Application of Passive Harmonic Filters in Power Distribution System with High Share of PV Systems and Non-Linear Loads

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Received: 25.01.2023 Accepted:. 15.03.2023

Abstract: The increasing demand of non-linear loads and the revolution towards renewable energy sources connected at the utility scale, would potentially increase harmonic distortion in power distribution networks. Therefore, mitigation measures should be considered to deal with high levels of harmonics. Traditionally, a combination of passive filters has been used as an effective solution. However, the efficacy of such solution has not been investigated thoroughly in networks with high share of renewable energy sources, such as PVs. This paper analyzes harmonic distortions caused by distributed generators (PV) and non-linear loads connected to the 480 V distribution feeder. It aims to model and implement a collection of single-tuned passive filters to mitigate the harmonic levels and improve the power factor. The results have demonstrated the efficacy of the proposed collection of single-tuned passive filters in mitigating the harmonic levels and improve the power factor with high share of PV systems (i.e., 59% PV penetration scenario).They have shown that, when designed and tuned properly, single-tuned harmonic filters can significantly reduce the 5th, 7th, and the 11th current harmonic distortions from 22.71%, 12.5%, and 6.102% before applying the filter down to 0.04199%, 0.1956%, and 0.1056%, respectively. The findings have been verified using a distribution feeder on MATLAB Simulink.

Keywords: Distributed Generators, Distribution Systems, Harmonic Filters, Power Quality, PV systems, Total harmonic distortion.

1. Introduction

Harmonics affect the quality of AC electricity delivered to residential areas and different kinds of facilities, impacting the performance of equipment that uses this electricity. Harmonics can also increase energy costs and reduce hardware lifespan; whereas it also causes overheating and creates a fire risk [1, 2]. The primary purpose of any electrical utility is delivering a pure voltage of a constant magnitude through the system continuously and to ensure the power quality [3-5]. This goal is not as easy as it seems, since some loads & power electronic devices may produce harmonics that affect and distort voltage and current.

The effect of voltage and current harmonics on electrical components and distribution power systems is something to be dealt with, such as dealing with the pollution that comes from any industrial area. The reduction of harmonics will result in a better power system performance and a better quality of the supply [6]. Renewable Energy Sources (RESs) play a key role in modern power networks either as large central generation units at transmission level or as small Distributed Generators (DGs) at the distribution level. PV systems are considered one of the widely spread and promising generation systems worldwide. As these generators are connected through power electronics converters to the grid, they may bring some challenges related to the harmonic level especially in high penetration scenarios [7, 8]. PV systems utilize switching devices such as IGBTs, thyristors and diodes in their grid interface for transmitting the generated DC power to the AC distribution network. These devices along with nonlinear loads produce harmonic currents and voltages with frequencies that are relatively high compared to the fundamental frequency, in a way that they are multiple times of the fundamental frequency [9]. It is essential to detect, analyze and reduce such harmonics that distort systems in so many ways as to cause heating problems, power losses, reducing life of equipment [10, 11]. This requires mitigating the impact of the increased harmonic levels when operating distribution networks with high penetration of PV systems [12]. Harmonic filters have been traditionally adopted for mitigating the impact of the harmonic distortion and to reduce the harmonics levels in the power networks [13-16]. For instance, the research in [13], has provided a comparison between the performance and the capability of both active and passive filters in mitigating the harmonics. Also, it has shown the advantages and weaknesses of each type. In [14], different mitigation solutions and techniques were studied in order to select an appropriate filter design for domestic single-phase application. The study has evaluated the steady-state and dynamic output of active power filters where the performance of two commonly used reference current extraction techniques were analyzed. Acoording to the results obtained, it was reported that it was possible to reduce the %THD to less than 5% as per the IEEE-519 standard recommendation.

Researchers in [15], has mitigated the harmonic voltage in a power system that contained the roughing mill (RM) and finishing mill (FM) motor drives. It was reported that a passive harmonic filter system with an optimal capacity in a power system with mill motor drive system could provide an economical solution by absorbing the harmonics and compensating for the reactive power simultaniously.

While the previous studies have proven the efficacy of harmonic filters in traditional networks, they have not investigated the suitability of harmonic filters in mitigating the harmonic distortion in systems with integrated PV systems.

Some other work tries to provide insights on the harmonics injection and mitigation in power systems with PV systems [17, 18]. For instance, the paper in [17], has analyzed the harmonic emission from PV inverters with varying solar irradiance. Researchers in [17], has also studied the effect of solar irradiance on the PV output current and voltage distortion. According to measured results, the PV system exhibits high THDI values relative to fundamental current during low generations. Yet, these dispersed PV inverter current harmonic injections might negatively impact the distribution network. The study has proposed a a control method , named as Solar-DSTATCOM, to mitigate the harmonic distortion. However, no harmonic filters have been applied.

On the other hand, the application of such solution in high PV penetration scenarios have not been investigated thoroughly in the literature. Hence, this necessitates the need for more understanding of the adequacy of such solution in modern and future power scenarios with high penetration of DGs such as PVs. This paper intends to provide a proper modelling and implementation of passive harmonic filters in power distribution systems considering the impact of high PV penetration besides the non-liner loads. It presents the analysis of harmonic distortions accompanied by high share of PVs and non-linear loads connected to 480 V distribution feeder. This is organized by designing a collection of single tuned passive filters to mitigate the harmonic levels according to the IEEE standards. The role of the filters would also target the power factor correction by compensating the load reactive power through the filter’s capacitance. For this purpose, a PV-rich distribution system, that already meant to supply a combination of linear and non-linear loads, have been modeled in Matlab/Simulink. Following, we examined the harmonics distortion in the system. The harmonics orders that have violated the IEEE standards were determined and a collection of single-tuned harmonic filters are designed to mitigate the harmonics level to accepted limits suggested by the standards. The efficacy of the designed harmonic filters has been tested and validated against the IEEE standards before and after the application of the proposed designed filters using the modelled distribution feeder in Matlab/Simulink.

The rest of the paper is organized as follows: Section 2, presents an overview about the concept of harmonics in power systems and harmonic contribution from non-linear loads and PV systems. Section 3, provide an insight about the harmonic filters and power factor correction. Section 3 proposes the methodology of the filters modelling and design., Section 4 analyzes the results and discusses the findings. And finally, Section 5 concludes the paper.

2. Harmonics in Power Systems

Harmonics in a power system are defined as undesirable sinusoidal voltages and currents components with a positive integer multiple of the fundamental frequency, which is the primary frequency intended in the system (in Europe, this is 50 Hz, whereas in the US, it is 60 Hz) [19]. Therefore, harmonics, with multiples of the fundamental frequency like the second, third, and so on, add frequency components to the voltage and current that are higher than the fundamental. For instance, the second harmonic frequency is equal to 100 Hz and the third harmonic frequency is equal to 150 Hz.

Harmonics in electrical power systems combine with the fundamental frequency, producing voltage and current distortion. This distortion will ultimately create a complicated waveform that combines all the harmonics. Such complicated produced waveforms have a significant impact on most of the

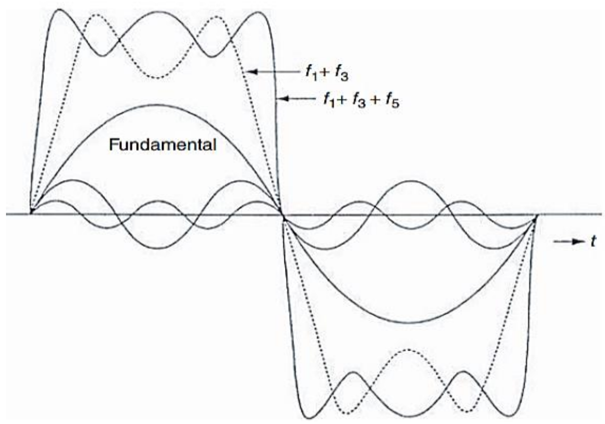


Fig. 1. Fundamental and Harmonics distorted Signal [20].

power system equipment and components. Fig.1 shows an example of a pure and distorted sinusoidal signal with first, third, and fives harmonics [20].

2.1. Harmonics Indices

Total Harmonic Distortion (THD) is the most common metric that is used to represent the harmonic content waveform. It measure the level at which the waveform of a voltage or current is distorted by accounting for the percentage of the harmonics with repspect to the fundamental component at the fundamental frequency. THD is the ratio of the square root of the sum of all harmonic components other than the fundamental to the fundamental component. According to the IEEE standard 519-2014, THD is defined as the proportion of the root mean square of the harmonic content to the fundamental [21]. The mathematical expression of the THD of the voltage is presented in (1).

$$V_{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{1}$$

Where,
h is the harmonic order
V_{THD} is the total harmonic distortion of the voltage.
V_1 is the RMS voltage at the fundamental frequency.
V_h is the RMS voltage at the harmonic frequency.

This expression can be also represented in percentage as shown in (2).

$$V_{THD}\,(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\% \tag{2}$$

THD can be also expressed in terms of the current. Like the case of the voltage, the square root of the total of all current harmonic components, excluding the fundamental current component, is used to calculate current THD, as expressed in (3).

$$I_{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{3}$$

Where,
h is the harmonic order
I_{THD} is the total harmonic distortion of the current.
I_1 is the RMS current at the fundamental frequency.
I_h is the RMS current at the harmonic frequency.

Similarly, the THD of the current can be also expressed in percentage as shown in (4).

$$I_{THD}\,(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\% \tag{4}$$

Note that the single harmonic distortion percentage can be also obtained for validation against the allowed limits defined by the standards. The individual harmonic distortion percentage can be represented in (5).

$$I_h\,(\%) = \frac{I_h}{I_1} \times 100\% \tag{5}$$

It can be noticed that the above metrics in (5) V_{THD} , I_{THD} are normalized against the fundamental values of the voltage and current respectively. This might result in high values in case of low values of fundamental currents [22]. Hence, the IEEE 159 has also introduced another metric which is referred to as the Total Demand Distortion (TDD) for current only [23]. Instead of normalizing with respect to the fundamental harmonic I_1, TDD normalizes the harmonic components with respect to the maximum value of the current demand, I_d. The expression of the TDD is presented in (6).

$$TDD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_d} \tag{6}$$

2.2. Harmonics of Non-linear Loads

The terms "linear" and "non-linear" are used to describe how AC electrical loads draw current from the waveform of the main power supply. With a linear load, the relationship between the voltage and current waveforms is linear, and the current is always proportional to the voltage according to Ohm's law. In other words, when given a sinusoidal voltage, a non-linear load is a consumer of electricity that pulls a non-sinusoidal current from the supply grid. In addition to the fundamental sinusoidal signal, these harmonic currents flow, cause additional losses in electrical installations, and may cause an overheating situation. Examples of linear loads would include transformers, motors, and capacitors. On the other hand, with a non-linear load, the current is not proportional to the voltage and varies according to the impedance of the alternating load. Non-linear loads include power electronic based devices such as rectifiers, motor drives, arc furnaces, and electronic equipment, including computers, printers, TVs, servers, and telecommunications systems that use switched-mode power supply (SMPS) technology [3][24]. Observe Fig.2 which shows the current drawn by linear and non-linear loads [13]. These non-linear loads alter the current waveforms of the grid and hence produce harmonics which also would distort the voltage of the grid too as depicted in Fig.3 [25]. This

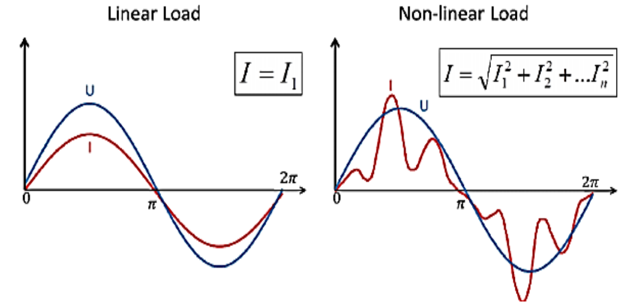


Fig. 2 Behavior of a linear load and a non-linear load in time domain [13].

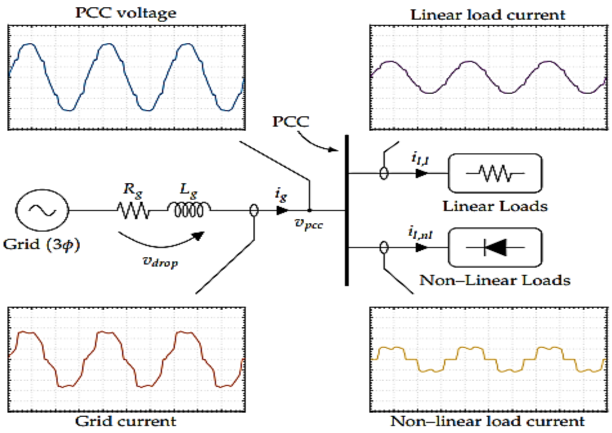


Fig. 3. Currents of linear and non-linear loads and their impact on grid current and voltage [25].

can cause power problems for the loads linked to the distribution system's equipment. When distorted current is applied to a non-linear load, it results in distorted voltage drops throughout the entire power system, which affects the grid's voltage. All users share the same voltage, and any distortion of this voltage on the grid can cause significant losses and negatively affect the operation of electrical devices. Therefore, it's crucial to restrict the flow of distorted current in the distribution system and the loads linked to it to lower the amount of distorted voltage.

2.3. Harmonics of PV systems

Besides the revolution towards renewable energy sources, the continuously rising demand for electricity leads to an increase in the share of PV systems at large & small scales in power networks. Such PV systems utilize the solar energy that comes from the sun to produce electricity. PV systems have been increasingly introduced over the distribution networks for domestic use, such as providing power for residential areas

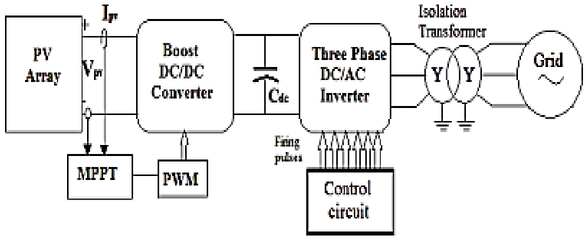


Fig. 4. Grid connected three phase PV system [17].

or storing energy in batteries for later usage. Also, this power could feed back to the electricity grid to reduce electricity bills.

As PV systems employ power electronic interfaces for converting the solar energy into electrical energy for grid connection. Typical PV systems contain power electronics devices such as DC/DC boost converters to change voltage levels and DC/AC inverters to convert the generated DC power to AC power that can be supplied to the loads and the grid as shown in Fig.4 [17]. These have switching devices such as IGBTs, thyristors, and diodes for their operation and power conversion tasks. This in turns would add more technical challenges in terms of maintaining the power quality in the system [26]. Harmonics produced by such power electronics-based technologies utilized in PV systems are considered one of the important issues that may rise especially when integrating PVs at high penetration scenarios. These devices along with nonlinear loads produce harmonic currents and voltages with relatively high frequencies compared with the fundamental frequency in a way that they are multiples of the fundamental frequency [27] [2, 3].
Therefore, it is essential to detect, analyze and reduce such harmonics that distort systems and may cause heating problems, power losses, and reducing the life of the equipment.

Table 1. IEEE-519 standard for harmonic voltage limits

Bus Voltage	**Individual Harmonics (%)**	**THD (%)**
$V \leq 1.0$ kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 2. Current distortion limits for systems rated 120 V – 69 kV according to IEEE-519 standard

I_{sc}/I_L	**Harmonics % of maximum demand load current**					**TDD**
	h<11	**11≤h<17**	**17≤h<23**	**23≤h<35**	**h≥35**	
<20	4.0	2.0	1.5	0.0	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

3. Harmonics Limitation According to The IEEE 519 Standards

The requirements for voltage and current harmonic distortion in electrical system design are specified in the IEEE 519 standard [23]. This standard describes the voltage and current waveforms that exist in every component of the system, and it establishes waveform distortion goals for the system designer [20].

This standard specifies objectives for the design of electrical systems with both linear and nonlinear loads. Waveform distortion objectives for the system designer are specified, and the voltage and current waveforms that could exist throughout the system are described. This standard addresses limits at steady-state [23]. Hence, the limits defined by the standards play a key role in ensuring the acceptable level of harmonics in the power systems. Once these limits are violated, mitigating measures would be initiated and hence reducing the harmonics level accordingly.
Table 1 & Table 2 show the voltage distortion harmonic limits and the current distortion limits according to the IEEE standards, respectively.

4. Harmonics Filters

Harmonics filters are traditionally employed for mitigating the impact of the harmonic distortion by eliminating the harmonics level itself. These are categorized as active and passive filters.

4.1 Active Filters

Active harmonic filters employ power electronics converters to generate current waveforms, that cancel the harmonics in the system. They provide a flexible and intelligent effective filtering solution by generating a current of equal and opposite in polarity to the harmonic current that is required to be filtered out from the system [28]. Beside the harmonics filtering task, active harmonics filters may contribute to other functions such as damping, isolation, and termination, reactive-power control for power factor correction and voltage regulation, load balancing, and voltage flicker reduction [17]. Moreover, active harmonic filters are used more often because they don't cause new resonances to form. Fig.5, shows the operational principle of active harmonic filter [13]. As a result, their performance is less reliant on the characteristics of the system. Regardless of the advancements in the active filters, fast switching of high currents in the circuit is necessary, but this potentially introduces new electromagnetic disturbances into the system [29]. The application of active filters technologies is expensive, require a complex control system and DC power supply for their operation.
Hence, other passive filters might be suitable for mitigating the harmonic contents in distribution networks at lower cost in more straightforward and simplified manner.

4.2 Passive Filters

Passive filters utilize series/parallel combination of passive elements represented by RLC components. These components are tuned in such a way to trap the harmonics content in the network. The usage of passive filtering

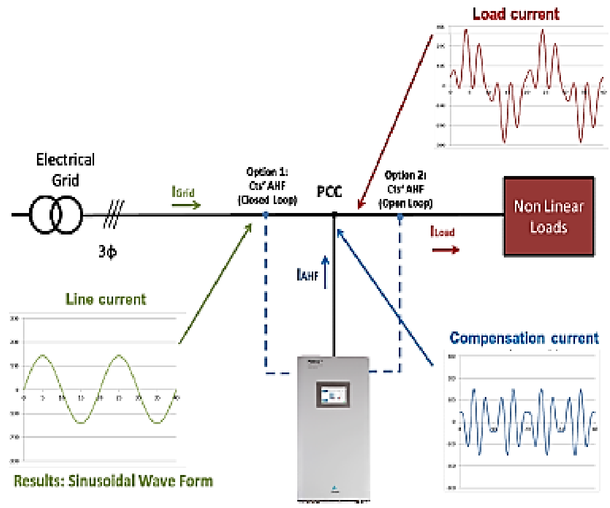


Fig. 5. Operation of a shunt active filter [13].

techniques is one of the most popular and efficient methods for controlling harmonics in the industry. Single-tuned, damped, and high-pass filters are the different passive filters that can be categorized based on their connections. Passive filters can be used as bandpass filters that can filter harmonics

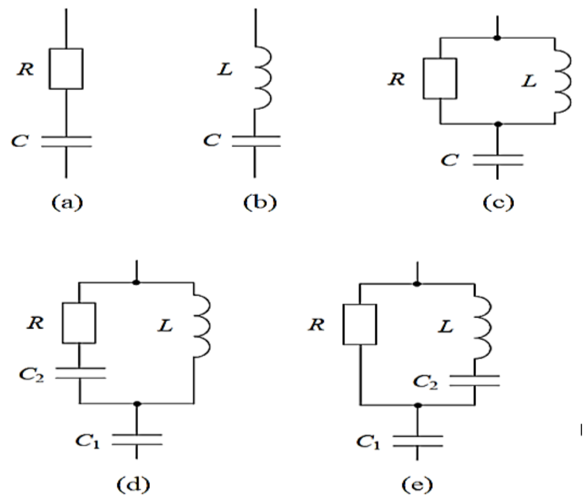


Fig. 6. Topologies of shunt passive filters: (a) single tuned, (b) first order, (c) second order, (d) third order, (e) C-type [36].

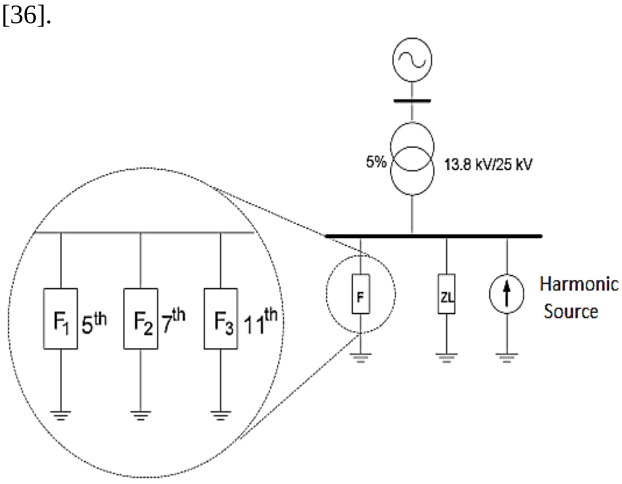


Fig. 7. Example of a three-branch filter [32].

over a range of frequencies. They can be designed to offer a low-impedance channel to harmonic currents at a fixed frequency known as the tuning frequency. Beside the harmonic filtering task, passive filters can be developed to adjust the load power factor together when tuned to the dominant load current harmonic [30]. Advantages of passive filters are their low cost and simplicity to design and implement as well as the high reliability of the filter.

By creating a path of low impedance for a specific frequency of harmonic currents to travel through, a single tuned passive filter has the capacity to be tuned to eliminate or filter one of the low order frequencies (third, fifth, seventh, ninth, etc.) [31]. Shunt passive filters are available in various topologies, as depicted in Fig. 6. The single-tuned passive filter and the high pass filter are the two most widely used filters. While the single-tuned passive filter is designed to suppress and reduce harmonic distortion at a single frequency chosen by the designer, high-pass filters are used to reduce harmonics above the selected frequency. First-order, second order, and third-order high-pass filters are among the many available options for high-pass filters. In practice, mitigation the harmonics may be accomplished by the application of different combination of shunt passive filters to increase the overall performance of their power systems. For example, the connection of two single tuned passive filters combined with a 2nd order high pass filer is considered as a combination. Also, a C-type high pass filter may be combined with two single tuned passive filters. According to [32], there are a total of 125 combinations of topologies.

This raises a question on the best combination of filters that should we use to meet certain harmonics filtering and power factor correction targets. Hence, the overall performance when designed should be evaluated based on technical and economic aspects including the cost, stress levels, and the performance, are the main concern in such sellection analysis. According to a sensitivity analysis on the number of the number of single-tuned branches described in [32], three or four filter branches are the optimum options as shown in Fig.7. More specifically, three branches filters may have a larger stress buffer and are less expensive too. Hence, in this research, we intend to apply single-tuned filters of three branches to test their capability in supressing the harmonics that may accompany the introducting of PV systems besdie non-linear loads in the distribution netweorks.

5. Power Factor Correction

Power factor correction is one of the additional benefits of application of harmonics filters. Most electrical loads in any power system are inductive in nature. As a result, the current drawn by them lags the voltage and they absorb reactive power where it usually would be fed by the supply. This would lead to voltage drop and power loss in the transmission line. Therefore, power factor correction tools like capacitor banks are typically employed for substituting for the required reactive power near to the load centers [33].

When the capacitor is connected in parallel with the inductive load, the leading current drawn by the capacitor will cancel the lagging current drawn by the inductive load, improving the power factor to primarily achieve or operate close to unity power factor. Hence, the power factor correction task is considered when designing the filters by accounting for the sizing of the capacitors utilized for the filters in such a way to inject decent amount of reactive power to substitute for the load requirement without stressing the components and to decrease the losses in the system. The size of the primary filter capacitor of the filter correlates to the quantity of injected reactive power [32].

6. Filters Design and Tuning

The design and tuning process of the selected filters is a matter of importance to ensure the efficacy of the proposed filters not only in mitigating the harmonics, but also for the power factor requirement of the system. This process includes the following steps [32, 34-36]:

- ***Step 1: The selection of the targeted harmonic frequency of the filter.***

The frequency of the harmonic order that need to be filtered is usually selected after monitoring the harmonic content that may result from the non-linear loads and the RESs such as PV systems. This is usually targeting the lower order harmonic orders which have values close to or above the allowed limits. It is a common practice to tune the filters below the targeted harmonic order h, in such a way to avoid the possibility of dangerous harmonic resonance and to limit the duty on the components of the filter.

- ***Step 2: Calculating the required capacitive reactance of the filter.***

The reactance of the filter, X_f., is found by accounting for the required reactive power (Q) that is needed for power factor purpose, which is obtained by considering the old and the new values of the power factor before and after adding the filter, as expressed in (7).

$$Q = Q_{old} - Q_{new} \tag{6}$$

Where, Q_{old} , Q_{new} , are the reactive power at the old and the new power factor in the system, respectively. Then, the reactance of the filter can be calculated using the obtained value of Q as expressed in (8).

$$X_f = \frac{V_L^2}{Q} \tag{8}$$

Where, V_L is the line-line voltage of the network.

- ***Step 3: Calculating the inductive reactance of the filter.***

The inductive reactance of the filter, X_L., is found by using the value of the previously calculated capacitive reactance and the harmonic order as expressed in (11).

$$X_L = \frac{X_C}{h^2} \tag{11}$$

Then, the corresponding value of the inductor L, can be calculated using (12).

$$L = \frac{X_L}{2\pi f} \tag{12}$$

Finally, this is used to find the value of the capacitor, C, as described in (10).

$$C = \frac{1}{2\pi X_C} \quad (10)$$

This reactance can be also used to calculate the capacitive reactance X_C, as described in (9).

$$X_C = \frac{h^2 X_f}{h^2 - 1} \quad (9)$$

- ***Step 4: Evaluating the duty requirements of the resulted filter.***

According to the IEEE standard for shunt power capacitors [37], the peak voltage, current, kVAR output, and RMS voltage are the filter duty requirements that need to be evaluated. This step is essential to avoid stressing the capacitor. For instance, the nominal fundamental voltage across the capacitor should be less than 110 % of the rated voltage. On the other hand, the peak voltage across the capacitor when loaded considering the harmonic distortion should be less than 120% of the rated voltage. Besides, a higher overloading percentage of 135% is allowed for both the current and KVA values according to the IEEE standard.

7. Case Study

A case study for a 11 kV distribution feeder is used for the purpose of investigating the impact of the harmonic distortion and for the application of the designed harmonic filters as well. The 11 kV feeder that feed a collection of non-linear loads through a step-down three-phase distribution transformer is modelled in MATLAB Simulink as shown in Fig. 8.

Table 3. Resulted harmonic distortion up to 11^{th} harmonics

Item	Individual Harmonic Order Distortion (%)			THD
	5^{th}	7^{th}	11^{th}	(%)
Current (I_{abc})	22.71	12.5	6.102	26.96
Voltage (V_{abc})	38.38	29.46	23.26	54.22

The 1500 KVA Three-Phase transformer is Y/Y_g connected as it steps down the voltage from 11 kV to 0.48 kV to feed a main non-linear load of 1.5 MW. Note that this load represents a factory with a poor power factor due to the excessive consumption of the reactive power. With the present of distributed generators (PV) to feed the load. Besides that, the system includes a group of five residential loads that consumes a total of 500 kW (i.e., 100 kW each). As for the DGs, a set of six PV systems are connected to the system as shown in Fig.8. Note that these PV systems are connected to the distribution feeder and provide a total of 1180 kW. It is worth noting that this represent a 59% PV penetration with respect to the total load in the system. Hence, the rest of 820 kW is powered by the grid through the step-down transformer. Both the residential area and the factory are represented by an AC/DC converter (6-pulse thyristor bridges) connected to resistive-inductive loads to represent non-linear loads that produce harmonics accordingly. The power factor of the system is assumed poor power factor of 0.6 lagging initially before adding any harmonic filters. Note that the short circuit level at the low voltage bus is set at 2973 A.

7.1 Harmonic Analysis in the Original System

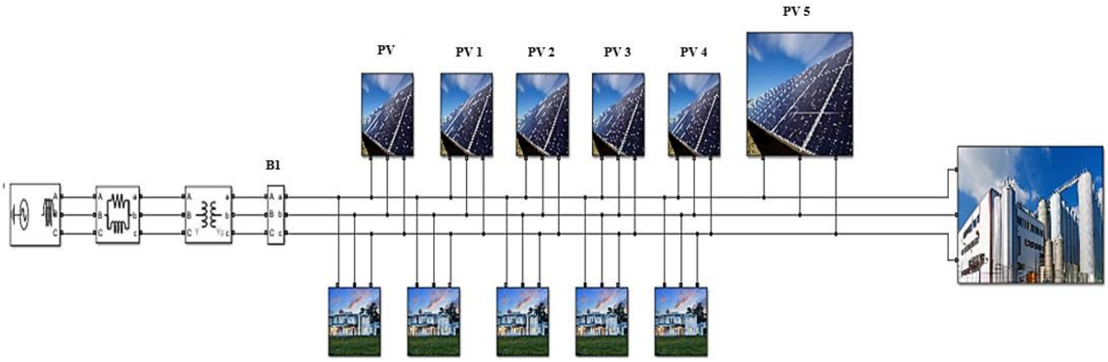


Fig. 8. The test distribution feeder with PV systems

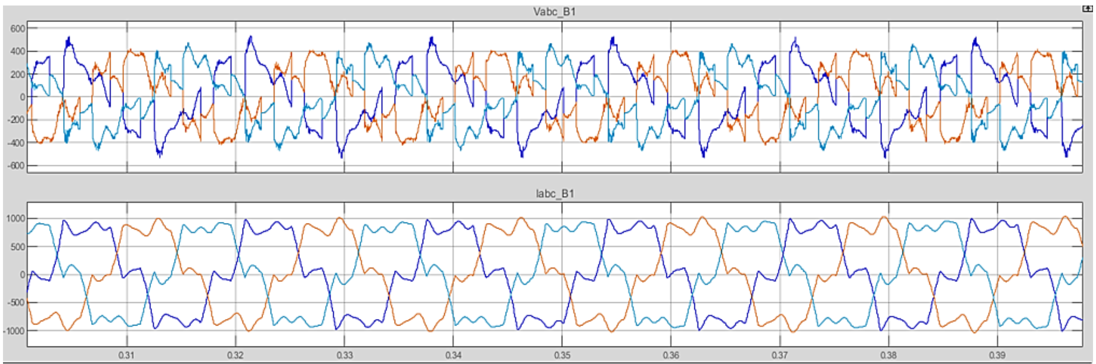


Fig. 9. Distorted voltage and current waveforms

To analyze the harmonic content in the system due to non-linear loads and PV systems, the voltage and the current waveforms are monitored and analyzed. Fig. 9, shows the distorted voltage and the distorted current at the low voltage bus B1, respectively. The waveforms show the significant distortion due to the harmonics injection to the system.
To have a better insight on the harmonic content, the FFT tool is used to obtain the THD, and the harmonic distortion associated with each harmonic order might be exist in the system. Accordingly, Table 3, shows the resulted THD percentages of the voltage and current waveforms are extracted and found at 54.2% and 26.97%, which are also

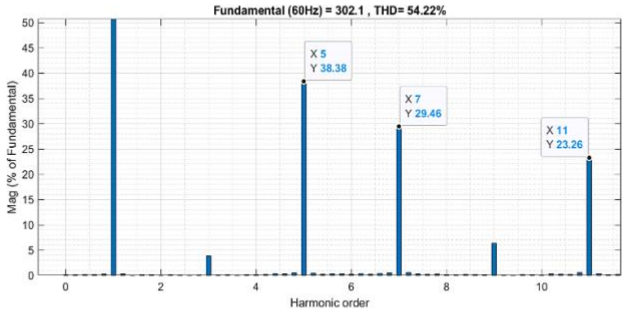


Fig. 10. Voltage THD and Harmonics Orders Magnitudes

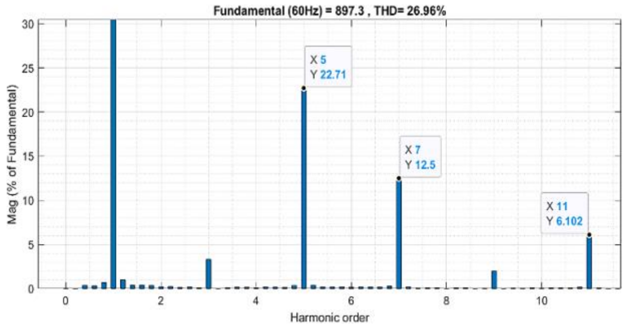
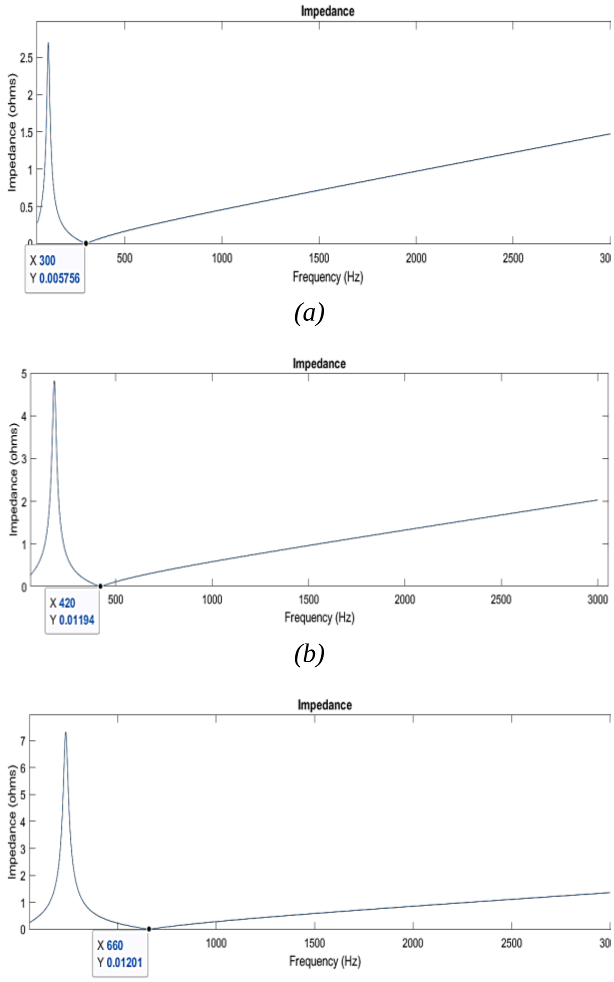


Fig. 11. Current THD and Harmonics Orders Magnitudes

shown in Fig.10 and Fig.11, respectively.

7.2 Characteristics of the designed Harmonic filters

As it is obvious that the harmonic distortion of both the voltage and the current is violating the allowed limits defined by the IEEE-519 standards decussed above in Tables 1 & 2. For instance, the individual harmonic voltage distorion of the 5th, 7th and 11th harmonics are 38.38%, 29.46%, and 23.26%, respectively. These violate the 5% acceptable limit defined by the standard. Moreover, it can be noted that the voltage THD is 26.96% which is almost 337% above the allowed limit of 8%. Hence, in this section, we have followed the previously described filiter design steps to reduce the harmonic distorion of these harmonic orders. Acoordingly, three single-tuned harmonic filters have been designed and modeld for this purpose near the source of harmonics, the load side, to eliminate the harmonics before it is distributed to other parts of the upstream grid. According to the outcome of the design, the applied filters are supposed to provide 619.07 kVAR, 198.55 kVAR, and 119.47 kVAR for the 5th , 7th, and 11th



(c)

Fig. 12. The frequency response of the harmonic filters: a) 5th harmonic, b) 7th harmonic, c) 11th harmonic

filters, respectively. This would improve the power factor of the system from 0.6 to 0.98. To validate the designed filters, the impedance curves for the 5th, 7th, and 11th filters are measures and displayed by computing the filters frequency response. The impedance-frequency curves shown in Fig. 12 clarify how the 5th,7th, and 11th harmonic filters provide a low impedance path at the tuned frequencies (300Hz, 420Hz, and 660Hz) of the harmonic orders. Observing the impedance values for the harmonic orders 5th, 7th, and 11th are 0.005756, 0.01194, and 0.01201, respectively. These values are negligible (almost zero), indicating the low impedance path created by the designed passive filters. Thus, these values prove that the filters were designed correctly, and hence they can provide a very low impedance path at the tuned frequencies as intended.

7.3 Harmonic Analysis after adding Harmonic filters

In order to analyze the impact of application of the designed filters that are connected to the system near to the loads as shown in Fig.13, the waveforms of the voltage and the current have been monitored and analyzed again. The individual harmonic distortion and the THD for both waveforms have been obtained using the FFT, as shown in Fig. 14. The results revealed that the application of the designed harmonic filters had significantly reduced the harmonic

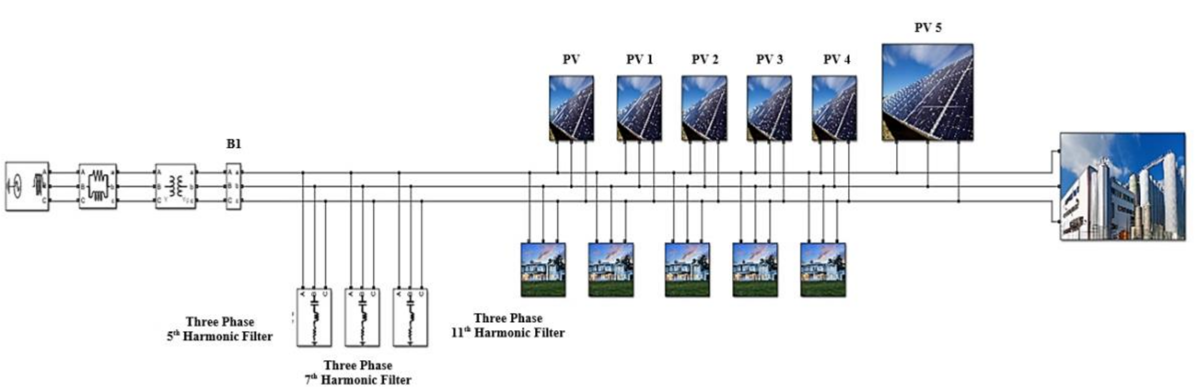


Fig. 13. The test distribution feeder with the designed harmonic filters

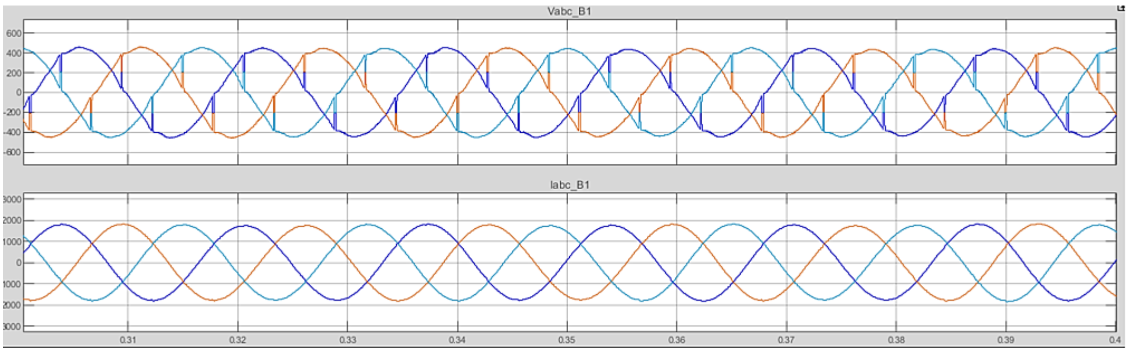


Fig. 14. voltage and current waveforms with harmonic filters

distortion in the other hand, the individual voltage distortion of the 5th, 7th, and 11th harmonics orders are 0.4143%, 0.7057%, and and 0.5847%,

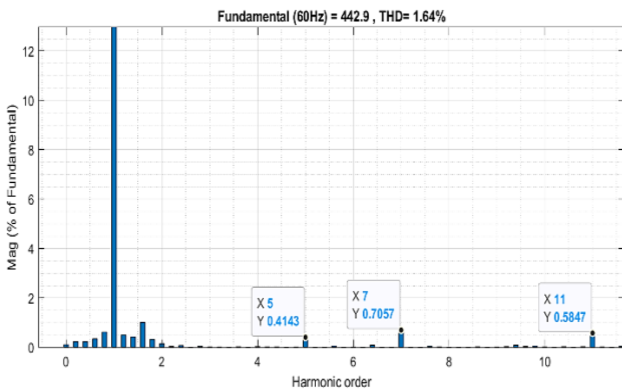


Fig. 15. Voltage THD and Harmonics Orders Magnitudes after application of the harmonic filters

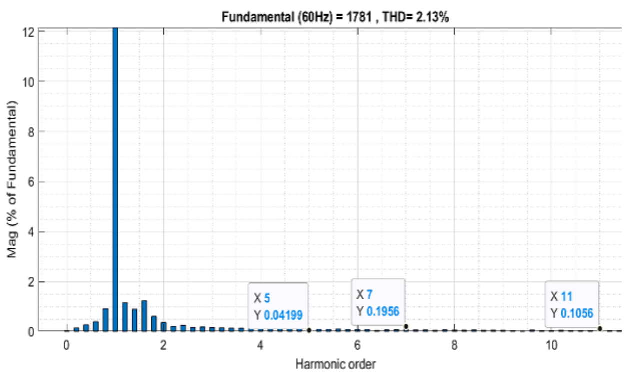


Fig. 16. Current THD and Harmonics Orders Magnitudes after application of the harmonic filters

respectively, where they decreased too much compared to the results before adding the filters.

The FFT analysis shows that the current's THD after application of the filters is 2.13%, and the individual current distortion of the 5th, 7th, and 11th harmonics orders are 0.04199, 0.1956, and 0.1056, respectively, where they also decreased significantly compared to the results before adding the filters. The THD results for the voltage and current harmonic distortion beside the individual harmonic orders are presented in Fig. 15, and Fig. 16, respectively. Observe the significant decrease in the values of the individual harmonics which are almost negligible when compared to the values of the current and voltage at fundamental frequency (i.e., 60 Hz). they dont exceed 0.8% which is also too much below the defined limit of 5%. Hence, these results when taken together show the suitability of application of single-tuned harmonic filters in mitigating the harmonics even in scenarios with high penetration of DGs such as PV systems.

7.4 Validating the results against the IEEE-519 Standard

For more verification of the results obtain by the application of the harmonic filters, the results of both THD and the individual harmonic distortion have been validated against the IEEE-519 standards. These results are listed in Tables 4 and 5, respectively. For instance, it can be noted that the newly observed values of the THD percentages are satisfactory when compared to the limits defined by the standard, as shown in Table 4. For instance, the THD of the voltage is reduced from 54.22% down to 1.64% which is too much below the accepted limit of 8% according to the IEEE-519 standards. In addition, the THD of the current is reduced from 26.96%, before the application of the filters, down to 2.13% after adding the filters

Table 4. Resulted THD and Power Factor values

Item	IEEE Standard	Before Filtering	After Filtering
Voltage THD (%)	8.0	54.22	1.64
Current THD (%)	5.0	26.96	2.13
Power Factor		0.6	0.98

Table 5. Validated Individual Harmonic Distortion against IEEE-519

Harmonic order	IEEE Standard (%)		Harmonics Magnitude (%)			
			Before adding the filters		After adding the filters	
	Voltage	Current	Voltage	Current	Voltage	Current
5th	5.0	4.0	38.38	22.71	0.4143	0.04199
7th	5.0	4.0	29.46	12.5	0.7057	0.1956
11th	5.0	2.0	23.26	6.102	0.5847	0.1056

to the system. On the other hand, it can be noted that the individual harmonic distortion are all within the limits as listed in Table 5. Observe the minimized levels of individual harmonics after adding the filters when compared to the case before the filtering. For example, the fifth harmonic order of the voltage has significantly reduced from 38.38% down to 0.4143%. Similarly, the fifth harmonic order of the current has significantly reduced from 22.71% down to 0.04199%.

8. Conclusions

The paper has investigated the suitability of the application of single-tuned harmonic filters in power distribution networks with the high share of distributed generators. At first, harmonic distortions caused by distributed generators, mainly PV systems, and non-linear loads have been analyzed. The system under study has included a 0.48 kV distribution feeder that is fed by 11 kV power grid through a 1500 KVA distribution transformer. The harmonic distortion injection to the system from both PV systems and non-linear loads have been monitored and analyzed before and after the application of the designed filters. The results have been verified using the IEEE-519 standard to ensure the efficacy of the modeled filters in mitigating the impact of harmonics in the system. The results have demonstrated the efficacy of the proposed collection of single-tuned passive filters in mitigating the harmonic levels and improve the power factor with high share of PV systems (i.e., 59% PV penetration scenario). The findings have been verified using the modeled distribution feeder in MATLAB Simulink.

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