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Research Article

ELIMINATION OF HARMONIC COMPONENTS IN SOLAR SYSTEM WITH L AND LC PASSIVE FILTERS

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Abstract: *As a result of the increase in the use of power electronics-based converters (DC/DC to DC/AC) and non-linear loads, harmonic components occur in the solar networks. It is quite common to use passive LC and L filters to eliminate harmonics in the solar PV systems. The solar system analyzed and modeled consists of solar panels, DC boost converter, PWM controlled solar inverter and six pulsed uncontrolled rectifier. Six pulse uncontrolled rectifier used as load in off-grid solar system produces 5^{th}, 7^{th}, 11^{th}, 13^{th} etc. harmonic components. LC and L filters are used to reduce the solar inverter output current total harmonic distortion (THD_I). In the solar system, the THD_I value has been reduced to the limit values given by the standards.. LC and L filters are commonly used to eliminate harmonics in solar system. Their widespread use is due to their easy structure and control. Modeling and simulation of the stand-alone PV power system was carried out with Matlab/Simulink program. While the value of THD_I was reduced from 91.57% to 2.62% with the LC filter, the value of THD_I was reduced to 5.73% with the L filter. It has been observed that the performance of the LC in eliminating the harmonic components is better than the L filter. As a result, LC filter improves both the system efficiency and reduce the THD_I value.*

Key Words: *L filter, LC filter, Solar Inverter, Off-Grid Solar System, Total Harmonic Distortion*

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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 [1-3]. 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 waveform of current and voltage signals. Non-linear waveforms contain harmonic components. These harmonic components occur in integer multiples of the main components [2-4]. Harmonic distortion is generally caused by non-linear elements in electrical solar power systems. Harmonic currents generated by power electronics circuit elements, such as thyristor transistor, diode, mosfet transistor and igbt transistor cause a decrease in the power quality of stand-alone PV systems.

As a result, the use of non-linear circuit elements in solar systems increases the efficiency of harmonic components in the solar system. In addition, rectifiers, inverters and dc boost converters are sources of harmonics in solar systems. Due to the stability problems of LC and L filter a damping resistor can be added to LC and L filters [5, 6]. However, the resistor has power loss in off-grid PV power system. The scheme of a stand-alone PV power system is given in Fig. 1.

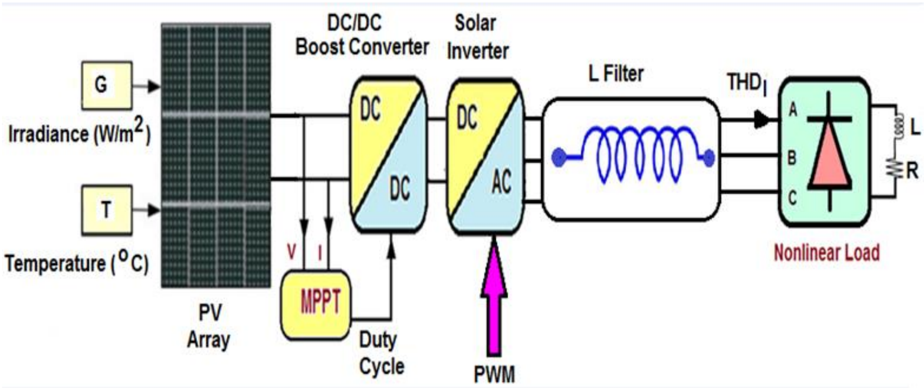

Figure1. Principle diagram of stand-alone PV system (with L filter)

There are many problems about power quality in off-grid PV systems. Among these problems, harmonics are one of the most important. Harmonic components must be eliminated absolutely. 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 [7-9]. 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. The maximum power point tracking (MPPT) occurs from a few hyperbolic curves [8-10].

Microcontroller based photovoltaic MPPT charge controller can be found by differentiating the cell power equation and setting the result equal to zero. This is known as the MPPT, and corresponds to the knee of the curve [11, 12]. The principle diagram of the elimination of harmonics with LC filter is as given in Fig. 2.

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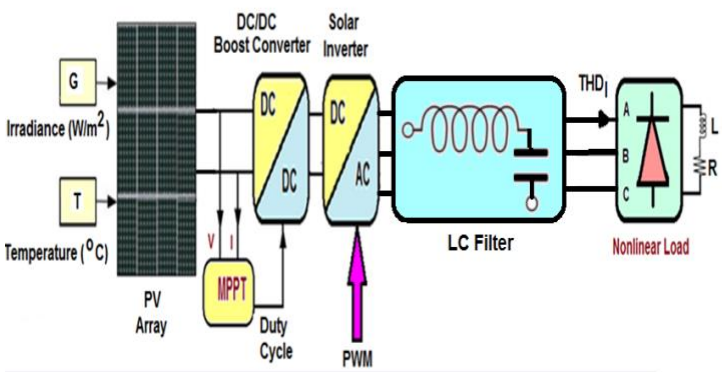

Figure 2. Principle diagram of off-grid PV system (with LC filter)

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 increase in harmonic components causes the THD value to increase [13-15].

2. Harmonic Components in Stand-Alone Solar System

As a result of the increasing use of power electronics-based converters in the solar system, they have increased the efficiency of harmonic components in the solar system. The reason for the distortion of the voltage and current waveform in the solar system is the use of non-linear converters and loads. Non-linear circuit elements and loads distort current and voltage waveforms in solar systems, even if at low power. Harmonic components cause serious problems in power systems and reduce the quality of the energy transferred to the load. Semiconductor elements in the power electronics devices generate the THD_I [14- 16]. They also cause line losses and resonance problems in the solar system.

A six-pulse rectifier with R-L inductive load is used as a load in the off-grid PV system. Single component harmonics in the solar system have a negative effect on power quality as they have high amplitudes. The harmonic components produced by the converters in the solar system vary depending on the number of pulses [17-19]. As a result of the increasing use of power electronics-based devices in solar systems, harmonic components are increasing day by day. Equations (1) relate the harmonic current generated by the six-pulse rectifier. Six-pulse rectifier used as a load in the off-grid system, and produces 5^{th}, 7^{th}, 13^{th}, 17^{th}, etc. harmonic compenents. The equation for these harmonics as given in Eq. (1).

$$i(\omega t) = 15\mathrm{Sin}(\omega t\text{-}0.16) + 2.99\mathrm{Sin}(5\omega t+178.3) + 2.12\mathrm{Sin}(7\omega t\text{-}179) + 1.35\mathrm{Sin}(11\omega t\text{-}0.88)+ \\ +1.13\mathrm{Sin}(13\omega t\text{-}0.49)+0.87\mathrm{Sin}(17\omega t+179)+0.78\mathrm{Sin}(19\omega t+179) \quad (1)$$

A result of changing spectrum of Eq. (1) is as shown in Fig. 3.

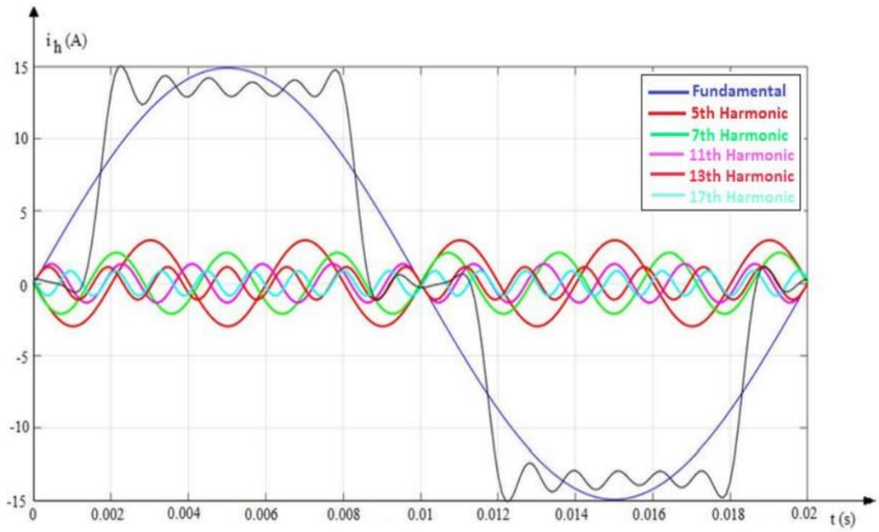

Figure 3. Six-pulse rectifier input current harmonics waveform

In the solar system, harmonic components cause distortion of the wavelength of the current and voltage and increase the THD_I. Increase in THDI value will cause damage or failure of devices in solar system. [18-20]. Some of the non-linear loads and converters that cause harmonic components in the solar system are as given below:

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

A common measure of the level of harmonic distortion present is THD_I. Total harmonic distortion is defined as the ratio of the harmonic components to the fundamental components. THD_I is defined as follows:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (2)$$

Where, In is the effective values of the harmonic components, I1 is the effective value of the basic component. The current and voltage for stable and safe operation of the solar energy system must be sinusoidal waveform. However, these fundamental magnitudes lose their sinusoidal form due to harmonic components in the solar system. High THDI value has many disadvantages. These are equipment overheating, oscillating motors, neutral overheating and low power factor.

3. Elimination of harmonic components in off-grid solar system with L and LC passive filters

Four passive filters, L, LC, LCL and LLCL, are used to eliminate harmonic components at the solar inverter output. These passive filters have advantages and disadvantages When compared to each other. Finding the transfer function of the passive filter L and performing its analysis is quite easy compared to other filters [21, 22].

The cost of the LC filter is higher than the L filter. However, lower THD values are obtained with this filter compared to the L filter. It is necessary to eliminate harmonic components caused by nonlinear loads and converter and reduce the THDI value. This is very important for the efficiency and quality of energy [23- 24]. LC and L filters are placed between the solar inverter and the non-linear load. These filters are designed to eliminate harmonic components of solar system. L passive filter consists of inductance circuit element. In Figure 4, the principle diagram of the L filter is given.

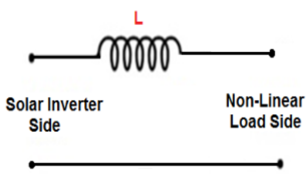

Figure 4. L filter modelling

A passive L filter has many advantages over an active harmonic filter, such as low power consumption, stable operation, reduction of THD_I and low cost. LC and L passive filters are generally used to eliminate harmonics in renewable energy sources such as wind power and solar power systems. These filters are used on the load side and improve the power quality of the solar energy produced in PV systems [25- 27]. The principle diagram of the LC filter is shown in Fig. 5.

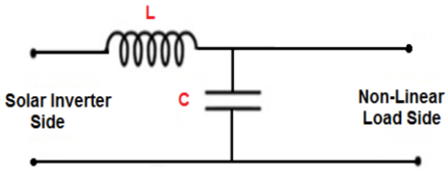

Figure 5. LC filter modelling

In solar off-grid power systems, passive LC filter is used to reduce harmonic components, improve power quality and reduce THD_I value. In the solar system, the harmonic components are eliminated by tuning L-C passive elements. LC filter should be used to keep the THD_I at the limit value specified in the standard. In the solar system, resonance has very destructive effects. To avoid resonance, the resonant frequency of the passive filter must be more than ten times the solar grid frequency and less than half of the inverter switching frequency [26- 28]. The resonant frequency should be in the range given in Eq. (3).

$$10\omega_0 \leq \omega_{res} \leq \frac{\omega_{sw}}{2} \tag{3}$$

Here, w_0 is the solar grid frequency (rad/s), w_{res} is the solar grid resonance frequency (rad/s) and w_{sw} is the inverter switching frequency (rad/s). The resonant frequency of the passive LC filter is defined as follows:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{4}$$

Capacitor reactive power is

$$Q_c = 3.(2\pi f)CV_{rated}^2 \leq \alpha P \tag{5}$$

The value of the capacitor used in the LC filter is defined as:

$$C = \frac{\alpha P_{rated}}{3(2\pi f)V_{rated}^2} \tag{6}$$

A high-capacity capacitor is used. In order to prevent high inrush currents in the solar system. The value of the L inductance was chosen according to equation (7) in order to keep the ripple rate low.

$$L = \frac{V_{dc}}{2\Delta I_{ripple} f_{res}} \tag{7}$$

Here, Vdc is the output voltage of the boost converter, ΔI current ripple ratio, this value is selected as 5% of the rated current, fres resonant frequency of the filter. Passive LC filter is placed between the solar inverter and the non-linear load [29- 30]. A second stage LC 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.

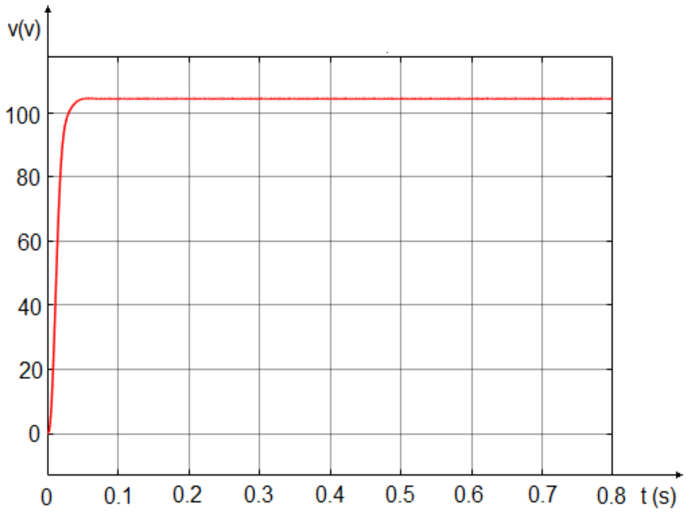

Figure 6. PWM inverter input voltage

Filter circuits must be installed for the elimination of harmonic components in the off-grid network. 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 91.57 %. This value of THD_I is quite high. If the necessary precautions were not taken, it would cause a lot of damage to the solar PV system.

4. Elimination of Harmonic Components in Off-Grid Solar System with L And LC Passive Filters

A passive L, LC filters are required between a PWM inverter and the nonlinear load imposing and reducing harmonic compenents of the inverter output current. Simulations were made to find the harmonic components in the solar power system and to analyse their effects on the PV system. In this study, passive LC or L filters are used to eliminate harmonic components in power systems and improve power quality of solar system. The voltage harmonics are inevitable factors due to the pulse-width modulation (PWM) by the switching frequency of the PWM inverter.

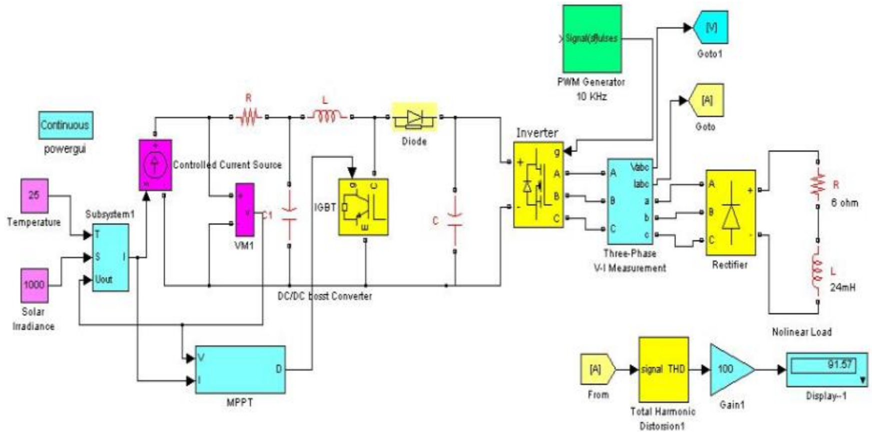

Figure 7. Matlab/Simulink model of stand-alone solar PV system (unfiltered)

For safety issues, disturbances caused by current harmonics should be avoided so they do not affect other loads connected to the same off-grid network. In order to attenuate current harmonics, input filters such as the simple inductive L and the LC combination structure are widely used in stand-alone PWM inverter applications

High-order harmonics in the solar power system affect the entire system, causing their distortion. In this study, two different filters, L and LC, were designed for the three-phase solar inverter and the performance analysis between them was made. The lowest size and the highest harmonic performance were obtained with the LC filter. A simulation model of the proposed off-grid solar system equivalent circuit is as shown in Fig. 8.

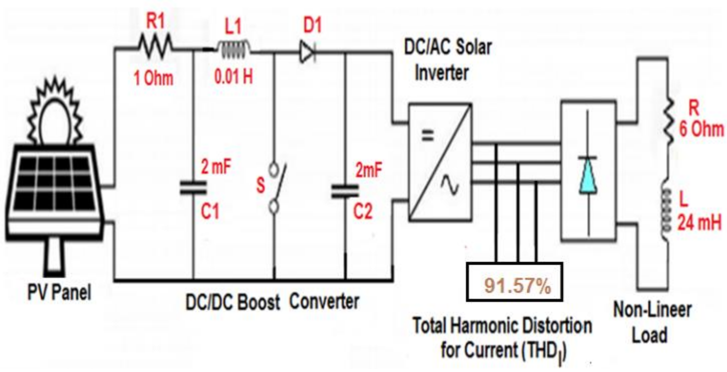

Figure 8. Equivalent circuit Model of stand-alone solar PV system (unfiltered)

As seen in Fig. 7, the total harmonic distortion was measured as 91.57%. This value is large enough to damage the off-grid system. It is absolutely necessary to reduce this value of harmonic distortion with passive filters. The six-pulse uncontrolled rectifier used as a load in the off-grid PV system is a harmonic source. The output voltage waveform of this uncontrolled rectifier is as shown in Figure 9.

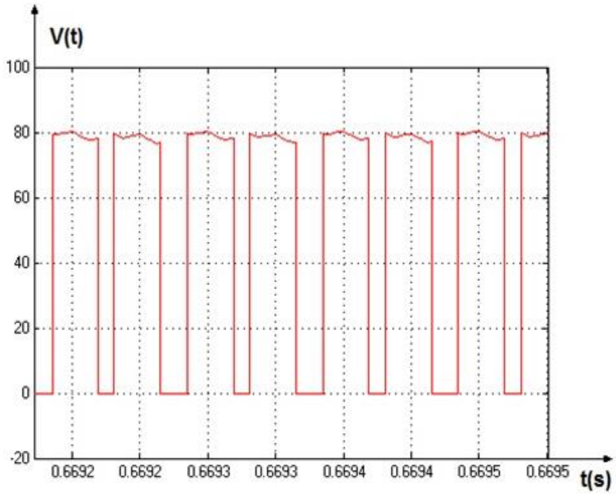

Figure 9. Six pulse uncontrolled rectifier output voltage

Matlab/Simulink program was used to perform performance analysis of passive LC and L filters in the solar PV system and to determine the THD_I value of the solar system. Harmonic components produced by converters and non-linear loads create resonance with the power system. Resonance has a great disruptive effect on the solar power system. Resonance conditions should be analysed for each harmonics in the solar system. The solar inverter output current waveform is as shown in Figure 10.

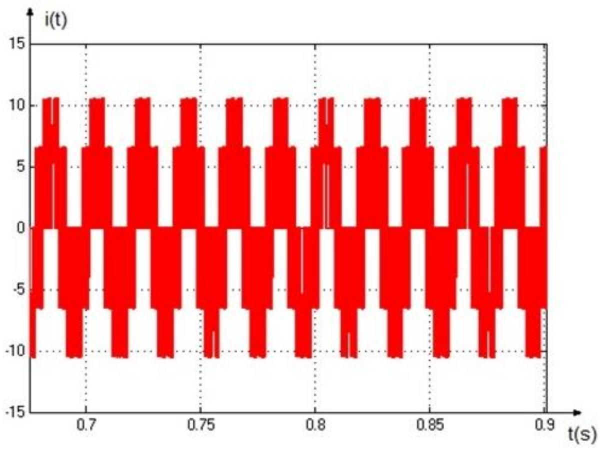

Figure 10. Inverter output current waveform (without filter)

The parameter values of the LC filter used in the stand-alone solar system are found from equ Eq.(6) and Eq. (7). These parameter values are as shown in Table 1.

Table1. Parameter values of the LC filter

Parameters of LC filter	The value of the parameters
C	82.99 μF
L	11.19 mH

The LC filter used to eliminate harmonics in renewable energy sources is a second order filter. There are some problems with the LC filter. One of them is that since the capacitor is connected in parallel with the coil, high frequency harmonics cannot be eliminated, even if the filter shows low impedance at high frequencies.

Converters used in solar systems, even at low power, distort current and voltage waveforms that are sinusoidal. As a result, harmonic components occur in the off-grid network. There are generally single and double harmonic components in the solar system. It has been obsessed that odd harmonic components are more effective than even harmonic components. After using LC filter, solar inverter output current THD decreased to 2.62%. It has been observed that the LC filter used to eliminate harmonic components provides high performance despite some risky situations.

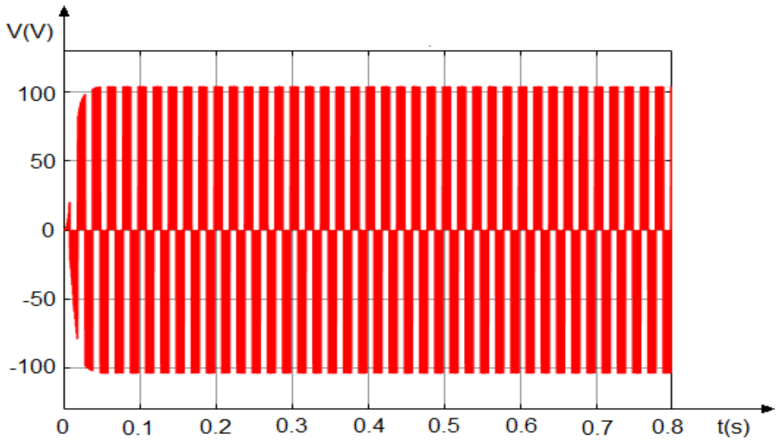

Figure 11. Inverter output voltage waveform

Passive LC and L filters are generally used to eliminate harmonic components in solar power systems. The cost of these filters is lower than the active filter. In addition, they are easy to use. Dominant harmonic components are detected in the solar power system and the passive LC and L filters are adjusted to eliminate them. In addition, the compensation process of the power system is carried out. Power quality is also improved by eliminating harmonic components in the solar system.

In this system, LC and L filters are used to eliminate low order harmonics, and improves off-grid PV power system efficiency. LC and L filters have many advantages. These advantages can be listed as follows:

- simple structures,
- Its low cost,
- To be highly efficient,
- Improvement of the power coefficient of the solar system.

In this study, models and analyses of passive LC and L filters were performed with Matlab/Simulink software program. The schematic diagram of the stand-alone PV power system after filtering with L filter is shown in Figure 12.

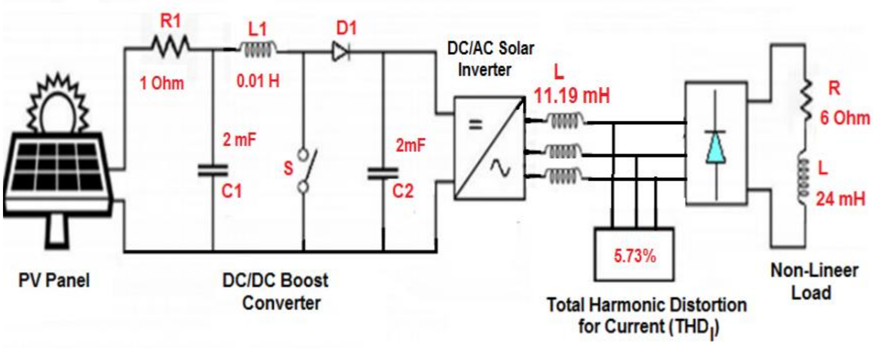

Figure 12. Off-grid PV system model with L filter

Non-linear elements cause serious harmonic pollution in stand-alone PV systems and reduce the quality of energy supplied to consumers. In this study, the elimination of harmonic components in the solar system and the improvement of the energy quality transferred to the load have been achieved. Considering the large number of non-linear loads connected to the power systems, it is inevitable that the THD_I value will increase. LC filter evaluation has been analyzed using Matlab/Simulink Power System ToolBox simulation environment, as shown in Figure 13. An LC passive filter is often used to interconnect an inverter to the load in order to filter the harmonic components produced by the PWM inverter. Although there is an extensive amount of literature available describing LC passive filter, there has been a gap in providing a systematic design methodology. The schematic diagram of the stand-alone PV power system after filtering with LC filter is shown in Fig. 13.

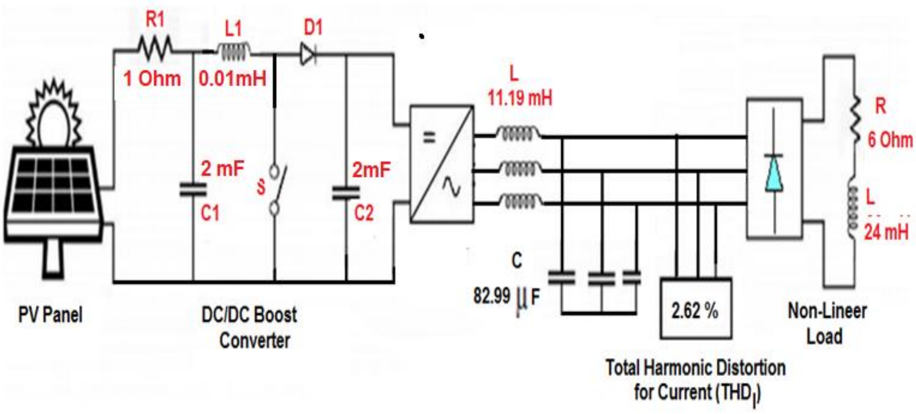

Figure 13. Off-grid PV system model with LC filter

After using LC filter in the solar system, the THD_I value was reduced from 91.57% to 2.67%. This value is below the limit value given by the standards. The results show that the harmonics distortion generated by solar inverter and non-linear load are reduced by using LC passive filter. In the off-grid solar grid, harmonic components cause increased losses, distortion in the sinusoidal waveform and a decrease in system efficiency. The most important harmonic source in solar systems are single-phase and three-phase converters. There are various precautions to reduce them. These precautions are as follows:

- Choosing a large cross-section of the neutral conductor,
- Preferring K factor transformers,
- Using passive LC or L filters,
- Using high-pulse converters.

As a result of connecting the LC passive filter between the inverter and the load in the off-grid network, the THDI value decreased below 5%. As the losses in the solar system decreased, the efficiency of the system increased. In addition, the minimum filter inductance is mathematically derived, which can reduce the size of the filter. The power loss in the LC filter can be decreased by using the minimum inductance. Furthermore, a stable current controller can be designed using the minimum damping resistance that is mathematically derived to obtain a lower power loss, less performance degradation in terms of the high frequency harmonic attenuation, and enough gain and phase margins of the current controller, which can guarantee the stable operation of the closed-loop system. The solar inverter output current waveform is shown in Fig. 14.

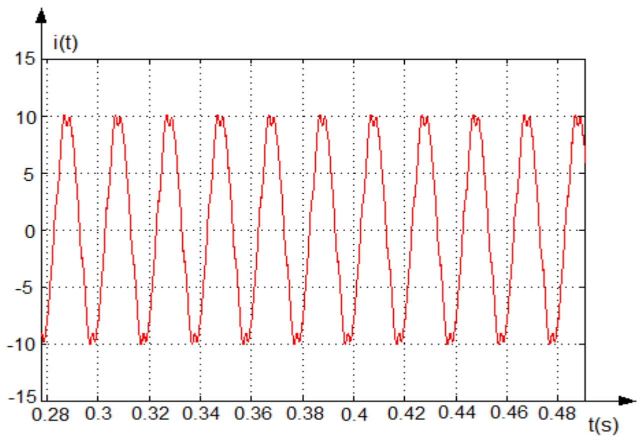

Figure 14. Inverter output current waveform

LC and L filters are used to reduce output current harmonics of output solar inverter, where THD_I% value exceed given in standards. LC filters have some disadvantages, such as current ripple on inductances, the total impedance of the filter, reactive power generated by the capacitor.

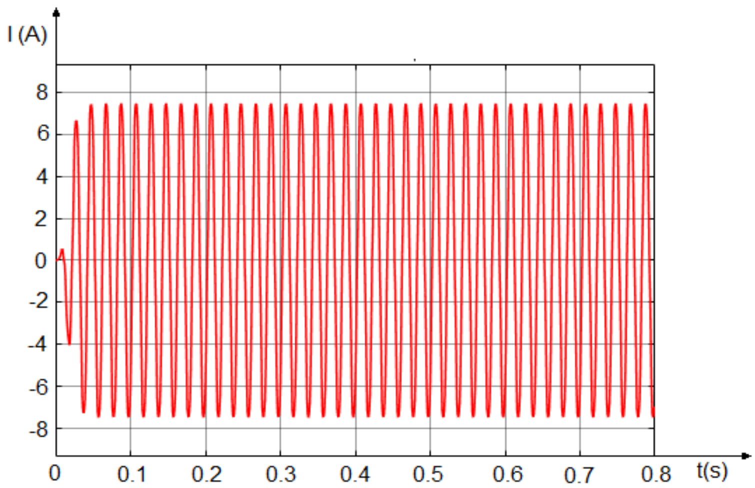

Figure 15. Load input current (with L filter)

LC and L filters application to mitigate harmonic component and improve the solar power quality of the off-grid PV system. The THD_I has been successfully decreased from 91.57 to 2.62% with LC filter and from 91.57 to 5.73% with L filter. In this study, LC and L filters design and performance analysis were performed. As a result, it has been observed that the LC and L filters provide a high performance.

Passive solar LC and L filters are placed between the solar inverter and the non-linear load. These filters are designed to eliminate harmonic components other than the fundamental component. However, these filters have risks such as creating series and parallel resonances. Therefore, the resonance conditions should be calculated separately for each harmonic components. Necessary measures can be taken against the resonance risk by using passive damping method. Since harmonic components affect all system elements in the solar system, they are pollution in the off-grid.

5. Results and Discussion

LC and L passive filters have many advantages in off-grid system, such as increasing the life of the stand -alone PV system devices, increasing the quality of energy transferred to the load and improving the power factor of solar system. LC and L filters also reduce many harmonics caused by six-pulse power uncontrolled converters and solar inverter. As a result, the THD_I value in the solar PV system falls below the limit values expressed by the standards.

LC and L passive filters are usually used to interconnect between solar inverter and non-linear load so as to filter the harmonics produced by solar inverter and non-linear load. As a result LC and L filters have been observed to suppress inverter side switching and non-linear load harmonic components. esign methodology for grid-interconnected inverter systems. The L and LC filters reduce the switching frequency ripple and helps in provides a low distortion current to the nonlinear load.

While the THD_I value was reduced with the LC filter from 91.57% to 2.62% in the solar system, the same value could only be reduced to 5.73% with the L filter. As a result, the performance of the LC filter is higher than the L filter in reducing the THD_I value.

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