Single-Phase Standalone Photovoltaic System

Naveed Ahmed, Arsalan Ansari, Muhammad Dawood Idrees, Abdul Sami, andKanzal

Abstract: Single-phase standalone photovoltaic systems (PV) are of great interest and benefit nowadays specially for rural areas. In this paper a complete model of single-phasestandalone PV system is designed with an emphasis on LC and LCL filter design for such systems.The complete model simulated in MATLAB Simulink environment and the results presented for output voltages and out current of the system with LC and LCL filters. Furthermore, the total harmonic distortion (THD) of the system also compared for LC and LCL filters. The designed LCL filter was found to be having acceptable percentage of THD i.e below5% as per IEEE standard.

Index Terms: DC-DC Boost Converter, DC-AC Converter, Higher Order Filters, Total Harmonic Distortion, Stand Alone PhotovoltaicSystem, Single Phase System, Filter Design.

1 INTRODUCTION

TThe global energy market is constantly growing, and the pollutant nature of fossil energies has raised the interest of the production of renewable energies[1]. Photovoltaic (PV) systems can be used for domestic use and store excess electricity in batteries for later use or tap into the electricity grid to minimize the electricity bill. Electronic equipment and nonlinear loads are commonly used in standalone PV systemsand causein significant harmonic distortion problems[2]. The standalone PV system is usually configured to work at 50Hz frequencies. While some types of loads generate current and voltage signal with frequencies that are integer multiples of the basic frequency of 50Hz. These higher frequencies are called electro-pollution, known as harmonics of the power system. Harmonics creates disruption to the normal functioning of the device or system[3]. Harmonics are created for different reasons, such as saturation of transformer core, switching of semiconductor devices and systems and adversely affect the whole PV system. The analysis, quantification, and reduction of these harmonics to a level that meets the IEEE 519-1992 standard are imperative[4].

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- *Kanzalis student of Department of Industrial Engineering, Dawood University of Engineering and Technology, Karachi, Pakistan.**Passive filter is one of them and is employed due to its simplicity, economical cost, and high reliability in power system.Several studies have been presented regarding the harmonics mitigation by using different types of filters in standalone PV systems. The authors in [5]studied the single-phase standalone PV system and proposed anti-islanding algorithms for the PV system. However, the design of filter for such system was not presented. A novel control method was proposed in [6] for single phase standalone PV systemwith modeling and design of the complete system.*

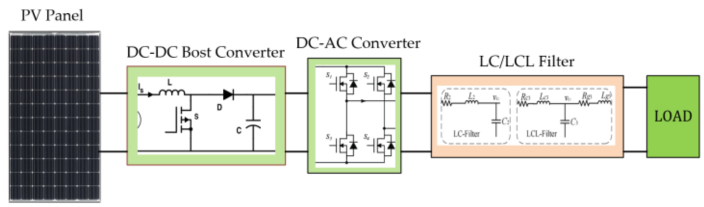


***Figure-1**. Block diagram of single-phase standalone PV system*

The authorsused LC filter in their work without any mathematical validation and the THD results not included.A design method for LC filter used in standalone PV system was presented in [7]. However, the design method is complex and not intuitive for understanding. An LC filter was also designed in [8]for only single-phase inverters. The LC filter presented in their work does not include the boost converter as the part of the single-phase standalone PV system. This paper presents an analysis and design of LC and LCL filters to minimize harmonics distortion caused by nonlinear loads in standalone PV system. The design of single-phase PV system consists of the design of boost converter, DC-AC converter, and filters.The selection of boost converter componentsis discussed in detail followed by the LC and LCL filter design. The whole single-phase standalone PV system is designed in MATLAB Simulink environment. The two types of filters i.eLC and LCL filters are then compared in terms of total harmonic distortion (THD). This paper is structured as follows. Section 2 describes the single-phase standalone PV systems with design of each part of it. Section 3 presents the simulation and results and finally the paper is concluded in Section 4.

2 SYSTEM'S DESCRIPTION

Figure-1 shows the single-phase standalone PV system. It consists of a boost converter, single phase DC-AC converter and LC/LCL filter between PV source and the load. The boost converter steps up the voltages coming from PV source which is then converted to single phase AC voltages. Filtration is applied to remove high frequency components in the output of the DC-AC converter.

2.1DC-DC Boost Converter

The circuit diagram of DC-DC boost converter is shown inFigure-2. The boost converter gain is given as [9].

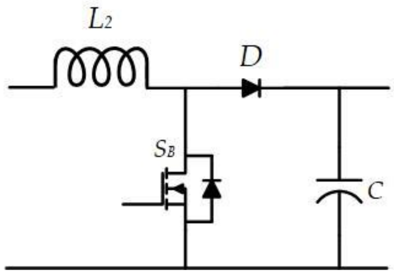


***Figure-2**. Boost DC-DC converter*

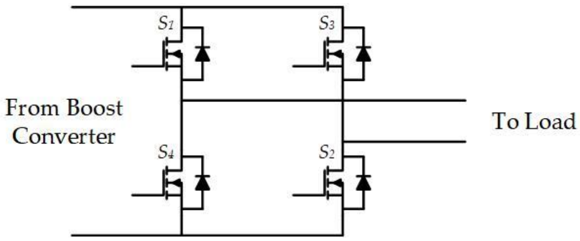


***Figure-3**. Single-phase DC-AC converter*

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (1)$$

The capacitor selection of the boost converter depends upon the equivalent series resistance (ESR). Since the ESR of the capacitor determines efficiency, low-ESR capacitors are used for the best output. A few capacitors can also be attached in parallel to minimize ESR. To satisfy an output voltage ripple, the output filter capacitors are selected as per (2)[10].

$$C = \frac{V_{out} D T_{sw}}{2 \Delta V R} \quad (2)$$

Where C=capacitance, D= duty cycle, T_{sw}=switching time, ΔV= output voltage ripple and R= load resistance of the boost converter.

The selection of the inductor of the boost converter must ensure that the inductor's saturation current is greater thanthe peak inductor current required by boost converter for that application. It should be noted that the circuit will slip into discontinuous mode when there is a light load which is a draw back for boost converters. Choosing a large enough inductor such that the ripple current is greater than twice the minimum load current is one way to counteract this drawback. The inductor is still in continuous conduction mode when the following is satisfied[10].

$$L = \frac{(V_{out} - V_{in} + V_D)(1-D)}{\min(i_{load}) f_{sw}} \quad (3)$$

Where L= inductance, V_D= diode voltage drop, f_{sw}=switching frequency and $\min(i_{load})$ is the minimum load current of the boost converter.

The voltage stress on the diode of the boost converter reverse is limited to the output voltage. Other important factors in diode selection. Fast switching characteristics, low reverse recovery, and low forward voltage drop are also capable of blocking the needed off-state voltage stress and have sufficient capacity for peak and average current handling.

***Table 1.** Switching States of Single-phase DC-AC Converter*

S. No.	Switch Status	Output Voltage (V_{out})
1	S_1& S_2	+ V_{dc}
2	S_3& S_4	$-V_{dc}$
3	S_1& S_3	0
4	S_2& S_4	0

2.2 Single-phase DC-AC Converter

A single-phase DC-AC converter is shown in Figure-3. Four switches S_1, S_2, S_3 and S_4 are used to convert DCvoltages from boost converter to AC voltage and then applied on the load. By turning the MOSFETs on and off at precise times. There are four distinct states, eachof which corresponds to a different output voltage level as summarized in the Table 1.

2.3 Filter Design

2.3.1 LC Filter Design

The inductance of LC filter is dependent upon the ripple current and the power consumption of the inverter system. Ripple current on the inductor is taken as 15% to 25% of the total current for unipolar modulation [11]. The single-phase inverters have typical voltage and current waveforms during any switching period as shown in Figure-4. The maximum value of current can then be calculated as in relation to the Figure-4.

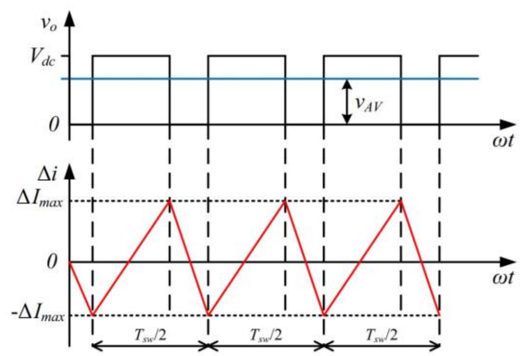


***Figure-4**. Relation between PWM and output of DC-AC converter*

$$\Delta I_{\max} = \frac{(V_{dc} - v_{av}) d}{L \; f_{sw}} \quad (4)$$

WhereΔI_{max}=maximum change in output current of theinverter,V_{dc}=dc value of the input to the inverter, v_{av}=average output voltage of the inverter.

The duty ratio can be obtained as

$$d = \frac{v_{av}}{V_{dc}} \quad (5)$$

substituting (5) into (4) and considering$v_{av}=V_{dc}/2$

$$\Delta I_{\max} = \frac{V_{dc}}{4 L f_{sw}} \quad (6)$$

$$L_1 \geq \frac{V_{dc}}{4 f_{sw} \Delta I_{max}} \quad (7)$$

The maximum output voltage ripple is given as

$$\Delta V_{o(max)} = \Delta I_{max} \frac{1}{2\pi f_{sw} C} \quad (8)$$

Substituting (6) into (8)

$$\Delta V_{o(max)} = \frac{V_{dc}}{4L f_{sw}} \frac{1}{2\pi f_{sw} C} \quad (9)$$

$$L\,C = \frac{V_{dc}}{8} \frac{1}{\pi f_{sw}{}^2 C \Delta V_{o(max)}} \quad (10)$$

2.3.2 LCL Filter Design

Substituting v_{av}=d$V_{dc}$and d=$m_a$sinωtinto (4) where $m_a$is the modulation index and $L_1$is the inverterside inductance.

$$\Delta I_{max} = \frac{V_{dc}(1 - m_a \sin \omega t) m_a \sin \omega t}{L_1 f_{sw}} \quad (11)$$

The maximum value of the current ripple occurs atωt= 60^o andm_a =1 the (11) becomes

$$\Delta I_{max} = \frac{V_{dc}}{8 L_1 f_{sw}} \quad (12)$$

$$L_1 = \frac{V_{dc}}{8 f_{sw} \Delta I_{max}} \quad (13)$$

The capacitance of the LCL filter can be obtained as

$$C = \frac{L_1 + L_2}{(V_{L(rms)} / P_a)^2} \quad (14)$$

Where $L_2$is load side inductance, $V_{L(rms)}$ is the rms value of the line voltage and P_a is the active power of the inverter system. Once the inverter side inductance $L_1$is determined the grid side inductance can be obtained as a suitable ratio as given by

$$r = \frac{L_2}{L_1} \quad (15)$$

2.4 Simulation and Results

A single-phase standalone PV system modeled in MATLAB Simulink is shown in Figure 5. It must be noted that the PV sources is considered as a constant voltage source in the simulations. The model consists of boost converter and single-phase full bridge converter as already depicted in the block diagram in Figure-1. The boost converter is further explored in Figure 5 (b). The simulation parameters are described in Table 2.

Figure-6 shows the duty cycle and inductor current of the boost DC-DC converter. The boost converter is operated in continuous conduction mode for the single-phase standalone PV system.

Figure-7 shows the output voltage and current waveforms of the system when LC filter is used. The values of L and

Table 2. *Simulation Parameters for the single-phase standalone PV system*

S. No.	Parameters	Values
Boost Converter Parameters		
1	Input Voltage	24 V
2	Output Voltage	48 V
3	C	200 µF
4	L	60 µH
5	Switching frequency (f_{sw})	20 kHz
Single-Phase DC-AC Converter Parameters		
6	Switching frequency (f_{sw})	1 kHz
LC filter		
7	L	
8	C	
LCL filter		
9	L_1	22 mH
10	L_2	11 mH
11	C	0.01 µF

Cobtained from the design procedure as

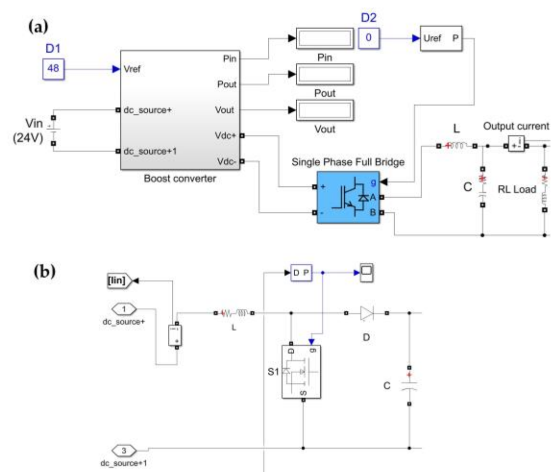


Figure-5. *Simulation model of single-phase standalone PV system (a) Complete Model (b) Boost converter further explored*

describedin section 2.3.2 and presented in Table 2. The results clearly show that the output voltage and current are not pure sinewave, but those contain harmonics. The LCL filter applied to the same system as depicted in Figure-1 to compare the results with that of LC filter. The values of L_1,L_2andC obtained from the design procedure asdescribed in section 2.3.3 and presented in Table 2.The output voltage and current of the system with LCL filter are shown in Figure-8. It can be seen that the voltage and current waveformsaresinusoidal. The sinusoidal voltages at the output of the DC-AC converter prevents the Load from malfunctioning and increase the Lifetime of the various types of Load used in domestic applications.

Figure-9 and Figure-10 provide the details of Fast Fourier Transform (FFT)depicting the THD for LC and LCL filter, respectively. When the results of Figure-9 are compared to that of Figure-10, the LC filter has a THD value of 19.50% and for the same parameters the THD obtained from LCL filter is 3.69% which is well below the value of 5% mentioned in IEEE-standard IEEE Std 519-1992.

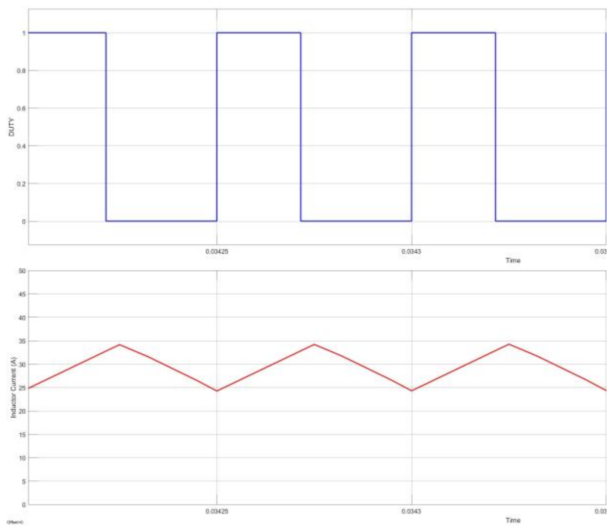
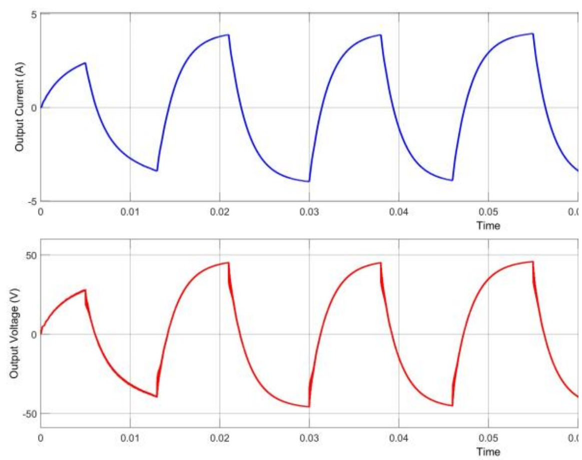


***Figure-**6. Duty cycle Vs inductor current of the boost*



converter

***Figure-7**. Output voltage and current of the system with LC filter*

4 Conclusion

This work has presented the modelling and design of single-phase standalone PV system.The design of boost DC-DC converter, operation of DC-AC converter and the detailed design of LC and LCL filter presented. The results presented for each part of the system followed by the harmonic mitigation in the standalone PV system, using two types of filters namely, LC and LCL filters. LC filters offer the advantages of low cost and simplicity in design. It achieves a significant reduction in THD. However, the THD achieved using LC filters is 19.50%. On the other side the application of the LCL filter to standalone PV system offers very low THD value of 3.69% in the output current and voltage of the system.

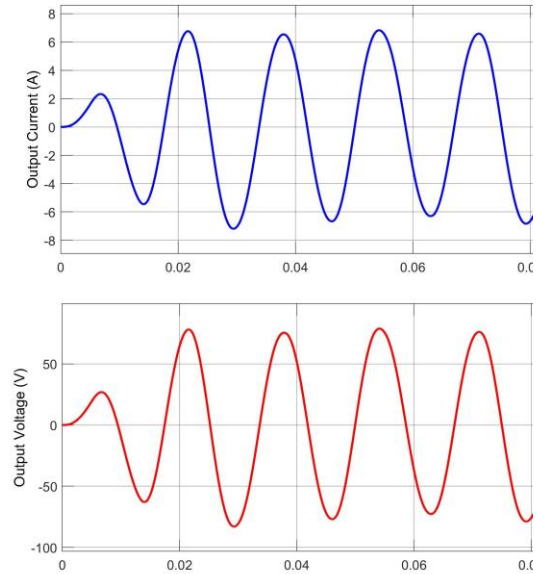
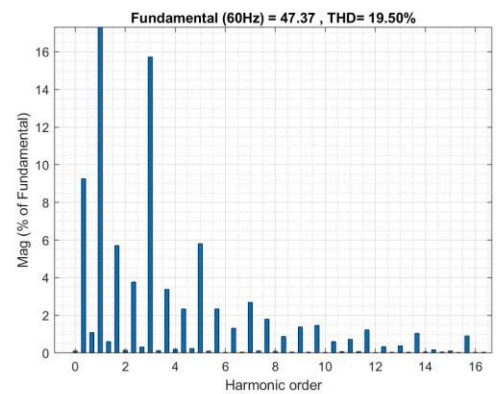
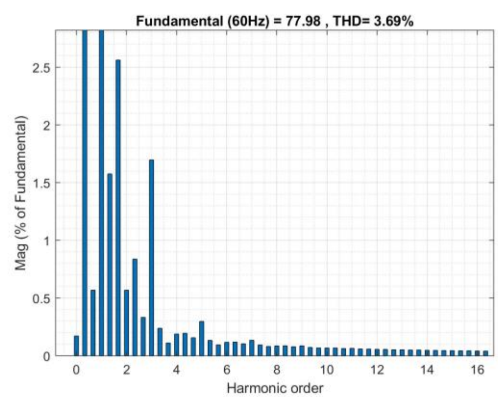


***Figure-8**. Output voltage and current of the system with LCL filter*





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References

[1] H.-J. K. Arsalan Ansari, Puyang Cheng, “A 3 kW bidirectional DC-DC converter for electric vehicles,” J. Electr. Eng. Technol., vol. 11, no. 4, pp. 860–868, 2016.

[2] I. Abdelsalam, G. P. Adam, D. Holliday, and B. W. Williams, “Single-stage ac-dc buck-boost converter for medium-voltage high-power applications,” IET Renew.

Power Gener., vol. 10, no. 2, pp. 184–193, 2016, doi: 10.1049/iet-rpg.2015.0136.
[3] P. E. Consulting, E. Yericho, T. H. Distortion, and E. Harmonics, "T "," 1996.
[4] Z. Gao, H. Zhao, X. Zhou, and Y. Ma, "Summary of power system harmonics," Proc. 29th Chinese Control Decis. Conf. CCDC 2017, no. 50877053, pp. 2287–2291, 2017, doi: 10.1109/CCDC.2017.7978896.
[5] S. A. O. Da Silva, L. P. Sampaio, and L. B. G. Campanhol, "Single-phase grid-tied photovoltaic system with boost converter and active filtering," IEEE Int. Symp. Ind. Electron., pp. 2502–2507, 2014, doi: 10.1109/ISIE.2014.6865013.
[6] O. Diouri, N. Es-Sbai, F. Errahimi, A. Gaga, and C. Alaoui, "Modeling and Design of Single-Phase PV Inverter with MPPT Algorithm Applied to the Boost Converter Using Back-Stepping Control in Standalone Mode," Int. J. Photoenergy, vol. 2019, 2019, doi: 10.1155/2019/7021578.
[7] N. Yanshu, "Single Phase Sine Wave PWM Inverter Circuit Simulation and the Design of Filter Based on Matlab," MATEC Web Conf., vol. 232, pp. 4–7, 2018, doi: 10.1051/matecconf/201823204030.
[8] A. A. Ahmad, S. Member, A. Abrishamifar, and M. Farzi, "A New Design Procedure for Output LC Filter of Single Phase Inverters," no. 1, pp. 86–91, 2010.
[9] W. Hart Danial, Power Electronics. 2010.
[10] H. Wang, "A Boost Converter Design with Low Output Ripple Based on Harmonics Feedback," arXiv, 2019.
[11] Y. Kim and H. Kim, "Optimal design of LCL filter in grid- connected inverters," IET Power Electron., vol. 12, no. 7, pp. 1774–1782, 2019, doi: 10.1049/iet-pel.2018.5518.