Performance Assessment of Low-pass Filters for Standalone Solar Power System

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***Abstract*—Nowadays, electricity demand significantly increases along with reduction of negative impacts to environment leads to a strong development of renewable energy which includes solar energy. In order to be able to provide power for the load, photovoltaic (PV) has to receive solar radiation to convert into electricity, through the converters to obtain such responses as voltage, frequency, etc. suitable for the load. However, this conversion creates the harmonics, one of the factors that reduce power quality and damages the devices. This paper studies two passive single-tuned and double-tuned passive filters coupled with converters for off-grid solar system. By means of simulation from Matlab/Simulink software, a solar conversion system and filters are built to meet the load requirements of 1kW and rated voltage of 220V. The results show that the double-tuned filter offers better harmonics filtering than the single-tuned filter, very low output voltage distortion for stable loads.**

Keywords—DC/AC converter; DC/DC converter; harmonic; low pass filter; photovoltaic; renewable energy; solar energy.

I. INTRODUCTION

Nowadays, fossil fuels are becoming increasingly exhausted, demand for electricity is rising, and environmental problems are worsening. This increases the burden on traditional electricity system, so the development of renewable energy sources is becoming increasingly essential. In particular, it can be said that the solar energy is a green and endless energy. In terms of solar energy source – this type of energy source tends to strongly develop in the years to come. However, when integrating it into the electrical system, it will cause some impacts on stability and change the operating state [1-2]. In addition, unstable weather phenomena such as obscuring the sun, thermal radiation will have negative effects on this type of energy [3]. To ensure the stability during supplying process, there must be converters to do the power conversion process of the solar system, but this process produces the harmonics, a factor that greatly affects power quality and stability of the system [4]. Therefore, harmonics filters need to be further integrated, in order to improve the quality of the power, ensuring stable operation of the load.

In Vietnam, passive filters are regularly used for standalone solar power system owing to economic condition and improving power quality. Besides, there are more and more Vietnam solar power plants projects being emphasized such as: Pho An PV, Binh Nguyen PV (Quang Ngai province); Long Son PV (Khanh Hoa province); etc. When these power plants are connected to the grid they must meet harmonics standards and operating conditions, therefore, the use of filters becomes a necessity. However, no research is conducted on real performance assessment of these filters. Hence, this paper analyzes the performance assessment of low pass filters combined with solar power conversion simulation using Matlab/Simulink software. In Fig. 1 is presented the model of standalone solar power system analyzed in the case study.

The topics covered include:

- Photovoltaic model
- Converter
- Low-pass filters
- Result
- Conclusion

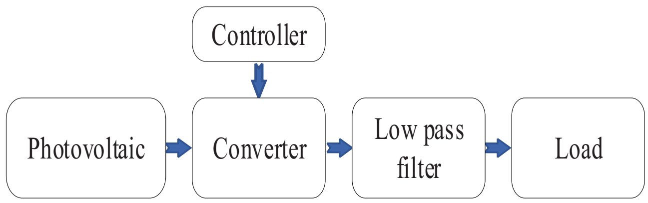

Fig. 1. Model of standalone solar power system.

II. PHOTOVOLTAIC PANEL MODEL

The photovoltaic panel mentioned in this paper is the one presented in references [5-6]. A similar PV system is presented in Fig. 2 and is installed in Da Nang-University of Science and Technology. Each PV panel has an equivalent circuit as a diode connected in parallel with a photovoltaic power supply. In addition, there is a resistor R_s and a parallel resistor R_{sh} with load as shown in Fig.3. PV panels are calculated and coupled into combinations to obtain the desired power and voltage.

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Fig. 2. PVs system in DaNang-University of Science and Technology.

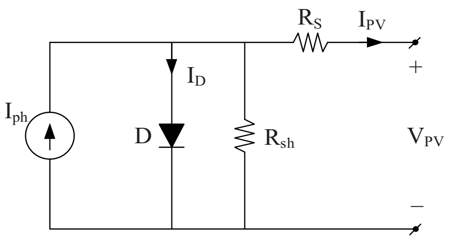

Fig. 3. Equivalent circuit of the PV panel.

According to the model above, the current generated from PV panels is [7]:

$$I = I_{ph} - I_D - I_{sh} \qquad (1)$$

The photocurrent mainly depends on the solar insolation and cell's working temperature, which is described as:

$$I_{ph} = [I_{sc} + K_i(T - T_r)]\frac{\lambda}{1000} \qquad (2)$$

where: I_{sc} - the cells short-circuit current, K_I - the cells short-circuit current temperature coefficient T, T_r - the cell's reference temperature (T_r = 25°C), λ(W/m^2) - solar insolation.

The current through diode can be calculated by:

$$I_D = I_s\left[e^{\frac{q(V+IR_S)}{kT}} - 1\right] \qquad (3)$$

The cell's saturation current varies with the cell temperature and is given as:

$$I_s = I_{RS}\left(\frac{T}{T_r}\right)^3 e^{\frac{qE_g}{Ak}\left(\frac{1}{T_r} - \frac{1}{T}\right)} \qquad (4)$$

where: V_{oc} - the open circuit voltage at standard conditions (V_{oc} = 22 V), E_g - the bang-gap energy of the semiconductor used in the cell (E_g = 1.1 eV), q - an electron charge, V - the cell's output voltage, A - the ideal factor (A = 1.3), k - the Boltzmann's constant (k = 1,38.10^{-23} J/K), R_s (Ω) - cell's resistance, R_{sh} (Ω) - shunt resistance .

The equation of the current passing through shunt resistance is:

$$I_{sh} = \frac{I_{sc}e^{AkT_r} - 1}{qV_{OC}} \qquad (5)$$

By the above equations, the characteristic lines of the PV are set in cases with the weather conditions change as shown in Fig.4 and Fig.5. As a consequence, many appropriate control methods are integrated in the converters to ensure the stability of the output responses supplying to the load.

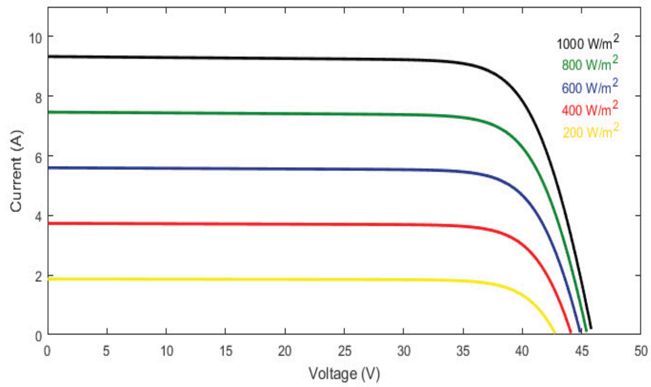

Fig. 4. *I-V* curve for different irradiation levels.

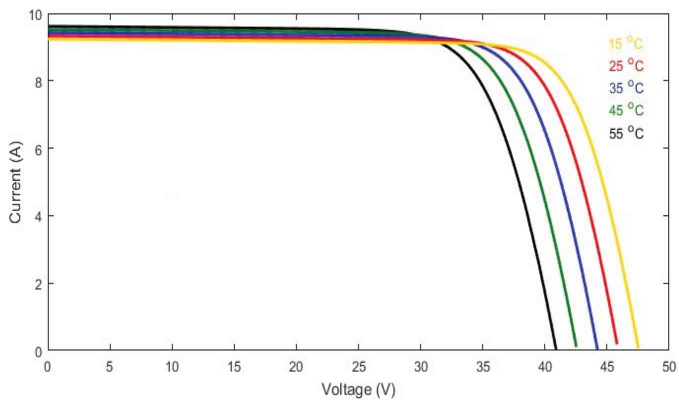

Fig. 5. *I-V* curve for different temperature levels.

III. CONVERTER

The power conversion system incorporates two main DC/DC and DC/AC converters [8-11].

In this paper, a specific Buck voltage reduction circuit is coupled with a single-phase H-bridge inverter to transfer the DC power from the PV panel to the AC power supply to the load.

These converters are dimensioned to provide power for specific loads with an output voltage of 220 V and a capacity (P_{Load}) of 1000 W.

The converter parameters are presented in Table 1, while Fig. 6 shows the circuit simulation diagram.

To control the Buck converter, we use the PWM - Pulse Width Modulation method [10-12].

TABLE I. PARAMETERS OF THE CONVERTER

DC/DC converter	
Input voltage	640-720 V
Output voltage	310 V
DC/AC converter	
Input voltage	310 V
Nominal Output voltage	220 V
Output frequency	50 Hz

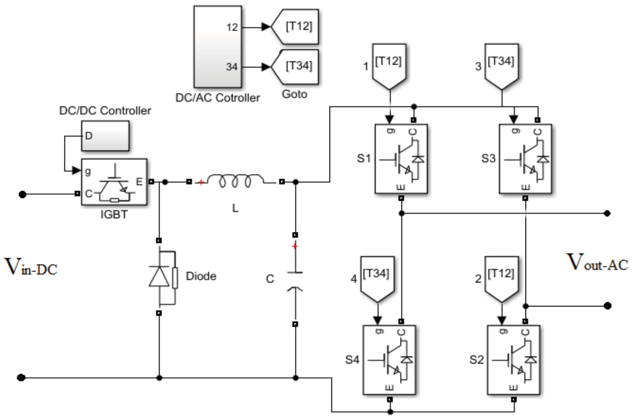

Fig. 6. The circuit simulation diagram.

The modulation based on square wave pulse width change is carried out in the on-off cyclical manner with the executive elements like IGBTs (or MOSFETs). However, the simulated input voltage is modified similar to the renewable power sources related to the change of the weather. So, the Proportional Integral (PI) method is integrated to control the Buck converter adapting to that change.

For PI controller, the proportional and integral factors are determined by the Ziegler-Nichols algorithm [13]. PI controller is designed by direct voltage regulation method using output voltage feedback then the output control results are used in the PWM modulator.

As a result, the pulse openings of the valve will have a variable width as illustrated, so that the output voltage of the buck circuit is not only controlled to the desired value but also stable (reference value).

The Sinusoidal Pulse Width Modulation (SPWM) method is the common method used in DC/AC converters, especially in standalone solar systems [10-12]. Basically, it is similar to the Buck PWM control circuit as mentioned above. The difference is that a sinusoidal signal will be compared to the triangle wave.

The sine wave is called the modulational wave and it determines the output voltage of the Inverter. In addition, to ensure the quality of the output voltage, the two factors to be considered are the frequency modulation and the amplitude modulation factor.

The frequency modulation factor:

$$m_f = \frac{f_{tri}}{f_{control}} \tag{6}$$

where: f_{tri} - the carrier wave frequency (triangle wave), $f_{control}$ - the tuning frequency (sine wave).

The Inverter factor is important for Inverters using the SPWM method. The choice of modulus determines the quality as well as the cost of the product.

From this control process, the harmonics generated are responsible for the effects on the connected equipment which are placed at the inverter output. Consequently, harmonic filters are importantly needed to be integrated.

Fig. 7 and Fig. 8 illustrates the output and input voltage of converters.

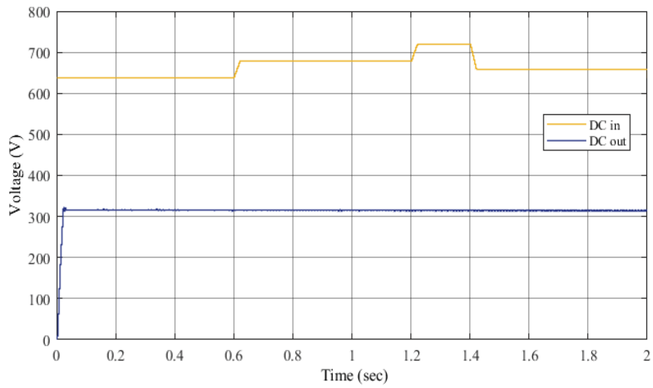

Fig. 7. The input and output voltage of DC/DC converter.

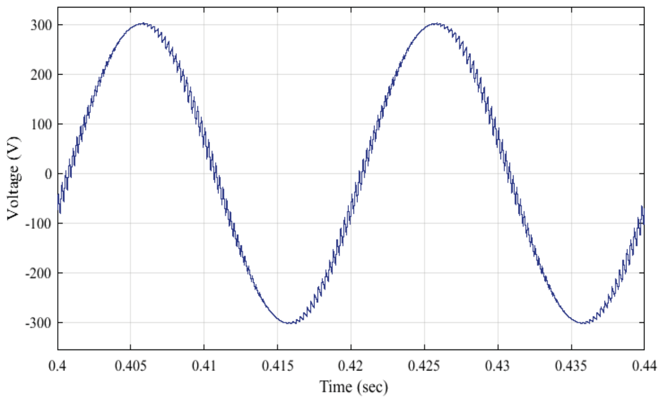

Fig. 8. The output voltage of DC/AC converter (without filter).

IV. LOW-PASS FILTERS

A. Single-tuned filter

A single-tuned filter consists of a series inductor and a capacitor connected in parallel with the load as shown in Fig.9, with the working frequency of the filter equal to the output frequency of the inverter [12], [14-16].

Thereby forming a serial impedance Z_s and a parallel impedance Z_p, the harmonics will be filtered and will give the fundamental wave voltage provided to the load.

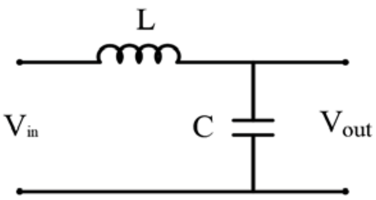

Fig. 9. Single-tuned filter.

The filter capacitance that can provide reactive power for converter, is given by:

$$C = \frac{Q_C}{2\pi f U^2} \tag{7}$$

The filter inductance is specified by:

$$L = \frac{Q_L}{2\pi f I} \tag{8}$$

And Q is the quality factor which can be determined by:

$$Q_c = \sqrt{\varepsilon_c} P \quad and \quad Q_L = \sqrt{\varepsilon_L} P_L \tag{9}$$

$$\frac{\varepsilon_L \varepsilon_c}{1 - \varepsilon_c^2} < \frac{1}{n^2} \tag{10}$$

where: U - the output voltage; I - the output current; ε_L and ε_c - the adjusted coefficients for the quality factor on L and C; n - the lowest order harmonic needed to be removed.

B. Double-tuned filter

The double-tuned filter is combined from a series LC and a parallel LC as presented in Fig.10 [12], [14-16].

Basically, the principle is the same as the single-tune filter. Thanks to it, high level harmonics (3rd, 5th, 7th, etc.) will be removed.

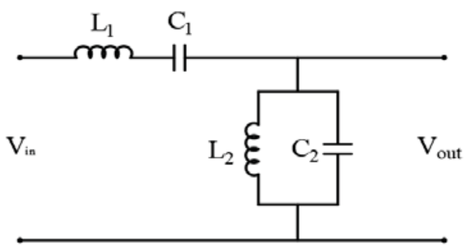

Fig. 10. Double-tuned filter.

For this filter, ε_L and ε_c are computed by:

$$\varepsilon = \varepsilon_L = \varepsilon_C < \frac{4n}{n^2 - 1} \quad and \quad Q = \sqrt{\varepsilon} P_L \tag{11}$$

With series LC, the formula computing elements is:

$$C_1 = \frac{I}{2\pi f Q} \quad and \quad L_1 = \frac{1}{(2\pi f)^2 C_1} \tag{12}$$

The value of LC parallel is:

$$C_2 = \frac{Q}{2\pi f U^2} \quad and \quad L_2 = \frac{1}{(2\pi f)^2 C_2} \tag{13}$$

V. RESULTS ANALYSIS

According to the simulation results, it can be seen that with the single-tuned filter, the voltage output is higher, at the value 304.3 V. The high-order harmonics have not been eliminated perfectly, and the 3-order harmonic still exists with a 1.1% percentage, while higher level harmonics appears in a smaller percentage (about 0.1%).

This will cause the voltage waveform distortion at the output voltage, but this distortion is too large to cause negative effects on the connected load and the quality of the output voltage.

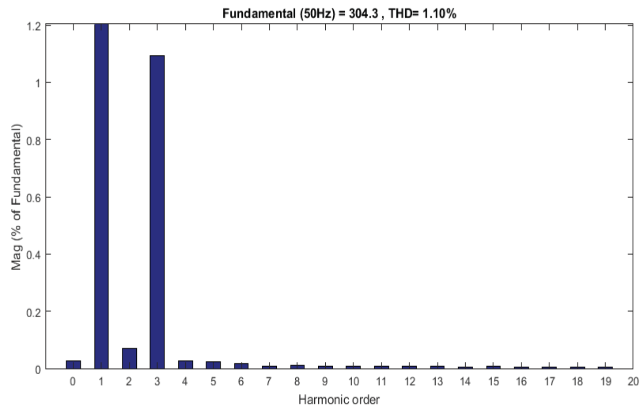

Fig. 11. Total harmonic distortion in frequency domain of single-tuned filter.

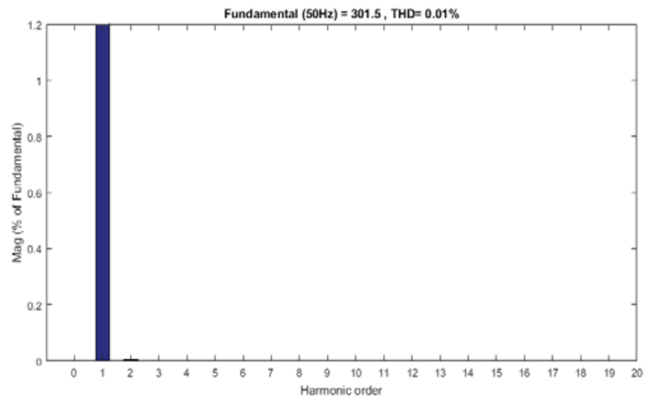

Fig. 12. Total harmonic distortion in frequency domain of double-tuned filter.

With a double-tuned filter, the inverter output voltage must undergo two filtering processes. Consequently, the 3-order and higher-order harmonics are virtually eliminated, the total distortion harmonic (TDH) of the output voltage is only 0.01%. Nevertheless, the output voltage is only 301.5 V, lower than the single-tuned filter. The main reason is because during the process of operation, the voltage is filtered for many times, causing the increase in voltage drop on the filter, which leads to a decrease in the output voltage.

Through the operation of the two filters, Fig.13 shows the output voltage wave supplying to the load. Since high-order harmonics still exist after the single-tuned filter (Fig. 11), the output waveform distorts causes an undesired waveform. On the other hand, with a better filtering capability (as illustrated in Fig.12), the voltage obtained from the double-tuned filter is similar to the standard sinusoidal waveform, the THD distortion is nearly zero.

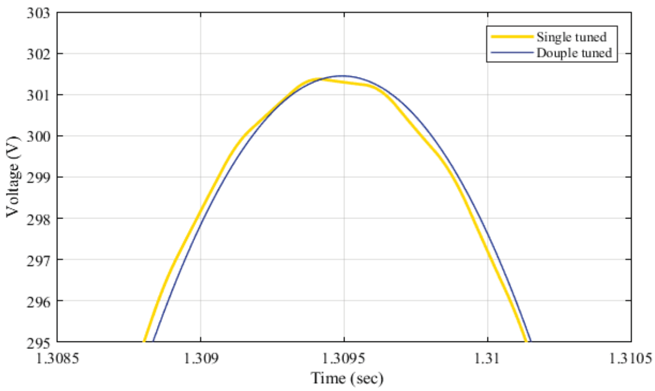

Fig. 13. The output voltage of two single tuned and double tuned filter.

VI. Conclusion

In this paper, the design of two single tuned and double tuned filters for the standalone solar system are described. Through modeling and simulation, performance of the filters has been specifically assessed.

The results show that the filtering ability of the double-tuned filter is much better than the single-tuned filter. Despite of a very low (almost zero) THD output voltage distortion and filtered high-frequency harmonics, the process going through many filters causes a loss of voltage.

However, it can be optimized by selecting the component with low voltage drop or changing the control method, aims to raise the voltage.

With the robust development of standalone solar power generator, the total power system can be increased several times compared to the circuit used in the paper, which increases the harmonics level.

As a result, a double-tuned filter is a good choice for power converters. It can be used in solar energy and can be extended to wind energy. Additionally, the method of selecting the filter element is only relative, due to the noise factor. In conclusion, the experimental circuit models need to be installed in the future research activities to be able to verify the actual operability.

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