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Sizing of a Filter (*L*-*C*) for a 180˚ Control Inverter Connected to a Medium Voltage Network

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Abstract

This paper studies the design and sizing of a filter (*L*-*C*) for an inverter with 180˚ control in Medium voltage (MV), based on formulas of the capacitance of the capacitor *C* and the inductance *L* of the filter (*L*-*C*) of an SPWM inverter. These formulas were obtained by minimizing two parameters: the reactive power of the capacitor (capped at 5% of the apparent power of the load) and the ripple of the current flowing through inductance *L* (capped at 10% of the current supplying the load). The application of these formulas for the calculation of the filter (*L*-*C*) of the 180˚ control inverter in MV is not conclusive. Studies have been carried out to make them applicable. The results show that limiting the current ripple in the inductor to 10% of the load current is a valid assumption and that limiting the reactive power of the capacitor to 5% of the apparent power of the load presents shortcomings. The results also show that setting the inductance *L* of the filter to L_{maxi} and the capacitor *C* from 35 × C_{maxi} to 400 × C_{maxi} gives voltage and current THDs that meet the 519 IEEE-2014 standards.

Keywords

Filter (*L*-*C*), Inverter with 180˚ Control and with SPWM Control, THD, Mathematical Iterations, Matlab-Simulink, MV

1. Introduction

In recent decades, the countries of sub-Saharan Africa have started to build photovoltaic plants with peak powers of around tens of megawatts [1]. These photovoltaic plants are built to reinforce the energy demand of these countries which does not cease growing.

For the transmission and distribution in MV in localities far from the national grid, of the energy produced in these photovoltaic plants, the use of three-phase voltage inverters is necessary. It is with this in mind that we propose to design and size a filter (*L*-*C*) for a 180˚ control inverter. This is because inverters do not provide sinusoidal voltage and current signals [2]. These signals contain harmonics generated by semiconductors. These harmonics hamper the proper functioning of electrical equipment [3].

The measurement parameter of these harmonics is the THD. It characterizes the quality of the voltage and current signals, and therefore the quality of the power. The lower the THD, the better the quality of the signal power, and the signal becomes closer to sinusoidal shape [3].

In order to obtain better filter efficiency (*L*-*C*) for the operation of an inverter with 180˚ control in MV, the main contribution proposed in this research article is:

- on the one hand, to discuss the applicability of existing formulas in newspapers [4];
- on the other hand, to improve them from studies so that they are applicable to the sizing of the filter (*L*-*C*) of the 180˚ control inverter connected to an MV network [5].

The document is structured as follows: section II presents the system model and the formulation of the problem; the filter (*L*-*C*) and its calculation formulas for the three-phase inverter with SPWM control are studied; in section III, the 180˚ control inverter is analysed; section IV presents the applicability of the filter formulas (*L*-*C*) of the three-phase inverter SPWM to the inverter with 180˚ control; in section V, studies to improve the parameters of the filter (*L*-*C*) for an inverter with control 180˚. Finally, section VI concludes the article.

2. System Model and Problem Formulation

The model is based on a medium voltage direct current (MVDC) electrical power transmission system. This is to improve the quality of the voltage and current signals on the AC side of the 180˚ control inverter connected to an MV network.

The scientific literature has been used to the best of our knowledge. No method of calculating a filter (*L*-*C*) for a 180˚ control inverter operating in MV. Then a method of calculating a filter (*L*-*C*) of the 180˚ control inverter operating in MV based on that of the filter (*LC*) of the SPWM control inverter is adopted, after verifying the applicability of the formulas of articles [4] [5] [6]. This is to reformulate the filter calculation method (*L*-*C*) of articles so that it can be used for a 180˚ control inverter connected to the MV network.

Filter (*L*-*C*)

Consider the diagram of a single-phase circuit of a filter (*L*-*C*) given in **Figure 1**.

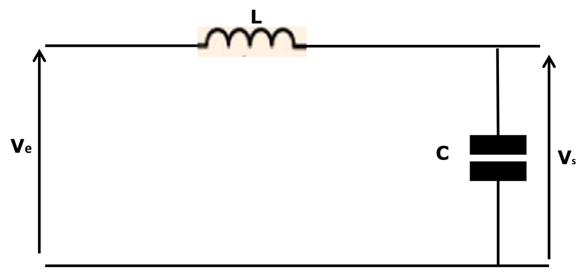

Figure 1. Single phase filter circuit (*L-C*).

Figure 1 makes it possible to obtain the transfer function $G(P)$:

$$G(P)=\frac{V_s(P)}{V_e(P)}=\frac{1}{LCP^2+1} \tag{1}$$

This filter makes an attenuation of 40 (dB)/decade [6].

Formulas of inductance L and capacitor C

According to articles [4] [5] [6], the calculation of L and C of the filter (L-C) for a three-phase inverter with SPWM control is done as follows:

$$C<\frac{0.05\times S_N}{3\times\omega\times U_{ph}^2} \quad \text{and} \quad L<\frac{3\times U_{ph}^2}{10\times\omega\times S_N} \tag{2}$$

These formulas given by Equation (2) were obtained by minimizing two parameters: the reactive power of capacitor C (capped at 5% of the apparent power of the alternating load) and the ripple of the current flowing through inductor L (capped at 10% of the phase-to-neutral voltage supplying the alternating charge).

3. 180˚ Control Inverter (Full Wave)

Consider the diagram of a three-phase inverter below (**Figure 2**).

In the three-phase two-level inverter (**Figure 2**), there are three arms. Each arm has two controllable switches K_i = (T_i; D_i) (with i = 1, 2, 3, 4, 5, 6). Each controllable switch consists of:

- Bipolar power transistor or IGBT or thyristor (controllable component);
- Diode mounted head-to-tail (antiparallel) on each controllable component.

The inverter is supplied by a DC source E.

In 180˚ control, each switch K_i of **Figure 2** conducts for 180˚ (π radians).

Two switches of the same arm have their control shifted by 180˚ (π radians).

Two consecutive switches have their control shifted by 120˚ (2π/3 radians).

Table 1 gives a summary of the operation of the 180˚ control inverter and **Figure 3** represents the voltage signals $V_1(\theta)$, $V_2(\theta)$ and $V_3(\theta)$.

Figure 3 represents the voltage signals $V_1(\theta)$, $V_2(\theta)$ and $V_3(\theta)$.

The Fourier series decomposition based on $V_1(\theta)$ of **Figure 3**, gives us:

$$V_1(\theta)=\frac{4\times E}{\pi}\times\sum_{p=0}^{\infty}\left(\frac{1+\cos\left(\frac{\pi}{3}\times(2p+1)\right)}{2p+1}\right)\times\sin\left(\theta(2p+1)\right) \tag{3}$$

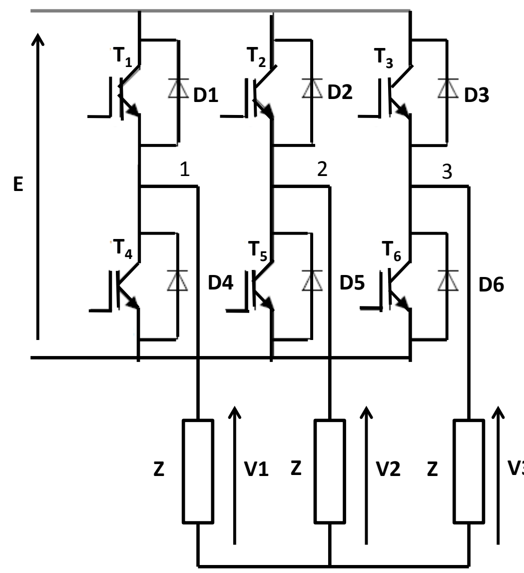

Figure 2. Three-phase inverter.

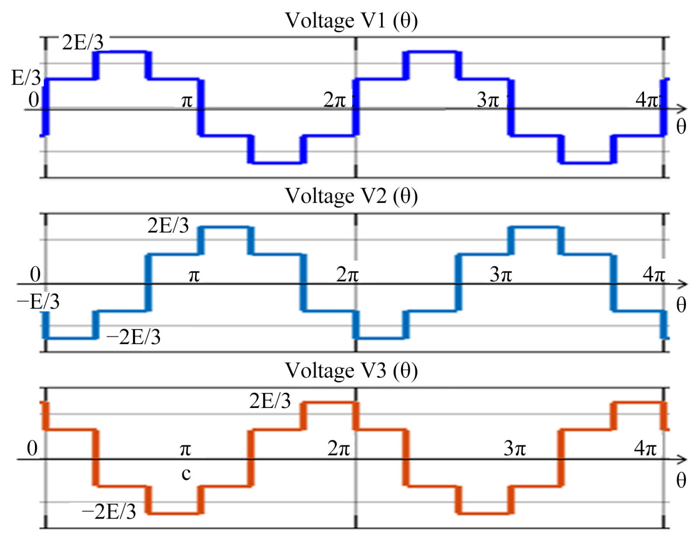

Figure 3. Voltage signals $V_1(\theta)$, $V_2(\theta)$ and $V_3(\theta)$.

Table 1. Summary of the operation of the 180˚ control inverter.

θ	0	$\frac{\pi}{3}$	$\frac{2\pi}{3}$	$\frac{3\pi}{3}$	$\frac{4\pi}{3}$	$\frac{5\pi}{3}$	2π
K_1	1	1	1	0	0	0	
K_2	0	0	1	1	1	0	
K_3	1	0	0	0	1	1	
K_4	0	0	0	1	1	1	
K_5	1	1	0	0	0	1	
K_6	0	1	1	1	0	0	
$V_1(\theta)$	$E/3$	$(2/3) \times E$	$E/3$	$-E/3$	$-2/3E$	$-E/3$	
$V_2(\theta)$	$-(2/3) \times E$	$-E/3$	$E/3$	$(2/3) \times E$	$E/3$	$-E/3$	
$V_3(\theta)$	$E/3$	$-E/3$	$-(2/3) \times E$	$-E/3$	$E/3$	$(2/3) \times E$	

By replacing the values of p in Equation (3), we can clearly see that the harmonics which pollute the phase-to-neutral voltage signals are of ranks: 5; 7; 11; 13; 17; 19 … 25.

The effective fundamentals of voltage and current are:

$$V_{11eff} = \frac{2 \times E}{\pi\sqrt{2}} \quad \text{et} \quad I_{11eff} = \frac{V_{11eff}}{|Z|} = \frac{2 \times E}{\pi\sqrt{2}|Z|}; \quad Z = r + j \times x \tag{4}$$

Remember that, without the filter (L-C), the harmonic distortion rate (THD = 31.08%). This does not comply with the IEEE 519 [7] standard, which requires that in MV, this THD is 8%.

4. Applicability of the Filter Formulas (*L*-*C*) of the Three-Phase Inverter SPWM to the Inverter with 180˚ Control

This is to use the formulas for calculating the inductance L and capacitance C of the filter capacitor (LC) of the SPWM control inverter to apply to the filter (LC) of the 180˚ control inverter. The formulas in articles [4] [5] [6] are used to designate the inductance L and the capacitor C:

$$C = C_{maxi} = \frac{0.05 \times S_N}{3 \times \omega \times U_{ph}^2} \quad \text{and} \quad L = L_{maxi} = \frac{3 \times U_{ph}^2}{10 \times \omega \times S_N} \tag{5}$$

The formulas of Equation (5) were applied for the calculation of L and C of the 180˚ control inverter filter in MV. The following curves show the quality of the voltage and current signals.

Figure 4 shows the voltage and current waveforms and their different THDs:

The load data are as follows:

S_N = 25 MVA

$\cos\varphi$ = 0.8

U_{ph} = 15 kV

E = 19,238.25 V

C = 5.895 microfarads and L = 8.594e-3 henrys

The results of **Figure 4** clearly show that for $C = C_{maxi}$ and $L = L_{maxi}$ of the three-phase inverter with SPWM control is not suitable for obtaining voltage and current THDs meeting the IEEE 519 standard [7].

5. Studies to Improve the Filter Parameters (*L*-*C*) for a 180˚ Control Inverter

In the scientific literature, the only method of calculating the filter (LC) for an inverter with 180˚ control is found in article [8], where it is a question of calculating a resistance R related to the quality factor Q, after having set the resonant frequency f_{Res} and the capacitor C and deduce the inductance L.

The SPWM inverter filter (L-C) formula verification approach applied to the 180˚ control inverter filter (L-C) has been completed. The results are inconclusive, ie the IEEE 519 [7] standard is not met.

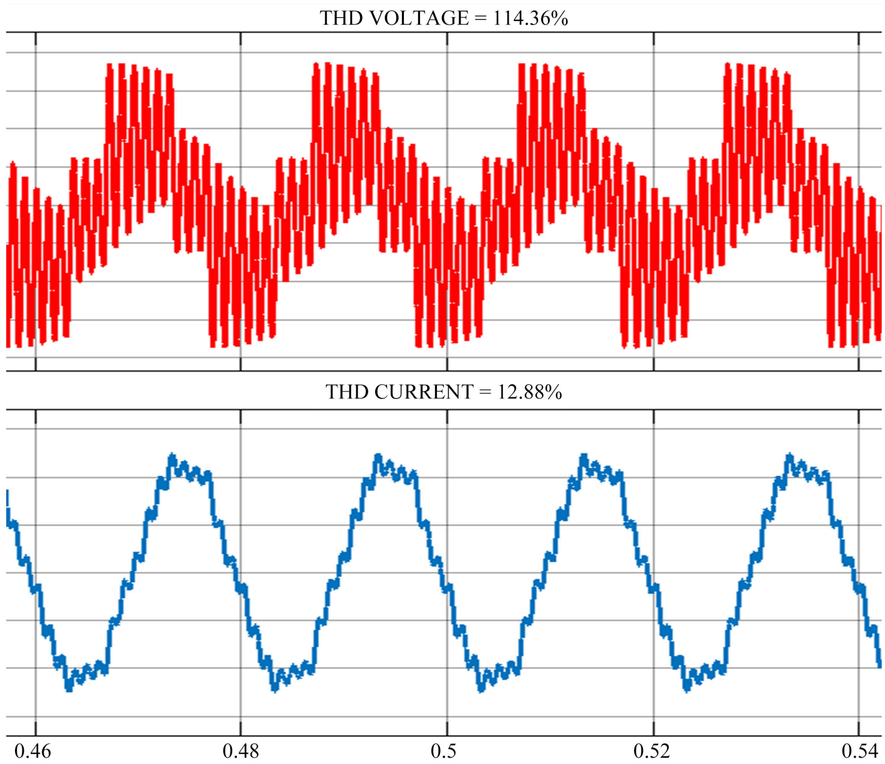

Figure 4. Voltage and current signals for $C = C_{maxi}$ and $L = L_{maxi}$.

For this reason, a first study is carried out in order to determine the choice ranges of the capacitor C and the inductance L of the filter (L-C) of the 180˚ control inverter. In this study, C_{maxi} is varied by multiplying it by q varying from 1 to 1000 and the value of L_{maxi} is kept unchanged.

From Table 2, Figures 5-7 are shown below.

Table 2 shows that from $C = 35 \times C_{maxi}$, the THD% obtained comply with the IEEE 519 standard [7]. But for Figure 6 and Figure 7, a resonance is observed beyond $C = 100 \times C_{maxi}$. Between $C = 35 \times C_{maxi}$ and $C = 100 \times C_{maxi}$, the THD% obtained in Table 2 comply with the IEEE 519 standard [7]. The choice of capacitance C of the capacitor can be made in the range [$35 \times C_{maxi}$; $100 \times C_{maxi}$] because of the resonance phenomenon observed in Figure 2 and Figure 3, which amplifies the RMS values of voltage and current on the one hand; and on the other hand from the large capacitance value which decreases its impedance and degrades the RMS values of voltage and current.

Another study is carried out by varying L_{maxi}. The inductance L_{maxi} is multiplied by q which varies from 0.01 to 25 while keeping the value of $C = C_{maxi}$ unchanged.

From Table 3, Figures 8-10 are shown below.

Figure 8 clearly shows that the THD% obtained does not comply with the IEEE 519 standard [7]. Figure 9 and Figure 10 show a continuous drop in RMS voltage and RMS current. This is due to the increased impedance of the inductance. It is therefore preferable to keep $L = L_{maxi}$. With this in mind, taking the value of the capacity C in the range of $35 \times C_{maxi}$ to $100 \times C_{maxi}$ would not be a bad choice for the inverter with 180˚ control in MV, if the resonance phenomenon is avoided.

The filter elements (L-C) of the 180˚ MV control inverter could be:

$$C = 35\times C_0 \sim 100\times C_0 \quad \text{with} \quad C_0 = \frac{0.05\times S_N}{3\times\omega\times U_{ph}^2}$$

$$\text{and} \quad L = L_{maxi} \quad \text{with} \quad L_{maxi} = \frac{3\times U_{ph}^2}{10\times\omega\times S_N} \tag{6}$$

Table 2. THD% and RMS voltage and current values

Voltage THD%	114.36	68.09	93.95	53.48	21.77	13.45	9.62	7.42	5.98
Current THD%	12.88	17	30.02	17.15	6.93	4.26	3.04	2.34	1.88
RMS VOLTAGE (V)	12,510	12,720	12,990	13,270	13,560	13,860	14,180	14,520	14,870
RMS CURRENT (A)	802.4	815.7	833	851	869.8	889.4	909.8	931.3	953.7
$C = q\times C_{maxi}$; q	1	5	10	15	20	25	30	35	40

Voltage THD%	4.97	4.23	2.25	1.39	0.27	0.24	0.38	0.47	0.58	0.66
Current THD%	1.56	1.33	0.7	0.43	0.08	0.07	0.12	0.15	0.18	0.21
RMS VOLTAGE (V)	15,230	15,620	17,860	20,800	49,960	37,480	17,560	11,180	6432	3919
RMS CURRENT (A)	977.2	1002	1146	1334	3205	2404	1126	717.2	412.6	251.4
$C = q\times C_{maxi}$; q	45	50	75	100	200	300	400	500	700	1000

Table 3. THD% and RMS voltage and current values.

Voltage THD%	57.17	79.62	64.95	125.19	80.95	57.91	49.72	51.83
Current THD%	7.52	7.62	7.62	8.39	7.89	7.66	7.66	7.76
RMS VOLTAGE (V)	14,970	14,930	14,870	14,800	14,760	14,740	14,480	14,220
RMS CURRENT (A)	960.5	958	953.8	949.6	947.1	945.4	928.7	912.1
$L = q\times L_{maxi}$; q	0.01	0.025	0.05	0.075	0.09	0.1	0.2	0.3

Voltage THD%	95.4	73.71	45.79	76.96	120.3	64.6	114.36
Current THD%	9.5	8.75	7.75	9.48	12.48	8.91	12.88
RMS VOLTAGE (V)	13,960	13,710	13,460	13,220	12,980	12,740	12,510
RMS CURRENT (A)	835.7	879.5	863.5	847.8	832.4	817.2	802.4
$L = q\times L_{maxi}$; q	0.4	0.5	0.6	0.7	0.8	0.9	1

Voltage THD%	45.63	86.9	49.74	48.94	59.66	47.67	39.34
Current THD%	8.17	12.51	8.72	8.85	10.36	8.89	7.96
RMS VOLTAGE (V)	10,470	8896	7684	6739	4110	2937	1862
RMS CURRENT (A)	671.6	570.6	492.9	432.3	263.7	188.4	119.6
$L = q\times L_{maxi}$; q	2	3	4	5	10	15	25

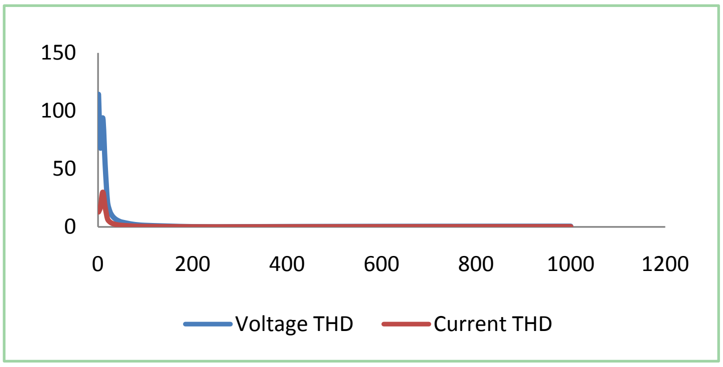

Figure 5. THD of voltage and current as a function of $q \times C_{maxi}$; $q \in [1;1000]$.

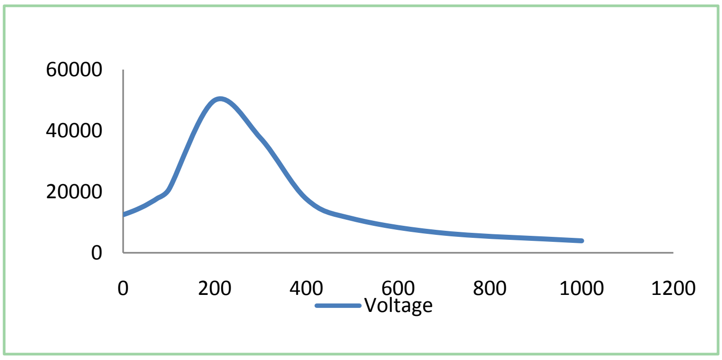

Figure 6. RMS voltage as a function of $q \times C_{maxi}$; $q \in [1;1000]$.

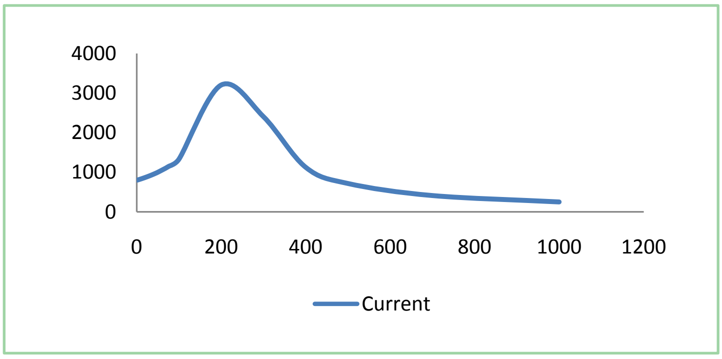

Figure 7. RMS current as a function of $q \times C_{maxi}$; $q \in [1;1000]$.

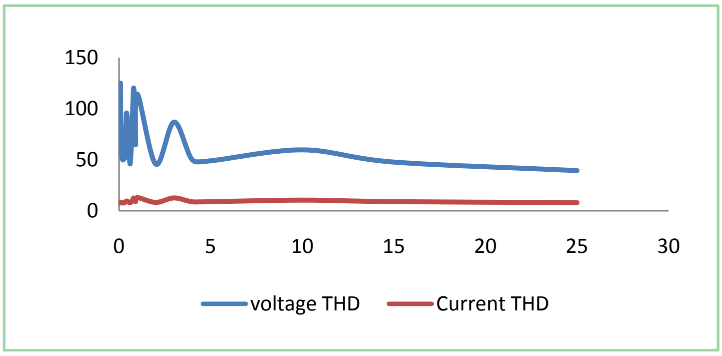

Figure 8. THD of voltage and current as a function of $q \times L_{maxi}$; $q \in [0.01;25]$.

If a damping resistor is not used in series with inductor L.

If a damping resistor is used in series with inductance L, the tuning range of capacitor C could reach 400 × C_0 because between 100 × C_0 and 400 × C_0, there is resonance.

Figures 11-14 show three operating cases with the different values of L and C:

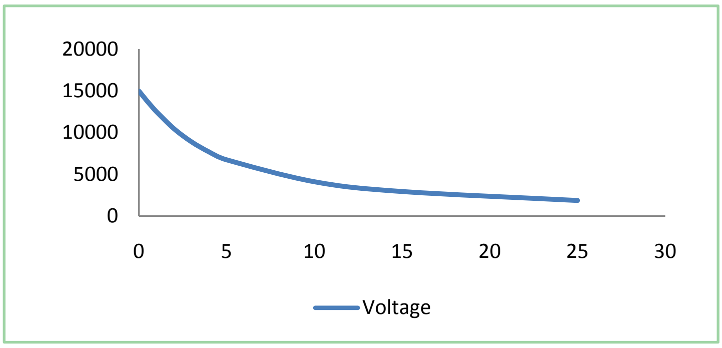

Figure 9. RMS voltage as a function of $q \times L_{maxi}$; $q \in [0.01; 25]$.

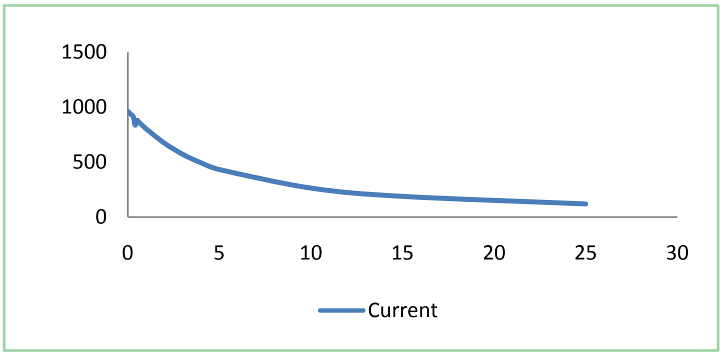

Figure 10. RMS current as a function of $q \times L_{maxi}$; $q \in [0.01; 25]$.

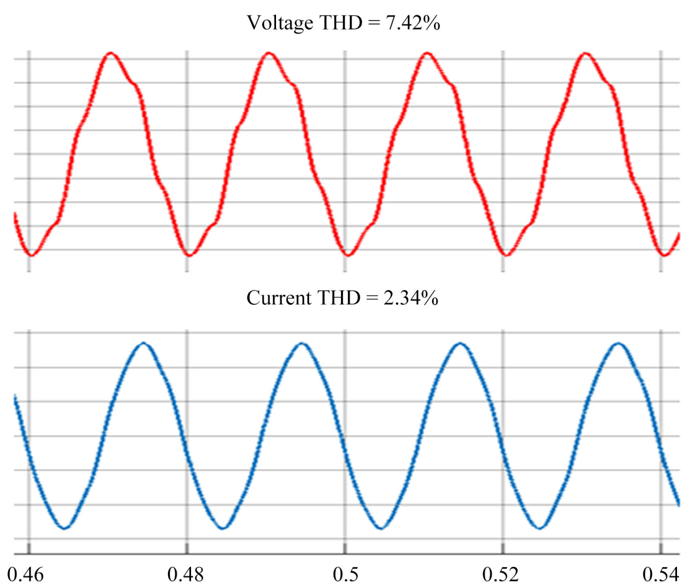

Figure 11. Voltage and current waveforms for $L = L_{maxi}$ and $C = 35 \times C_0$.

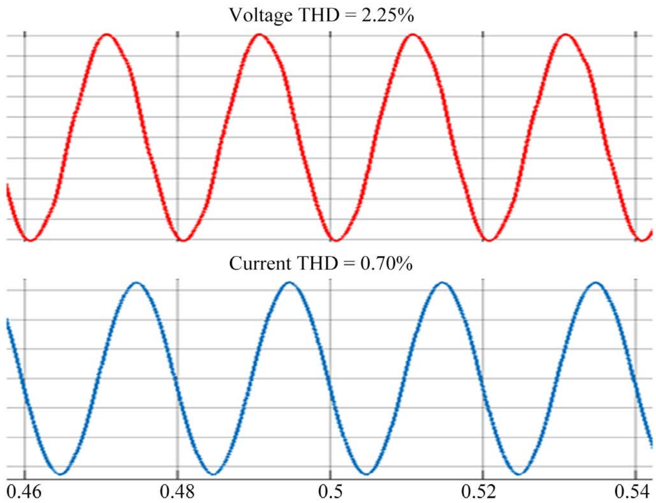

Figure 12. Voltage and current waveforms for $L = L_{maxi}$ and $C = 75 \times C_0$.

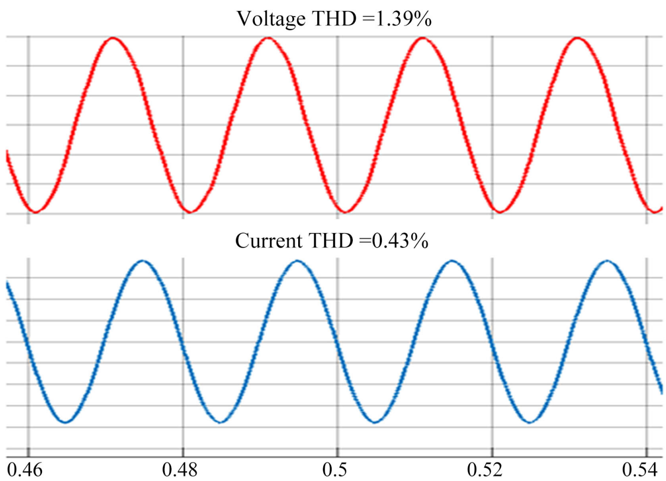

Figure 13. Voltage and current waveforms for $L = L_{maxi}$ and $C = 100 \times C_0$.

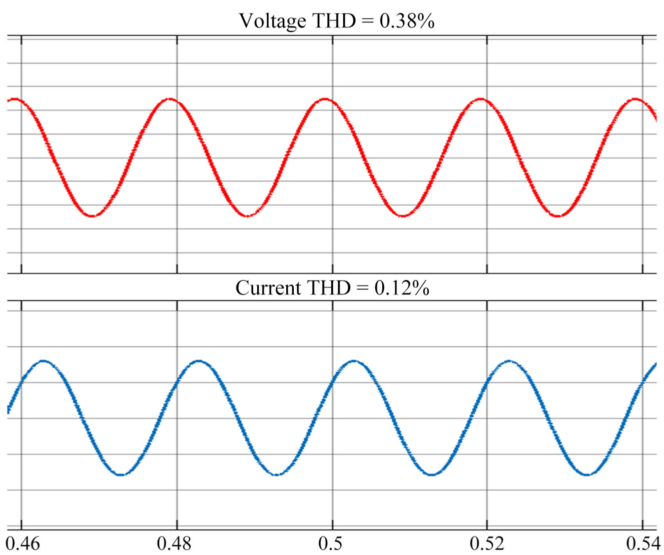

Figure 14. Voltage and current waveforms for $L = L_{maxi}$ and $C = 400 \times C_0$.

Viewing **Figures 11-14**, confirms that to size a filter (L-C) for an inverter with 180˚ control in MV, articles [4] [5] [6] dealing with the case of the inverter SPWM too reduced the proportion of reactive power allowing the calculation of the capacitance of the capacitor C. On the other hand, the proportion of the inductance L suits that of our study. **Figures 11-14** show that the study carried out makes it possible to calculate a filter (L-C) for a 180˚ control inverter which meets the standard of the article [7].

6. Conclusions

In this article, a method was adopted: that of using the formulas of a filter (L-C) of a three-phase inverter with SPWM control obtained by minimizing the reactive power of the capacitor C and the current ripple in the inductor. L, that is to say, limits the reactive power of the capacitor to 5% of the apparent power of the load and limits the ripple of the current flowing through the inductor L to 10% of the current in the load.

The formulas applied to the filter (L-C) of the 180˚ MV control inverter did not allow the voltage and current THDs to be obtained which comply with the IEEE 519 standard.

Therefore, from these formulas, studies have been carried out with a view to obtaining a good compromise, where the voltage and current THDs comply with the IEEE 519 standard. From these studies, it emerges that taking the inductance $L = L_{maxi}$ is a valid assumption and that the limitation of the reactive power of the capacitor to 5% of the apparent power of the load has shortcomings. The results also show that setting the inductance L of the filter to L_{maxi} and the capacitor C from $35 \times C_{maxi}$ to $400 \times C_{maxi}$ gives voltage and current THDs that meet the IEEE 519 standard. The simulations on the MATLAB/Simulink software made it possible to justify this method. Also for the range, $100 \times C_0$ to $400 \times C_0$, the sizing of a resonance damping resistor is to be expected.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

SPWM	Sinusoidal Pulse-Width-Modulation
THD	Total Harmonic distortion
S_N	apparent power of the alternating load
MV	Medium voltage alternating voltage (1 kV - 50 kV)
U_{ph}	phase-to-phase voltage at the ac load
MVDC	medium voltage direct current
R, L, C	Resistance, Inductance, Capacitor