Calculation of the number of modules and the switching frequency of a modular multilevel converter using near level control

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Abstract: This paper is focused on the Modular Multilevel Converter (MMC) topology that uses the Near Level Control (NLC) method. Specifically, it addresses the relationship between the number of levels or switching modules, the switching frequency and the harmonics superimposed on the generated voltages and currents, making a comparison with the high and medium voltage AC codes. Furthermore, it also assesses the possibility of connecting the MMC to the electrical grid without using any coupling inductor, either using a transformer or simply directly. Finally, it shows how to automate the simulations necessary to select the number of levels and the switching frequency.

Keywords: High voltage direct current (HVDC); modular multilevel converter (MMC); multilevel; near level control (NLC); near level modulation (NLM)

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1. Introduction

MMC topology has drawn the attention of the R&D community and of the industry in the last few years. Its main application is high voltage DC transmission (HVDC), but there are also others related to its ability to control the DC current in the case of a DC bus short-circuit, etc.

Many papers have recently been published addressing such subjects as capacitor balancing, [1][2], voltage modulators [3], converter modeling [4], circulating current reduction [5], direct current (DC) fault handling capability [6], control under unbalanced voltage conditions [7], among others.

The most important electrical grid installers have chosen the MMC topology as the most suitable for HVDC transmission [8] and one of the most important recent applications has been offshore wind parks [9].

MMCs can be controlled in high frequency using several types of modulation, or in low frequency, by using the near level control (NLC) algorithm [10]. The latter is preferred in high power applications because of its lower power losses in the semiconductors.

MMCs (Figure 1) are made up of three phases, where each phase is split into an upper and a lower part made up of an arm and one inductance. The arm comprises n switching modules (SM).

In turn, each SM comprises, in the half bridge (HB) topology, two IGBTs, two diodes and one capacitor.

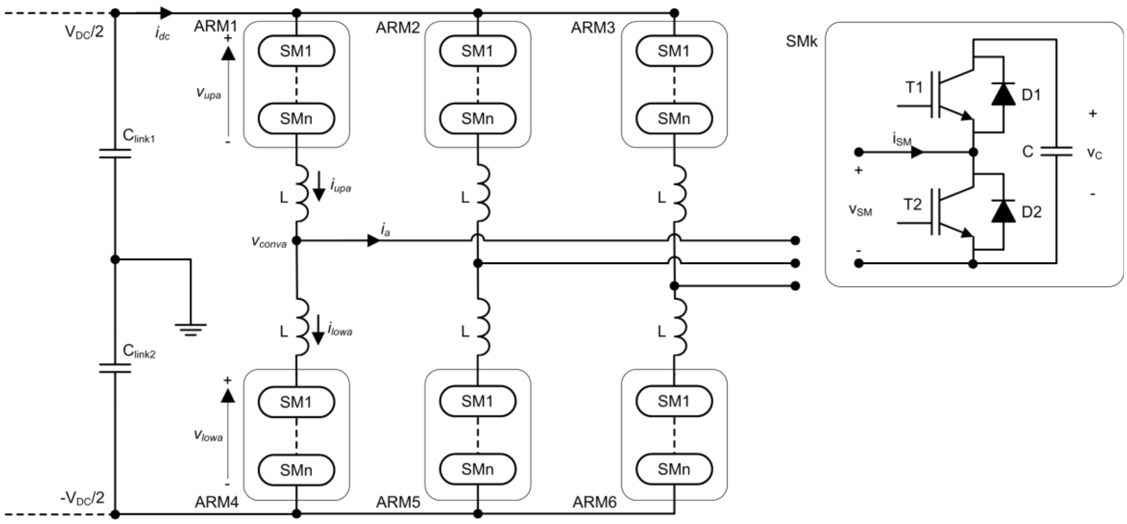


Figure 1. Modular multilevel converter (MMC) scheme and half-bridge switching module (HB-SM) structure.

The choice of the number n of SM has important consequences in the NLC algorithm. When n is high, alternating current (AC) voltages are made up of many steps and their total harmonic distortion (THD) is low. Because all the SM are identical, increasing the number of levels does not increase the power electronics by very much, but it does increase the complexity of the control due to the high number of control signals to be handled. Systems to reduce the complexity of the communications are currently still under study [11].

Each country has its own grid code related to the current and voltage harmonics that the MMC must fulfill. These codes are more restrictive as the voltage and current increase, and they establish the limits for the THD and for the individual harmonics. There are several aspects that influence the harmonic level: the number of SM, switching frequency, and the in-series inductance (sum of the coupling inductance used by the MMC, the transformer leakage inductance and the electrical line inductance).

This paper aims to provide answers to several questions related to MMCs that use NLC: How many SM should be used? What switching frequency? Is it necessary to use a coupling inductor, or is it sufficient to use the transformer leakage inductance, or it can even be directly connected to the grid?

The following features are desirable when designing an MMC:

- Using a low number of SM can reduce the complexity of the control hardware (buses with a lot of cables) and also the software complexity (communication system between the central control and each module control). However, this probably helps to generate high voltage and current harmonics that can exceed the grid code limits.
- Reducing the number of SM, in order to make the control simpler and reduce the cost, allows the use of this electronic converter in low power applications. Indeed, a low number of SM and an effort to integrate power electronics + control hardware + communications makes it easier to use in low cost and low rated power applications. They can even be packaged in one or several big chips, as is done with the low power IGBT bridges.
- Using a low switching frequency to reduce the switching losses and the complexity of the control. The limit is then the harmonics in voltages and currents.
- Removing the coupling inductor (and even the coupling transformer). This depends on the level of harmonics present in the output voltage, and the transformer and line inductances.

- For a given number of levels, determine the maximum switching period limited to getting just one level step in the output voltage.

This study is carried out using analytic techniques and simulations in Matlab/Simulink. The waveforms are generated depending on the number of SM and the switching period, after which the harmonics are calculated. Depending on the line inductance value, the current harmonics are then studied. Finally, a methodology is developed that automates the Matlab/Simulink simulations and the results obtained.

The paper is organized as follows. Firstly, section 2 presents the fundamentals of MMC and NLC. In section 3, the maximum allowed value of the commutation period is calculated. In section 4, the voltage and current harmonics are calculated as a function of the number of SM and the commutation period. Sections 5 and 6 show detailed MMC numeric and real time simulations aimed at validating the previous harmonics calculations. Finally, the conclusions of the paper are presented.

2. Fundamentals of modular multilevel converters and near level control

2.1. Fundamentals of MMC

The simplest SM topology (Figure 1) is called half-bridge (HB). It comprises two IGBTs, two diodes in anti-parallel configuration and one capacitor. There are other more complex topologies that perform better in cases of short-circuits, such as full bridge (FB) and the double clamp submodule topology [12].

The SM operation can be explained using the HB topology (Table 1). When the SM is in the ON state, T1 is also ON and T2 is OFF; depending on whether the current i_{SM} is positive or negative, the capacitor voltage v_C rises or falls respectively. When the SM state is OFF, T1 is also OFF and T2 is ON; then, the capacitor voltage remains constant, independently of the sign of the current i_{SM}.

Table 1. Relationship between the elements and variables of the SM

SM state	T_1 state	T_2 state	i_{SM}	Δv_C	i_{SM} flows through	v_{SM}
ON	ON	OFF	> 0	$+$	D_1	v_C
ON	ON	OFF	< 0	$-$	T_1	v_C
OFF	OFF	ON	> 0	0	T_2	0
OFF	OFF	ON	< 0	0	D_2	0

The sum of the number of SMs in the ON state in the upper arm n_{up} and in the lower one n_{low} is equal to the number n of SMs per arm,

$$n_{up} + n_{low} = n \tag{1}$$

The equations that establish the relation between the DC voltage V_{DC}, the output voltage v_{conva}, the voltages in the upper arms v_{upa} and in the lower ones v_{lowa}, as well as the currents in the upper arms i_{upa} and in the lower ones i_{lowa} (Figure 1), are:

$$v_{conva} = \frac{V_{DC}}{2} - v_{upa} - L\frac{di_{upa}}{dt} \tag{2}$$

$$v_{conva} = -\frac{V_{DC}}{2} + v_{lowa} + L\frac{di_{lowa}}{dt} \tag{3}$$

where the voltages in the upper and lower arms depend on the ON/OFF state of each upper SM $S_{upak} = 1/0$, or lower SM, $S_{lowak} = 1/0$, and on the voltage in every SM of the upper arms v_{Cupak} and lower arms v_{Clowak}.

$$v_{upa} = \sum_{k=1}^{n} S_{upak}\, v_{Cupak} \tag{4}$$

$$v_{lowa} = \sum_{k=1}^{n} S_{lowak}\, v_{Clowak} \tag{5}$$

The current in the upper arm is the sum of half the phase current i_a plus one third of the DC current i_{dc}, plus the circulating current in the phase i_{za} [13].

$$i_{upa} = \frac{i_a}{2} + \frac{i_{dc}}{3} + i_{za} \tag{6}$$

$$i_{lowa} = -\frac{i_a}{2} + \frac{i_{dc}}{3} + i_{za} \tag{7}$$

The circulating current is calculated from (6) and (7) as:

$$i_{za} = \frac{i_{upa} + i_{lowa}}{2} - \frac{i_{dc}}{3} \tag{8}$$

and the sum of the three circulating currents is zero:

$$i_{za} + i_{zb} + i_{zc} = 0 \tag{9}$$

The circulating current does not affect the DC part or the AC part of the circuit, but it does cause an increase in the arm current and the voltage ripple of the capacitors [2].

Assuming that the voltages of all the capacitors are equal, $v_C = V_{DC}/n$, the output voltage in each phase is:

$$v_{conv} = -\frac{V_{DC}}{2} + n_{low} v_C \tag{10}$$

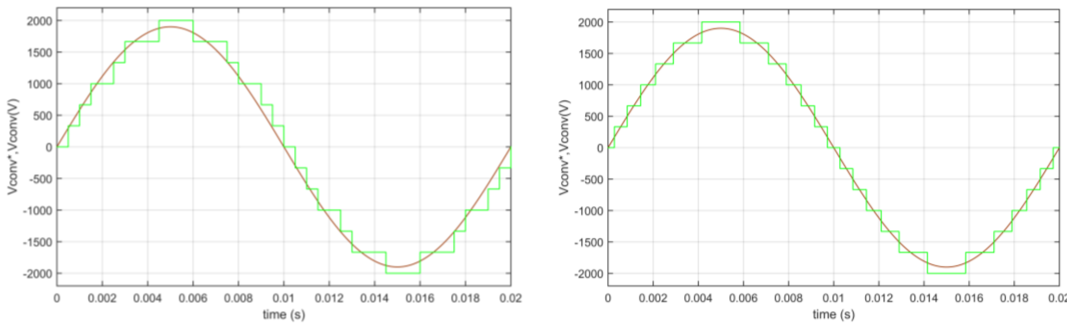
2.2. Fundamentals of Near Level Control

MMCs have been used with high frequency modulators: sinusoidal pulse-width modulation (PWM) [14], multilevel PWM [1] and multilevel space vector modulation (SVM) [15]; but also low frequency voltage modulators: selective harmonic elimination (SHE) [16][17], nearest vector control (NVC) [18] and NLC; and even high frequency current modulators [19].

In high power applications, low frequency modulators are preferred in order to reduce losses and electromagnetic interference (EMI). The SHE modulation removes undesirable low frequency harmonics, but its dynamic is slow [20]. In comparison to the rest of the modulators, NLC is more suitable for very high power MMCs with a high number of levels [21] [22]. This control system is also known as near level modulation (NLM) [10].

The type of modulator chosen depends on the number n of SM in each arm. When n is low, high frequency modulation is preferred in order to reduce the harmonic content of the output voltage. Conversely, when n is high, low frequency modulation is chosen to reduce the switching losses. Likewise, in high power applications, a high value of n is chosen.

The sampling period used in NLC can be fixed or variable. When it is fixed (Figure 2a), the level chosen in every sampling period is the closest to the reference voltage. If the number of levels is high, the sampling period must be small enough to ensure that all the levels of output voltage are used [23]. It is possible to multiply by two the number of output voltage levels without increasing the number of SM in each arm by shifting the commutation in the upper and lower arms half the sampling period [24]. When the switching period is variable, the transition between two levels takes place when the reference voltage matches the intermediate value between two levels (Figure 2b) [25].



(a) (b)

Figure 2. Generation of the MMC output voltage steps v_{conv} using the near level control (NLC) with switching period: (a) fixed, (b) variable.

3. Maximum switching period in near level control

The output voltage steps of the converter v_{conv} follow the sinusoidal reference voltage $v_{conv}{}^*$ (Figure 3). Calling n the number of SM, the number of phase to neutral voltage levels is $n+1$. Each voltage step has an amplitude V_{DC}/n and the step width is determined by the sampling period T_r. For a given number of levels, it is good to know what the maximum switching period, T_r, should be to avoid getting steps larger than just one level of the output voltage. It becomes more probable around the zero crossing of the sinusoidal reference voltage.

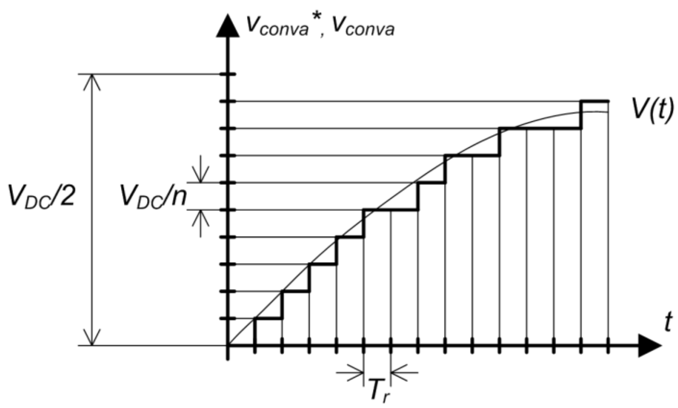


Figure 3. Sinusoidal voltage reference $v_{conv}{}^*$ used in the MMC, and the actual MMC voltage v_{conv} made up of steps.

The reference voltage $v_{conv}{}^*$ equation is:

$$v_{conv}{}^*(t) = V_p \sin \omega t \tag{11}$$

The rate of change for the output voltage is:

$$\frac{dv_{conv}{}^*(t)}{dt} = V_p \omega \cos \omega t \tag{12}$$

The maximum rate of change takes place at $t = 0$,

$$\left.\frac{dv_{conv}{}^{*}(t)}{dt}\right|_{máx} = V_p\omega \leftrightarrow cos\,\omega t = 1 \leftrightarrow t = 0 \quad (13)$$

At $t = 0$ is when the probability of missing one voltage step is higher. The value of the maximum switching period to avoid that is:

$$\frac{dv_{conv}{}^{*}(0)}{dt} = V_p\omega = \frac{\Delta v_{conv}}{\Delta t} = \frac{\frac{V_{DC}}{n}}{T_r} \leftrightarrow T_r = \frac{V_{DC}}{nV_p\omega} \quad (14)$$

4. Number of switching modules and switching period as a function of voltage and current harmonic limits

An electronic converter injects voltage and current harmonics into the grid it is connected to, whose admissible limits are established by the regulations. The larger the number of levels in an MMC is, the lower the voltage harmonics; whereas the current harmonics depend on the voltage harmonics and the inductance that the current goes through, comprising the sum of the coupling inductance, leakage transformer inductance and line inductance.

It is not possible to obtain general equations of the harmonics as a function of the number of levels; so, instead, the method to be used is shown by analyzing a study case. The objective is to determine the number of SM in the MMC, the switching frequency and whether or not a coupling inductance is necessary. Certainly, using a coupling inductance reduces the amplitude of the current harmonics, but it is unclear whether the transformer inductance is sufficient, or it is necessary to add an external coupling inductance.

Voltage harmonic constraints are different depending on the grid voltage; in high voltage (HV), the permitted levels of voltage harmonics are lower than in medium voltage (MV). The limits of current harmonics depend on the relation I_o/I_{sc} (I_o converter current, I_{sc} short-circuit line current) and on the voltage level (HV or MV).

4.1. Voltage harmonics: direct coupling to the PCC

Two cases are considered. In the first one, the electronic converter is directly connected to the grid voltage, through the short-circuit line inductance L_{sc} (transformer inductance, $L_t = 0$) (Figure 4); then, the voltage harmonics in the PCC v_o are those of the converter v_{conv}.

In the second case, the electronic converter is coupled to the grid through the transformer inductance L_t, and the PCC voltage v_o presents a lower harmonic content. In case a supplementary coupling inductance L_c is used, it is calculated as in the previous case, by simply adding L_c to the transformer inductance, $L_c + L_t$.

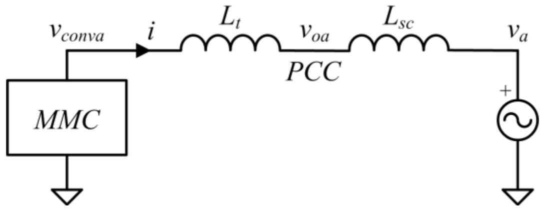


Figure 4. Grid connection per phase: comprises the MMC, transformer inductance L_t, line inductance L_{sc} and grid voltage v_a.

The n^{th} voltage harmonic, $V_{conv,n}(\%)$, can be calculated as a percentage from the rms (root medium square) values of the n^{th} harmonic $V_{conv,n}$ and the fundamental harmonic $V_{conv,1}$ of the converter voltage,

$$V_{conv,n}(\%) = \frac{V_{conv,n}}{V_{conv,1}}100 \quad (15)$$

The THD of the converter voltage is calculated as

$$THD_{V_{conv}} = \frac{\sqrt{\sum_{n=2}^{\infty} {V_{conv,n}}^2}}{V_{conv,1}} \tag{16}$$

and the THD of the converter voltage as a percentage is calculated as

$$THD_{V_{conv}}(\%) = THD_{V_{conv}} \cdot 100 = \frac{\sqrt{\sum_{n=2}^{\infty} {V_{conv,n}}^2}}{V_{conv,1}} \cdot 100 = \sqrt{\sum_{n=2}^{\infty} V_{conv,n}(\%)^2} \tag{17}$$

The voltage harmonic limits to be used belong to the Grid Code summarized in Table 2, and depend on the grid voltage level, MV or HV.

Table 2. Indicative planning levels for harmonic voltages (in percent of the fundamental voltage) in medium voltage (MV), high voltage (HV) and extra high voltage (EHV) power systems, from Technical Report IEC/TR 61000-3-6 [26].

$THD_{MV} = 6.5\%$, $THD_{HV-EHV} = 3\%$

Odd harmonics non-multiple of 3			**Odd harmonics multiple of 3**		
Harmonic order h	Harmonic voltage %		Harmonic order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2
7	4	2	9	1.2	1
11	3	1.5	15	0.3	0.3
13	2.5	1.5	21	0.2	0.2
$17 \leq h \leq 49$	$1.9\frac{17}{h} - 0.2$	$1.2\frac{17}{h}$	$21 \leq h \leq 45$	0.2	0.2

MV: $1kV \leq U_n \leq 35kV$
HV: $35kV \leq U_n \leq 230kV$
EHV: $230kV \leq U_n$

The voltage harmonics of a multilevel converter depend on the number of levels and on the switching period. They also depend on certain application parameters, specifically, the peak voltage $V_{o,1,p}$ and the maximum value of the DC voltage V_{DC}. In consequence, no general equations can be obtained and it is necessary to use simulation tools to carry out the analysis of any specific application. In this paper, a procedure to tackle the study in order to obtain the suitable number of levels and the switching period is presented. The paper also studies whether it is possible to make a direct connection to the grid, for both an HV and an MV application.

For the HV application, the MMC is connected to a 230kV grid (rms line to line voltage). The first phase to neutral voltage harmonic has an rms value $V_{o,1} = 230kV/\sqrt{3} = 132.79kV$ and a peak value $V_{o,1,p} = 132.79kV \cdot \sqrt{2} = 187.79kV$. The voltage steps are simulated using a DC voltage V_{DC} =395.36kV.

As an example, Figure 5 shows the phase to neutral voltage made up of 7 level steps (green) obtained from the sinusoidal reference (red). In order to speed up the simulation, an ideal simulation is carried out instead of using an electronic converter model. To simulate the phase to neutral voltage, a sinusoid is generated in Simulink, which is approximated to the closest level by a Matlab function. To simulate the line to line voltage, two 120-degree de-phased sinusoids are generated, which are approximated to the closest level by a Matlab function, and then the values are subtracted to obtain the line to line voltage. Later on, numeric and real time simulations are carried out using an MMC detailed model to validate the earlier results.

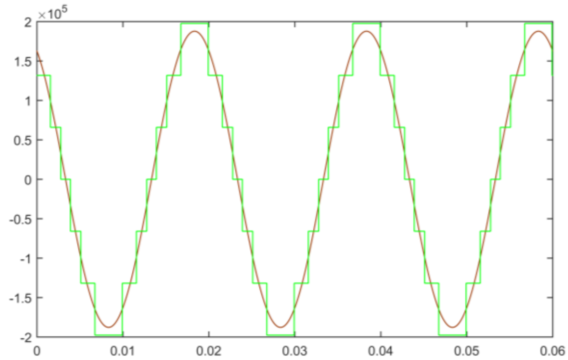


Figure 5. Sinusoidal voltage reference and output voltage.

The NLC modulator is simulated for a number of SM values and the level of each harmonic and the THD are calculated. The sampling period of the simulation is $T_s = 2.5\mu s$. In the two first simulations, a fixed switching period T_r is not used, instead the change from one level to another takes place when the reference voltage surpassed the intermediate value of two adjacent steps (variable switching period T_r).

The results are presented as tables and are valid for HV and MV, as long as the relation between the peak value of phase to neutral voltage $V_{o1,p}$ and the DC voltage value V_{DC} keep the same value. Table 3 show the phase to neutral results; it can be seen that the THD is reduced as the number n of SM increases. Although in the phase to neutral voltage the multiples of three harmonics are high, in the line to line voltage they disappear. Considering that the phase to neutral voltage only appears in the case of connecting the DC side with the AC side, which is never done, only the line to line voltage harmonics are studied. Table 4 show the THD and harmonics of the line to line voltage. The harmonics fulfilling the HV grid code are typed in red. It must be considered that the MV code is less strict than the HV code.

Table 3. MMC phase to neutral voltage harmonics.

n	THD (%)	Phase to neutral voltage harmonics (%)								
		V_3	V_5	V_7	V_9	V_{11}	V_{13}	V_{15}	V_{17}	V_{19}
3	23.91	5.25	3.84	13.78	11.48	1.10	1.73	6.18	6.26	0.43
4	18.99	4.64	0.93	6.38	7.50	10.44	1.01	0.78	4.29	1.19
5	15.78	3.89	2.28	1.87	6.46	2.73	8.73	2.41	2.08	2.95
6	13.54	3.25	2.59	0.34	3.47	5.19	0.56	6.52	3.04	3.05
7	11.87	2.73	2.53	1.34	1.24	4.04	3.32	2.47	4.15	2.98
8	10.59	2.34	2.33	1.77	0.14	2.30	3.77	1.39	3.13	2.00
9	9.57	1.99	2.11	1.90	0.95	0.88	2.86	2.91	0.16	2.85
10	8.74	1.69	1.86	1.91	1.41	0.16	1.66	2.87	1.80	1.10
11	8.05	1.44	1.64	1.79	1.60	0.84	0.58	2.11	2.44	0.73
12	7.46	1.21	1.41	1.64	1.67	1.25	0.27	1.18	2.19	1.75
13	6.95	0.97	1.21	1.46	1.62	1.52	0.86	0.27	1.50	1.92
14	6.51	0.76	0.99	1.25	1.52	1.59	1.27	0.44	0.69	1.55
15	6.12	0.57	0.77	1.06	1.34	1.55	1.49	0.98	0.07	0.90
17	5.44	0.16	0.33	0.58	0.89	1.24	1.46	1.48	1.13	0.45
19	4.83	0.4	0.27	0.06	0.21	0.55	0.91	1.19	1.27	1.06

21	4.16	1.07	1	0.89	0.71	0.47	0.18	0.12	0.35	0.42
23	3.73	0.76	0.75	0.7	0.62	0.49	0.29	0.06	0.18	0.35
25	3.37	0.54	0.55	0.54	0.52	0.45	0.34	0.18	0.01	0.22
27	3.09	0.37	0.38	0.41	0.42	0.39	0.36	0.25	0.1	0.07
29	2.85	0.24	0.25	0.28	0.32	0.33	0.32	0.28	0.19	0.06
31	2.65	0.11	0.15	0.18	0.22	0.25	0.28	0.28	0.23	0.15

Table 4. Line to line voltage harmonics in the PCC using direct coupling. In red, the values that comply with the regulations used for HV harmonics.

	Line to line voltage harmonics HV (%)									
Limit allowed (%)	3	2	2	2	1	1.5	1.5	0.3	1.2	1.07
n	**THD**	V_3	V_5	V_7	V_9	V_{11}	V_{13}	V_{15}	V_{17}	V_{19}
3	18.4	0.01	3.84	13.78	0.01	1.09	1.73	0	6.26	0.44
5	12.6	0	2.29	1.85	0.01	2.74	8.73	0.01	2.09	2.94
7	9.66	0.02	2.52	1.34	0.01	4.03	3.32	0.01	4.16	2.98
9	7.9	0	2.11	1.9	0.01	0.89	2.86	0.01	0.15	2.85
11	6.7	0.01	1.64	1.78	0.02	0.84	0.59	0	2.44	0.73
13	5.83	0.01	1.2	1.46	0.01	1.51	0.87	0	1.5	1.93
15	5.15	0	0.78	1.06	0.01	1.54	1.48	0.01	0.07	0.9
17	4.59	0.01	0.33	0.58	0.01	1.24	1.47	0	1.12	0.44
19	4.06	0.01	0.27	0.06	0	0.56	0.91	0	1.27	1.07
21	3.41	0.01	1	0.89	0	0.47	0.18	0	0.35	0.43
23	3.03	0.01	0.75	0.71	0.01	0.48	0.29	0.15	0.18	0.35
25	2.72	0.01	0.55	0.54	0	0.45	0.34	0.01	0.02	0.22

From the results shown in Table 4, it can be said that for $n \geq 25$ in HV and for $n \geq 15$ in MV (see Table 2), an MMC can be directly connected to the PCC (without transformer) since, from these values onwards, both grid codes are fulfilled. In case a lower number of SM is desired, it is necessary to add a coupling inductance, which may even be the leakage transformer inductance itself.

Up to this point, a variable switching period has been considered. Next, line to line converter voltages are obtained by simulation as a function of the number n of SM and the switching period T_r. The results are presented in Table 5 and Table 6. In order to fulfill the THD, for HV $n \geq 25$ and $T_r \leq 100\mu s$ (or $n \geq 27$ and $T_r \leq 200\mu s$) is needed; while, for MV (see Table 2), $n \geq 13$ and $T_r \leq 200\mu s$ (or $n \geq 17$ and $T_r \leq 400\mu s$) is needed.

Table 5. Variation of the THD (%) of the phase to neutral voltage of the MMC versus the SM number and the switching period.

n	**Variable** T_r	**Fixed** $T_r(\mu s)$				
		100	**200**	**400**	**800**	**1600**
3	23.91	23.66	24.23	25.55	26.22	29.17
4	18.99	18.66	19.19	20.48	21.47	24.97
5	15.78	15.51	15.21	15.21	16.41	18.55
6	13.54	13.70	13.90	13.68	15.08	19.77
7	11.87	11.75	11.80	12.35	13.83	18.55
8	10.59	10.60	10.69	11.56	13.18	17.58

9	9.57	9.54	9.80	10.43	12.17	17.42
10	8.74	8.76	8.89	8.65	10.71	16.53
11	8.05	8.05	8.32	9.14	11.08	16.82
12	7.46	7.49	7.53	8.26	10.39	16.33
13	6.95	7.09	7.40	7.79	10.00	16.11
14	6.51	6.54	6.65	7.11	9.51	15.74
15	6.12	6.20	6.41	7.42	9.72	15.70

Table 6. Variation of the THD (%) of the line to line voltage of the MMC versus the SM number and the switching period. In red, the values that comply with the regulations used for HV harmonics.

n	Variable T_r	Fixed $T_r(\mu s)$				
		100	**200**	**400**	**800**	**1600**
3	18.40	18.37	18.76	18.83	19.63	23.73
5	12.60	12.39	12.65	12.10	13.92	17.43
7	9.66	9.78	9.53	10.76	11.99	16.29
9	7.90	8.07	8.09	8.37	9.79	15.59
11	6.70	6.88	6.68	7.38	9.62	16.55
13	5.83	6.16	6.50	7.25	9.62	16.02
15	5.15	5.22	5.69	6.70	9.25	15.69
17	4.59	4.69	4.89	5.97	8.55	15.09
19	4.06	4.33	4.59	5.48	8.29	15.19
21	3.41	3.55	3.97	5.23	8.16	15.22
23	3.03	3.21	3.69	4.80	7.93	15.07
25	2.72	2.99	3.50	4.84	7.97	14.95
27	2.48	2.46	2.91	4.21	7.60	14.88
29	2.28	2.36	2.80	4.21	7.54	14.76

4.2. Voltage harmonics: coupling by transformer to the PCC

It has to be taken into account that, if an electrical line is stiff, its short-circuit inductance is low; whereas, if the line is weak, this inductance is high. The limit case between both situations is studied below, considering a short-circuit impedance 10 times larger than that of the power of the application.

Next, the calculation of the short circuit impedance for an application, presenting an apparent power $S = 200MVA$ connected to an HV line with a line to line rms voltage $V_{ph-ph} = 230kV$, is carried out. A short circuit power 10 times larger than the application power, $S_{sc} = 10 \cdot S = 10 \cdot 200MVA = 2000MVA$, is considered. The short circuit impedance per phase is

$$Z_{sc} = \frac{\left(\frac{V_{ph-ph}}{\sqrt{3}}\right)^2}{\frac{S_{sc}}{3}} = \frac{V_{ph-ph}{}^2}{S_{sc}} = \frac{(230 \cdot 10^3)^2}{2000 \cdot 10^6} = 26.45\Omega \quad (18)$$

The short circuit inductance is:

$$L_{sc} = \frac{Z_{sc}}{2\pi f} = \frac{26.45}{2\pi 50} = 84.2mH \quad (19)$$

The rms value of the n harmonic of the neutral phase voltage at the PCC $V_{o,n}$ is calculated as an inductive voltage divider of the n^{th} harmonic value of the converter neutral phase voltage $V_{conv,n}$ (Figure 4), if it is assumed that the grid voltage has only fundamental harmonic.

$$V_{oa,n} = V_{conva,n}\frac{X_{sc}}{X_t + X_{sc}} = V_{conva,n}\frac{n\omega L_{sc}}{n\omega L_t + n\omega L_{sc}} = V_{conva,n}\frac{L_{sc}}{L_t + L_{sc}} = V_{conva,n}\frac{1}{1 + L_t/L_{sc}} \quad (20)$$

The rms value of the n^{th} harmonic of the line to line voltage in the PCC is calculated by subtracting the voltages of two phases:

$$V_{oab,n} = V_{oa,n} - V_{ob,n} = \left(V_{conva,n} - V_{convb,n}\right)\frac{1}{1 + L_t/L_{sc}} = V_{convab,n}\frac{1}{1 + L_t/L_{sc}} \quad (21)$$

A transformer 230kV/230kV and 200MW can have a leakage inductance $L_t = 134.7\text{mH}$. If the constant $\frac{1}{1+L_t/L_{sc}}$ is called k, its value is:

$$k = \frac{V_{oab,n}}{V_{convab,n}} = \frac{1}{1 + L_t/L_{sc}} = \frac{1}{1 + 0.1347/0.0842} = 0.3847 \quad (22)$$

Taking into account that the rated voltage in the converter and transformer must be equal, $V_{oab,1} = V_{convab,1}$, the THD of the line to line voltage in the PCC is:

$$THD_{V_{oab}} = \frac{\sqrt{\sum_{n=2}^{\infty} {V_{oab,n}}^2}}{V_{oab,1}} = \frac{\sqrt{\sum_{n=2}^{\infty} \left(kV_{convab,n}\right)^2}}{V_{oab,1}} = k\frac{\sqrt{\sum_{n=2}^{\infty} {V_{convab,n}}^2}}{V_{convab,1}} = k \cdot THD_{V_{convab}} \quad (23)$$

Hence, it is only necessary to multiply the values in Table 4 **¡Error! No se encuentra el origen de la referencia.**by the constant k in order to obtain the tables for the THD and the PCC line to line voltage harmonics when a transformer is used. Calculations for HV and MV applications (Table 7) use equations (18), (19) and (22).

When the grid coupling is carried out by means of a transformer, the number of necessary SM to fulfill the grid codes is reduced; in HV $n = 11$ is sufficient, and $n = 11$ in MV (see Table 8 and Table 9).

Table 7. Parameters of the HV and MV lines.

	$V_{1,ph-ph,rms}(kV)$	$V_{2,ph-ph,rms}(kV)$	$P(MVA)$	$S_{sc}(MVA)$	$f(Hz)$	$L_{sc}(H)$	$L_t(H)$	k
HV	230	230	200	2000	50	0.0842	0.1347	0.3847
MV	3	3	1	10	50	0.002865	0.002292	0.5556

Table 8. Line to line voltage harmonics in the PCC of the HV line using transformer coupling. In red, the values that comply with the regulations.

	Line to line voltage harmonics HV (%)									
Limit allowed (%)	3	2	2	2	1	1.5	1.5	0.3	1.2	1.07
n	**THD**	V_3	V_5	V_7	V_9	V_{11}	V_{13}	V_{15}	V_{17}	V_{19}
3	7.08	0.00	1.48	5.30	0.00	0.42	0.67	0.00	2.41	0.17
5	4.85	0.00	0.88	0.71	0.00	1.05	3.36	0.00	0.80	1.13
7	3.72	0.01	0.97	0.52	0.00	1.55	1.28	0.00	1.60	1.15
9	3.04	0.00	0.81	0.73	0.00	0.34	1.10	0.00	0.06	1.10
11	2.58	0.00	0.63	0.68	0.01	0.32	0.23	0.00	0.94	0.28

13	2.24	0.00	0.46	0.56	0.00	0.58	0.33	0.00	0.58	0.74
15	1.98	0.00	0.30	0.41	0.00	0.59	0.57	0.00	0.03	0.35
17	1.77	0.00	0.13	0.22	0.00	0.48	0.57	0.00	0.43	0.17
19	1.56	0.00	0.10	0.02	0.00	0.22	0.35	0.00	0.49	0.41
21	1.31	0.00	0.38	0.34	0.00	0.18	0.07	0.00	0.13	0.17
23	1.17	0.00	0.29	0.27	0.00	0.18	0.11	0.06	0.07	0.13
25	1.05	0.00	0.21	0.21	0.00	0.17	0.13	0.00	0.01	0.08

Table 9. Line to line voltage harmonics in the PCC of the MV line using transformer coupling. In red, the values that comply with the regulations.

	Line to line voltage harmonics MV (%)									
Limit allowed (%)	6.5	4	5	4	1.2	3	2.5	0.3	1.7	1.5
$\boldsymbol{n}$	**THD**	$\boldsymbol{V_3}$	$\boldsymbol{V_5}$	$\boldsymbol{V_7}$	$\boldsymbol{V_9}$	$\boldsymbol{V_{11}}$	$\boldsymbol{V_{13}}$	$\boldsymbol{V_{15}}$	$\boldsymbol{V_{17}}$	$\boldsymbol{V_{19}}$
3	10.22	0.01	2.13	7.66	0.01	0.61	0.96	0.00	3.48	0.24
5	7.00	0.00	1.27	1.03	0.01	1.52	4.85	0.01	1.16	1.63
7	5.37	0.01	1.40	0.74	0.01	2.24	1.84	0.01	2.31	1.66
9	4.39	0.00	1.17	1.06	0.01	0.49	1.59	0.01	0.08	1.58
11	3.72	0.01	0.91	0.99	0.01	0.47	0.33	0.00	1.36	0.41
13	3.24	0.01	0.67	0.81	0.01	0.84	0.48	0.00	0.83	1.07
15	2.86	0.00	0.43	0.59	0.01	0.86	0.82	0.01	0.04	0.50
17	2.55	0.01	0.18	0.32	0.01	0.69	0.82	0.00	0.62	0.24
19	2.26	0.01	0.15	0.03	0.00	0.31	0.51	0.00	0.71	0.59
21	1.89	0.01	0.56	0.49	0.00	0.26	0.10	0.00	0.19	0.24
23	1.68	0.01	0.42	0.39	0.01	0.27	0.16	0.08	0.10	0.19
25	1.51	0.01	0.31	0.30	0.00	0.25	0.19	0.01	0.01	0.12

Next, the THD analyzed when a fixed switching period is used. THD for the PCC line to line voltage $V_{o,ab}$ (Figure 4) in couplings using transformer is obtained from THD line to line voltage $V_{conv,ab}$ by means of (23). Hence, the tables for the THD using transformer (Table 10 and Table 11) are obtained by multiplying tables without transformer (Table 6) by those corresponding to HV or MV constant k (Table 7).

From these tables, it can be said that $n \geq 11$ and $T_r \leq 400\mu s$ are needed in HV (note: $n \geq 13$ and $T_r \leq 200\mu s$ without transformer); while $n \geq 7$ and $T_r \leq 400\mu s$, or $n \geq 9$ and $T_r \leq 800\mu s$, are needed in MV (note: $n \geq 13$ and $T_r \leq 200\mu s$ are needed without transformer).

Table 10. Variation of the THD (%) of the line to line voltage in the PCC versus the SM number and the switching period, using coupling by transformer. In red, the values that comply with the regulations used for HV harmonics.

$\boldsymbol{n}$	**Variable** $\boldsymbol{T_r}$	**Fixed** $\boldsymbol{T_r(\mu s)}$				
		100	**200**	**400**	**800**	**1600**
3	7.08	7.07	7.22	7.24	7.55	9.13
5	4.85	4.77	4.87	4.65	5.36	6.71
7	3.72	3.76	3.67	4.14	4.61	6.27
9	3.04	3.10	3.11	3.22	3.77	6.00

11	2.58	2.65	2.57	2.84	3.70	6.37
13	2.24	2.37	2.50	2.79	3.70	6.16
15	1.98	2.01	2.19	2.58	3.56	6.04
17	1.77	1.80	1.88	2.30	3.29	5.81
19	1.56	1.67	1.77	2.11	3.19	5.84
21	1.31	1.37	1.53	2.01	3.14	5.86
23	1.17	1.23	1.42	1.85	3.05	5.80
25	1.05	1.15	1.35	1.86	3.07	5.75
27	0.95	0.95	1.12	1.62	2.92	5.72
29	0.88	0.91	1.08	1.62	2.90	5.68

Table 11. Variation of the THD (%) of the line to line voltage in the PCC using transformer coupling, versus the SM number and the commutation period. In red, the values that comply with the regulations used for MV harmonics.

n	Variable T_r	Fixed $T_r(\mu s)$				
		100	**200**	**400**	**800**	**1600**
3	10.22	10.21	10.42	10.46	10.91	13.18
5	7.00	6.88	7.03	6.72	7.73	9.68
7	5.37	5.43	5.29	5.98	6.66	9.05
9	4.39	4.48	4.49	4.65	5.44	8.66
11	3.72	3.82	3.71	4.10	5.34	9.20
13	3.24	3.42	3.61	4.03	5.34	8.90
15	2.86	2.90	3.16	3.72	5.14	8.72
17	2.55	2.61	2.72	3.32	4.75	8.38
19	2.26	2.41	2.55	3.04	4.61	8.44
21	1.89	1.97	2.21	2.91	4.53	8.46
23	1.68	1.78	2.05	2.67	4.41	8.37
25	1.51	1.66	1.94	2.69	4.43	8.31
27	1.38	1.37	1.62	2.34	4.22	8.27
29	1.27	1.31	1.56	2.34	4.19	8.20

Generally speaking, it can be said that, if it is necessary to reduce the level of harmonics or the number of SM, or to increase the switching period, it is possible to introduce an additional inductance to that of the transformer.

4.3. Current harmonics: direct coupling and via transformer to the PCC

From the phase to neutral voltage harmonics and the inductance between the MMC and the electrical grid, it is possible to obtain the current harmonics. The inductance is calculated as the sum of the coupling inductance, if it exists; that of the transformer, if a transformer exists, and that of the line.

Current harmonics that must be lower than a certain level, imposed by the grid codes, depend on the voltage harmonics and the line inductance, if it is assumed that the grid voltage has only fundamental harmonic. THD limits and odd harmonic limits, according to the code [27], have the values shown in Table 12. The larger the line to line voltage is, the stricter the limits and also the larger the quotient I_{sc}/I_L is, where I_{sc} is the short circuit current of the line and I_L is the rated current of the line. Table 12 shows the strictest limits, corresponding to low values of I_{sc}/I_L; the limits are less strict for higher values of I_{sc}/I_L.

Table 12. Limits of THD and odd harmonics of current.

		120V–69kV	**69kV–161kV**	**>161kV**
		$I_{sc}/I_L < 20$	$I_{sc}/I_L < 20$	$I_{sc}/I_L < 20$
THD (%)		5	2.5	1.5
Odd harmonics (%)	3–11	4	2	1
	11–17	2	1	0.5
	17–23	1.5	0.75	0.38
	23–35	0.6	0.3	0.15
	35-50	0.3	0.15	0.1

The rms value of the fundamental harmonic of the line current I_1 is calculated, using the parameters of Table 7, as follows:

$$\text{HV: } S = 3I_1V_{o1} \rightarrow I_1 = \frac{S}{3V_{o1}} = \frac{200 \cdot 10^6}{3 \cdot 132.79 \cdot 10^3} = 502.05A \quad (24)$$

$$\text{MV: } S = 3I_1V_{o1} \rightarrow I_1 = \frac{S}{3V_{o1}} = \frac{1 \cdot 10^6}{3 \cdot 1.732 \cdot 10^3} = 192.46A \quad (25)$$

The rms value of the current n^{th} order harmonic I_n is the quotient between the rms value of the n^{th} harmonic of the converter phase to neutral voltage $V_{conv,n}$ and the impedance of the series inductances (see Figure 4). It must be taken into account that the grid voltage v only has fundamental harmonic.

$$I_n = \frac{V_{conv,n}}{n\omega(L_t + L_{sc})} \quad (26)$$

Its value as a percentage $I_n(\%)$ is obtained by dividing by the rms value of the fundamental current harmonic I_1,

$$I_n(\%) = \frac{I_n}{I_1}100 = \frac{\frac{V_{conv,n}}{n\omega(L_t + L_{sc})}}{I_1}100 \quad (27)$$

The rms value of the n^{th} harmonic of the MMC voltage and current as a percentage are:

$$V_{conv,n}(\%) = \frac{V_{conv,n}}{V_{conv,1}}100 \quad (28)$$

$$I_n(\%) = \frac{\frac{V_{conv,n}}{n\omega(L_t + L_{sc})}}{I_1}100 = \frac{\frac{V_{conv,n}(\%) \cdot V_{conv,1}}{n\omega(L_t + L_{sc}) \cdot 100}}{I_1}100 = \frac{V_{conv,n}(\%) \cdot V_{conv,1}}{I_1 n\omega(L_t + L_{sc})} \quad (29)$$

Current THD in p.u. and percent is:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} {I_n}^2}}{I_1} \quad (30)$$

$$THD_I(\%) = THD_I \cdot 100 = \frac{\sqrt{\sum_{n=2}^{\infty} I_n{}^2}}{I_1} \cdot 100 = \sqrt{\sum_{n=2}^{\infty} I_n(\%)^2} \quad (31)$$

The current harmonics can be seen in the following tables, for the case of a variable switching period T_r. They have been obtained from Table 3 of the phase to neutral voltages and equations (29) and (31). Although the converter phase to neutral voltage (Table 3) has harmonics multiples of three, the line current does not have these harmonics because the neutral of the load and the midpoint of the DC voltage are not connected. In the HV line, when the coupling is direct, $n \geq 27$ is needed (Table 13); and when the coupling is by transformer, $n \geq 14$ is needed (Table 14). In the MV line, when the coupling is direct $n \geq 10$ is needed (Table 15); and when the coupling is by transformer, $n \geq 6$ is needed (Table 16).

Table 13. MMC current harmonics using direct coupling. In red, the values that comply with the regulations used for HV harmonics.

		Current harmonics (%)								
n	THD(%)	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{15}	I_{17}	I_{19}
Limit allowed (%)	1.50	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.38
SM=3	21.51	0.00	7.68	19.68	0.00	1.00	1.33	0.00	3.68	0.23
SM=4	13.56	0.00	1.86	9.11	0.00	9.49	0.78	0.00	2.52	0.63
SM=5	9.11	0.00	4.56	2.67	0.00	2.48	6.71	0.00	1.22	1.55
SM=6	7.43	0.00	5.18	0.49	0.00	4.72	0.43	0.00	1.79	1.61
SM=7	7.60	0.00	5.06	1.91	0.00	3.67	2.55	0.00	2.44	1.57
SM=8	6.74	0.00	4.66	2.53	0.00	2.09	2,90	0,00	1,84	1,05
SM=9	5,74	0.00	4.22	2.71	0.00	0.80	2.20	0.00	0.09	1.50
SM=10	4.94	0.00	3.72	2.73	0.00	0.15	1.28	0.00	1.06	0.58
SM=11	4.50	0.00	3.28	2.56	0.00	0.76	0.45	0.00	1.44	0.38
SM=12	4.16	0.00	2.82	2.34	0.00	1.14	0.21	0.00	1.29	0.92
SM=13	3.79	0.00	2.42	2.09	0.00	1.38	0.66	0.00	0.88	1.01
SM=14	3.31	0.00	1.98	1.79	0.00	1.45	0.98	0.00	0.41	0.82
SM=15	2.86	0.00	1.54	1.51	0.00	1.41	1.15	0.00	0.04	0.47
SM=17	2.04	0.00	0.66	0.83	0.00	1.13	1.12	0.00	0.66	0.24
SM=19	1.38	0.00	0.54	0.09	0.00	0.50	0.70	0.00	0.75	0.56
SM=21	2.43	0.00	2.00	1.27	0.00	0.43	0.14	0.00	0.21	0.22
SM=23	1.88	0.00	1.50	1.00	0.00	0.45	0.22	0.00	0.11	0.18
SM=25	1.43	0.00	1.10	0.77	0.00	0.41	0.26	0.00	0.01	0.12
SM=27	1.06	0.00	0.76	0.59	0.00	0.35	0.28	0.00	0.06	0.04
SM=29	0.76	0.00	0.50	0.40	0.00	0.30	0.25	0.00	0.11	0.03
SM=31	0.53	0.00	0.30	0.26	0.00	0.23	0.22	0.00	0.14	0.08

Table 14. Current harmonics in the PCC of the HV line using transformer coupling. In red, the values that comply with the regulations.

		Current harmonics (%)								
n	THD(%)	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{15}	I_{17}	I_{19}

Limit allowed (%)	1.50	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.38
SM=3	8.27	0.00	2.95	7.57	0.00	0.38	0.51	0.00	1.42	0.09
SM=4	5.22	0.00	0.72	3.51	0.00	3.65	0.30	0.00	0.97	0.24
SM=5	3.51	0.00	1.75	1.03	0.00	0.95	2.58	0.00	0.47	0.60
SM=6	2.86	0.00	1.99	0.19	0.00	1.81	0.17	0.00	0.69	0.62
SM=7	2.92	0.00	1.95	0.74	0.00	1.41	0.98	0.00	0.94	0.60
SM=8	2.59	0.00	1.79	0.97	0.00	0.80	1.12	0.00	0.71	0.40
SM=9	2.21	0.00	1.62	1.04	0.00	0.31	0.85	0.00	0.04	0.58
SM=10	1.90	0.00	1.43	1.05	0.00	0.06	0.49	0.00	0.41	0.22
SM=11	1.73	0.00	1.26	0.98	0.00	0.29	0.17	0.00	0.55	0.15
SM=12	1.60	0.00	1.08	0.90	0.00	0.44	0.08	0.00	0.50	0.35
SM=13	1.46	0.00	0.93	0.80	0.00	0.53	0.25	0.00	0.34	0.39
SM=14	1.27	0.00	0.76	0.69	0.00	0.56	0.38	0.00	0.16	0.31
SM=15	1.10	0.00	0.59	0.58	0.00	0.54	0.44	0.00	0.02	0.18

Table 15. Current harmonics in the MMC using direct coupling. In red, the values that comply with the regulations used for MV harmonics.

		Current harmonics (%)								
n	**THD(%)**	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{15}	I_{17}	I_{19}
Limit allowed (%)	5.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	2.00	1.50
SM=3	21.51	0.00	7.68	19.68	0.00	1.00	1.33	0.00	3.68	0.23
SM=4	13.56	0.00	1.86	9.11	0.00	9.49	0.78	0.00	2.52	0.63
SM=5	9.11	0.00	4.56	2.67	0.00	2.48	6.71	0.00	1.22	1.55
SM=6	7.43	0.00	5.18	0.49	0.00	4.72	0.43	0.00	1.79	1.61
SM=7	7.59	0.00	5.06	1.91	0.00	3.67	2.55	0.00	2.44	1.57
SM=8	6.74	0.00	4.66	2.53	0.00	2.09	2.90	0.00	1.84	1.05
SM=9	5.74	0.00	4.22	2.71	0.00	0.80	2.20	0.00	0.09	1.50
SM=10	4.94	0.00	3.72	2.73	0.00	0.15	1.28	0.00	1.06	0.58
SM=11	4.50	0.00	3.28	2.56	0.00	0.76	0.45	0.00	1.44	0.38
SM=12	4.16	0.00	2.82	2.34	0.00	1.14	0.21	0.00	1.29	0.92
SM=13	3.79	0.00	2.42	2.09	0.00	1.38	0.66	0.00	0.88	1.01
SM=14	3.31	0.00	1.98	1.79	0.00	1.45	0.98	0.00	0.41	0.82
SM=15	2.86	0.00	1.54	1.51	0.00	1.41	1.15	0.00	0.04	0.47

Table 16. Current harmonics in the PCC of the MV line using transformer coupling. In red, the values that comply with the regulations.

		Current harmonics (%)								
n	**THD(%)**	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{15}	I_{17}	I_{19}
Limit allowed (%)	5.00	4.00	4.00	4.00	4.00	4.00	2.00	2.00	2.00	1.50
SM=3	11.95	0.00	4.27	10.93	0.00	0.56	0.74	0.00	2.05	0.13
SM=4	7.53	0.00	1.03	5.06	0.00	5.27	0.43	0.00	1.40	0.35

SM=5	5.06	0.00	2.53	1.48	0.00	1.38	3.73	0.00	0.68	0.86
SM=6	4.13	0.00	2.88	0.27	0.00	2.62	0.24	0.00	0.99	0.89
SM=7	4.22	0.00	2.81	1.06	0.00	2.04	1.42	0.00	1.36	0.87
SM=8	3.74	0.00	2.59	1.40	0.00	1.16	1.61	0.00	1.02	0.58
SM=9	3.19	0.00	2.34	1.51	0.00	0.44	1.22	0.00	0.05	0.83
SM=10	2.74	0.00	2.07	1.52	0.00	0.08	0.71	0.00	0.59	0.32
SM=11	2.50	0.00	1.82	1.42	0.00	0.42	0.25	0.00	0.80	0.21
SM=12	2.31	0.00	1.57	1.30	0.00	0.63	0.12	0.00	0.72	0.51
SM=13	2.10	0.00	1.34	1.16	0.00	0.77	0.37	0.00	0.49	0.56
SM=14	1.84	0.00	1.10	0.99	0.00	0.80	0.54	0.00	0.23	0.45
SM=15	1.59	0.00	0.86	0.84	0.00	0.78	0.64	0.00	0.02	0.26

4.4. Automated harmonic calculation procedure

To decide the number n of SM and the commutation period T_r, it is convenient to have a tool that calculates the distortion according to these two parameters. In Matlab, it is possible to program several Simulink simulations based on these parameters. Below is a simulation of the THD (Figure 6), performed with the same simplified scheme of the previous sections, when the SM number varies between $3 < n < 15$, the switching period varies between $50\mu s < T_r < 800\mu s$ and the sampling period is $T_s = 2.5\mu s$. The three-dimensional graph of Figure 6 allows to have an initial idea of the THD values and the level of influence of n and T_r.

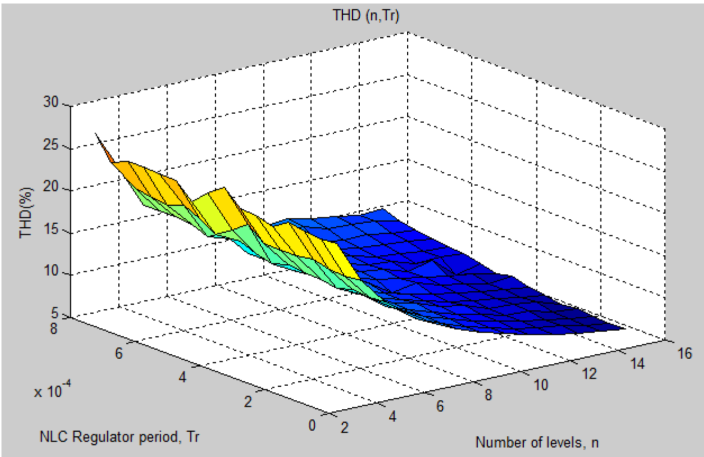


Figure 6. THD versus the number of levels n and the switching period T_r.

The Matlab program used is:

```
function THD_2var(n,Tr)

mdl = 'NLM_v07';
isModelOpen = bdIsLoaded(mdl);
open_system(mdl);

n_sweep = n*(1.5:-0.1:0.3);
Tr_sweep = Tr*(8:-0.5:0.5);
iterations_n = length(n_sweep);
iterations_Tr = length(Tr_sweep);
simout(iterations_n,iterations_Tr) = Simulink.SimulationOutput;
```

```
for idx = 1:iterations_n
    for idy = 1:iterations_Tr
        load_system(mdl);
        set_param([mdl '/bloque'],'MaskValues',...
            {num2str(n_sweep(idx)),num2str(Tr_sweep(idy))});
        simout(idx,idy) = sim(mdl,'SimulationMode','normal');
    end
end

for i = 1:iterations_n
    for ii = 1:iterations_Tr
        si = simout(i,ii);
        ts = si.get('logsout').get('distorsion').Values;
        Z(i,ii) = mean(ts*100);
    end
end

[X,Y] = meshgrid(n_sweep, Tr_sweep);
surf(X,Y,Z');

title('THD (n,Tr)');
xlabel('Number of levels n');
ylabel('NLC regulator period Tr (us)');
zlabel('THD (%)');

end
```

5. Simulation of the detailed model of the modular multilevel converter

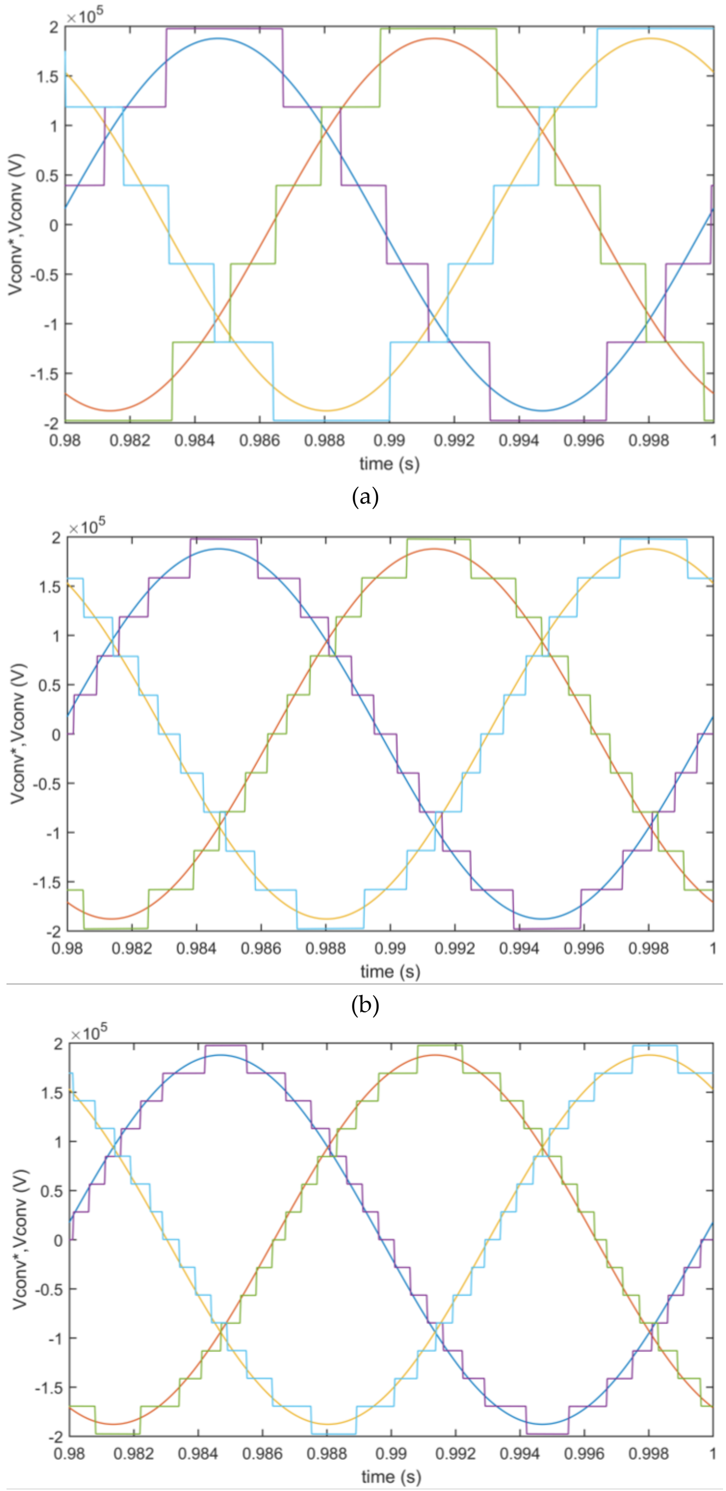
To validate the calculations and simplified simulations carried out previously, an MMC is simulated with the parameters of Table 17, corresponding to the HV and direct coupling to the grid case (without transformer) studied previously.

The THD (%) obtained in the detailed simulation of the MMC for 5 (Figure 7a), 10 (Figure 7b) and 14 (Figure 7c) SMs is, respectively, 15.77, 8.74, 6.56; while the values calculated in simplified form are 15.51, 8.76 and 6.54 (Table 5). The difference is extremely small, so the procedure followed can be validated. This is important as it makes the detailed simulation of the converter depending on the parameters n and T_r unnecessary, which slows down the procedure considerably. In any case, using the detailed Simulink diagram of the MMC, a THD graph of current versus n and T_r can be made, although the simulation is a slow process, using the Matlab programming used in section 4.4.

Table 17. Simulation parameters.

n	5
V_{DC}	$395.36kV$
I_1	$502.05\text{Arms} - 710\text{Apeak}$
V_{o1}	$132.79kVrms, ph-n$
ω	$314.16rad/s$
L	375μH
C	30mF
L_{sc}	$84.2mH$
T_s	2.5μs

T_r	100µs



(a)

(b)

(c)

Figure 7. Simulation of the phase to neutral voltage of an MMC V_{conv} and its reference value $V_{conv}{}^{*}$ with n SM per arm, with $T_r = 100\mu s$ and $T_s = 2.5\mu s$, when: (a) $n = 5$, (b) $n = 10$, and (c) $n = 14$.

The voltages in the capacitors of the SMs are simulated to see if it is necessary to increase the switching frequency or increase the capacitor value in order to avoid variations in the voltage levels within the switching period. It must be taken into account that the current flowing through the SM capacitors is the same as that of the branch, $i_{upa} = i_a/2 + i_{dc}/3 + i_{za}$, where i_{dc} is continuous, i_a

has the same frequency as the grid (50Hz) and i_{za} has twice the grid frequency (100Hz). Therefore, the switching frequency has no influence, being much higher than the arm current frequency. This is also verified in the simulation (Figure 8), where it is observed that the voltage of the capacitors remains approximately constant.

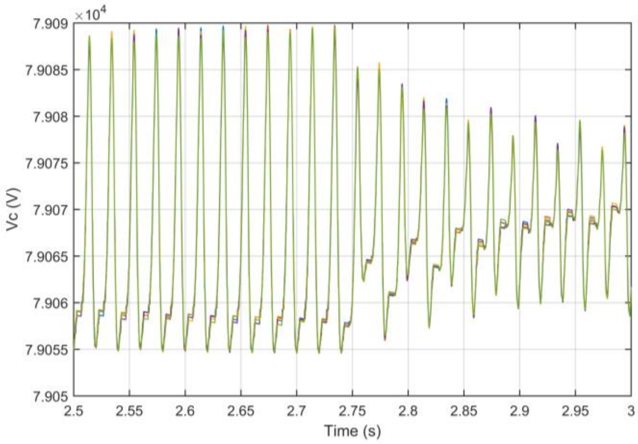


Figure 8. Simulation of the capacitor voltages of the upper arm of phase a in the case of $n = 5$. The voltages of the 5 capacitors are superimposed.

6. Experimental results

For further validation of calculations and simplified simulations carried out in Section 4, experimental results have been obtained using a real-time simulator (RTS) named RTbox 240 from accuRTpower.com (Figure 9). It has been implemented the same scheme for $n = 5$ SM that has been simulated in Section 5 using Simulink.

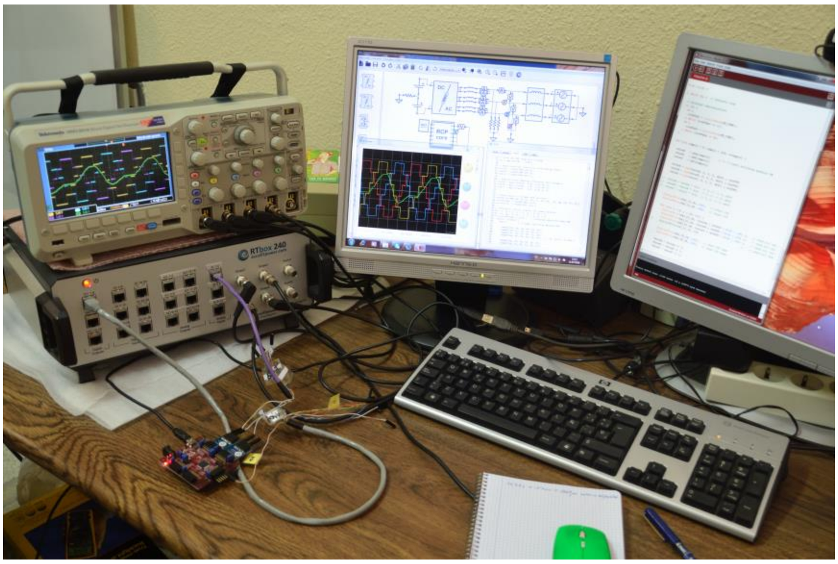


Figure 9. Photograph of the tests with the real-time simulator.

Figure 9 shows the experimental setup, where an external controller based on a microcontroller was synchronized to the simulated grid and then used to generate references to switch the appropriate semiconductors in a simulated MMC converter. The controller was an Arduino-like board based on a PIC32MX320F128H processor running at 80 MHz, it synchronizes to the grid waiting every 20 milliseconds for a negative to positive transition on the first grid voltage and then it generates three references every 100 microseconds, reading 0 to 5 values from a table computed using Matlab, and managing the SPI signals to provide those values using three external digital to analog converters; the microcontroller is loaded at 90% to manage these tasks. Meanwhile, the RTS has two floating-point cores, one core is used to simulate the MMC converter, the inductive filters and the grid, including the computation of the 30 voltages of the SM capacitors; the other core reads the analog references supplied by the external controller and decides which SM semiconductors must be fired in order to get the correct voltage and at the same time it tries to keep balanced all capacitor voltages; first core is described using a graphical tool and the plant simulation code is automatically generated by the software provided for the RTS, including the converter and the grid, the second core was programmed for this application using a high level language, C in this case, and using embedded functions to access the analog inputs to read the references from the external controller and also to access the digital outputs used to control the MMC converter; the voltage of the 30 capacitors was sent from the first core to the second using shared memory. In this case for 5 SM the first core has had a period of 4 microseconds and has been loaded at 81%, the second core executes its program every 100 microseconds to reduce the converter commutation frequency, but the execution of the generated code in the worst case is below 12 microseconds.

In Figure 10, the MMC phase to neutral voltages and the SM capacitor voltage are observed. The first harmonic of the MMC phase to neutral voltage can be seen in Figure 11 and the following harmonics in Figure 12. The MMC phase to neutral voltages generated in the RTS (Figure 10) are similar to those obtained by Simulink (Figure 7a and Figure 8). The harmonics of the phase to neutral voltage are also similar to those obtained by Simulink, as can be seen in Table 18.

From the results obtained through Simulink (Section 5) and through the RTS (Section 6) it can be concluded that the simplified simulations carried out in Section 4 are sufficient to be able to determine the number n of SM and the switching time T_r in an MMC with NLC.

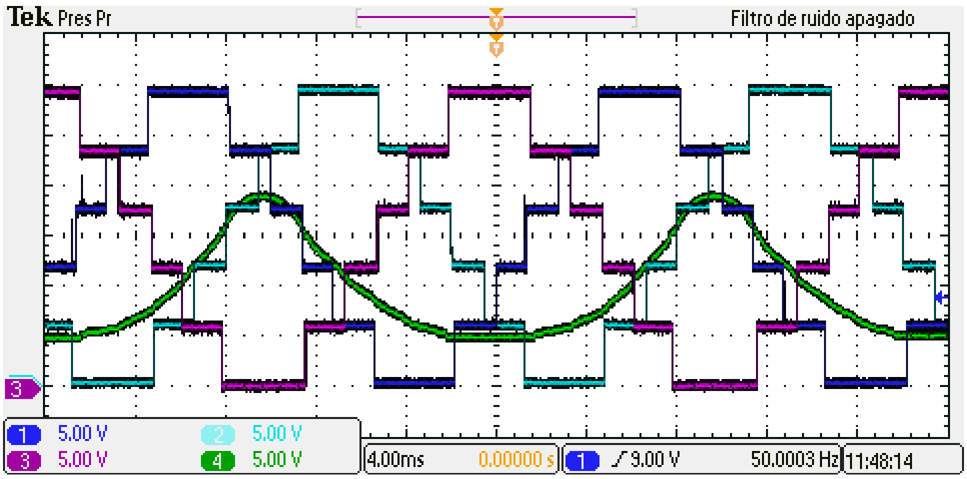


Figure 10. Oscilloscope measurements: MMC phase to neutral voltages V_{conv} (66.7kV/div) and SM capacitor voltage (7.15V/div).

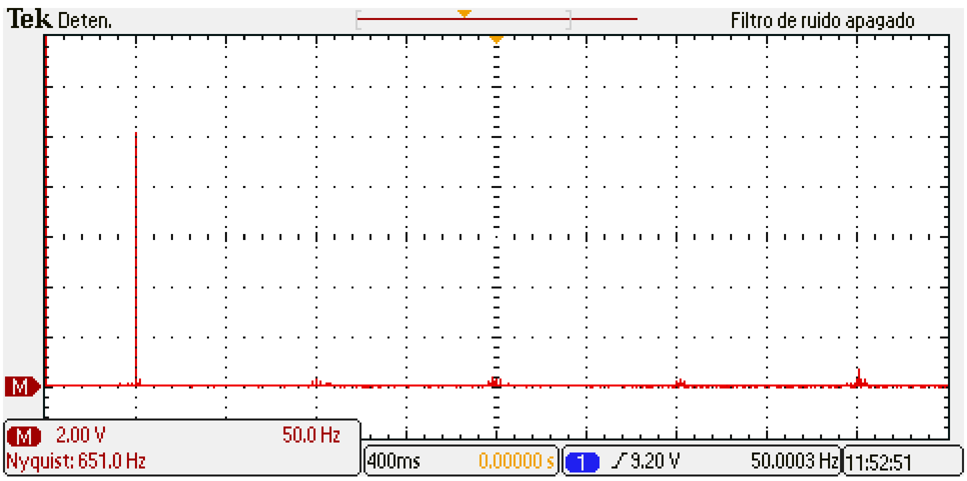


Figure 11. Oscilloscope measurements: First harmonics of the MMC phase to neutral voltage (38.6kV/div).

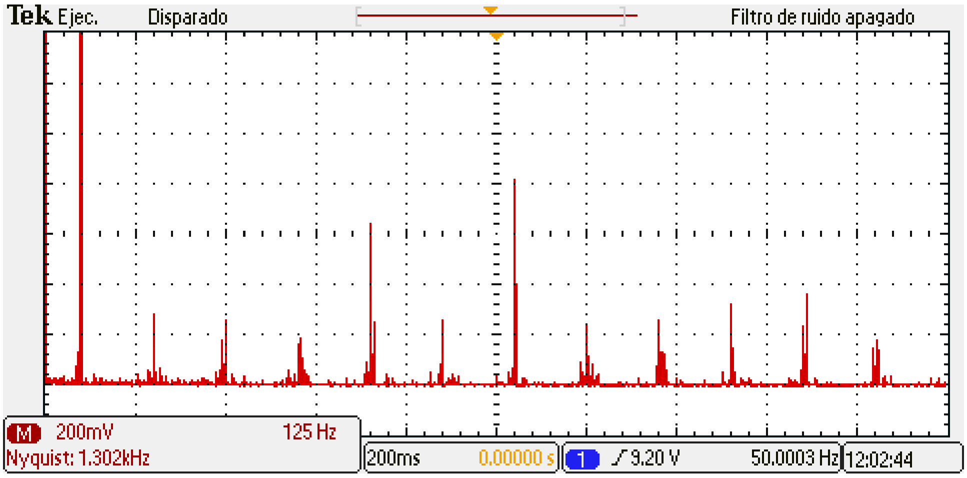


Figure 12. Oscilloscope measurements: 1st to 23th harmonics of the MMC phase to neutral voltage (3.86kV/div).

Table 18. Comparison of the harmonics of the MMC phase to neutral voltage, between Simulink and the Real Time Simulator, for $n = 5$.

Harmonic order	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**
Simulink (%)	3.38	3.00	2.00	6.88	2.39	8.20	2.39	2.74	3.44	2.44	1.95
Real Time Simulation (%)	2.76	2.70	1.65	6.46	2.70	8.18	2.27	2.64	3.19	2.27	1.84

7. Conclusions

The choice of the number of SM in an MMC is a delicate matter, since a balance between distortion, power losses and the complexity of the power circuit and control has to be looked for.

This paper is focused on the study of the distortion in relation to the number of SM using simulation techniques, since no general mathematical equation can be obtained.

Grid codes determine, for each country, the limit of voltage and current harmonics in the PCC. MMCs generate harmonics that depend on the number of SM, but also on the coupling, transformer and line inductances. If the number of SM is high, the MMC can even be directly connected to the grid.

A high number of simulations where the THD and harmonics are compared with the limits imposed by the grid codes have to be carried out in order to choose the most suitable number of SM and the switching period. Simulations can be simplified or include a detailed MMC model.

A number of simulations are carried out to obtain the THD as a function of the parameters to be chosen, the number of SM and the switching period. It is revealed as an efficient and convenient way to obtain, graphically, an approximation of the possible THD values.

The article is useful for the reader to find the SM number and the commutation period that an MMC needs to comply with harmonic regulations. A first approximation of the values can be found, along with the methodology that should be used to make a detailed study of its application.

It has been discovered that it is possible to make the direct connection of an MMC, without exceeding the limits of harmonics, through a transformer, or even without a transformer, without the need to use a coupling inductance. For this, a sufficiently high number of SM must be used, but it does not have to be an extraordinarily high number, which makes it a feasible situation.

8. Acknowledgments

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