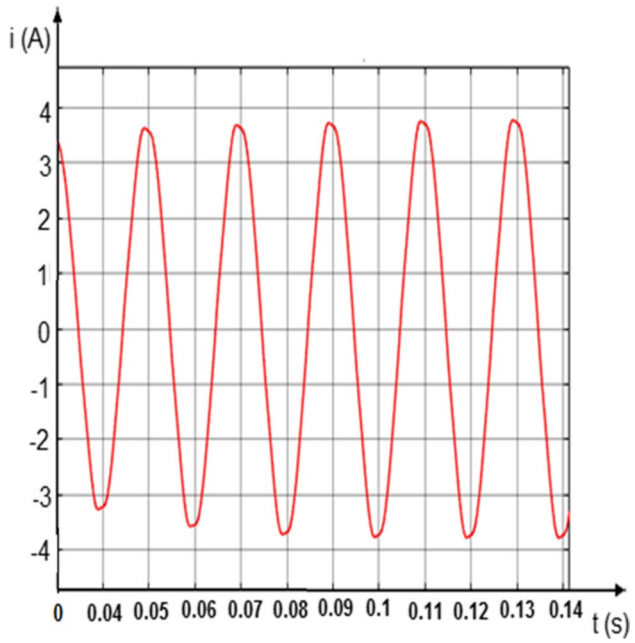

Fig. 7 Inverter output current (after filtering)

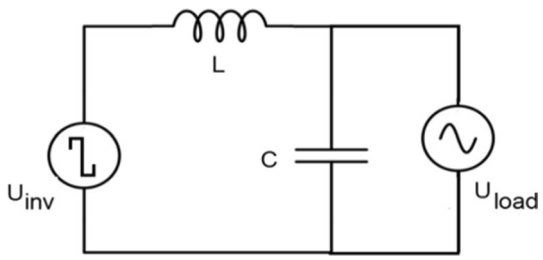

Fig. 8 Passive LC filter connected between inverter and load

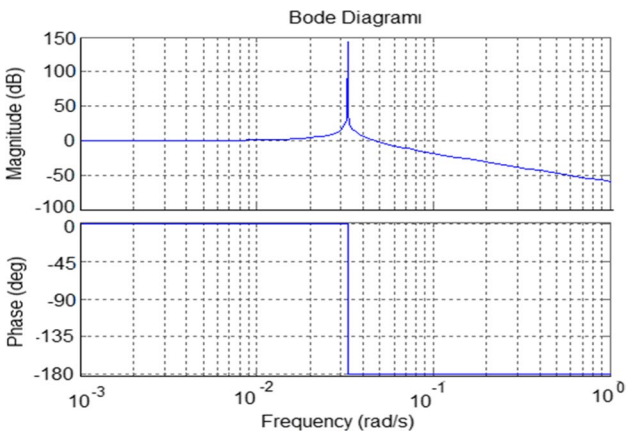

Fig. 9 Bode plot of LC filter

firstly, and then THDI belong to the power system analysis based on the simulation.

5 Conclusion

Off-grid PV systems are generally installed in remote areas where there is no main grid. The quality factor of the energy transferred from the inverter to the load must be high. Therefore, the THD_I value must be below the values expressed by the standards.

In order to reduce the high THD value which occured at the output of the load, an LC passive filter must be connected between inverter and load. The result obtained from Matlab/Simulink shows that the LC filter used in the off-grid system can effectively reduce the inverter output current THD from 91.56 to 2.62% that is highly efficient in reduction for harmonic components. As a consequence, this result meets the THD_I standard recommended by IEEE 519.

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