Performance of Grid-Connected Solar Photovoltaic Systems with Single-Tuned and Double-Tuned Harmonic Passive Filters

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Abstract – *The generated solar photovoltaic power can be stand-alone or grid-connected. In both systems, power quality issues arise and can affect the network. The harmonic distortions can affect the system significantly if they are not mitigated. This paper presents the performance of grid-connected solar photovoltaic systems with single-tuned and double-tuned filters for harmonics mitigation. The design aspects of each filter are presented and discussed. The simulation results are analyzed and validated using ETAP software.*

***Keywords**: Grid-connected systems, Passive filters, Photovoltaic energy systems, Power quality, Power system harmonics, Tuned filters.*

I. Introduction

Throughout the last decades, world energy generation using high greenhouse emission gas sources has been increased with the catastrophic warming of the earth. The majority of those energy comes from burning coal, gas, and fossil fuels around the world. Right now, a lot of studies around the world are going on to find better ways of generation of energy to reduce the undesirable impacts of conventional fossil fuel-based technologies. As a result of progressive advance in technology, policy, and finance; the solar power generation is currently becoming more reliable, efficient, and commercially competitive source of energy [1], [2]. Nowadays, the renewable energy plays a significant role in electrical power generation and among them, the solar photovoltaic (PV) energy plays a major role in the electrical power generation as it is clean and green energy product as well as its technical benefits [3], [4].

Each source of energy has unique requirements and benefits. However, the sun, mother of all energy resources, is a uniquely clean and infinite source of free energy that has brought a global potential for rapid growth of photovoltaic power generation with different application technologies. At present, solar PV power generation has taken a remarkable place in the electrical power generation, and it is almost keeping an average of 25 % to 30 % of the annual growing rate in most of the developed countries around the world. Nevertheless, these renewable energy generation units are connected to the power system by different ways depending on the real source availability on the ground. Further with the aspect of achieving high security and reliability of the power system, the renewable sources interconnects to the power networks. As a result, the current power system becomes not a one-way route of power generation [5].

This scenario of power systems becomes a challenging task to maintain a good power quality (PQ) of the network. Before the 1960s, there was no much interest toward PQ, but nowadays most of the power system equipment are more sensitive to PQ variations, especially power electronic equipment and microprocessor-based equipment. The growing use of more electronic equipment will also add more and more PQ problems to the power system [6], [7].

Harmonic distortion is one of the significant PQ problems. When the electrical energy is being generated using solar PV panels, harmonics will be created as power electronics-based equipment is used to convert the DC power into AC power. The increased harmonic distortion will reduce the efficiency of the system. Thus, it is important to measure these harmonics, and then take corrective actions to reduce their negative impacts on the system [8].

Still, most industrial applications use the harmonic passive facilities for harmonics mitigation and reactive power compensation for their simplicity, reliability, and their economic aspects compared with other harmonics reduction methods [9]. During the last decade, more studies have been done on different passive filter schemes for harmonics mitigation in both stand-alone and grid-connected solar PV systems. In its broad sense, these studies usually present the basic structure and components of the PV system, the causes of harmonics and their consequences. Then they discuss how to improve the power quality of the system and protect the equipment connected to the system under study using a different combination of passive harmonic filters [4], [10]- [13].

In this paper, tuned filters represented by single-tuned and double-tuned passive filters are introduced for enhancing the performance of a harmonic distorted grid-connected PV system. The level of harmonic distortion is measured and compared with the standard harmonic levels reported in the international standards, *i.e.* IEEE Standard 519-2014 [14]. The design and mathematical formulation of both passive filter configurations are presented, advantages and disadvantages of the double-tuned filters compared to the single-tuned filters in a PV system is discussed to achieve the final outcomes. In addition, the grid-connected PV system, nonlinear loads, and the passive filters are modeled and simulated using ETAP software.

II. Single-tuned Filter Design

This section presents the design considerations of a single-tuned passive filter. A single-tuned filter consists of a series combination of the resistance (R_S), inductor (L_S), and capacitor (C_S) as shown in Fig. 1.

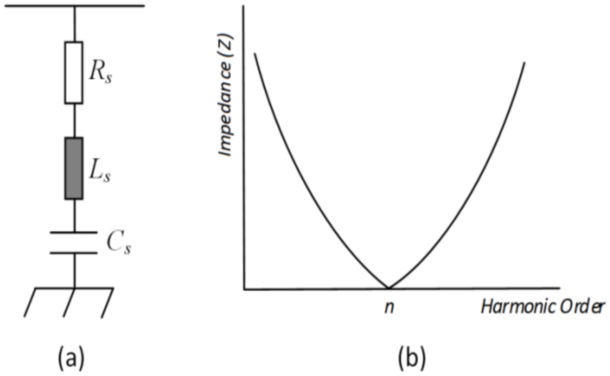

Fig. 1. Single-tuned filter configuration
(a) Its equivalent circuit
(b) Its impedance (Z) versus the harmonic order (n)

The principal aim of this filter is to create a low impedance path at a particular harmonic frequency to divert the corresponding harmonic. As shown in Fig. 1, one can notice that the total impedance (Z) of the filter will be minimum at a particular harmonic frequency, *i.e.* $n*f_1$ by making the inductive and capacitive reactance values equal at this tuning frequency, where n is the harmonic order and f_1 is the fundamental frequency. The total filter equivalent impedance $Z_S(\omega)$ as a function of the harmonic angular frequency ω is given in (1).

$$Z_S(\omega) = R_S + j\left(\omega L_S - \frac{1}{\omega C_S}\right) \tag{1}$$

Generally, the capacitor C_S is determined for a known reactive power compensation required to improve the initial power factor to a desired initial power factor value in the power system. In particular, the required value of the capacitor can be calculated from Equation (2) at a specific harmonic order, at which the filter shall resonate [10], [15].

$$C_S = \frac{Q_c}{(2\pi f_1)V^2}\left(1 - \frac{1}{n^2}\right) \tag{2}$$

where V is the rms value of the rated load voltage. The fundamental value of the filter inductor (L_S) is given in terms of C_S and the tuning frequency (f_n), as follows:

$$L_S = \frac{1}{(2\pi f_n)^2 C_s} \tag{3}$$

At the tuning frequency (f_n), Z_S will become resistive, and it will equal to the filter resistance (R_S), or zero for an ideal filter with high-quality factor circuit.

The value of R_S can be calculated, as given in Equation (4), at a given quality factor (q), which is defined as the ratio of the inductive reactance to the resistance ($\omega_n L_S/R$) at the resonant frequency. In most cases, the value of q varies between 20 and 100. When q is high, the filter will give the best harmonics attenuation but with higher filter cost [10], [15].

$$R_S = \frac{(2\pi f_n) L_S}{q} \tag{4}$$

III. Double-tuned Filter Design

For the design of a double-tuned passive filter, a secondary set of an inductor (L_P) and a capacitor (C_P) will be included as shown in Fig. 2. The conventional double-tuned filter consists of a series and a parallel resonance circuits. This filter eliminates two specific harmonic frequencies, n_1*f_1 and n_2*f_1, where n_1 and n_2 represent the tuned harmonic orders. The total filter equivalent impedance $Z_T(\omega)$ as a function of the harmonic angular frequency ω is given in Equation (5) in terms of the series impedance $Z_S(\omega)$ that represent the series resonant circuit, and the parallel impedance $Z_P(\omega)$ that represent the parallel resonant circuit of the filter. In the literature, two parallel single-tuned filters can be considered as equivalent double-tuned filter model as shown in Fig. 3 in order to determine the parameters of the double-tuned filter [16].

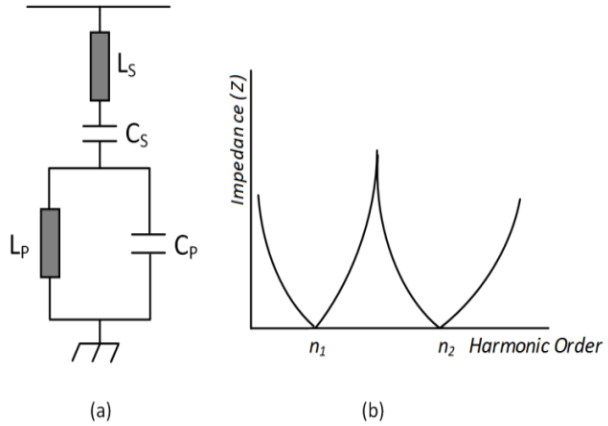

Fig. 2. Double-tuned filter configuration
(a) Its equivalent circuit
(b) Its impedance (Z) versus the harmonic order (n)

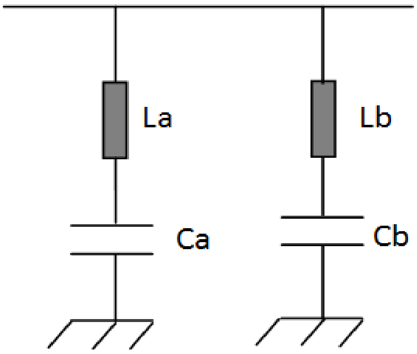

Fig. 3. Parallel two single-tuned filters

$$Z_T(\omega) = Z_S(\omega) + Z_P(\omega) \tag{5}$$

where,

$$Z_S(\omega) = j\,\omega L_S + \frac{1}{j\,\omega C_S} \tag{6}$$

$$Z_P(\omega) = \left(j\,\omega C_P + \frac{1}{j\,\omega L_P} \right)^{-1} \tag{7}$$

Accordingly, one can find the total filter equivalent impedance $Z_T(\omega)$ as a function of the harmonic angular frequency ω is given in Equation (8).

$$Z_T(\omega) = \left(j\,\omega L_S + \frac{1}{j\,\omega C_S} \right) + \left(j\,\omega C_P + \frac{1}{j\,\omega L_P} \right)^{-1} \tag{8}$$

Regarding the two single-tuned parallel filters given in Fig. 3, they resonate at frequencies ω_a and ω_b which can be expressed as follows:

$$\omega_a = \frac{1}{\sqrt{L_a C_a}} \tag{9}$$

$$\omega_b = \frac{1}{\sqrt{L_b C_b}} \tag{10}$$

Ref. [16] used the analogy of the two equivalent circuits of the double-tuned filters that are shown in Figs. 2 and 3 to calculate the parameters of the filter as follows:

$$C_S = C_a + C_b \tag{11}$$

$$L_S = \frac{1}{C_a \omega_a^2 + C_b \omega_b^2} \tag{12}$$

$$\omega_S = \frac{1}{\sqrt{L_S C_S}} \tag{13}$$

$$\omega_P = \frac{\omega_a \omega_b}{\omega_S} \tag{14}$$

where ω_S, ω_P are the resonant frequencies of the series L_S and C_S circuit, and the parallel L_P and C_P circuit, respectively. Hence, one can find L_P, C_P as follows:

$$L_P = \frac{\left(1 - \frac{\omega_a^2}{\omega_S^2}\right)\left(1 - \frac{\omega_a^2}{\omega_P^2}\right)}{C_1 \omega_a^2} \tag{15}$$

$$C_P = \frac{1}{L_P \omega_P^2} \tag{16}$$

IV. The System under Study: Modeling and Simulation

Fig. 4 shows the system under study with a connected photovoltaic system (PV) at bus 1. Different types of linear and nonlinear loads are introduced at different buses to simulate and analyze the performance of the overall system and to evaluate the harmonic levels and distortions.

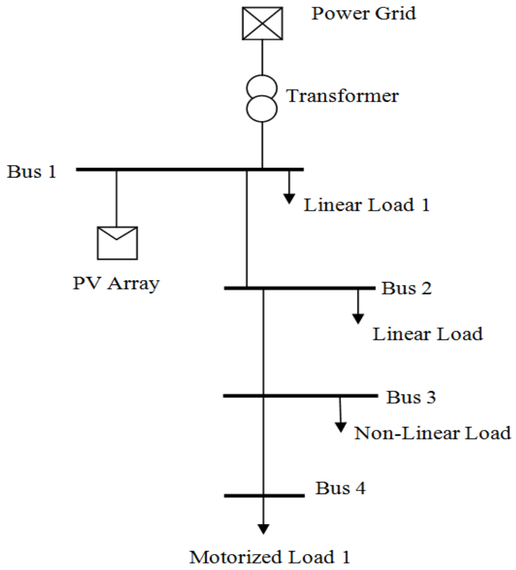

Fig. 4. Single-line diagram of the system under study

The solar technology used is Mono-Crystalline, manufactured by the Philadelphia Solar with the product number of PS-M72H [17]. The used inverter model is Sunny Central (630 MV), built by Sunny Central [17]. As shown in Fig. 4, a 20 MVA transformer connects the 60 kV system to the 20 kV system.

The transformer parameters, the transmission line parameters, the technical data of loads, and the technical data of the transmission system are given in Tables I to IV, respectively.

TABLE I
TRANSFORMER PARAMETERS

Parameters	**Values**
Rated power	20 MVA
Rated voltage HV side	60 kV
Rated voltage LV side	20 kV
Copper losses	102.76 kW
No-load losses	10.96 kW

TABLE II
TRANSMISSION LINE PARAMETERS

From bus	To bus	Resistance (Ω)	Reactance (Ω)
1	2	0.1256	0.1404
2	3	0.1912	0.0897
3	4	0.4874	0.2284

TABLE II
TRANSFORMER PARAMETERS

Parameters	Values
Rated power	20 MVA
Rated voltage HV side	60 kV
Rated voltage LV side	20 kV
Copper losses	102.76 kW
No-load losses	10.96 kW

TABLE III
TECHNICAL DATA OF LOADS

Type	Bus	P_L (MW)	Q_L (Mvar)
Linear load	1	7.6517	1.1607
Linear load	2	0.4523	0.2003
Nonlinear load	3	0.7124	0.3115

Motorized load	Bus	Parameter	Value
	4	Nominal power	0.6 MVA
		Nominal voltage	4160 V
		Stator resistance	0.019 pu
		Stator inductance	0.06 pu
		Rotor resistance	0.019 pu
		Rotor inductance	0.06 pu

TABLE IV
TECHNICAL DATA OF TRANSMISSION SYSTEM

Parameters	Values
Maximum short-circuit power	249 MVA
Minimum short-circuit power	228 MVA
Maximum R/X ratio	0.1
Maximum Z_2/Z_1 ratio	1
Maximum X_0/X_1 ratio	1
Maximum R_0/X_0 ratio	0.1

V. Simulation Results of the System under Study: The Uncompensated System

A simulation study was carried out using ETAP software. Table V gives the individual harmonic distortion as a percentage of the fundamental value. Also, the voltage total harmonic distortion (VTHD) at the different buses are provided.

For comparison purposes, Table VI presents the IEEE Standard 519-2014 limits [14].

TABLE V
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE VTHD AT DIFFERENT BUSES BEFORE COMPENSATION

Harmonic	% Voltage harmonic level			
order	Bus 1	Bus 2	Bus 3	Bus 4
5	23.06	23.04	23.03	23.01
7	10.27	10.26	10.26	10.25
11	8.21	8.22	8.22	8.22
13	3.25	3.23	3.22	3.21
17	4.20	4.19	4.19	4.19
19	3.36	2.43	3.36	3.36
23	2.85	2.85	2.85	2.85
25	1.76	1.77	1.78	1.78
VTHD (%)	27.50	27.48	27.47	27.45

TABLE VI
IEEE STD. 519-2014 LIMITS [14]

Voltage level (kV)	Individual Harmonic distortion (%)	Total harmonic distortion, THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq$ 69 kV	3.0	5.0
69 kV < $V \leq$ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

From the data provided in Tables V and VI, one can observe that there are harmonic levels that do not comply with the permissible standard limits.

VI. Simulation Results of the Compensated System using the Single-tuned Filter Scheme

Four simulation studies were carried out using ETAP software for the system results with the single-tuned filter connected. Case 1 represents the filter design to mitigate the distortion of one harmonic order, *i.e.* the 5th harmonic, Case 2 represents the filter design to mitigate distortions of two harmonic orders, *i.e.* the 5th and the 11th harmonic orders, Case 3 represents the same but for mitigating the distortions of three harmonic orders, *i.e.* the 5th, 7th, and the 11th harmonic orders, and finally Case 4 represents the filter design to mitigate the distortions of four harmonic orders, *i.e.* 5th, 7th, 11th, and 17th harmonic orders.

VI.1. Case 1: Single-tuned filter for mitigating the 5th harmonic order

The designed filter parameters are given in Table VII. Furthermore, Table VIII shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses.

TABLE VII
SINGLE-TUNED FILTER RESULTS: CASE 1

Parameters	Designed values
C_S (μF)	18.0214
L_S (mH)	22.489
R_S (Ω)	0.3532

TABLE VIII
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE SINGLE-TUNED FILTER: CASE 1

Harmonic	% Voltage harmonic level			
order	Bus 1	Bus 2	Bus 3	Bus 4
5	0.09	0.09	0.09	0.09
7	5.66	5.65	5.65	5.64
11	5.90	5.90	5.91	5.90
13	2.64	2.44	2.42	2.42
17	3.43	3.43	3.43	3.42
19	2.40	2.39	2.39	2.39
23	2.98	3.00	3.01	3.01
25	1.55	1.55	1.55	1.55
VTHD (%)	10.1	10.1	10.1	10.09

Table VIII provides that the 5th harmonic voltage level is reduced significantly from 23.06 % to 0.09 %. However, there are still other individual harmonic levels and total harmonic distortion that are not within the standard levels of the IEEE Std. 519.

VI.2. Case 2: Single-tuned filter for mitigating the 5th and the 11th harmonic orders

The designed filter parameters for the two single-tuned filters are given in Table IX.

Furthermore, Table X shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses.

Again, it is noted that both levels of the 5th and the 11th voltage harmonics are reduced significantly from 23.06 % and 8.2 % to 0.14% and 0.16 %, respectively. However, there are other individual voltages harmonic levels that are not within the standard levels of the IEEE Std. 519-2014. Also, the voltage total harmonic distortion does not comply with its permissible limit.

Accordingly, one more single-tuned filter branch may be needed as presented in Case 3.

TABLE IX
SINGLE-TUNED FILTERS PARAMETERS: CASE 2

Parameters	Designed values	
	5th	11th
C_S (μF)	17.2574	0.7892
L_S (mH)	23.4846	106.107
R_S (Ω)	0.3688	3.666

TABLE X
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE SINGLE-TUNED FILTER: CASE 2

Harmonic	% Voltage harmonic level			
order	Bus 1	Bus 2	Bus 3	Bus 4
5	0.14	0.14	0.14	0.14
7	5.96	5.96	5.96	5.95
11	0.16	0.18	0.19	0.19
13	2.31	2.11	2.09	2.09
17	3.25	3.24	3.24	3.24
19	2.29	2.29	2.29	2.29
23	2.89	2.91	2.92	2.92
25	1.51	1.51	1.51	1.51
VTHD (%)	8.18	8.18	8.17	8.17

VI.3. Case 3: Single-tuned filter for mitigating the 5th, 7th, and the 11th harmonic orders

The designed filter parameters for the three single-tuned filters are given in Table XI.

TABLE XI
SINGLE-TUNED FILTERS PARAMETERS: CASE 3

Parameters	Designed values		
	5th	7th	11th
C_S (μF)	10.1069	4.49	3.6302
L_S (mH)	40.09	46.053	23.066
R_S (Ω)	0.6279	1.0127	0.7971

Table XII shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses.

TABLE XII
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE SINGLE-TUNED FILTER: CASE 3

Harmonic	% Voltage harmonic level			
order	Bus 1	Bus 2	Bus 3	Bus 4
5	0.18	0.18	0.18	0.18
7	0.08	0.08	0.08	0.07
11	0.02	0.04	0.06	0.06
13	1.34	1.31	1.29	1.29
17	2.55	2.55	2.55	2.55
19	1.88	1.88	1.88	1.88
23	2.50	2.52	2.54	2.53
25	1.31	1.31	1.31	1.30
VTHD (%)	4.49	4.50	4.50	4.50

As given in Table XII, all the individual harmonic levels, and the total harmonic distortion percentage are well-below the IEEE standard levels.

VI.4. Case 4: Single-tuned filter for mitigating the 5th, 7th, 11th, and the 17th harmonic orders

The designed filter parameters for the four single-tuned filters are given in Table XIII. Table XIV shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses.

TABLE XIII
SINGLE-TUNED FILTERS PARAMETERS: CASE 4

Parameters	Designed values			
	5th	7th	11th	13th
C_S (μF)	9.20	4.08	3.29	1.68
L_S (mH)	44.03	50.62	25.38	20.85
R_S (Ω)	0.69	1.11	0.87	1.11

TABLE XIV
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE SINGLE-TUNED FILTER: CASE 4

Harmonic order	% Voltage harmonic level			
	Bus 1	Bus 2	Bus 3	Bus 4
5	0.21	0.20	0.20	0.20
7	0.08	0.08	0.08	0.08
11	0.02	0.05	0.07	0.07
13	1.79	1.77	1.75	1.75
17	0.01	0.01	0.01	0.01
19	1.02	1.02	1.02	1.01
23	1.92	1.94	1.96	1.95
25	1.07	1.05	1.05	1.04
VTHD (%)	3.06	3.06	3.06	3.06

Table XIV shows that the voltage harmonics are reduced significantly from 23.06 %, 10.27 %, 8.2 %, and 4.2 % to 0.21 %, 0.08 %, 0.02 %, and 0.01%, respectively.

VII. Simulation Results of the Compensated System using the Double-tuned Filter Scheme

Two additional simulation studies were carried out using ETAP software for the system results with the double-tuned filter connected. Case 5 represents the filter design to mitigate distortions of two harmonic orders, *i.e.* the 5th and the 11th harmonic orders, while Case 6 represents the system with two double-tuned filters connected to mitigate distortions of four harmonic orders, *i.e.* 5th, 11th, and the 7th, and 17th harmonic orders.

VII.1. Case 5: Double-tuned filter for mitigating the 5th, and the 11th harmonic orders

The designed filter parameters for the double-tuned filters are given in Table XV. Table XVI shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses.

TABLE XV
DOUBLE-TUNED FILTER PARAMETERS: CASE 5

Parameters	Designed values
C_S (μF)	18.0465
L_S (mH)	19.228
C_P (μF)	39.9129
L_P (mH)	2.4502

TABLE XVI
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE DOUBLE-TUNED FILTER: CASE 5

Harmonic order	% Voltage harmonic level			
	Bus 1	Bus 2	Bus 3	Bus 4
5	0.49	0.49	0.48	0.47
7	5.95	5.94	5.94	5.94
11	0.43	0.45	0.46	0.46
13	2.12	2.09	2.08	2.08
17	3.22	3.22	3.22	3.21
19	1.02	1.02	1.02	1.01
23	2.86	2.88	2.90	2.90
25	1.43	1.44	1.44	1.43
VTHD (%)	8.17	8.16	8.16	8.16

From the results presented in Tables XVI, one can see that both voltage levels of the 5th and the 11th harmonic orders are reduced significantly from 23.06 % and 8.2 % to 0.49 % and 0.43 %, respectively. Also, one can observe that the double-tuned filter can be designed to eliminate two dominant harmonic orders. However, there are other individual harmonic levels and total harmonic distortion that are not within the standard levels.

VII.2. Case 6: Double-tuned filter for mitigating the 5th, 11th, and the 7th, 17th harmonic orders

The designed filter parameters for the two double-tuned filters are given in Table XVII.

TABLE XVII
DOUBLE-TUNED FILTER PARAMETERS: CASE 6

Parameters	Designed values	
	5th &11th	7th &17th
C_S (μF)	12.5037	5.7658
L_S (mH)	16.100	14.769
C_P (μF)	17.694	6.869
L_P (mH)	9.5263	12.3919

Table XVIII shows the individual harmonic level as a percentage of the fundamental value and the VTHD percentage at the different buses. Table XVIII shows that all individual harmonic levels and the total harmonic distortion percentage become well below the standard levels with the two double-tuned filters connected.

TABLE XVIII
INDIVIDUAL VOLTAGE HARMONIC LEVELS AND THE %VTHD AT THE DIFFERENT BUSES WITH THE DOUBLE-TUNED FILTER: CASE 6

Harmonic order	% Voltage harmonic level			
	Bus 1	Bus 2	Bus 3	Bus 4
5	0.54	0.54	0.53	0.53
7	0.29	0.29	0.28	0.27
11	0.37	0.38	0.39	0.39
13	1.76	1.74	1.72	1.72
17	0.29	0.29	0.29	0.29
19	1.03	1.02	1.02	1.01
23	1.88	1.90	1.92	1.92
25	1.06	1.05	1.04	1.04
VTHD (%)	3.10	3.10	3.11	3.10

It is demonstrated that two double-tuned filters can be used instead of using four single-tuned filters under the same conditions, while having a similar performance in minimizing both individual harmonic and total harmonic distortion levels. Keeping in mind the higher power losses, the larger size, and the increased cost of the multiple-arm single-tuned filters compared to the double-tuned filter; therefore, utilizing of the double-tuned filter is more reliable than the single-tuned passive filter type.

VIII. Implementation Considerations in Practice

All loads should work at reasonable power factors. This ensures service continuity and good service quality for consumers as the probability of service interruption is more with low power factor loads. Therefore, applying power factor correction capacitors or shunt passive filters requires special considerations concerning harmonics to avoid capacitor failures because of harmonic resonance. Accordingly, the resonant frequencies should be safely away from any significant harmonic orders.

Ignoring the harmonic resonance in the analysis would lead to inaccurate results. In practice, filters are tuned slightly lower than the harmonic to be filtered. This is to provide a safety margin in case there are changes in parameters of the system. Besides, filters are added to the system starting with the lowest significant harmonic orders found in the system to avoid this problem with this resonance [18].

Finally, filters should be designed with the capacity of the bus in mind. The popular appeal is to size the current-carrying capacity based solely on the load that is producing harmonics. However, a small amount of background voltage distortion on a bus may impose an excessive duty on the filter. Hence, based on IEEE Standard 18-2012 [19]; capacitors are capable of safe, and continuous operation provided not to exceed 135% of the nominal rms current, 110% of the nominal rms voltage, and 135% of the nominal kvar. Compliance with these guidelines is imperative for capacitor as they are voltage-sensitive components of passive filters. The filters that do not follow these conditions may suffer from high costs; also, their unreliable operation may be expected.

IX. Conclusion

This paper presents a harmonic mitigation study in grid-connected solar PV system using both single-tuned and double-tuned filters, while investigating and analyzing their performances. The simulation results in the ETAP environment shows that the double-tuned filters give better performances compared to the single-tuned filters under the same non-sinusoidal conditions. The single-tuned filter can only attenuate a particular harmonic frequency, while the double-tuned filter can efficiently attenuate two harmonic frequencies at once. Further, the single-tuned filter has some drawbacks such as the higher power losses, larger size, and the high operating costs compared to the double-tuned filter. However, both filter types are well performing in service, and they are considered maintenance and trouble free for years. Finally, the performance and effectiveness of the proposed shunt passive filters were verified by the various simulation results presented, and it is evident that harmonics mitigation with double-tuned filters is more economically viable compared to the single-tuned filter.

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