

A New Iterative Approach for Designing Passive Harmonic Filters for Variable Frequency Drives

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Abstract: The extensive usage of variable frequency drives (VFDs) in industrial applications has caused significant concern regarding the quality of power in electrical distribution systems. VFDs are nonlinear loads that cause harmonic voltages across system impedance by injecting harmonic currents into the power system. The performance of other sensitive loads in the system may be harmed as a result of this harmonic distortion. This study presents a new method for designing and specifying low-voltage harmonic filters for 6-pulse VFDs. An electrical distribution system feeding a group of variable frequency drives was analyzed using the proposed methodology. MATLAB software was used to conduct this study. The minimum value of the filter's reactive power and its specifications were determined using an iterative technique. To validate the proposed methodology, two case studies are presented. The results demonstrate that the method is effective.

Keywords: Variable frequency drive, passive filter design, iterative method, MATLAB.

1 Introduction

Variable frequency drives (VFDs) have become increasingly popular in a variety of applications in recent years. A VFD is an electronic device that controls the speed of an AC motor by varying the frequency and voltage of the power supplied to the motor [1]. However, the switching action of VFDs can generate harmonics in a power system. These harmonics flow through the power system, causing a variety of issues such as supply voltage distortion, overloading of electrical distribution equipment such as transformers, and reduction in system efficiency [2–3]. Several methods can be used to improve the performance of a VFD, including appropriate motor and design selection, application of a suitable control method, and improvement of the converter's input and output waveforms [4].

Reduction of harmonics can be accomplished through a variety of methods. In cases in which preventive actions, such as installation modifications and special devices in the supply system, are insufficient, filtering systems must be

installed. Because of their mature technology, reliable operation, and lower installation and maintenance costs, passive filters, which are tuned to each harmonic order to be filtered and installed in parallel with the nonlinear load, are widely used in industries [5].

Passive filters are commonly used for harmonic reduction in VFDs [6]. They work by providing an alternative path for the flow of harmonic currents, effectively bypassing the load and reducing the amount of harmonic distortion in the system [7]. The filters are made up of combination sets of inductance and capacitance, each resonantly tuned to a specific frequency. A small amount of resistance is also included to act as a harmonic current limiter (damper), which are designed to create a resonant circuit that can filter out specific harmonic frequencies [8–9]. These are preferred over other harmonic reduction techniques due to their simplicity, low cost, and high reliability [10]. They do not require any active components, such as semiconductors or controllers, and they do not introduce any additional harmonics or disturbances to the

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system [11]. The effectiveness of a passive filter in reducing harmonics depends on the design of the filter, including the type and values of the reactive components used [12]. However, the design and installation of passive filters must be carefully considered to ensure that they are effective and do not interfere with the operation of other equipment in the system.

The design of passive filters for harmonic reduction of VFDs involves several key considerations. The authors in [13] provided the basis for the design guidelines for passive filters for distribution systems with VFDs. With proper design and implementation, passive filters can significantly improve power quality and protect equipment from damage caused by VFD-generated harmonics.

This study discusses how to design harmonic passive filters for an electrical system that feeds VFDs using an iterative methodology. Through an iterative process, the filter's specifications are estimated to keep the total harmonic distortion within an acceptable range. MATLAB software was used to simulate system performance. This program is also used to analyze an electrical distribution system that feeds a group of VFDs.

The rest of this paper is organized as follows. Section 2 discusses the VFD's components and the harmonic currents it generates. Section 3 presents the application of passive filters to divert a selected portion of the harmonic currents produced by the VFD. Section 4 explains the proposed methodology used in this study. Section 5 discusses the simulation results. Finally, Section 6 concludes the paper.

2 Variable Frequency Drives' Harmonic Currents

VFDs are electrical power conversion devices used as motor controllers to adjust a motor's voltage amplitude and frequency to meet the demands of the motor's load. VFDs offer the most efficient method of controlling the speed of 3-phase AC motors. A VFD can be broken down into three pieces: the AC-DC rectifier, the DC bus storage, and the DC-AC inverter, as shown in **Fig. 1**. The AC-DC diode bridge power conversion stage that creates the classic 6-pulse drive input current harmonic signature is shown in **Fig. 2** [14].

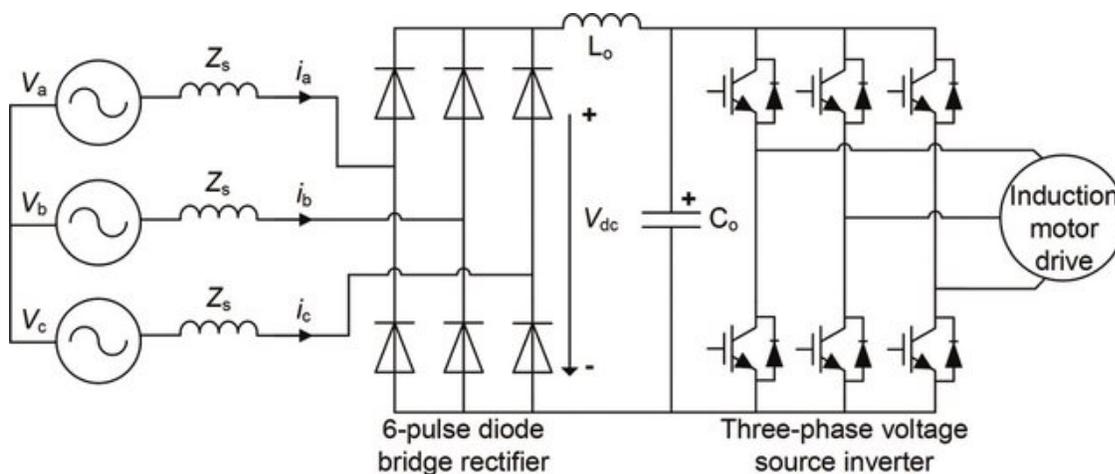


Fig. 1: Schematic showing the three major components of a typical 6-pulse diode rectified 3-phase VFD. [15]

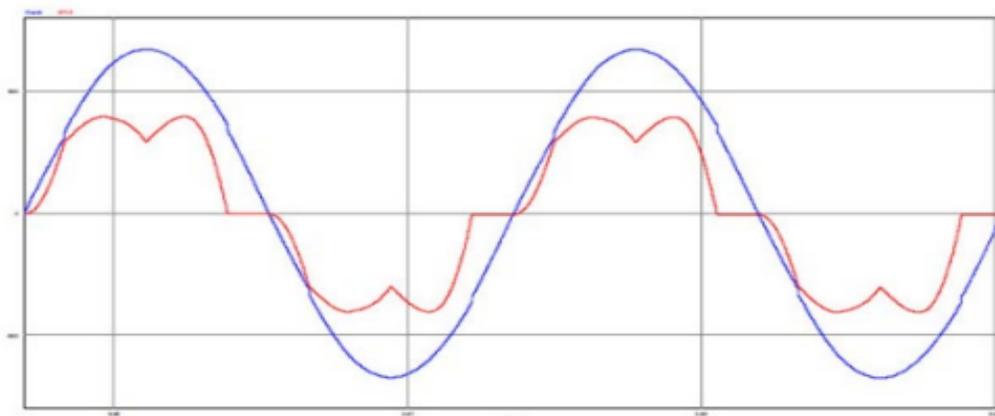


Fig. 2: Six-pulse rectifier circuit current: (blue) input voltage and (red) input current. [14]

Fig. 3 depicts the harmonic spectrum of a 6-pulse diode bridge rectifier and shows the amplitudes of different harmonics plotted against their harmonic numbers. Typically, this is presented as a histogram. Harmonic amplitudes are often expressed in relation to the fundamental frequency. In **Fig. 3**, the amplitude of the fifth harmonic current is almost 50% greater than that of the fundamental current. As the harmonic number increases, the amplitude of the current decreases, as demonstrated in the figure [16].

3 Passive Filters to Mitigate VFD Harmonics

Undesired harmonic currents may be prevented from flowing into the power system by one of two methods: diversion using a low-impedance shunt path (shunt filters) or the use of a high-series impedance to block them (series filters) [17].

When the shunt filter method is utilized to prevent the flow of harmonic currents into the power supply system, the shunt filter effectively short-circuits these currents as

close as possible to the source of distortion. This technique is the most commonly used type of filtering due to its cost-effectiveness, ability to smooth load voltage, and elimination of harmonic current. In contrast, the series filter approach involves blocking harmonic currents by presenting high impedance to the harmonic current using a parallel-tuned circuit. However, this technique is challenging to insulate and can lead to a heavily distorted load voltage, so it is not widely used. Alternatively, active filters can be utilized to supply the harmonic component of the current into a nonlinear load by electronic means [18].

To control harmonic currents and meet regulatory requirements, the most commonly used method is to install a shunt filter. Typically, a filter is installed, as illustrated in **Fig. 4**, to redirect a chosen portion of the VFD-generated harmonic currents [19]. Combining the inductor within the capacitor circuit creates a low-impedance path for the dominant harmonics generated by a standard 6-pulse diode-rectified VFD; these are typically the 5th and 7th harmonics [14].

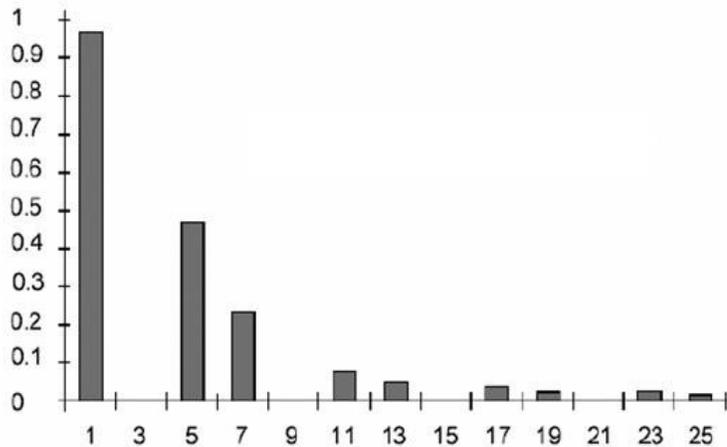


Fig. 3: Harmonic spectrum of a 6-pulse diode rectifier. [16]

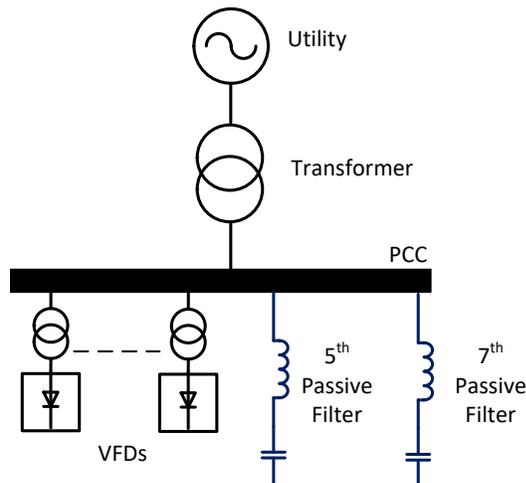


Fig. 4: Power system with shunt filters.

Fig. 5 shows how passive filters consist of elements such as inductance, capacitance, and resistance [18]. It is a well-known fact that the series L-C circuit has the lowest impedance at its resonant frequency, where it behaves like a capacitor below the resonant frequency; it behaves like an inductor above it [13]. The single-tuned filter and high-pass filter are the most frequently used shunt filters since they are easy to design and less costly to implement [17]. **Fig. 6** depicts the equivalent circuit, which includes a harmonic current generator representing the source of the harmonics. The presence of voltage distortion is demonstrated by a harmonic voltage generator in the circuit [20].

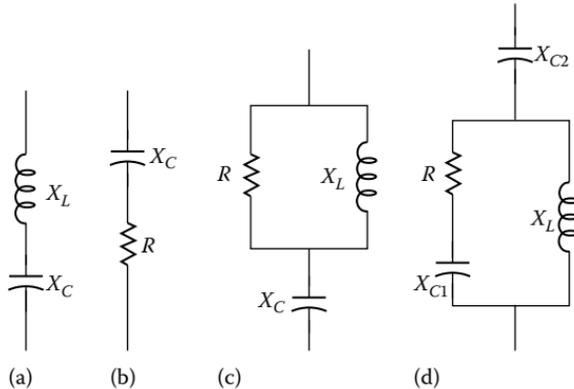


Fig. 5: Common passive filter configurations: (a) single-tuned filter, (b) first-order high-pass filter, (c) second-order high-pass filter, and (d) third-order high-pass filter. [18]

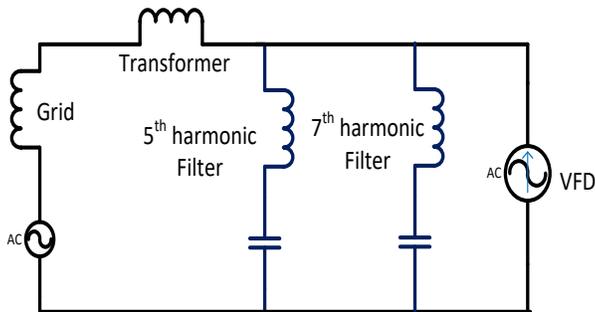


Fig. 6: Equivalent circuit for passive harmonic filtering.

Ideally, to effectively reduce the specific harmonic that it is intended to suppress, the filter should be tuned precisely to its characteristic frequency. For instance, in a 3-phase, 6-pulse VFD, the 5th and 7th harmonic filters work best when tuned exactly to 300 Hz and 420 Hz, respectively. However, in practical applications, the filters are often tuned to a frequency slightly below the nominal resonant frequency to prevent the occurrence of parallel resonance, which could occur if the filter component parameters change due to temperature or aging. Another reason for this tuning frequency is that the VFD typically generates harmonics at integer multiples of the fundamental

frequency of the power system. When the resonant frequency of the harmonic filter is set slightly below the fundamental frequency, the filter can effectively attenuate the harmonic currents and reduce the level of distortion in the power system. Therefore, as a general rule of thumb, the resonant frequency of the harmonic filter is typically set at about 0.95 times the nominal resonant frequency for VFDs [13].

4 Methodology

The proposed methodology used to estimate the value of the filter needed to maintain the total harmonic distortion within the specified limits is shown in **Fig. 7**. The methodology of this study is based on the following assumptions:

- This methodology is related to the system shown in **Fig. 4**.
- Only the VFDs' loads are considered to be present on the low-voltage side of the transformer.

The following sections describe the proposed methodology of this study.

4.1 Needed Data

The tested system shown in **Fig. 4** comprises the utility, the transformer, and the group of VFDs. The specifications for each component are shown in Table 1.

Table 1: Tested system specifications.

Component	Ratings
Utility	13.8 kV, 50 MVAsc, 50 Hz
Transformer	1000 kVA, 13.8/0.48 kV, Z = 5.75%
VFD	6-pulse, PWM VFD with isolation XFMR 480 V, 900 kVA, Displacement PF (DPF) = 0.9

As shown in Table 1, the needed data for the grid are the rated voltage and the short-circuit MVA (MVAsc,u), and the data required for the transformer are the rated capacity, primary and secondary voltages, percent impedance, and short circuit MVA. The short-circuit MVA (MVAsc,tr) of the transformer was calculated as in the following equation:

$$MVAsc, tr = \frac{\text{Rated Capacity in MVA}}{\text{Transformer impedance in \%}} \tag{1}$$

This system feeds a group of VFDs, as shown in **Fig. 4**, with a total load of 900 kVA operating at 0.9 displacement PF at 480 V. The key to performing a harmonic analysis is obtaining data on the harmonic currents that are drawn by VFDs. Characteristic harmonics are related to the pulse number by the following equation:

$$h = p \times n \pm 1. \tag{2}$$

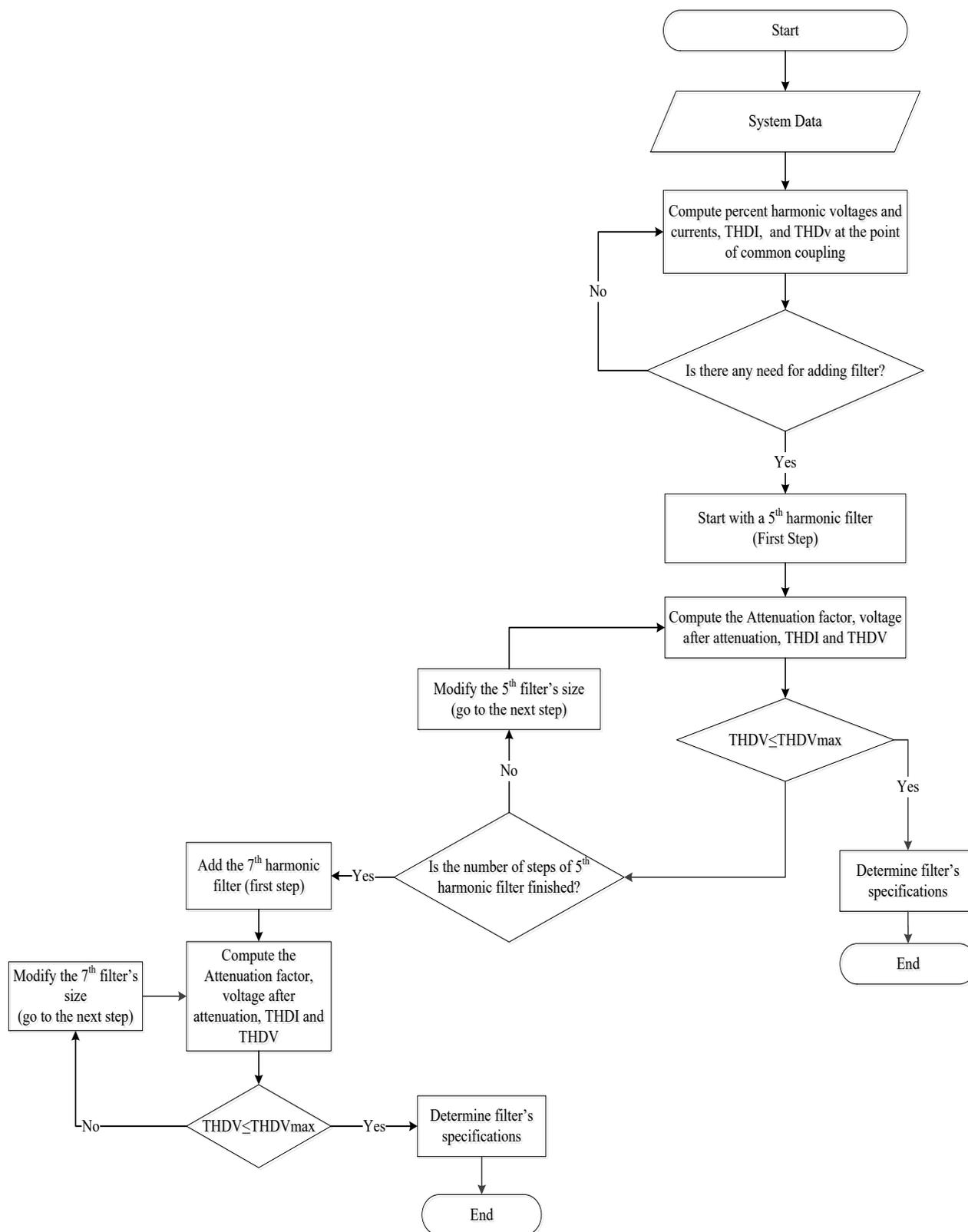


Fig. 7: Flowchart of the proposed methodology.

where h is the harmonic order, p is the pulse number of the converter, and n is an integer having values of 1, 2, 3, and so on.

This means that a 6-pulse converter at the front end of a VFD draws harmonic currents of orders 5, 7, 11, 13, 17, 19, 23, 25, etc. The harmonic current magnitudes for the 6-pulse VFD are given in Table 2.

Table 2: Harmonic current magnitudes for 6-pulse VFDs.

Harmonic order	Harmonic current (A)	Harmonic order	Harmonic current (A)
5	364.8	25	15.2
7	11.8	29	8.7
11	79.8	31	9.7
13	37.9	35	6.5
17	37.9	37	5.4
19	22.7	41	4.3
23	17.3	43	3.2

For each of the harmonic filters, the tuning frequency, the maximum Var rating of the filter, the starting value of the filter's Var, and the step size should be specified.

4.2 Harmonics Calculation

After obtaining the specification of each of the tested system elements and the harmonic signature of the VFDs, the next step was to perform the following harmonic calculations:

- Calculation of the percent harmonic current for each harmonic order. The following equation was used to perform the percent harmonic current:

$$\%I_h = \frac{I_h}{I_1} * 100. \quad (3)$$

where I_h is the Rms current of harmonic order (h), and I_1 is the Rms fundamental current ($h = 1$).

- Calculation of the percent harmonic voltage for each harmonic order. The following equation was used to perform the percent harmonic current:

$$V_H = \%I_h * \frac{\text{Capacity of VFD}}{S_{CS,VFD}} * h. \quad (4)$$

$S_{CS,VFD}$ was calculated as follows:

$$S_{CS,VFD} = \frac{MVAsc,u * MVAsc,tr}{MVAsc,u + MVAsc,tr}. \quad (5)$$

- Calculation of the total harmonic current distortion (THDI). Equation (6) defined $THDI$ as follows:

$$THDI = \sqrt{\frac{I_{rms}}{I_1} - 1}. \quad (6)$$

I_{rms} was computed as follows:

$$I_{rms} = \sum_{h=1}^h I_h^2. \quad (7)$$

- Calculation of the total harmonic voltage distortion

(THDV). This was defined as follows:

$$THDV = \sqrt{\sum_{h \neq 1}^h V_H^2}. \quad (8)$$

4.3 Need for Adding Filters

The THDV at the point of common connection (PCC) for low-voltage and medium-voltage systems is limited by IEEE Std. 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," as shown in Table 3 [13].

Table 3: Limits of the THDV.

System nominal voltage (V)	THD, % General systems
120–600	5
69 kV and below	5
69–161 kV	2.5
161 kV and above	1.5

The THDV limits listed in Table 3 refer to THDV at the source-to-distribution system interface. Thus, the value of THDV serves as the criterion for deciding whether to add a filter. For our study, we decided that adding a filter was necessary if THDV was larger than 5%.

4.4 Filter Calculation

If the THDV is larger than 5%, a harmonic filter should be added to reduce the THDV to be within acceptable limits. A harmonic filter reduces the amplitude of all harmonic voltages present at the point where it is installed. The highest level of reduction occurs at the frequency that matches or is in close proximity to the resonant frequency of the filter [13]. The effectiveness of compensation is measured by assessing the degree of attenuation achieved in a power distribution system that supplies high-power non-linear loads and is equipped with passive filters [21]. The attenuation factor is defined as follows:

$$a_n(h) = \sqrt{\frac{V(h)}{V_f(h)}}. \quad (9)$$

where $a_n(h)$ is the attenuation factor due to the n -th-order filter of the h^{th} order harmonic voltage. $V(h)$ is the h^{th} harmonic voltage without the filter at the point of connection, and $V_f(h)$ is the h^{th} harmonic voltage with the filter at the point of connection.

It is desirable to have a high attenuation factor $a_n(h)$. A value equal to one indicates that there is no reduction in the harmonic voltage due to the filter. A value less than unity shows that the filter is amplifying the harmonic voltage instead of reducing it. A positive attenuation factor at a certain frequency means that the filter circuit's impedance

is inductive for that harmonic frequency. Conversely, a negative value indicates that the impedance is capacitive at that frequency [13].

Fig. 8 demonstrates the basic circuit used to determine the h -th harmonic attenuation factor produced by the n^{th} harmonic filter. In this circuit, $I(h)$ represents the h^{th} harmonic injected by the variable frequency drive, $Z_s(h)$ accounts for the system impedance, and $Z_n(h)$ represents the n^{th} harmonic filter impedance at the h^{th} harmonic.

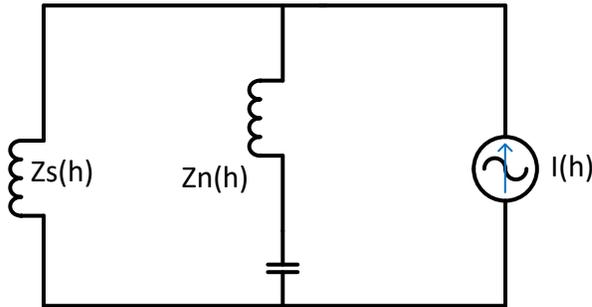


Fig. 8: Circuit used for harmonic voltage calculation.

The n^{th} harmonic filter impedance at the harmonic frequency (h) can be expressed in terms of the filter kvar (kVA $_f$) and its tuning frequency (h_n) as:

$$Z_n(h) = \frac{j}{\text{kVA}_f} \left(\frac{h}{h_n^2} - \frac{1}{h} \right). \tag{10}$$

where

$$\delta = \frac{h^2 h_n^2}{h^2 - h_n^2}. \tag{11}$$

The attenuation factor is expressed as follows [22]:

$$a_n(h) = 1 + \frac{\delta \text{kVA}_f}{S_{cs,VFD}}. \tag{12}$$

When multiple filters with nominal frequencies are connected in parallel, the combined attenuation factor for the h^{th} harmonic voltage can be calculated using the following equation [13]:

$$a_f(h) = 1 + \frac{\delta_1 \text{kVA}_{f1}}{S_{cs,VFD}} + \frac{\delta_2 \text{kVA}_{f2}}{S_{cs,VFD}} \dots + \frac{\delta_k \text{kVA}_{fn}}{S_{cs,VFD}}, \tag{13}$$

Where

$$\delta_k = \frac{h^2 h_n(k)^2}{h^2 - h_n(k)^2}. \tag{14}$$

Harmonic currents flowing into the tuned filters $I_n(h)$ and into the utility $I_s(h)$ with the connected filter(s) can be calculated as follows:

$$I_n(h) = \frac{V(h)}{Z_n(h)}, \tag{15}$$

$$I_s(h) = \frac{I(h)}{a_n(h)}. \tag{16}$$

4.5 Iterative Process

The proposed method consists of two loops. The first loop involves incorporating a filter that suppresses the 5th harmonic, and the second loop involves adding a filter that suppresses the 7th harmonic. The filter's step size and maximum kvar value are specified. If the THD $_V$ is smaller than the THD $_{Vmax}$, the first loop is terminated after the first filter is added and before it reaches the last step of the filter Var that was provided. If the THD $_V$ is higher than the THD $_{Vmax}$, the first loop is terminated and the second loop, which adds the second filter, is started. If the THD $_V$ is less than the THD $_{Vmax}$, the second loop is terminated.

4.6 Filter Specifications

The specifications of the filter were obtained using the following equations:

- Calculation of the actual fundamental frequency compensation provided by a derated capacitor bank. It is recommended in [13] to choose the voltage rating (V_{rated}) of the capacitors higher than the distribution system voltage (V_{actual}).

$$Q_c = Q_{rated} \left(\frac{V_{actual}}{V_{rated}} \right)^2, \tag{17}$$

where the Q_{rated} is the filter's kvar obtained after the iterative process.

- Calculation of the full-load fundamental frequency current of the capacitor bank:

$$I_c = \left(\frac{Q_c}{\sqrt{3} V_{rated}} \right)^2. \tag{18}$$

- Determination of the reactance of the capacitor:

$$X_c = \frac{V_{rated}^2}{Q_c}. \tag{19}$$

- Determination of the size of the reactor:

$$X_l = \frac{X_c}{h_{tuned}^2}, \tag{20}$$

where h_{tuned} is the tuned harmonic frequency.

- Calculation of the full-load current of the filter:

$$I_{f(FL)} = \frac{V_{actual}}{\sqrt{3} (X_c + X_l)}. \tag{21}$$

- Calculation of the filter reactive power:

$$Q_{f(FL)} = \sqrt{3} V_{actual} I_{f(FL)}. \tag{22}$$

5 Results

Two case studies are presented to validate the proposed methodology. The first case involves simulating the system depicted in **Fig. 4** at a rated voltage of 480 V on the transformer's low voltage side, while in the second case, the rated voltage is lowered to 240 V. The aim is to find the minimum value of a filter's rating and to determine the effects of these harmonic filters on harmonic voltages and current distortion. The 5th harmonic filter has a maximum rating of 300 kvar with a 50-kvar step size, whereas the 7th

harmonic filter has a maximum rating of 150 kvar with a 50-kvar step size. A detuning factor of 0.95 was used.

In the first case study, the system in **Fig. 4** is simulated at a rated voltage of 480 V at the low side of the transformers. The simulation results are presented as follows:

Table 4 shows the percentage of harmonic currents ($\%I_H$), voltages ($\%V_H$), THD_V, and THD_I of the VFDs, and the source current before the filter (I_s) is added.

The proposed methodology's iterative process for determining the minimum filter size required to maintain the THD_V below 5% is illustrated in Table 5. At each iteration, the source current, attenuation factor, and harmonic voltage were evaluated.

The simulation results show that this system requires a 300-kvar 5th harmonic filter and a 150-kvar 7th harmonic filter. **Fig. 9** illustrates how the source current value changes when passive filters are added to the system. After the filter has been added, it is noted that the source current is reduced. The effect of adding passive filters on the THD_V value is demonstrated in **Fig. 10**. The addition of the filter resulted in a drop in THD_V, as illustrated. The effect of the addition of a passive filter on the attenuation factor value is shown in **Fig. 11**. The value of the attenuation factor is increased, which means there is attenuation in the harmonic voltages.

To verify the effectiveness of the proposed methodology, a second case study was performed, involving a reduction in the rated voltage on the VFD terminals to 240 V. The simulation results were obtained after the MATLAB code was developed with the same procedures followed previously.

Table 7 illustrates the percentage of harmonic currents ($\%I_H$), and voltages ($\%V_H$), as well as THD_V and THD_I values of the VFDs. Additionally, the table presents the source current (I_s) values before the addition of the filter.

Table 8 demonstrates the iterative process of the proposed methodology to identify the minimum required filter size to maintain THD_V below 5%. In each iteration, the calculations were performed for source current, harmonic voltage, and attenuation factor.

It was revealed that this system needs only a 100-kvar 5th harmonic filter after the simulation results have been obtained.

After determining the required size of the filter to ensure that THD_V remains below 5%, the simulation software calculates the filter's specifications, which are presented in Table 9.

Table 4: Percentage of harmonic currents ($\%I_H$), voltages ($\%V_H$), source current before filtering (I_s), THD_V, and THD_I for 480-V rated voltage.

h	$\%I_H$	$\%V_H$	I_s
5	33.6988	11.7524	364.8000
7	1.0900	0.5322	11.8000
11	7.3716	5.6559	79.8000
13	3.5011	3.1746	37.9000
17	3.5011	4.1514	37.9000
19	2.0969	2.7790	22.7000
23	1.5981	2.5638	17.3000
25	1.4041	2.4484	15.2000
29	0.8037	1.6256	8.7000
31	0.8960	1.9375	9.7000
35	0.6004	1.4658	6.5000
37	0.4988	1.2874	5.4000
41	0.3972	1.1359	4.3000
43	0.2956	0.8866	3.2000
%THD _I = 35.0268		%THD _V = 15.1748	

The simulation software determines the filter's specifications, which are shown in Table 6, after the size of the filter necessary to maintain THD_V less than 5% is determined.

Table 5: Results of the iterative process to determine minimum filter size for THDv minimization: Kvar of the filter, %THDV, %THDI, source current (I_{sf}), attenuation factor, voltage after attenuation (V_f).

kvar _{f1}	50 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	192.3326	10.1545	72.0562	34.4264	34.6171	20.7636	15.8523
kvar _{f2}	0	a _n (h)	1.8967	1.162	1.1075	1.1009	1.0948	1.0933	1.0913
		V _f (h)	6.1962	0.4580	5.1070	2.8836	3.7918	2.5419	2.3492
%THD _v	10.7119	h	25	29	31	35	37	41	43
		I _{sf} (A)	13.9360	7.9828	8.9029	5.9684	4.9592	3.9500	2.9398
%THD _i	19.7639	a _n (h)	1.0907	1.0898	1.0895	1.0891	1.0889	1.0886	1.0885
		V _f (h)	2.2448	1.4916	1.7783	1.3460	1.1823	1.0435	0.8145
kvar _{f1}	100 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	130.5922	8.9118	65.6824	31.5360	31.8577	19.1316	14.6282
kvar _{f2}	0	a _n (h)	2.7934	1.3241	1.2149	1.2018	1.1897	1.1865	1.1826
		V _f (h)	4.2072	0.4019	4.6553	2.6415	3.4895	2.3421	2.1678
%THD _v	9.0558	h	25	29	31	35	37	41	43
		I _{sf} (A)	12.8660	7.3749	8.2269	5.5172	4.5849	3.6526	2.7187
%THD _i	14.4288	a _n (h)	1.1814	1.1797	1.1791	1.1781	1.1778	1.1772	1.1770
		V _f (h)	2.0725	1.3780	1.6432	1.2442	1.0930	0.9649	0.7532
kvar _{f1}	150 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	98.8579	7.9401	60.3445	29.0934	29.5056	17.7375	13.5796
kvar _{f2}	0	a _n (h)	3.6901	1.4861	1.3224	1.3027	1.2845	1.2798	1.2740
		V _f (h)	3.1848	0.3581	4.2769	2.4369	3.2319	2.1714	2.0124
%THD _v	8.0657	h	25	29	31	35	37	41	43
		I _{sf} (A)	11.9486	6.8530	7.6463	5.1294	4.2631	3.3969	2.5286
%THD _i	11.6862	a _n (h)	1.2721	1.2695	1.2686	1.2672	1.2667	1.2659	1.2655
		V _f (h)	1.9247	1.2805	1.5273	1.1567	1.0163	0.8974	0.7006

Table 5 (Continued)

kvar _{r1}	200 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	79.5315	7.1594	55.8090	27.0020	27.4770	16.5327	12.6712
kvar _{r2}	0	a _n (h)	4.5869	1.6482	1.4299	1.4036	1.3793	1.3730	1.3653
		V _f (h)	2.5622	0.3229	3.9555	2.2617	3.0097	2.0240	1.8778
%THD _v	7.3489	h	25	29	31	35	37	41	43
		I _{sf} (A)	11.1534	6.4001	7.1422	4.7925	3.9835	3.1747	2.3633
%THD _i	9.9835	a _n (h)	1.3628	1.3594	1.3581	1.3563	1.3556	1.3545	1.3540
		V _f (h)	1.7966	1.1959	1.4266	1.0808	0.9497	0.8387	0.6548
kvar _{r1}	250 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	66.5260	6.5185	51.9077	25.1911	25.7094	15.4812	11.8768
kvar _{r2}	0	a _n (h)	5.4836	1.8102	1.5373	1.5045	1.4742	1.4663	1.4566
		V _f (h)	2.1432	0.2940	3.6790	2.1101	2.8161	1.8952	1.7601
%THD _v	6.7819	h	25	29	31	35	37	41	43
		I _{sf} (A)	10.4574	6.0033	6.7005	4.4972	3.7384	2.9797	2.2183
%THD _i	8.8011	a _n (h)	1.4535	1.4492	1.4477	1.4454	1.4445	1.4431	1.4425
		V _f (h)	1.6845	1.1217	1.3384	1.0142	0.8912	0.7872	0.6146
kvar _{r1}	300 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	57.1761	5.9830	48.5161	23.6078	24.1555	14.5555	11.1761
kvar _{r2}	0	a _n (h)	6.3803	1.9723	1.6448	1.6054	1.5690	1.5596	1.5479
		V _f (h)	1.8420	0.2698	3.4386	1.9774	2.6459	1.7819	1.6562
%THD _v	6.3119	h	25	29	31	35	37	41	43
		I _{sf} (A)	9.8431	5.6529	6.3102	4.2361	3.5217	2.8073	2.0901
%THD _i	7.9183	a _n (h)	1.5442	1.5390	1.5372	1.5344	1.5334	1.5317	1.5311
		V _f (h)	1.5855	1.0563	1.2604	0.9553	0.8396	0.7416	0.5791

Table 5 (Continued)

kvar _{r1}	300 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	59.2456	3.1637	41.6737	20.6259	21.3965	12.9357	9.9715
kvar _{r2}	50 kvar	a _n (h)	6.1574	3.7298	1.9149	1.8375	1.7713	1.7548	1.7349
		V _f (h)	1.9087	0.1427	2.9536	1.7277	2.3437	1.5836	1.4777
%THD _v	5.6339	h	25	29	31	35	37	41	43
		I _{sf} (A)	8.7931	5.0584	5.6500	3.7963	3.1571	2.5180	1.8751
%THD _i	7.7090	a _n (h)	1.7286	1.7199	1.7168	1.7122	1.7105	1.7077	1.7066
		V _f (h)	1.4164	0.9452	1.1285	0.8561	0.7526	0.6652	0.5195
kvar _{r1}	300 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	61.4705	2.1504	36.5227	18.3128	19.2031	11.6403	9.0013
kvar _{r2}	100 kvar	a _n (h)	5.9346	5.4874	2.1849	2.0696	1.9736	1.9501	1.9219
		V _f (h)	1.9803	0.0970	2.5886	1.5339	2.1034	1.4250	1.3339
%THD _v	5.1268	h	25	29	31	35	37	41	43
		I _{sf} (A)	7.9454	4.5771	5.1148	3.4392	2.8609	2.2827	1.7002
%THD _i	7.5017	a _n (h)	1.9130	1.9008	1.8964	1.8900	1.8875	1.8837	1.8822
		V _f (h)	1.2799	0.8552	1.0216	0.7756	0.6820	0.6030	0.4710
kvar _{r1}	300 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	63.8690	1.6287	32.5050	16.4662	17.4176	10.5808	8.2032
kvar _{r2}	150 kvar	a _n (h)	5.7117	7.2450	2.4550	2.3017	2.1760	2.1454	2.1089
		V _f (h)	2.0576	0.0735	2.3038	1.3792	1.9078	1.2953	1.2157
%THD _v	4.7402	h	25	29	31	35	37	41	43
		I _{sf} (A)	7.2469	4.1794	4.6723	3.1435	2.6155	2.0877	1.5551
%THD _i	7.4290	a _n (h)	2.0975	2.0817	2.0761	2.0678	2.0646	2.0597	2.0577
		V _f (h)	1.1673	0.7809	0.9332	0.7089	0.6235	0.5515	0.4309

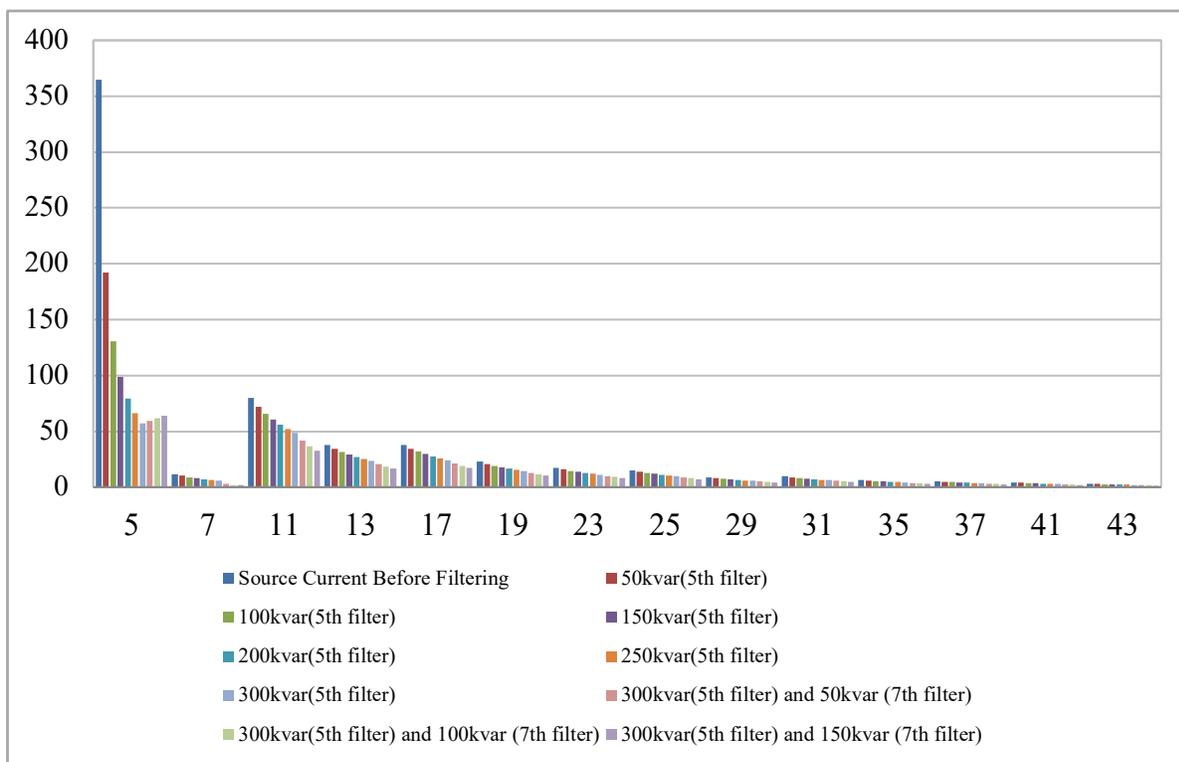


Fig. 9: The effect of adding harmonic filters on the source current value.

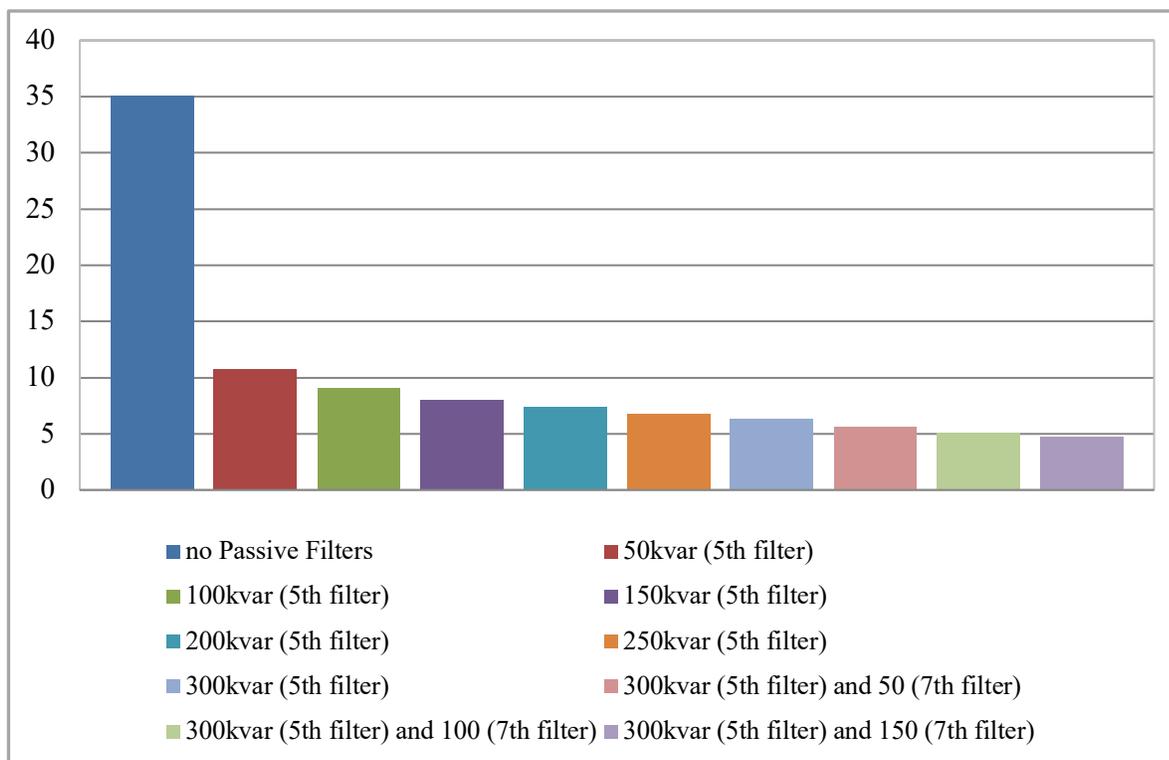


Fig. 10: The effect of adding a harmonic filter on the THD_v value.

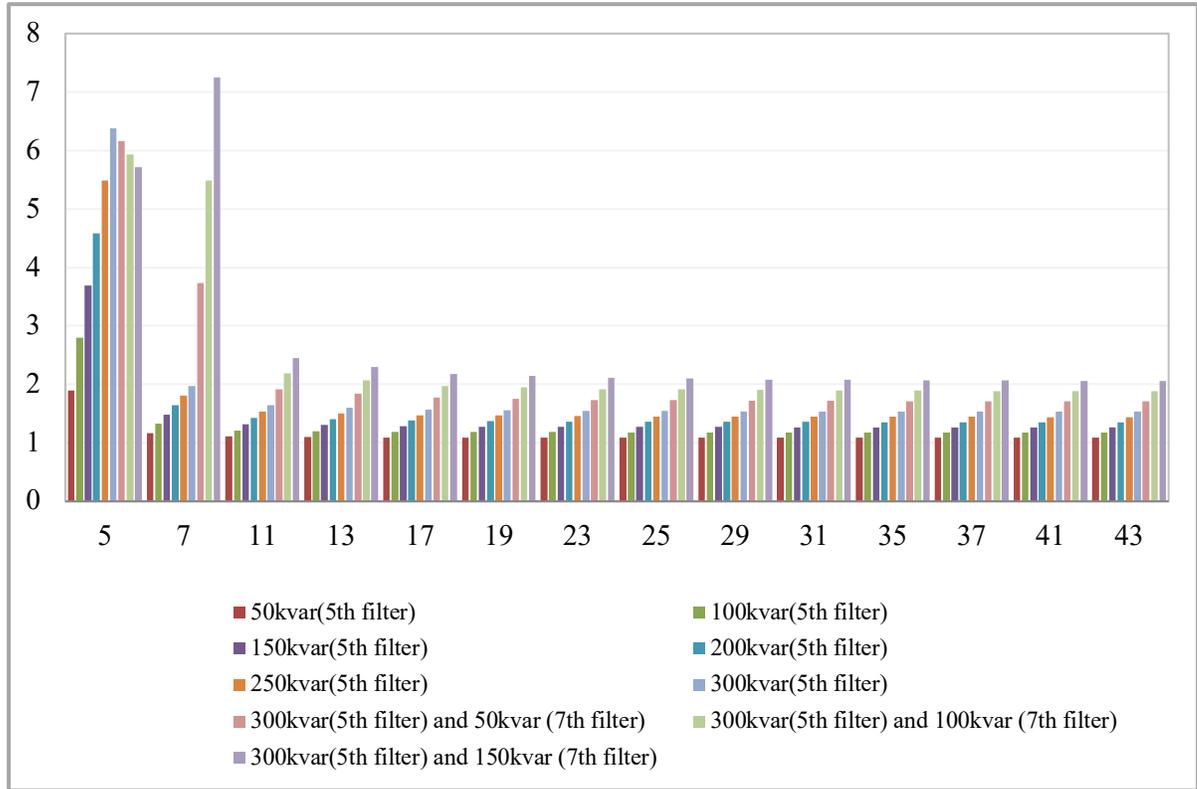


Fig. 11: The effect of adding a harmonic filter on the attenuation factor value.

Table 6: Filter’s specifications obtained from the simulation.

Harmonic order	5 (5th harmonic filter)		
Filter tuning harmonic	4.75	Rated frequency	50 Hz
Rating	468.75 kvar	Available rating	500 kvar
Capacitor actual current	360.8439 A	Xc	0.768
X_l	0.034	$I_{f(FL)}$	377.56 A
Rated voltage	600 V	Actual voltage	480 V
Supplied compensation		313.897 kvar	
Harmonic order	7 (7th harmonic filter)		
Filter tuning harmonic	6.65	Rated frequency	50 Hz
Rating	234.3750 kvar	Available rating	250 kvar
Capacitor actual current	180.4220 A	Xc	1.5360
X_l	0.0347	$I_{f(FL)}$	184.592 A
Rated voltage	600 V	Actual voltage	480 V
Supplied compensation		153.467 kvar	

Table 7: Percentage of harmonic currents (%I_H), voltages (%V_H), source current before filtering (I_s), THD_V, and THD_I for 240-V rated voltage.

<i>h</i>	%I _H	%V _H	I _s
5	16.8494	5.8762	364.8000
7	0.5450	0.2661	11.8000
11	3.6858	2.8279	79.8000
13	1.7505	1.5873	37.9000
17	1.7505	2.0757	37.9000
19	1.0485	1.3895	22.7000
23	0.7991	1.2819	17.3000
25	0.7021	1.2242	15.2000
29	0.4018	0.8128	8.7000
31	0.4480	0.9687	9.7000
35	0.3002	0.7329	6.5000
37	0.2494	0.6437	5.4000
41	0.1986	0.5680	4.3000
43	0.1478	0.4433	3.2000
%THD _I = 17.5134		%THD _V = 7.5874	

Table 8: Results of the iterative process to determine minimum filter size for THD_V minimization: Kvar of the filter, %THD_V, %THD_I, source current (I_{sf}), attenuation factor, voltage after attenuation (V_f).

kvar _{f1}	50 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	192.3326	10.1545	72.0562	34.4264	34.6171	20.7636	15.8523
kvar _{f2}	0	a _n (h)	1.8967	1.162	1.1075	1.1009	1.0948	1.0933	1.0913
		V _f (h)	3.0981	0.2290	2.5535	1.4418	1.8959	1.2710	1.1746
%THD _V	5.3560	h	25	29	31	35	37	41	43
		I _{sf} (A)	13.9360	7.9828	8.9029	5.9684	4.9592	3.9500	2.9398
%THD _I	9.8819	a _n (h)	1.0907	1.0898	1.0895	1.0891	1.0889	1.0886	1.0885
		V _f (h)	1.1224	0.7458	0.8891	0.6730	0.5911	0.5217	0.4072
kvar _{f1}	100 kvar	h	5	7	11	13	17	19	23
		I _{sf} (A)	130.5922	8.9118	65.6824	31.5360	31.8577	19.1316	14.6282
kvar _{f2}	0	a _n (h)	2.7934	1.3241	1.2149	1.2018	1.1897	1.1865	1.1826
		V _f (h)	2.1036	0.2010	2.3276	1.3208	1.7448	1.1711	1.0839
%THD _V	4.5279	h	25	29	31	35	37	41	43
		I _{sf} (A)	12.8660	7.3749	8.2269	5.5172	4.5849	3.6526	2.7187
%THD _I	7.2144	a _n (h)	1.1814	1.1797	1.1791	1.1781	1.1778	1.1772	1.1770
		V _f (h)	1.0362	0.6890	0.8216	0.6221	0.5465	0.4825	0.3766

Table 9: Filter's specifications obtained from the simulation.

Harmonic order	5 (5th harmonic filter)		
Filter tuning harmonic	4.75	Rated frequency	50 Hz
Rating	416.6667 kvar	Available rating	500 kvar
Capacitor actual current	360.8439 A	Xc	0.3840
X_l	0.0170	$I_{f(FL)}$	377.56 A
Rated voltage	400 V	Actual voltage	240 V
Supplied compensation		156.948 kvar	

6 Conclusion

This paper proposes a new iterative method for obtaining the rating of the minimum filter needed to maintain a THD_v less than the maximum allowable. In this study, a comprehensive methodology was provided that can be used to determine whether harmonic filtering is required and to select an appropriate rating for a filter that will achieve acceptable harmonic performance. Two case studies were simulated to evaluate the effectiveness of the proposed method. The results demonstrated that the suggested methodology can be applied to estimate the required filter rating and define filter specifications to maintain harmonic distortion within allowable limits.

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