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COMPARISON OF THE EFFECT OF FILTER DESIGNS ON THE TOTAL HARMONIC DISTORTION IN THREE-PHASE STAND-ALONE PHOTOVOLTAIC SYSTEMS

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ABSTRACT

The world has turned their attention to renewable energy with the increasing demand of power supply and the limited source of fossil fuel. In Malaysia, solar PV energy is growing steadily as the sunlight is easily available throughout the year. As more solar PV system being installed, stand-alone operation is being looked into to bring solar PV to rural areas. However, in stand-alone operations there is no voltage support from the grid which will lead to harmonic problems. Passive filter is one of the methods used to mitigate the harmonic issues in a stand-alone system. This paper focuses on the design of passive filters and the effects of the filter on the total harmonic mitigation in a 8kW three-phase stand-alone PV system are compared. The design of the proposed filters is validated by simulation results in PSCAD software. The simulation results show that the double tuned filter design is able to meet the THD and individual harmonic limit standards better as compared to the single tuned filter and LC filter design.

Keywords: double tuned filter, total harmonic distortion, photovoltaic system, stand-alone, passive filter.

INTRODUCTION

Over the last few years, implementation of solar PV in Malaysia have been rising steadily with the governments' initiative of the Feed-in-tariff. Most Solar PV systems installed are being connected to the utility grid either through commercial or residential where there is a strong inertia support provided by the national grid system [1]. As more solar PV system being installed, stand-alone operation is being looked into to bring solar PV to rural areas [2]. However, in stand-alone operations there is no voltage support from the grid for an AC coupled system [3]. This will lead to power quality problems when the system is operated in stand-alone mode.

Harmonics are inevitable in stand-alone PV system as power converters are widely used for the operation of the system. Harmonics in stand-alone PV system are generated from the switching of the diodes/transistors in the inverter. These harmonics may affect the operation of the inverter or the stand-alone PV system resulting in low power quality. For stand-alone PV systems to be able to supply high quality power, the harmonic level of the current supplied must meet the standard set by the international bodies and can be found in IEEE 519-1992, ER G5/4, IEC 61000-3-6, and IEC 61727-2004 [4, 5, 6, 7]. Out of the many standards, Malaysia follows the IEC standards set by the governing commission.

Passive filter is one of the methods for harmonics mitigation in a system. This paper focuses on the design of passive filters and the effects of the filter on the total harmonic distortion are compared. Among the types of passive filters are single tuned filters and double tuned filters. A single tuned filter is made from a series of RLC components while the double tuned filter has many topologies such as the series-parallel RLC components or parallel-parallel RLC components.

The function of a single tuned filter is to filter out specific frequency by creating a low-impedance path to ground. The dominant harmonics currents will flow out of the load resulting in a lower total harmonic distortion (THD). A single tuned filter can be tuned on a specific frequency by making the inductive and capacitive cancel each other out. The most dominant frequency is usually selected to obtain better harmonic mitigation from the single tuned filter. The double tuned filter design is an improvement from the single tuned filter design. It is designed to improve the performance of the single tuned filter [7].

This paper focuses on the design of passive filters and the effects of the filter on the total harmonic mitigation in a 8kW three-phase stand-alone PV system are compared. The design of the proposed filters is validated by simulation results in PSCAD software. This paper is organized in five sections. In section II, the modelling of the solar PV is discussed. Section III discusses the various filter designs for harmonic mitigation. The results and simulation from the design is discussed in Section IV. Section V concludes and summarizes the key points of the paper.

MODELING OF STAND-ALONE PV SYSTEM

The stand-alone PV system rated at 8kW is modeled in PSCAD using an array of monocrystalline PV cells. The PV cells are then connected to a DC/DC buck converter controlled by MPPT to obtain the maximum power output from the PV cell. This is followed by a three phase inverter. To mitigate the harmonics from the three phase inverter output, a filter must be inserted after the inverter. Figure-1 shows the general block diagram of the stand-alone PV system.

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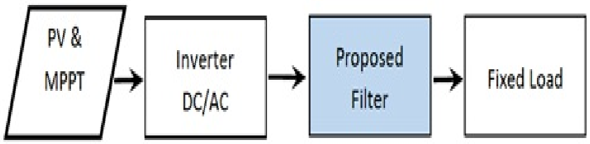

Figure-1. Block diagram of the stand-alone PV system.

PV cell

A solar cell is a semiconductor device that absorbs light to generate electricity. PV cell is arranged in series and parallel to match the system current and voltage requirement [8, 9]. The simplest modeling of a solar cell is built from a current source in parallel with diode, shunt resistor, R_{sh}, and in series with a resistor R_s as shown in Figure-2.

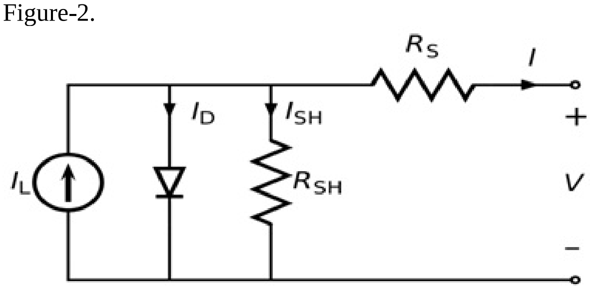

Figure-2. Model of a PV cell.

From the calculation for the equivalent circuit of the solar cell, the output current I can be calculated as:

$$I = I_L - I_D - I_{SH} \tag{1}$$

I_L is the current generated by the solar cell. I_D is the current flowing though the diode which relies on the solar cell temperature. I_{SH} is the current flowing in the equivalent shunt resistance of the solar cell. [10]

$$V_D = V + R_S I \tag{2}$$

$$I_{SH} = \frac{(V + R_S I)}{R_{SH}} \tag{3}$$

$$I_D = I_s[\exp(\frac{qV_D}{nKT}) - 1] \tag{4}$$

where:-

n = diode ideality factor (1 for an ideal diode)
V_D = voltage across the diode
q = elementary charge : 1.602 X 10^{-19} C
K = Boltzmann's constant : 1.38 X 10^{-23}
T = absolute temperature in Kelvin scale
I_s = rated short circuit current of solar cell

MPPT and DC/DC buck converter

DC/DC Buck converter is chosen because it has a higher efficiency than other converters and it is able to step down the higher voltage from the solar array. This is designed together with the Maximum Power Point Tracker (MPPT) controller in this stand-alone system. With the help of the DC/DC Buck converter and MPPT, maximum power from the solar array can be obtained. Incremental Conductance (IC) method is selected for this MPPT [12, 13]

Three phase inverter

The function of the Three Phase Inverter is used to convert the DC power from the DC/DC converter to 3 Phase AC power to feed the loads.

Sine Wave Pulse Width Modulation (SPWM) method is used to create the switching signal and inject to the IGBT of the inverter. The switching signal is created by comparing the modulating signal (sin wave) with the carrier signal (triangular wave).

FILTER DESIGNS FOR HARMONIC MITIGATION

The output voltage and current of inverter usually 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 a filter. Hence, a filter is designed and used to filter out the high frequency harmonic contents in the inverter output power.

Passive filter is one of the methods for harmonics mitigation in a system. In this research, LC filter, single tuned filter and double tuned filter are designed and the effects of the filter on the total harmonic mitigation are compared. The preliminary results from the stand-alone PV system with LC filter are used as a reference to design the single tuned and double tuned filter.

LC filter

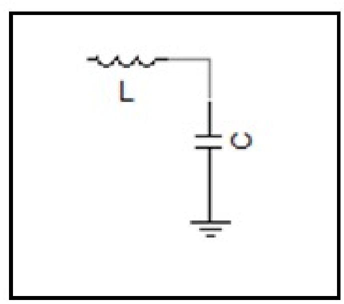

Figure-3. LC filter model.

LC filter is widely used to filter out the harmonics in the inverter output power to generate a cleaner output power. The LC filter is connected between the inverter and the load in the stand-alone PV system. The filter inductance value L is designed such that the current ripple across the inductor is limited to 15% [14]. The model of the LC filter is shown in Figure-3.

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$$L = \frac{V_p}{2\sqrt{6} f_s i_{ripple,peak}} \quad (5)$$

$$i_{ripple,peak} = 15\% I_{rated} \quad (6)$$

where:-

V_p = rms phase voltage

f_s = inverter switching frequency

The filter capacitance value is then calculated from the resonance equation as given in:

$$C_1 = \frac{1}{(2\pi f_0)^2 L} \quad (7)$$

where:-

f_0 = cut-off frequency

Single tuned filter

The single tuned filter can be designed if the dominant harmonic is known. In a single tuned filter, an inductor, L1 is added in series with the capacitor to create a low path impedance line at the dominant harmonic frequency. From this design, the inductive and capacitive reactance from L1 and C1 will cancel each other out at the n-th order frequency. The model of the single tuned filter is shown in Figure-4.

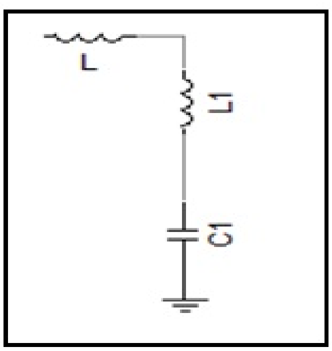

Figure-4. Single tuned filter model.

The inductance L1 is calculated from equation (8).

$$L_1 = \frac{1}{(2\pi f_r)^2 C_1} \quad (8)$$

where:-
= resonance frequency

From the design of the single tuned filter, the output total harmonic distortion should be lower compared to the initial LC filter. If the THD does not decrease, the filter should be redesigned with a different dominant harmonic.

Double tuned filter

To design a double tuned filter, a second n-th order harmonic must be determined to improve on the single tuned filter design. The model of the double tuned filter is shown in Figure-5.

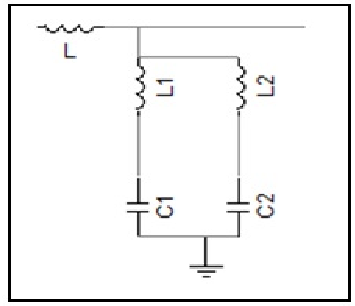

Figure-5. Double tuned filter model.

For the design of the double tuned filter, a secondary set of inductor and capacitor, Lb and Cb must be calculated using equation (8) at the second n-th order harmonic to create another zero impedance path. The first set of inductor and capacitor are used for La and Ca [15].

After obtaining the values for La, Ca, Lb, and Cb, the main inductors and capacitors in the double tuned filter design are calculated with (9) to (12) as below:-

$$C_1 = C_a + C_b \quad (9)$$

$$C_2 = \frac{C_a C_b (C_a + C_b)(L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \quad (10)$$

$$L_1 = \frac{L_a L_b}{L_a + L_b} \quad (11)$$

$$L_2 = \frac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \quad (12)$$

SIMULATION RESULTS AND DISCUSSION

Simulation is carried out to analyze the quality of the output voltage and current when the system is connected with an LC filter, single tuned filter and double tuned filter. The current individual harmonic content for each simulation is measured and compared with the international standards. The results discussed in this paper applies the Standard Test Condition (STC) parameters which are 1000W/m2 and 25oC. The focus of the analysis will be on the THD voltage and current and individual harmonic content according to the international standard IEC 61727-3000 as shown in Table-1.

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Table-1. Current distortion limits (IEC 61727-3000) [7].

Odd harmonics	Distortion Limit (%)
3-9	< 4.0
11-15	< 2.0
17-21	< 1.5
23-33	< 0.6
Even harmonics	**Distortion Limit (%)**
2-8	< 1.0
10-32	< 0.5

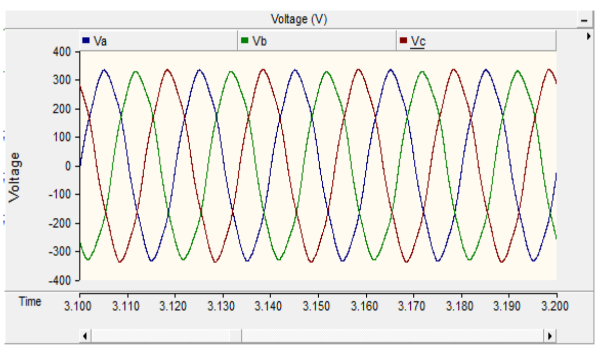
LC filter

To determine the parameters for the LC filter the values are calculated from equation (5), (6) and (7). The parameters used for L and C1 are shown in Table-2.

Table-2. LC filter parameters.

Parameters	Values
V_p	230 V
f_s	5000 Hz
L	5 mH
C_1	200 uF

The results from the simulation of the stand-alone PV system with the LC filter is shown in Figure-6.



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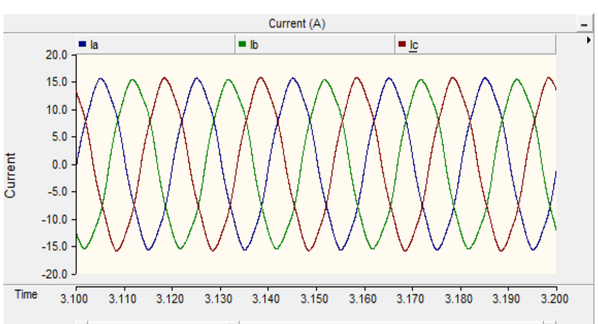

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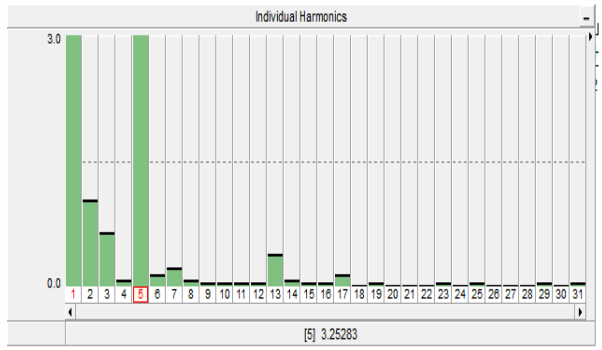

(c)

Figure-6. Simulation results of LC filter (a) Output voltage graph (b) Output current graph (c) Current individual harmonic profile.

From this simulation, it was found that the dominant harmonics is found on the 5th harmonic of the output current at 3.25% while the 2nd harmonic of the output current is found at 1%. The total harmonic distortion (THD) of the current is 3.5%.

According to the IEC 61727-3000 standard, the 5th harmonics result is very close with the 5th harmonic standard which is at 4% while the 2nd harmonics result borders on the 2nd harmonic standard limit at 1%. These results are not ideal as it is too close to the border. As this simulation is simulated at STC, the intermittent nature of the solar irradiance will have a small effect on the output harmonics in a practical environment. Therefore, the harmonics level must be lowered in order to keep the system within the limits of the IEC standard.

Single tuned filter

From the preliminary results, the dominant harmonic is used to calculate the filter parameters of the single tuned filter design according to equation (8). The single tuned filter is designed to filter the 5th order harmonic as it is the most dominant harmonic from the result with the LC filter. The filter parameters used are shown in Table-3.

Table-3. Single tuned filter parameters.

Parameters	Values
C1 (single tuned)	$200e^{-6}$ F
L1 (single tuned)	$5e^{-3}$ H

The result of the simulation of the single tuned filter is shown in Figure-7.

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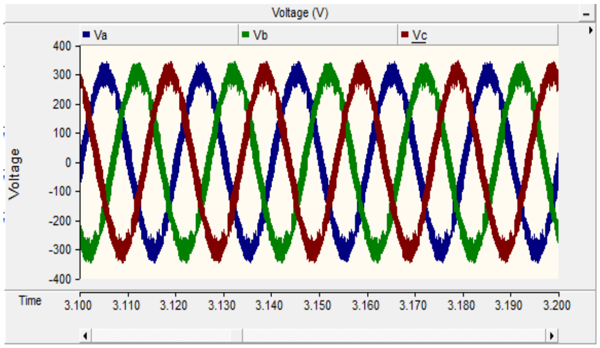

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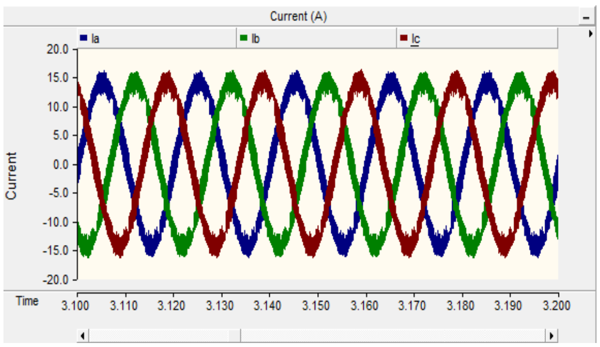

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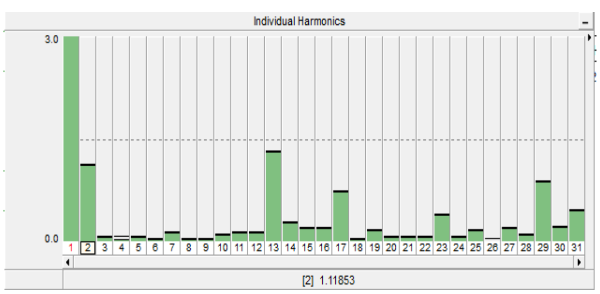


(c)

Figure-7. Simulation results of Single tuned filter (a) Output voltage graph (b) Output current graph (c) Current individual harmonic profile.

From the single tuned filter results in Figure 7, it can be seen that the 5th order harmonics has been reduced significantly compared to the stand-alone PV system with LC filter. Although the THD of the system decreased with the single tuned filter, the 2nd order harmonics however, has increased and it is now 1.11% which is above the limit of 1%.

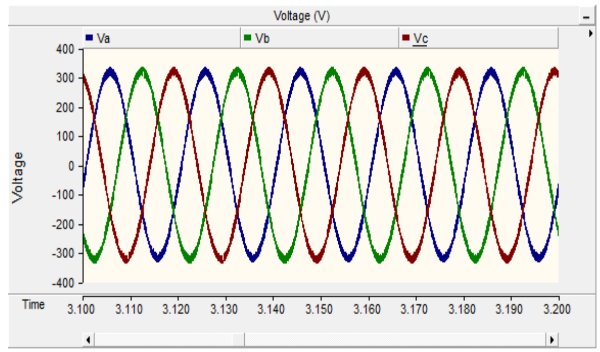
Double tuned filter

The dominant harmonics from the results from the LC filter and single tuned filter are used to calculate the filter parameters of the double tuned filter design according to equation (9) to (12). The double tuned filter is designed to filter both the 2nd order and 5th order harmonics. The filter parameters used are shown in Table-4.

Table-4. Double tuned filter parameters.

Parameters	Values
C1 (double-tuned)	$400e^{-6}$ F
L1 (double-tuned)	$1.73e^{-3}$ H
C2 (double-tuned)	$759e^{-6}$ F
L2 (double-tuned)	$1.92e^{-3}$ H

The result of the simulation of the double tuned filter is shown in Figure-8.



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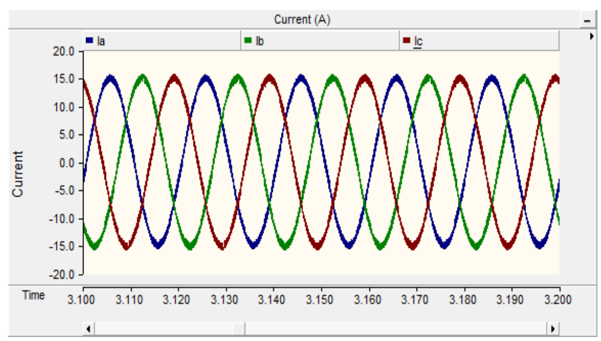

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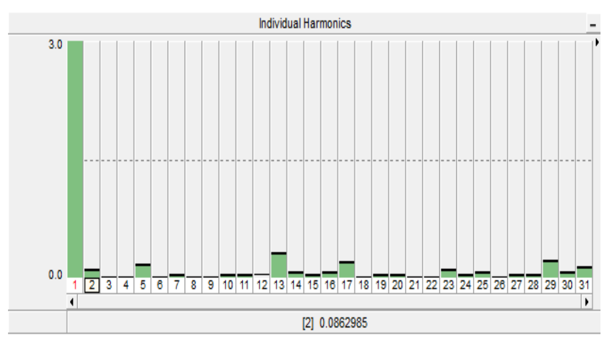


(c)

Figure-8. Simulation results of Double tuned filter (a) Output voltage graph (b) Output current graph (c) Current individual harmonic profile.

This problem is rectified in the double tuned filter and can be seen in the results. With the design of the double tuned filter, the 2nd order harmonics is reduced to only 0.08%. The output THD of the stand-alone PV system with the double tuned filter is reduced to 0.5%. This generated a smooth sine wave at the output current and is able to provide high quality power to the loads.

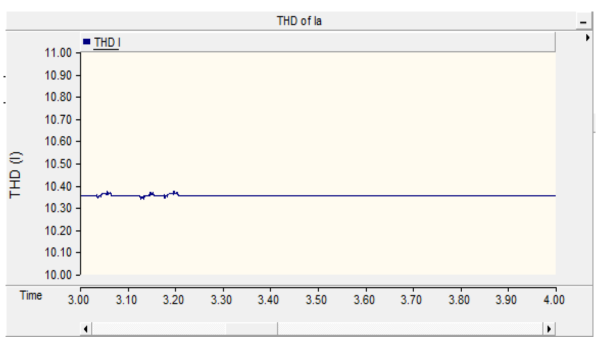
Comparison of the effect of filter designs on the total harmonic distortion

The effect of the filter designs on the Total Harmonic Distortion (THD) of the output current of the stand-alone PV system are compared. When the system is simulated without any filter, the system gives a THD of 10.35%. This shows that there is a high harmonic level in a stand-alone PV system when there is no filter to filter the high frequency harmonic contents. Thus, with the filter designs, the THD level is reduced to 3.5%, 2.2% and 0.5% with LC, single tuned filter and double tuned filter respectively. The overall comparison of THD results of the stand-alone PV system with the LC, single tuned and double tuned filter designs and without filter are shown in Table-5.

Table-5. THD results without filter, with LC filter, with single tuned filter and double tuned filter.

THD	THD_V (%)	THD_I (%)
Without filter	10.35	10.35
LC filter	3.5	3.5
Single tuned filter	2.2	2.2
Double tuned filter	0.5	0.5

The Total Harmonic Distortion of Stand-alone PV system without filter, with LC filter, with single tuned filter, and with double tuned filter are shown in Figure-9.



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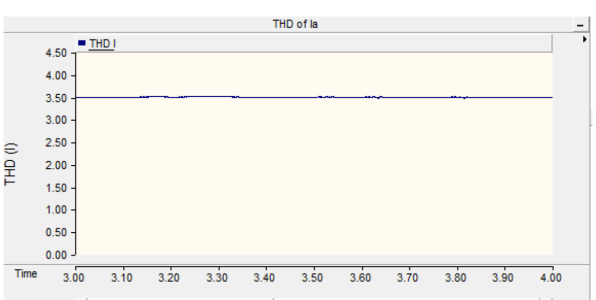

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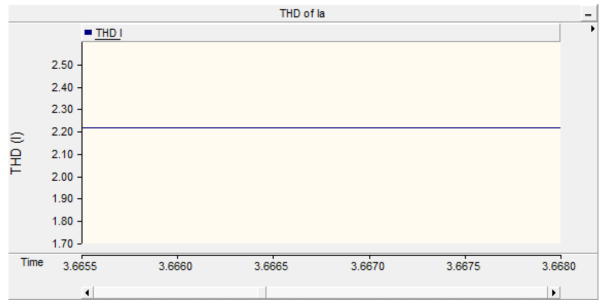

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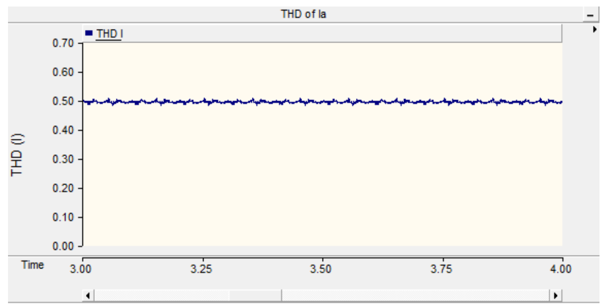

(d)

Figure-9. Total Harmonic Distortion of stand-alone PV system (a) without filter (b) with LC filter (c) with single tuned filter (d) with double tuned filter.

CONCLUSIONS

This paper has presented a comparison of the effect of the filter designs on the current THD in a 8kW stand-alone PV system. The result obtained from the PSCAD simulation shows that the double tuned filter can effectively reduce Current THD from 10.35% to 0.5%. This shows the importance of designing double tuned filters for harmonic mitigation in future stand-alone PV systems. However, this design depends heavily on the budget available to construct the system as additional costs have to be incurred to include the extra components of the double tuned filter.

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