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Control of an Active Filter Based Three-Level Grid Connected Converter for Wind Turbine Applications

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Abstract.

This paper presents a control design and implementation analysis of a three level grid connected converter to be deployed in large scale wind turbine applications, which main purpose is to obtain enhanced grid interaction by limiting its harmonic injection capability. The implementation of advanced power converter control in high power converters allows the proposed wind turbine system to provide active and reactive power supply while performing active filter functionalities for the 5th and 7th harmonic current components. Finally, the performance of the system is verified under several practical study cases by performing a laboratory analysis of the obtained results.

Key words

Wind Power Generation, Active Filter, Power Quality

1. Introduction

In the recent decade, a considerable move towards renewable energy utilization is taking place. This trend is mainly motivated due to the negative environmental impacts associated with fossil fuels. Additionally, renewable energies emerge as a suitable solution in ensuring energy diversification while improving the security of supply [1]. In this context, wind energy arises as the leading technology, which has experienced the major installed power capacity among renewables in the past years [2]. The recently achieved high penetration levels of wind energy into the electrical networks lead to an increased concern regarding the power quality of supply, which is mainly affected due to the inherent stochastic variability of the wind resource. As wind power plants (WPPs) will tend to increase considerably its capacity, the impact of the perturbations introduced by such power plants into the network cannot longer be avoided and need to be limited. As a result, the TSO reinforced their grid connection demands, and required that wind farms should behave as any other conventional power plant. In order to achieve these power plant characteristics and to overcome several of these grid code requirements, power electronic converters play an important role by providing active control capabilities and improving the grid interaction of wind power plants. Power converters are able to provide several advantageous functionalities, which usually increase the electrical performance in wind turbine applications. However, as a main drawback, the use of power electronic converters generates harmonic currents which will be injected to the grid. Finally, it is worth noting that in wind power plants a large number of high power converters are usually used, therefore each wind turbine unit output power provides a high level of harmonics. By applying an active filter solution output harmonics can be alleviated in order to accomplish with the required power quality standards [3-4].

2. Proposed Study Case Modelling

The main configuration of the study system consists of a grid side three-level converter installed in a wind turbine, which in addition of providing rated power supply, is able to contribute with active filter functionalities for 5th and 7th harmonics. The system description is proposed in Fig. 1, where the NPC converter and filter are highlighted. It is worth to mention that the main objective of this work relies on the implementation of an advanced control strategy for these type of applications.
Since WPPs are prone to be structured around high power wind turbine units, the system under study has been considered for high power applications, i.e. it is characterized by the use of reduced switching frequency. Therefore, the use of three-level converters appears as a requisite in case of high control performance is desired for 5^{th} and 7^{th} harmonic current injection. As a result,

reduced filter dimensions will be achieved, as reduced THD and dv/dt characteristics are obtained [5].

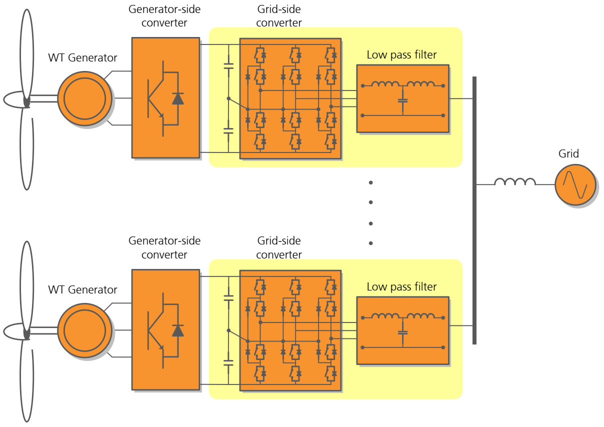


Fig. 1. Entire system description of the system under study

Taking [6] into consideration, the used switching frequency for a two-level converter should be at least ten times bigger than the highest harmonic bandwidth that has to be controlled. Due to the fact that the necessary switching frequency for controlling a certain harmonic bandwidth in three-level converters is lower than in the two-level case, the starting point in determining the switching frequency was selected to be 3.5kHz ($10\times f_{7th}$).By testing the system performance it has been observed that the minimum switching frequency required, in order to achieve high controllability in 7th harmonic voltage compensation, is 3kHz.

In order to obtain the desired converter behavior, a suitable set of duty-cycles has to be provided to the IGBTs by using SVM technique. Due to the fact that the system performance will be validated with a laboratory prototype, a smaller scale converter of 20kW, which is connected to a 400V electrical network, has been considered. Additionally, it has been assumed that the converter is connected to a step up transformer. Regarding the LCL filter design, Fig. 2 shows the single phase representation while its transfer function is given in (1). Furthermore, the frequency response of this filter is depicted in Fig. 3 in case the filter parameters from Table I are considered.

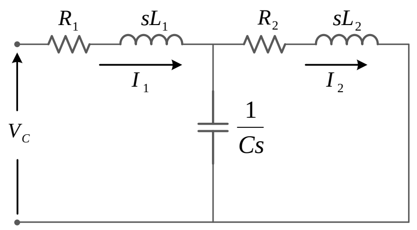


Fig. 2. Single phase representation of the LCL filter

$$F_{LCL}=\frac{I_g(s)}{V_c(s)}=\frac{K}{s^3+\lambda_2 s^2+\lambda_1 s+\lambda_0} \qquad (1)$$

$$K=\frac{R_f}{L_c C_f R_f L_g}$$

$$\lambda_2=\frac{C_f R_f R_g L_c + C_f R_f R_c L_g + L_c L_g}{L_c L_g C_f R_f}$$

$$\lambda_1=\frac{R_c R_g C_f R_f + R_g L_c + R_c L_g + R_f L_c + R_f L_g}{L_c L_g C_f R_f}$$

$$\lambda_0=\frac{R_c R_g + R_c R_f + R_g R_f}{L_c L_g C_f R_f}$$

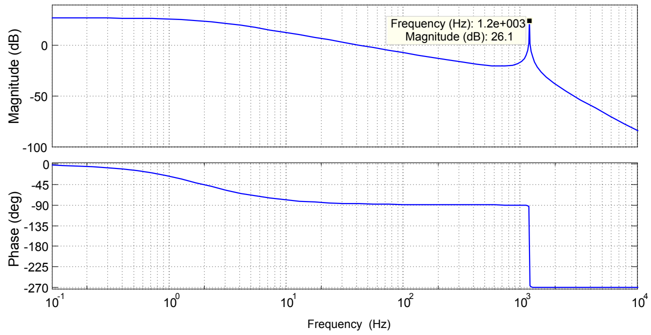


Fig. 3. Frequency response of the proposed LCL filter

Table I LCL grid filter parameters

Filter parameters	
$L_c=1.44mH$	$R_c=20m\Omega$
$L_g=2.24mH$	$R_g=25m\Omega$
$C_f=20\mu F$	

From Fig. 3 it can be noted that the filter resonance was carefully placed at 1.2 kHz. In this manner, it does not interfere with the controller bandwidth while ensuring sufficient harmonic attenuation. Additionally any characteristic harmonic frequency is being stimulated by the filter resonance.

3. Control Strategy Implementation

A control implementation of a grid connected three-level converter which is able to perform as an Active Filter for achieving 5th and 7th harmonics voltage mitigation is introduced. The main contribution of this paper relies on the implementation of active filter functionalities directly integrated in a wind turbine unit. In this way, active and reactive power is injected into the grid while providing harmonic compensation for the 5th and 7th harmonic frequencies. This harmonic mitigation of the WT output voltage will be achieved by means of injection reactive currents to the grid. It is worth noting that the main functionality of the WT is to provide rated power supply. However, in case this is not possible due to lower wind conditions, the proposed system will be able to contribute towards the harmonic attenuation of the generated output voltage. Fig. 4 introduces the proposed control strategy which is based on the implementation of three independent resonant controllers. Each of them will be in charge of providing selective current control for the fundamental, 5^{th} and 7^{th} harmonic frequencies [7-8]. Therefore, 5^{th} and 7^{th} harmonic voltages can be reduced by providing reactive current injection. The control system from Fig. 4 shows that suitable converter voltage references will be provided by measuring grid voltages and currents (V_{g_abc} and I_{g_abc}). In addition, it is worth to note that the 5^{th} and 7^{th} harmonic voltages will be obtained by implementing an M-SOGI grid synchronization technique [9]. In this manner, the magnitude of the 5^{th} and 7^{th} output harmonic voltages can be instantaneously monitored while simultaneously providing the required frequency component for each of the resonant controllers.

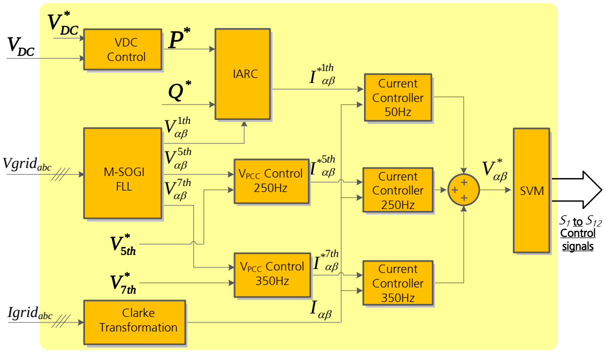


Fig. 4. Proposed control strategy structure

Finally, the current references for the 5th and 7th harmonic frequency components will be determined by using droop controllers. As a result, the proposed system will provide as much harmonic voltage compensation as possible according to a specified droop characteristic.

4. Current Controllers Design

The proposed current control algorithm has been designed in discrete time since the control structure is later implemented in the laboratory setup by using a digital processor. In order to achieve the desired behavior of the current control system, proportional plus resonant controllers are used, since, they offer an accurate and selective control by providing infinite gain for the desired resonant frequencies. In (2) the transfer function of the implemented control structure is introduced.

$$C_{P+RES}(s) = K_p + \frac{K_i s}{s^2 + \omega_g^2} \qquad (2)$$

By considering that a pole in continuous time domain is placed in discrete time as $z = exp(s\Delta t)$, the pole from equation (2) placed at $s = \pm j\omega_g$ is mapped in z-domain as described in (3). The final discrete transfer function of the controller is given in (4).

$$s = \pm j\omega \Rightarrow z = e^{(\pm j\omega_g \Delta t)} = \cos(\omega_g \Delta t) \pm j\sin(\omega_g \Delta t) \qquad (3)$$

$$C_{P+RES}(z) = K\frac{z^2 + \alpha_1 z + \alpha_2}{z^2 - 2\cos(\omega_g \Delta t)z + 1} \qquad (4)$$

Where K and the zeros of the controller transfer function are the design parameters, and Δt is the sampling period. Current controllers for fundamental, 5th and 7th harmonic frequencies are required as the purpose of this control structure deals with the implementation of a grid connected converter which is able to provide rated power delivery and to provide harmonic compensation for 5th and 7th harmonics. As a result, a power quality improvement will be achieved by independently controlling the injection of non-active currents into the grid. Finally, each of the implemented controllers is tuned individually in order to fulfill the required specifications for the different compensation frequencies. Therefore, the design parameters obtained for controlling 50Hz, 250Hz and 350Hz are described in the following subsections.

A. 50Hz Current Controller Design

In the study case, the design specifications are based on obtaining a very selective control for 50Hz and a settling time smaller than 20ms, as the grid codes require that in case of severe grid voltage variations rated reactive power has to be injected in less than one fundamental frequency period [10]. Then special attention is given in order to fulfill these two requirements. Thus, the obtained design parameters for the 50Hz current controller are given in the transfer function introduced in (5).

$$C[z] = 2.1704\frac{z^2 - 1.8875z + 0.8904}{z^2 - 1.9973z + 1} \qquad (5)$$

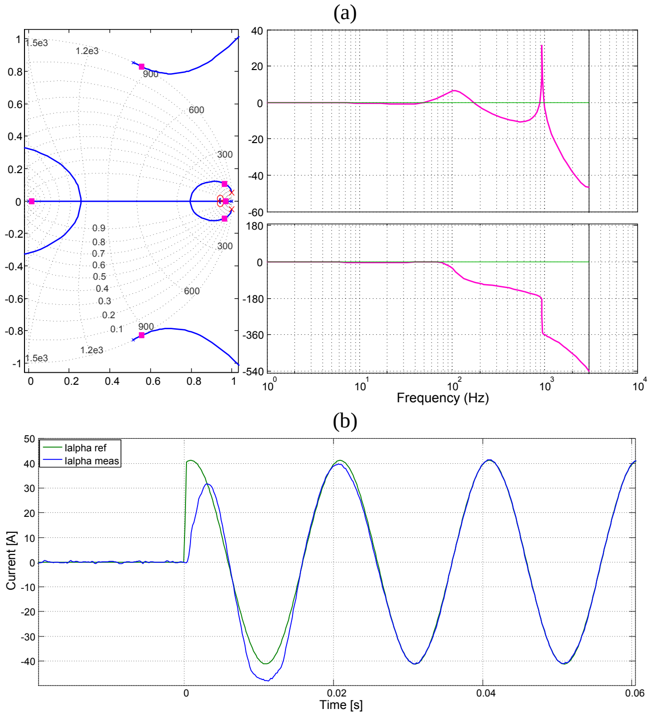


Fig. 5. (a) Root-locus and closed loop bode response for 50Hz current control design parameters. (b) Current alpha reference and measured obtained in the experimental results

From Fig. 5, it can be deducted that the system is stable, as all the closed loop zeros and poles are placed within the unity circle, and that the bandwidth of the system is around 60Hz. Therefore it can be stated that 50Hz AC signals will be selectively controlled by using the proposed resonant current controller. From Fig. 5(b), it can be noted that the fundamental current injection achieves the desired reference setpoint after 20ms.

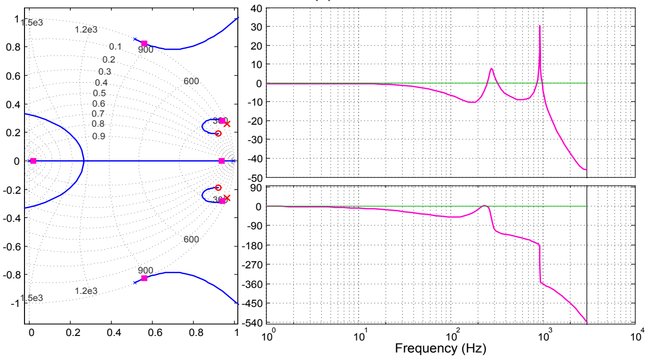
B. 250Hz Current Controller Design

The only noticeable difference introduced in this case is that the tuning frequency of the resonant controller corresponds to 250Hz. Then, as it was presented in the previous section, the gain and the zeros of the controller have to be determined in order to obtain the desired system dynamics. The design specifications in this case

are mainly based on obtaining a very selective control, since a minimum settling time for the injection of 5th harmonic currents is not required by the grid codes.
As a result 250Hz AC currents can be controlled without affecting other frequency signals. Equation (6) shows the proposed current controller design parameters.

$$C[z] = 3.2007\frac{z^2 - 1.3283z + 0.6380}{z^2 - 1.9318z + 1} \qquad (6)$$

(a)



(b)

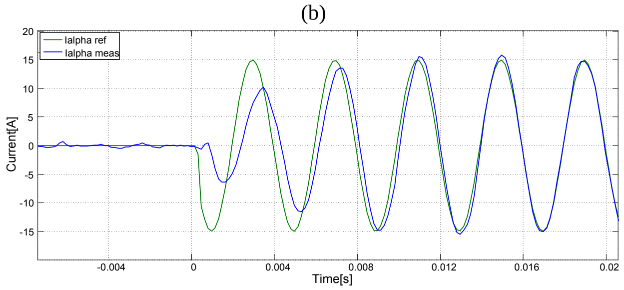


Fig. 6(a) Root-locus and closed loop bode response for 250Hz current control design parameters. (b) Current alpha reference and measured obtained in the experimental results

According to Fig. 6, it can be stated that the system is stable, as the closed loop poles and zeros are placed in the unity circle (root-locus) and that a selective control will be achieved for 250Hz control signals (closed-loop bode response). The design specifications in this case are mainly based on obtaining a very selective control, since a minimum settling time for the injection of 5th harmonic currents is not required by the grid codes. As a result 250Hz AC currents can be controlled without affecting other frequency signals.

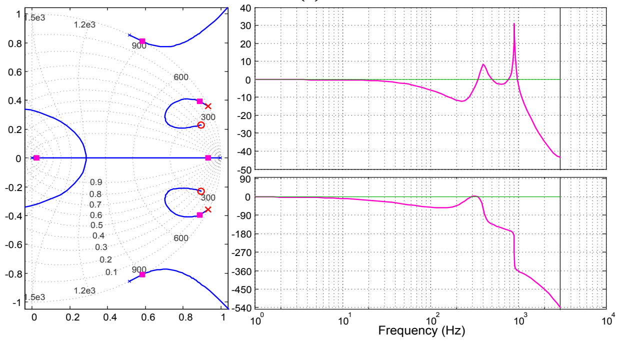
C. 250Hz Current Controller Design

In this case, similar design specifications as in the case of 5th harmonic controller are required. Thus, the controller should perform a selective control for 7th harmonic currents in order not to influence the control of other current frequency signals. Then the design specifications are mainly based on obtaining a very selective control, since a minimum settling time for the injection of 7th harmonic currents is not required by the grid codes.
Equation (7) introduces the tuning parameters of the 350Hz resonant controller.

$$C[z] = 3.2007\frac{z^2 - 1.7892z + 0.8532}{z^2 - 1.8671z + 1} \qquad (7)$$

Fig. 7 shows that the system is stable and selective for 350 Hz signals, by using the root-locus and closed loop bode diagram respectively.

(a)



(b)

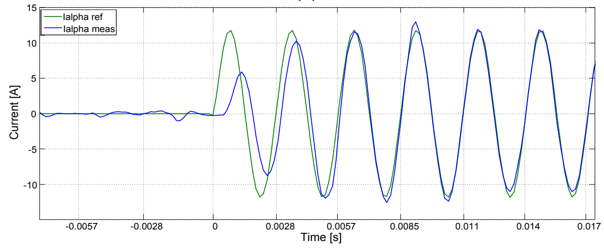


Fig. 7(a) Root-locus and closed loop bode response for 350Hz current control design parameters. (b) Current alpha reference and measured obtained in the experimental results

As a final conclusion, it can be stated that each of the controllers have been properly designed, as their response was tested in the laboratory with successful results. It is worth to mention that all three controllers are able to work simultaneously, without interfering between them.

5. Experimental Results

The laboratory setup consists of a 20 kW DNPC converter connected to a grid simulator through a LCL filter. The purpose of the grid connected converter is to instantaneously inject the required amount of compensation non-active currents in order to provide maximum PCC voltage quality according to the rated parameters of the system. Furthermore, the voltage distortion introduced by the wind turbine (5th and 7th harmonics) is provided to the PCC by using a California Instruments grid simulator. In this way the described system functionalities can be tested. Finally the desired system controllability is achieved by implementing the designed control algorithm using a dSPACE 1006 which includes a DS5101 FPGA board. The laboratory setup schematic is given in Fig. 8.

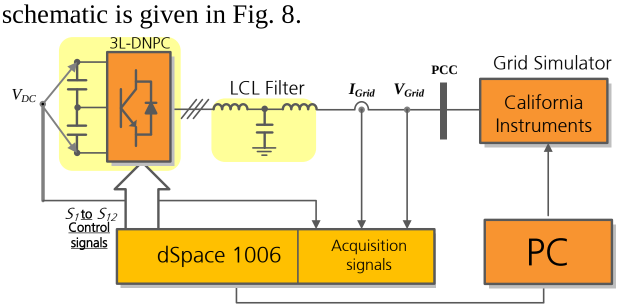


Fig. 8 Laboratory setup schematic

Two main study cases are introduced as follows, in which the proposed system is performing the two possible functionalities described in this paper: rated power supply and active filter operation.

A. WT Rated Power Supply

In the present study case, the controller performance has been tested in case the wind turbine unit is supplying rated power to the grid. In this case the rated current is injected to the grid and no harmonic compensation is achieved. Fig. 9(a) introduces the active/reactive power measurements and its reference setpoints, while Fig. 9(b) shows the grid injection/absorption of the rated currents.

(a)

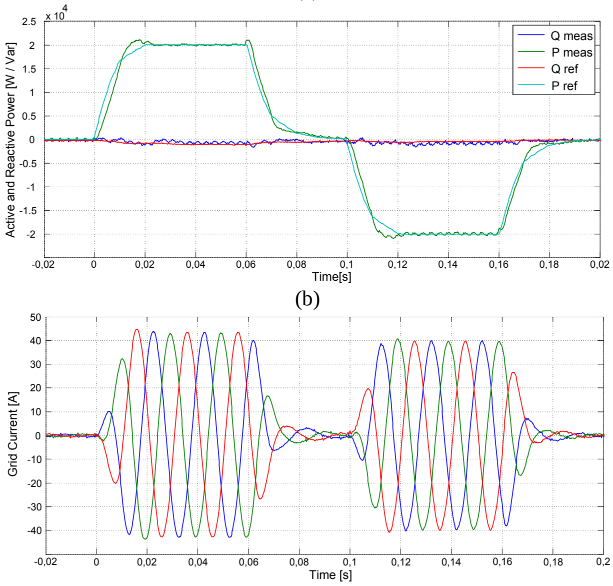


Fig. 9 (a) Active and Reactive Power Measured and References, (c)Measured Grid Currents

From Fig. 9(a) it can be observed that the proposed wind turbine controller achieves rated power injection within 20ms, as the German EON Netz grid connection codes require [10].

B. WT 5th and 7th Harmonic Voltage Compensation Active Filter Functionality

In case the active filter functionality is analyzed, the wind turbine unit main effort is focussed in providing PCC voltage grid harmonic compensation for 5th and 7th harmonics. This situation would be characterized for the case in which the wind turbine is providing zero power exchange with the grid due to reduced or adverse wind conditions (wind turbine disconnection).

This scenario is analyzed by providing external harmonic PCC voltage distortion from the California Instruments grid simulator. In Fig. 10(a) it can be observed that in the period of time before 0 seconds a severe harmonic pollution is present at the grid connection terminals. In Fig.10(b) it can be recognized that before harmonic compensation the harmonic levels of the PCC reach approximately 8% of the fundamental voltage for both 5th and 7th harmonic components. After the active filter functionality is enabled (after t = 0 seconds) the wind turbine provides maximum harmonic voltage compensation by absorbing rated reactive currents for 5th and 7th harmonics (Fig.10 (c-d)). In this case, the wind turbine achieves a voltage harmonic mitigation of approximately 2 and 3% for both 5th and 7th harmonics (Fig.10(b)). From [11] it can be identified that the maximum allowed voltage harmonic distortion must stay within 6% and 5% for 5th and 7th harmonics frequencies respectively. Therefore, the grid connection of the proposed wind turbine application would achieve grid connection compliance by implementing the presented converter control strategy.

(a)

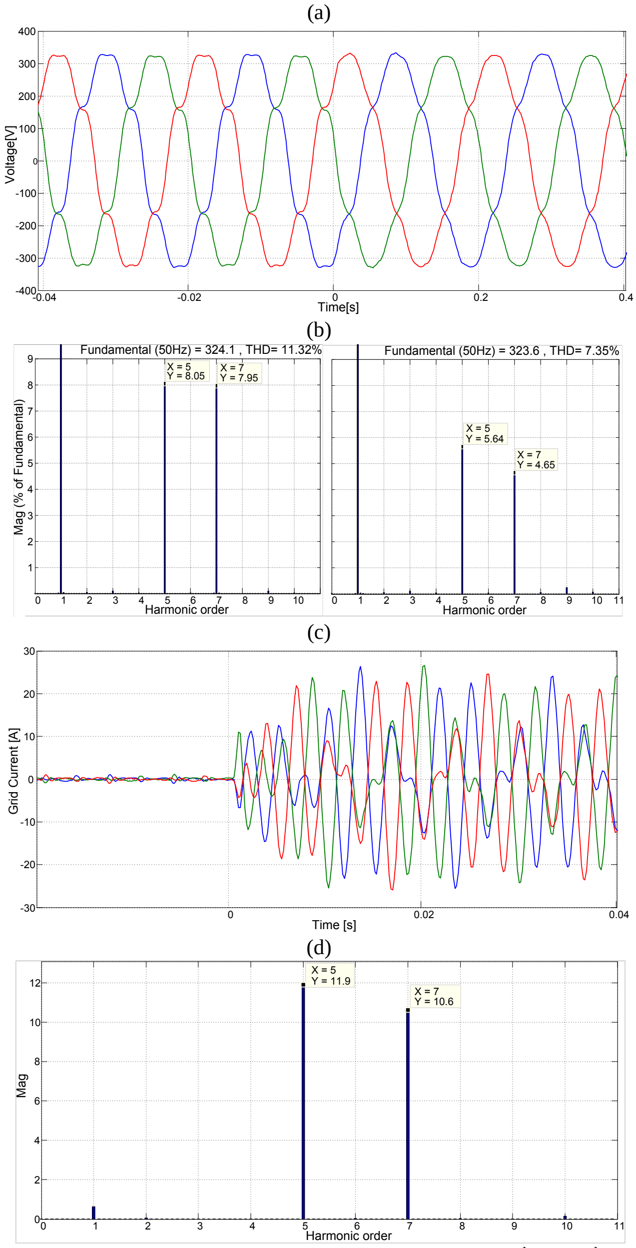


Fig. 10 Active Filter operation mode when rated 5th and 7th harmonic currents are compensated at t = 0 seconds. (a)Measured voltage at the PCC, (b)FFT analysis of the PCC measured voltages before and after current harmonics compensation, (c)Measured Grid Currents, (d)FFT analysis of the measured grid current,

6. Conclusions

This paper introduced an advanced grid converter control design intended for deployment in high power wind turbine applications. The system under consideration has been introduced, which is based on the grid connection of a three-level DNPC converter through an LCL filter. The main purpose of the advanced converter control application is to provide enhanced grid connection interaction by providing 5^{th} and 7^{th} PCC voltage harmonic mitigation. In this way, the wind turbine operation modes have been described. The main functionality consists in providing rated power supply in case of suitable wind power conditions. However, in case the rated power cannot be supplied to the grid, the wind turbine unit will improve the power quality delivered by performing harmonic voltage mitigation.

In order to achieve these wind turbine functionalities, resonant controllers were implemented for fundamental, 5^{th} and 7^{th} harmonic frequencies in order to achieve accurate current control capability. Finally the laboratory results were validating the proposed control design, since both main operation modes were successfully achieved.

Acknowledgement

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References

[1] IEA (2012). “Renewable Energy medium term market report 2012”

[2] European Wind Energy Association, "Pure Power. Wind Energy Targets from 2020 and 2030," 2011.

[3] T. Ackermann, *Wind Power in Power Systems* .Royal Institute of Technology Stockholm, Sweden.

[4] Muljadi, E.; Butterfield, C.P.; Chacon, J.; Romanowitz, H.; , "Power quality aspects in a wind power plant," *Power Engineering Society General Meeting, 2006.*

[5] Akagi, H.; , "Active Harmonic Filters," *Proceedings of the IEEE* , vol.93, no.12, pp.2128-2141, Dec. 2005 doi: 10.1109/JPROC.2005.859603

[6] B. Wu, *High Power Converters and AC Drives*. John Wiley and Sons, 2006.

[7] Liserre, M.; Teodorescu, R.; Blaabjerg, F.; , "Multiple harmonics control for three-phase grid converter systems with the use of PI-RES current controller in a rotating frame," *Power Electronics, IEEE Transactions on* , vol.21, no.3, pp.836-841, May 2006

[8] Blaabjerg, F.; Teodorescu, R.; Liserre, M.; Timbus, A.V, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," *Industrial Electronics, IEEE Transactions on* , vol.53, no.5, pp.1398-1409, Oct. 2006

[9] Rodriguez, P.; Luna, A.; Candela, I.; Teodorescu, R.; Blaabjerg, F.; , "Grid synchronization of power converters using multiple second order generalized integrators," *Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE* , vol., no., pp.755-760, 10-13 Nov. 2008

[10] “Requirements for Offshore Grid Connections in the E.ON Netz Network”.E.ON,2008

[11] EN 50160 “Voltage characteristics of electricity supplied by public electricity networks”, 2010