LCL Filter design for grid-connected NPC inverters in offshore wind turbines

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Abstract— This paper deals with the analysis, design and optimization of a LCL filter topology to connect a 7MW NPC inverter to the grid. Following the requirements based on the IEEE 519-1992 recommendation and the German Guideline VDEW, simulation results were evaluated in order to access the performance of the proposed filter and the quality of the current injected into the grid.

I. INTRODUCTION

The trend towards multi MW wind turbine units has called up for new concepts in the design of wind energy conversion systems. Economic viability of offshore wind turbines clearly scales with power and efficiency of generators and power conversion systems. Within this trend, power electronic multilevel converters have been seen as an appropriate technology for the wind energy conversion system because they can operate at high power and high voltage [1].

Among several proposed multilevel topologies the three-level diode-clamped, or simply called Neutral-Point Clamped - NPC inverter was the first widely implemented by the industry and it continues to be extensively used in high voltage and high power applications.

A NPC inverter leg is shown in Fig. 1. It is composed by four switches S_1 to S_4 and the anti-parallel diodes D_1 to D_4.

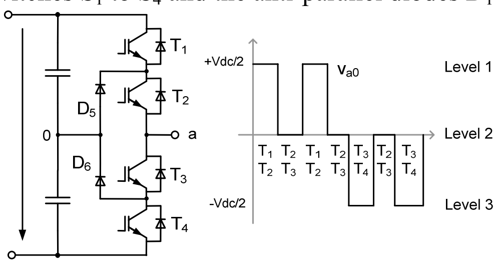

Fig. 1: NPC inverter leg and AC waveform.

Voltages across the switches are only half of the DC input voltage because diodes D5 and D6 are connected to the neutral point [2].

The three-phase NPC inverter presents a line-to-line voltage with five voltage levels which leads to a lower Total Harmonic Distortion (THD) and dv/dt; also resulting in lower Electromagnetic Interference EMI when compared to the conventional two-level inverter. On the other hand, as the number of levels of the inverter increases the THD of the output voltage waveform presents little improvement [3].

This paper will focus the filter design aiming to minimize the harmonic content of the current injected by the grid side NPC inverter at the Point of Common Coupling (PCC), as depicted in Fig. 2. As a remark, this is a full converter solution in order to avoid dealing with slip rings and possible Low Voltage Ride Through difficulties.

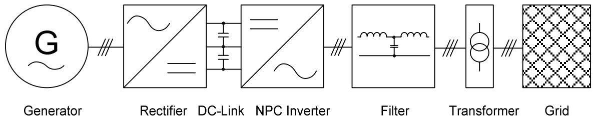

Fig. 2: System diagram.

Several requirements can be considered when analyzing the power quality and grid-compatibility of wind turbines connected to the grid. According to [4] and [5], the following topics are important when studying the grid compatibility of a device: average and maximum produced power, reactive power levels, coupling procedure to the grid, grid short-circuit current (weak or stiff grid conditions), voltage fluctuations (under normal and transient operation), flicker and harmonics.

Concerning wind turbines, almost all of the above listed requirements are influenced either by the behavior of the wind profile or by the dynamic of the mechanic system (including rotor and generator characteristics). However, for this analysis the inverter DC link voltage is strong enough to avoid flicker or voltage fluctuation caused by wind speed variation.

II. STANDARDS REGARDING THE QUALITY OF THE POWER INSERTED INTO THE GRID

The usual diagnosis of harmonic distortion is done by calculating each harmonic component present in the produced current and then determining the distortion on the voltage due to the grid impedance at the considered harmonic frequency level. Knowing that at the design phase, no further information is available about the grid connection and impedances, the analysis will be limited to the harmonic components of the produced current.

For such purpose, standards that presented limits for the currents will be shortly analyzed. Those limits were proposed as guidance for designers that do not have information about the grid characteristics.

A. IEEE Std. 519-1992: Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems [4]

The limits for currents at this recommendation are presented in three tables, depending on the system voltage level and on the ratio between the grid short-circuit current capability and equipment maximal fundamental current. For voltage levels below 69 kV, the established limits are presented in Table 1:

TABLE 1
Current Distortion Limits for General Dist. Systems (120 V – 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<25	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed						
* All power generation equipment is limited to these values current distortion, regardless of actual I_{SC}/I_L						

As stated on the table, for generators the limits do not actually depend on the currents ratio. As a remark, Table 1 has been developed for 6 pulse rectifiers. Therefore, the limits may be increased in the case of converters operating with a higher number of pulses per period, which is the case of an inverter operating at a few kHz.

Though clearly stated that the voltage harmonic analysis should be done up to the 50th order, no order limit is actually proposed on this standard for harmonic current components.

B. VDEW - Guideline for connection and parallel operation of generators at the medium voltage grid [6].

The maximum allowed values for harmonic current components ($I_{v,\mu,allowed}$) can be obtained by multiplying the constants of Table 2 ($i_{v,\mu,allowed}$) by the short-circuit power at the connecting point (S_{kv}), as shown in (1):

$$I_{v,\mu,_{allowed}} = i_{v,\mu,zul} \cdot S_{kv} \quad (1)$$

Limits for other voltage levels can be directly calculated with the given values, knowing that those are inversely proportional to the voltage value.

Triple harmonic components and harmonics up to 25th order have their limits based on the ones of next given order (for example, the 9th harmonic order limit is equal to the 11th one), with the condition that produced zero-sequence currents are not inserted on the grid.

TABLE 2
Allowed rated Harmonic Currents

Harmonic Order ν, μ	Allowed rated Harmonic Currents $I_{v,\mu,zul}$ in A/MVA	
	10-kV-Grid	20-kV-Grid
5	0.115	0.058
7	0.082	0.041
11	0.052	0.026
13	0.038	0.019
17	0.022	0.011
19	0.018	0.009
23	0.012	0.006
25	0.010	0.005
>25 or Pairs	0.06/ν	0.03/ν
μ < 40	0.06/μ	0.03/μ
μ > 40*	0.18/μ	0.09/μ

* Integer and not integer within a Bandwidth of 200 Hz

The values presented on Table 2 were chosen in such a way to be valid with a grid inductive impedance under high frequencies; for example in overhead lines. Nevertheless, in grids with noticeable underground cable share, the grid impedance under higher frequencies (over 2000 Hz) is generally smaller in such a way that high frequency components can be neglected. A requirement for such a procedure is the calculation of either the voltage distortion or grid impedances along such harmonic orders at the connection point; keeping in mind that a limit of 0.2% for harmonic voltage components between 2000 and 9000 Hz may not be surpassed.

Since the frequency band from 2000 Hz to 9000 Hz was considered as being important to the characterization of frequency converters by this standard, it was interpreted that the harmonic analysis of the current should be made until this level of frequency.

C. EN 61400-21 Measurement and evaluation of the grid compatibility of grid-connected wind energy installations [7]

Similar to what was proposed by [4], voltage harmonic analysis is done up to the 50th order for integer harmonics and up to 2.5 kHz for inter-harmonics.

Nevertheless, the current standard considers that wind turbines connected to the grid via power converters operating with a switching frequency on the range of kHz will most likely produce harmonic components greater than the 50th order, but this range is still being analyzed by the IEC committee.

The limits assumed by this standard are in accordance with the standard IEC 61000-3-6 (Electromagnetic Compatibility – Limits Assessment of emission limits for distorting loads in MV and HV power systems – basic EMC publication)

In order to perform the harmonic analysis, values of the produced harmonic current components are used to calculate the percentage in relation with the rated current (that means, under nominal power, voltage and frequency conditions). Components with a value under 0.1% may not be considered.

The measurements and stated limits may be valid for both sides of the transformer (primary and secondary) – this means that if the system was approved for a certain level of voltage, it may be also in accordance if a transformer with another turns ratio is used.

Finally, another recommendation of this standard is that the short-circuit power may be at least 50 times greater than the maximum active power produced by the equipment.

III. REVISION ON FILTER TOPOLOGIES

In order to choose an optimal filter topology considering a NPC inverter for offshore wind turbines, parameters like efficiency, weight and volume have to be considered.

Regarding efficiency, filter topologies with reduced losses are required, though those are relatively small when compared to losses in the inverter. Weight and volume are considered as critical characteristics at offshore applications due to difficulties with transportation, installation and maintenance. The filter cost depends basically on the amount of components and materials used, for example the magnetic material for the core of inductors. Last, but certainly not least, the filter shall be able to perform its task within a certain degree of independence of the grid parameters, like resonance susceptibility and dynamic performance are of major importance.

As proposed in [8], filters connected to the output of an inverter have basically the following four-pole circuit configuration as seen in Fig. 3.

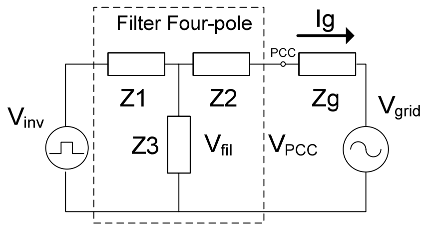

Fig. 3: Generic diagram of a three element filter.

A. L Filter

This topology (Z1 is finite, Z3 is infinite and Z2=0) consists on just an inductive filter connected in series with the converter. Although being the topology with the fewer number of components the system dynamics is poor due to the voltage drop across the inductor causing long time responses.

B. LC Filter

This topology (Z1 is finite, Z3 is finite and Z2=0) has Z3 as a result of association of a capacitor and an inductor. With higher values of capacitance, the inductance can be reduced, leading to reduction of losses and cost. Nevertheless, very high capacitance values are not recommended, since problems may arise with inrush currents, high capacitance current at the fundamental frequency, grid side resonance and dependence of the filter on grid impedance for overall harmonic attenuation.

C. LCL Filter

When compared with the previous topology, the LCL filter has the advantage of providing a better decoupling between filter and grid impedance (reducing the dependence on grid parameters) and a lower ripple current stress across the grid inductor (since the current ripple is reduced by the capacitor, the impedance at the grid side suffers less stress when compared with the LC topology).

Like the LC filter, increasing the capacitor value reduces filter cost and weight but with similar drawbacks. The split factor between the inductances at the inverter and grid side offers a further design flexibility.

D. Tuned Filter with LC Filter

An alternative to the above described topologies is the LC filter with a secondary branch tuned to the switching frequency and connected in parallel. An advantage is that the tuned filter needs to be set up to the harmonic current components only.

IV. LCL FILTER DESIGN

Though the LCL filter can sometimes cost more than other more simple topologies, its small dependence on the grid parameters is of major importance at high power applications, in order to guarantee a stable power quality level. Furthermore, it provides better attenuation than other filters with the same size and by having an inductive output; it is capable of limiting current inrush problems. This topology is, therefore, the one proposed for the NPC grid side inverter, and analyzed in this paper.

Considering that the future generation of offshore wind energy conversion system points towards turbines in the range of 7 to 10MW [9] the filter will be designed taking into account the following parameters for the grid and the inverter:

TABLE 3
Design Parameters

Grid Line Voltage	V_n = 1380 V
Grid Phase Voltage	V_{ph}=796.73 V
NPC DC-Link Voltage	V_{dc} = 2200 V
Output Power of the Inverter	P_n = 7 MW
Grid Frequency	f = 50 Hz
NPC Switching Frequency	f_{sw} = 2000 Hz

The nomenclature for the components is based on the schematic of Fig. 4:

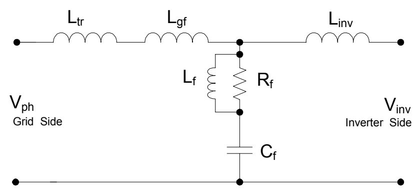

Fig. 4. LCL filter circuit with components nomenclature.

The first step is to design an inductor capable of limiting the ripple at the output current to 10% of the rated amplitude value. The ripple value of a periodic waveform refers to the difference between the instantaneous value of the waveform and its fundamental frequency. However, considering the switching nature of the inverter, it is still necessary to find an appropriate equation to calculate the filter inductance for this particular inverter topology.

For the filter inductance design, the NPC inverter can be modelled at the switching frequency as one half wave buck converter with the condition that the NPC neutral point is connected to the Y (star) point of the grid, and the grid is modelled as a half sinusoidal waveform voltage, as shown in Fig. 6. If the neutral point is not connected to the star point, the common-mode voltage needs to be taken into account and the calculation becomes more complex.

For simplicity reasons, (2), [11], shall be used for both cases:

$$L_{inv} = \frac{\frac{V_{dc}}{2} - V_{ph}}{2 \cdot \Delta I_L} \cdot \frac{D}{f_{sw}} \tag{2}$$

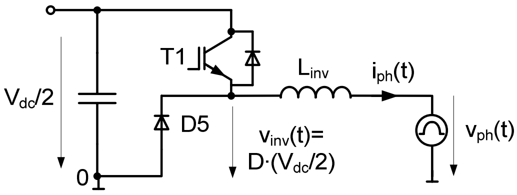

Fig. 5. NPC simplified circuit.

The phase current ripple as a function of time is depicted in Fig. 6, providing a duty-cycle function $D(t) \approx M\cos(\omega t)$, with a modulation index M=1.

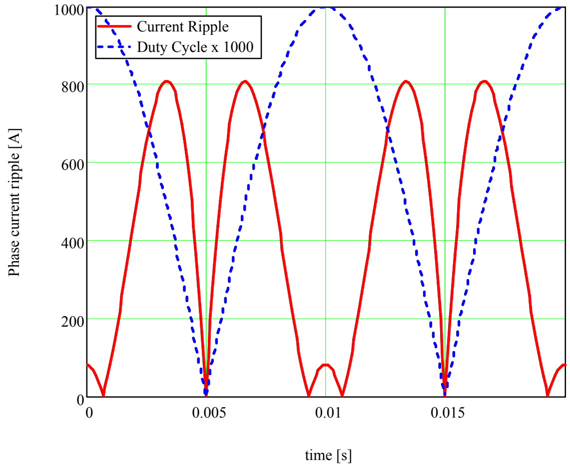

Fig. 6. Phase current ripple (peak-to-peak) for L_{inv}=166uH, f_{sw}= 2kHz, V_{ph}=796V, P=7MW and corresponded duty-cycle value multiplied by 1000.

The current ripple at the output of a dc-dc converter is the largest for a duty cycle of 50%. Therefore:

$$L_{inv} = \frac{\frac{V_{dc}}{2} - \frac{V_{dc}}{4}}{2 \cdot \Delta I_{L\max}} \cdot \frac{1}{2 \cdot f_{sw}} = \frac{V_{dc}}{16 \cdot f_{sw} \cdot \Delta I_{L\max}} \tag{3}$$

A 10% ripple of the rated current for the design parameters presented in Table 3 is given by (4).

$$\Delta I_{L\max} = 0.10 \cdot \frac{P_n \cdot \sqrt{2}}{3 \cdot V_{ph}} = 414.165A \tag{4}$$

The value of the inverter side inductance (L_{inv}) using (3) and (4) is 166 μH or 0.192 pu.

For the design of the filter capacitance, it is considered that the maximum power factor variation seen by the grid is 5%, as it is multiplied by the value of base impedance of the system in (5).

$$C_f = 0.05 \cdot C_b = 585\mu F = 20pu \tag{5}$$

It is important to notice that factors higher than 5% can be used, since they will compensate the inductive reactance of the inductors on the filter and therefore the influence at the power factor of the system will be lesser than expected. In addition, the greater the capacitance, the smaller is the inductor [9]. Nevertheless, if too large capacitors are used, the ripple on the inductor current will tend to increase [10].

As stated in [14], the main objective of this LCL filter design is in fact to reduce the expected 10% current ripple limit to 20% of its own value, resulting in a ripple value of 2% of the output current. In order to calculate the ripple reduction, the LCL filter equivalent circuit is firstly analyzed considering the inverter as a current source for each harmonic frequency, as seen in Fig. 7.

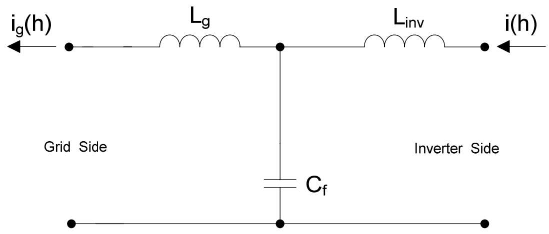

Fig. 7. Simplified LCL Filter scheme at h^{th} order harmonic component.

Equation (6) gives the relation between the harmonic current generated by the inverter and the one injected in the grid (respectively i(h) and ig(h)).

$$\frac{i_g(h)}{i(h_{sw})} \approx \frac{z^2_{LC}}{\left|w^2_{res} - w^2_{sw}\right|} \tag{6}$$

Equation (6) is a ratio between the filter impedance and the difference between resonant frequency and switching frequency (that will be later calculated). Simplifying this equation using the already developed relations for the inductance at the inverter side, results in (7) that represents the ripple attenuation factor:

$$\frac{i_g(h)}{i(h_{sw})} = \frac{1}{\left|1 + r \cdot [1 - (L \cdot Cb \cdot w^2_{sw}) \cdot x]\right|} \tag{7}$$

The constant r is defined as the relation between the inductance at the inverter side and the one at the grid side:

$$L_g = r \cdot L_{inv} \tag{8}$$

The value of r for a desired ripple attenuation can be obtained from the Fig. 8.

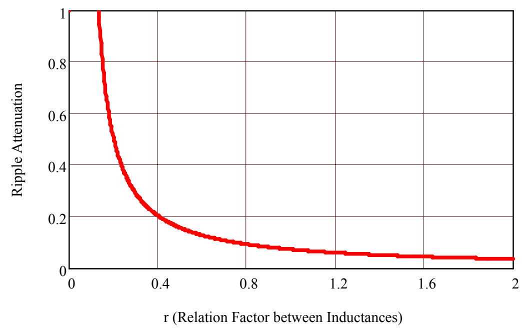

Fig. 8. Ripple attenuation as a function of the relation factor between inductances.

The calculated grid side inductance value is 69.8μH. Since the inverter will be connected to the grid via a power transformer, the transformer leakage inductance shall be considered as part of L_g.

A. Design Optimization Potential

By providing different ripple attenuation factors between the inductances at the inverter and grid side, it is possible to optimize the size of the total inductance. This is particularly interesting in order to reduce the voltage drop across the inductors and therefore avoid the use of high values for the modulation index. In Fig. 9 is presented the plot of the total necessary inductance as a function of the admitted ripple at the inverter side inductor. Nevertheless, the optimization was not carried out due to the necessity of physical design considerations, which are out of the scope of this publication.

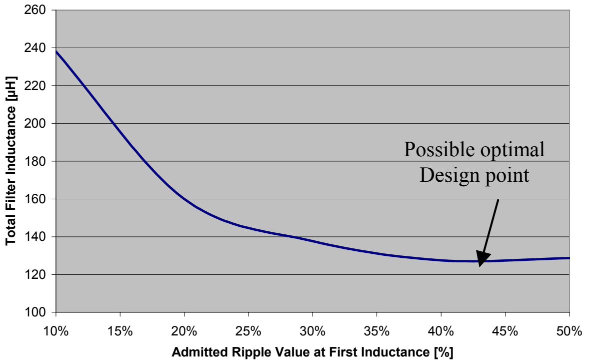

Fig. 9: Total inductance of the filter as a function of the admitted current ripple at first inductance.

B. Damping Branch

The attenuation mentioned above is only effective after considering a damping factor. This is necessary since the transfer function of the filter presents some peaks that may in fact increase the ripple at particular resonant frequencies with the grid impedance.

Instead of using active damping, which would make the control of the inverter more complex, the choice was made for passive damping. A resistance added in series with the capacitor attenuates part of the ripple on the switching frequency in order to avoid the resonance. The value of this resistor should be one third of the impedance of the filter capacitor at the resonant frequency (calculated by (10)).

$$w_{res} = \sqrt{\frac{L_{inv} + L_{gf}}{L_{inv} \cdot L_g \cdot C_f}} = 5144 rad/s \qquad (9)$$

The resistor in series with the filter capacitance is:

$$R_f = \frac{1}{3 \cdot w_{res} \cdot C_f} = 0.111\Omega = 0.408 pu \qquad (10)$$

The resistor losses, rated at 9.4 kW for this given system design (or 0.134% for the inverter operating at nominal power), can be reduced if the resistor value is increased, but with the drawback of reducing the damping effectiveness.

A technique to reduce the filter losses and keeping the damping performance of the filter is proposed in [9]. It consists of adding an inductor in parallel with the damping resistor. The inductor is designed to have an impedance value smaller than the resistor impedance for operation below the resonant frequency (f_{res}). The value of the inductance in parallel with the resistor is determined by (11).

$$L_f = \frac{Rf}{2 \cdot \pi \cdot f_{res}} \approx 22\mu H = 0.025 pu \qquad (11)$$

A value of 25µH is adopted considering the possible presence of further inductive components caused by the cables that may increase the value of the resonant frequency. The resistance of the windings was neglected. With this inductance, the expected losses on the resistances of the three phases were reduced to 1.9 kW or 0.027% of the inverter rated power, without noticeable prejudice to the damping effectiveness of the filter.

V. SIMULATION RESULTS

Fig. 10 and 11 depict the simulated output current waveforms of the NPC filter with a L filter and with the designed LCL filter.

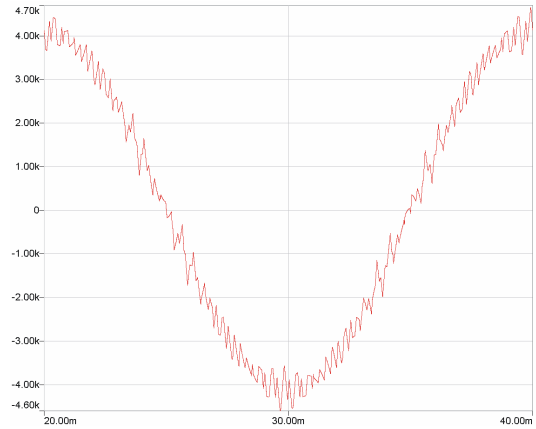

Fig. 10. Output current waveform with L filter [A/ms].

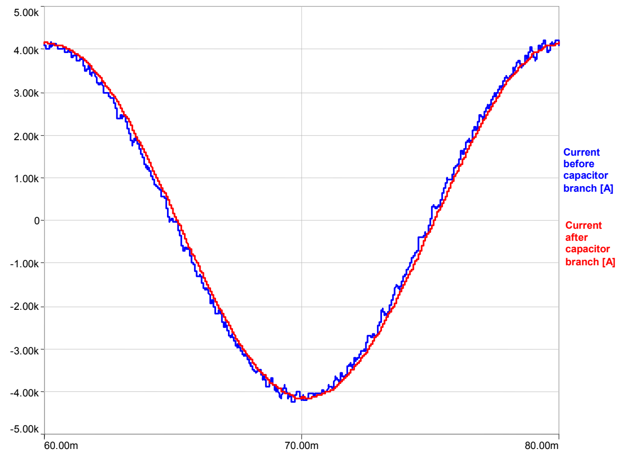

Fig. 11. Output current waveform with LCL filter before and after filter capacitor branch [A/ms].

The performance of the LCL filter design was analyzed using an Excel application that, by receiving the FFT of the output current calculated by Simplorer®, generated the recommended limits based on the standards [1] and [3] for specific system parameters, as illustrated in Fig. 12 and 13.

As a remark, since the frequency band from 2000 Hz to 9000 Hz was considered as being important to the characterization of frequency converters [3], it was interpreted that the harmonic analysis of the current should be made up to this level of frequency, though it is of common sense that the voltage distortions shall be analyzed up to the 50th order. Additionally, according to the recommendations of [11], harmonic components smaller than 0.1% of the fundamental were neglected.

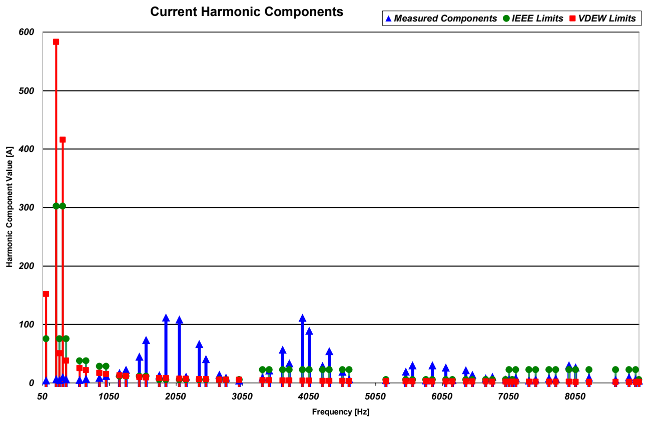

Fig. 12. Harmonic spectrum of the output current and corresponding recommended limits for the simulations with L filter.

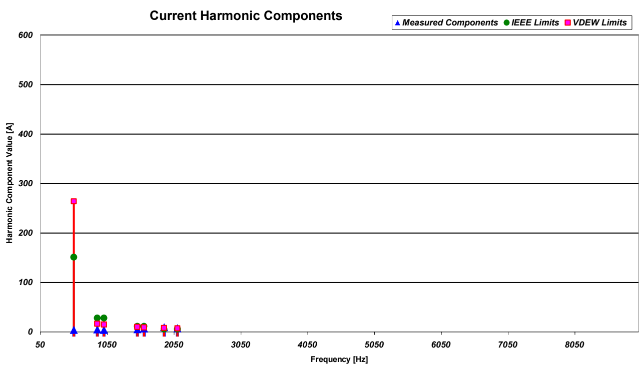

Fig. 13. Harmonic spectrum of the output current and correspondent recommended limits for the simulations with filter.

It was noticeable that the produced harmonics were mostly concentrated around the so-called "characteristic harmonic orders" [1]. After the application of the filter, most of the components were eliminated, though further improvement can be achieved by optimizing control parameters.

VI. CONCLUSIONS

This paper proposed the design and application of a LCL filter aiming to enhance the grid compatibility of a high power Wind Turbine connected to the utility grid via a NPC inverter. In order to evaluate the filter effectiveness, the power quality of the inverter was analyzed through the output currents, using procedures in accordance with the VDEW Standard and IEEE Recommendation.

At the end, the LCL filter topology showed as main advantages: the design flexibility, which allows further optimization; reduced size in comparison to other topologies and finally good capability of operation in a wide range of frequency and voltage.

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