Three-Level Three-Phase Neutral-Point-Clamped Back-to-Back Converter Applied to a Wind Emulator

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«Multilevel converters», «Wind Energy», «Three-phase systems».

Abstract

This paper presents a three-level three-phase neutral-point-clamped back-to-back converter applied to a wind emulator, where a wind power generator is connected to the grid through the back-to-back converter. The converter regulates the power extracted from the generator and controls how this power is injected to the grid with the desired power factor. Two phase locked loops are in charge of synchronizing the generator-side and the grid-side converters, regardless of the rotor speed of the generator. DC-link neutral point voltage balance is performed by the modulation strategy of the back-to-back converter. Simulation and experimental results are provided to verify the correct performance of the system.

Introduction

Nowadays, renewable energy systems are undergoing an important development. Among them wind energy stands out for its installed capacity, power generation and steady growth [1] - [3].

Due to the expected rated power growth of the wind turbines [4], the high power converter topologies acquire an increasing interest. Multilevel converters are particularly interesting for power values above 2-3 MW. Among the different multilevel converters topologies [5] the three-level neutral-point-clamped (NPC) converter [6] is the most widely used.

The three-level NPC converter adds some improvements over the standard two level converters, most commonly used in wind energy applications. One of them is that the power devices and the DC-link capacitors have to stand only one half of the DC-link voltage, so the converter can deal with double voltage and power values. Another one is that the output voltage spectrum obtained is better than the one from the standard two-level converter, which allows the reduction of the reactive components, such as the inductors used for a grid-connected converter.

The drawbacks of this topology are the higher number of power devices, which adds complexity to the modulation scheme, and the need to keep balanced the DC-link neutral point voltage balance. In this paper, the switching strategy [7], [8] allows the control of the two converters in a back-to-back connection and solves the problem of voltage balancing.

A back-to-back converter (Fig. 1) provides an indirect AC-DC-AC connection, required in variable speed windmills in order to make independent the rotational speed of the blades and the frequency of the load connected. This connection gives some advantages: voltage and frequency (if needed) control of the local grid, improvement of the power quality and better integration of wind energy to the electrical grid, both on steady-state or under transient operation.

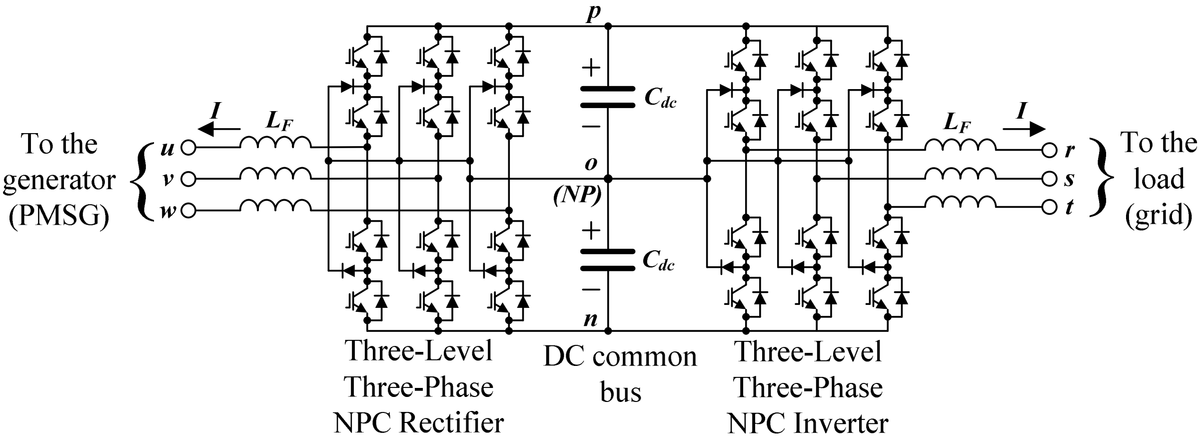

Fig. 1: Three-level three-phase back-to-back converter.

The paper is organized as follows. First, an overview of the wind emulator replacing the windmill is presented. Next, the control scheme of the two three-level NPC converters is explained. Finally, simulation and experimental results are presented to validate the system.

The wind emulator

In a University research context, there is frequently no access to an installation with a wind generator for investigation purposes. To solve this problem a wind emulator was implemented.

The emulator presented here basically consists in a commercial motor drive system (Siemens Simovert Masterdrive MC) that controls a permanent magnet synchronous motor (PMSM), whose purpose is to transmit a mechanical torque, similar to the one the wind applies to the windmill blades axis. This hardware allows the control of the rotational speed or the torque that the PMSM can develop.

The generator connected to a wind turbine can be of a synchronous or an asynchronous type. Therefore, in order to have a flexible installation, both types are installed along the shaft that supports the machines of the emulator (as shown on Fig. 2), allowing to choose between them in the setup.

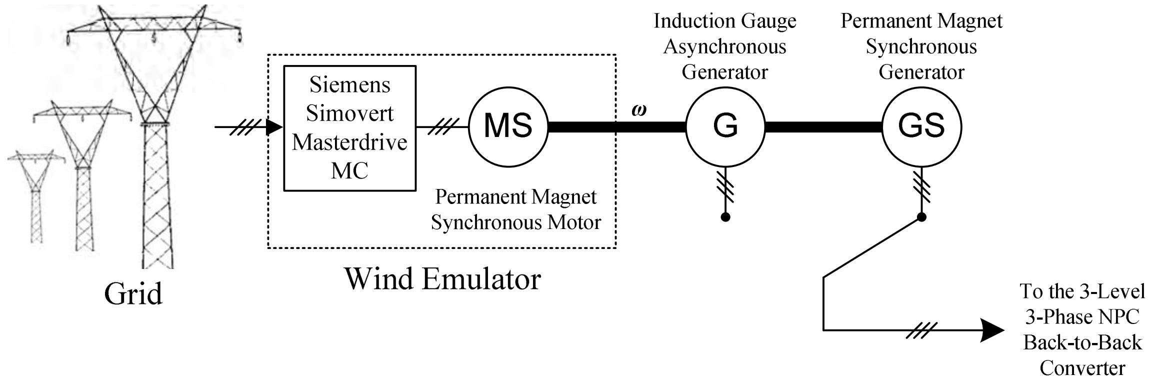

Fig. 2: Wind emulator and the two installed generators.

The experimental results shown on this paper have been obtained extracting power from a permanent magnet synchronous generator (PMSG) and controlling the PMSM to provide a constant rotational speed in the shaft connecting the PMSM and the PMSG.

Control of the converters

The key point of the system (Fig. 3) is the modulation and control of the two three-level three-phase NPC converters of the back-to-back. The goals for the control and modulation of the back-to-back NPC converter are: To extract the power from the generator, to deliver the power to the grid with unity power factor, the synchronization of the converters with the generator and the grid voltages, and to keep balanced the dc-link capacitor voltages.

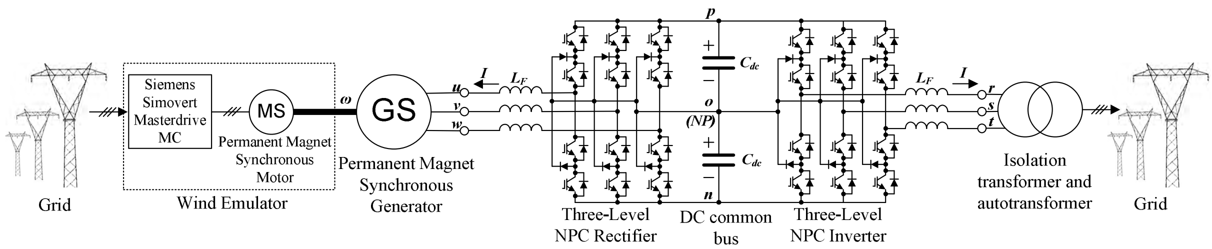

Fig. 3: General diagram of the whole system connected to the grid.

Both the control scheme (Fig. 4) and the modulation strategy ([7] and [8]) to meet the above mentioned goals have been programmed with MATLAB-Simulink and executed in a dSPACE DSP PC-embedded board (DS1103).

The voltages and currents for control and modulation purposes are acquired from the corresponding sensors placed in the two three-level NPC converters and driven to the analog inputs available in the dSPACE hardware.

In order to monitor the different signals and internal variables of the converters and to change the reference variable values of the system, a user interface has been designed and implemented using ControlDesk, a program included with the dSPACE control platform.

Synchronization

The two NPC converters in the back-to-back structure have to be synchronized with the generator and the grid voltages, respectively, in order to achieve some correct system performance.

The block *synchro* in the control diagram shown in Fig. 4 is the responsible of this function. Inside it two phase locked loops (PLL) [9] are implemented and adjusted. One of them obtains the angle needed to synchronize the PMSG and the rectifier from the generator voltages; the other one obtains the angle required to synchronize the grid and the inverter from the grid voltages.

These two angles are used for the coordinate transformations of the variables needed for the converters control and modulation.

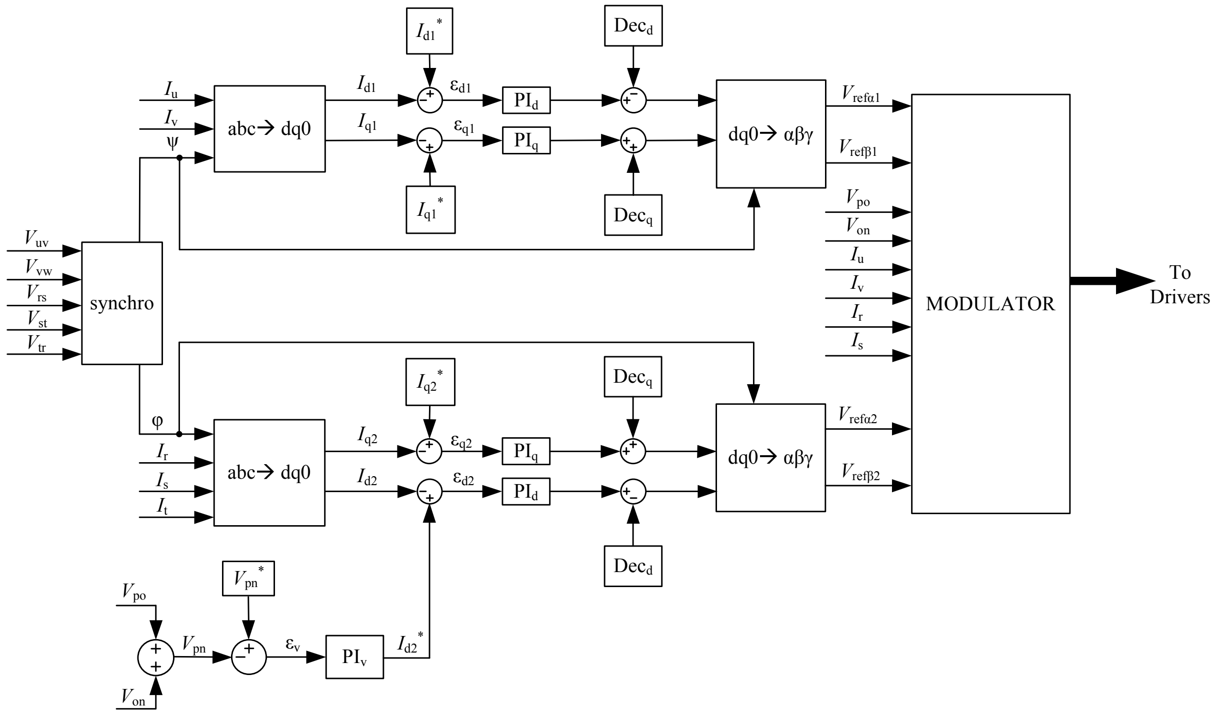

Fig. 4: Control scheme for the three-level three-phase NPC back-to-back converter.

Unity power factor

In order to transfer the maximum amount of active power to the grid, it is very important that both generator extracted currents and grid injected currents operate at unity power factor.

Reference variables I_{q1}^* and I_{q2}^* have to be set to zero to achieve this goal. I_{d1} and I_{q1} are the d-q components of the generator current. I_{d1} controls the amount of the PMSG active power extracted (negative value) or injected (positive value). Variable I_{q1} controls the amount of PMSG reactive power injected (positive value) or extracted (negative value). Variable I_{q2} controls the amount of grid reactive power injected (positive value) or extracted (negative value). The amount of grid injected or extracted active power is controlled by I_{d2}, whose reference value depends on the DC-link voltage level controlled by the reference variable V_{pn}^*.

The values of I_{d1}^*, I_{q1}^*, I_{q2}^*, and V_{pn}^* can be modified on-line by means of the user interface (ControlDesk).

Unity power factor has been chosen for simplicity but it is also possible to work with different power factor values on each side. This is achieved by changing the values of I_{q1}^* and I_{q2}^*, allowing different power factor on both generation-side and grid-side.

Moreover, with the proposed emulator, other control methods can be also implemented to control generator- and grid-side converters. No restriction is imposed by the control system implementation.

Modulation and DC-link voltage balance

The voltage balance between the capacitors of the DC-link is accomplished by the modulation strategy ([7] and [8]) of the two three-level NPC converters of the back-to-back. The block *Modulator* of the control scheme (Fig. 4), where the modulation strategy is implemented, receives different feedback variables (V_{PO}, V_{ON}, I_u, I_v, I_r, and I_s) and control references ($V_{ref\alpha 1}$, $V_{ref\beta 1}$, $V_{ref\alpha 2}$, and $V_{ref\beta 2}$) needed for the modulation and sends the duty signals to the transistor drivers.

Simulation results

MATLAB-Simulink simulations of the PMSG – back-to-back – grid system were performed. The generator is modeled as a three-phase voltage system due to the rotational speed control performed in the wind emulator. The amplitude and frequency of the voltages generated in the PMSG are a function of the PMSM rotor speed; some data points (obtained through experimental measurements) are shown on Table I.

Table I: Rotor speed – Voltage amplitude – Voltage frequency relations

PMSM rotor speed [rpm]	Line-to-line voltage amplitude [V_{rms}]	Voltage frequency [Hz]
225	43.4	15
450	86.5	30
675	130.2	45
750	144.6	50
900	173.2	60

The simulated operating point corresponds to the experimental set up; i. e., V_{rs}= V_{st}= V_{tr}= 144 V (rms line-to-line), lower than the grid voltage (V_{grid}= 400 V_{rms} line-to-line) by means of the autotransformer, f_{grid}= 50 Hz, L_F= 6mH, C_{dc}= 2.2 mF, V_{dc}= 300 V, I_{d1}^*= -6 A, I_{q1}^*= I_{q2}^*= 0 A, and switching frequency of f_s= 4 kHz for the two converters.

The rotational speed of the wind emulator PM synchronous motor is ω_{PMSM}= 750 rpm, with this speed the voltage generated in the PMSG (Table I) has the following amplitude and frequency: V_{PMSG}= 144.6 V (rms, line-to-line) and f_{PMSG}= 50 Hz.

Figs. 5 to 8 show the simulation results obtained for the conditions specified before. PMSG line-to-line voltages (V_{uv}, V_{vw}, and V_{wu}) (Fig. 5). Phase currents extracted from the PMSG (I_u, I_v, and I_w) (Fig. 6). Grid line-to-line voltages (V_{rs}, V_{st}, and V_{tr}) (Fig. 7). Phase currents injected to the grid (I_r, I_s, and I_t) (Fig. 8)

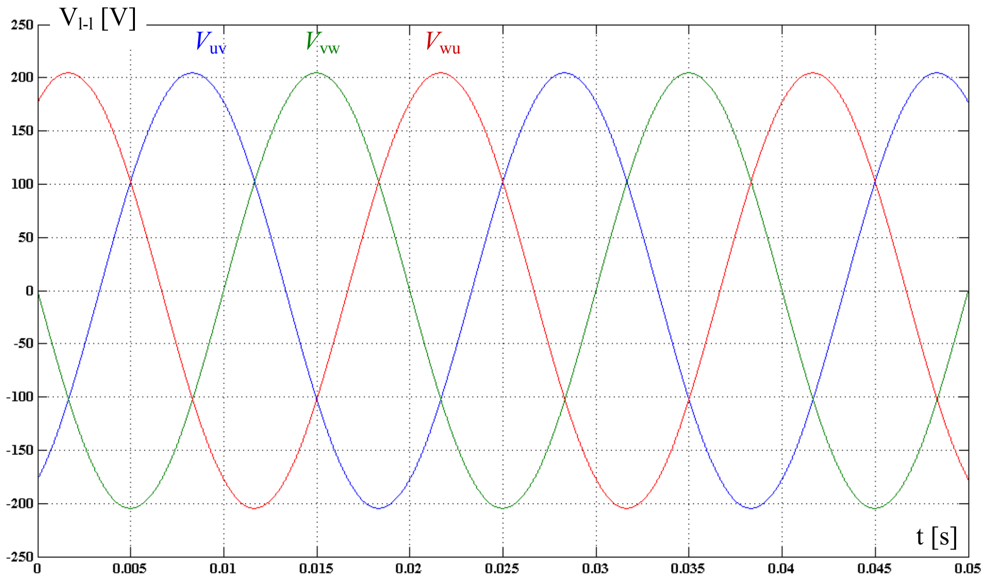

Fig. 5: Simulated PMSG line-to-line voltages.

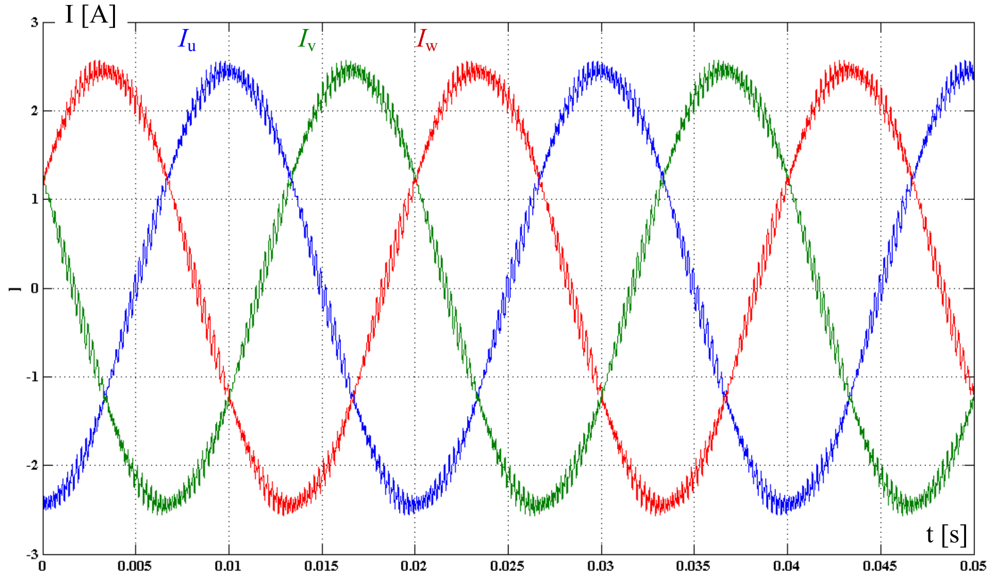

Fig. 6: Simulated PMSG extracted phase currents.

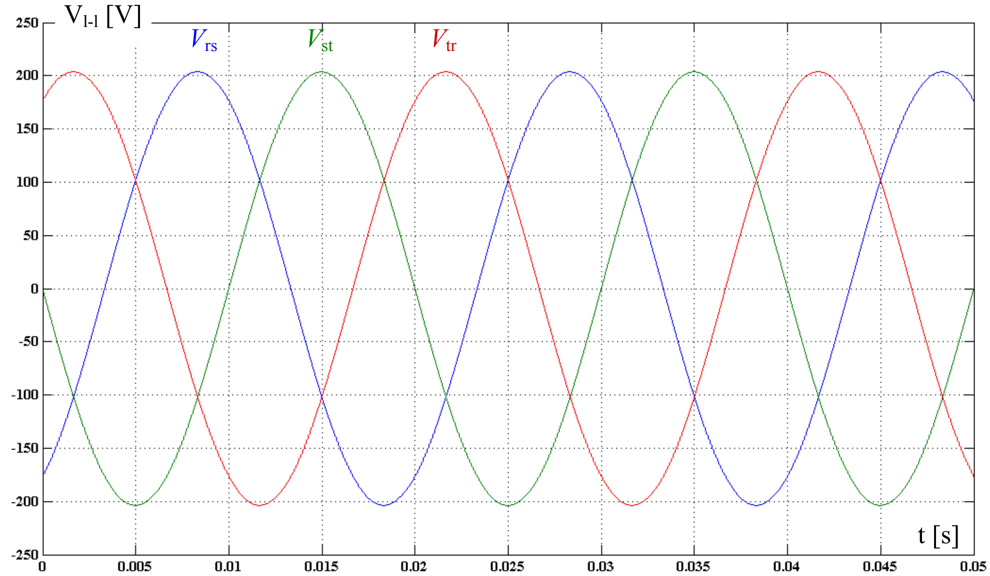

Fig. 7: Simulated grid line-to-line voltages.

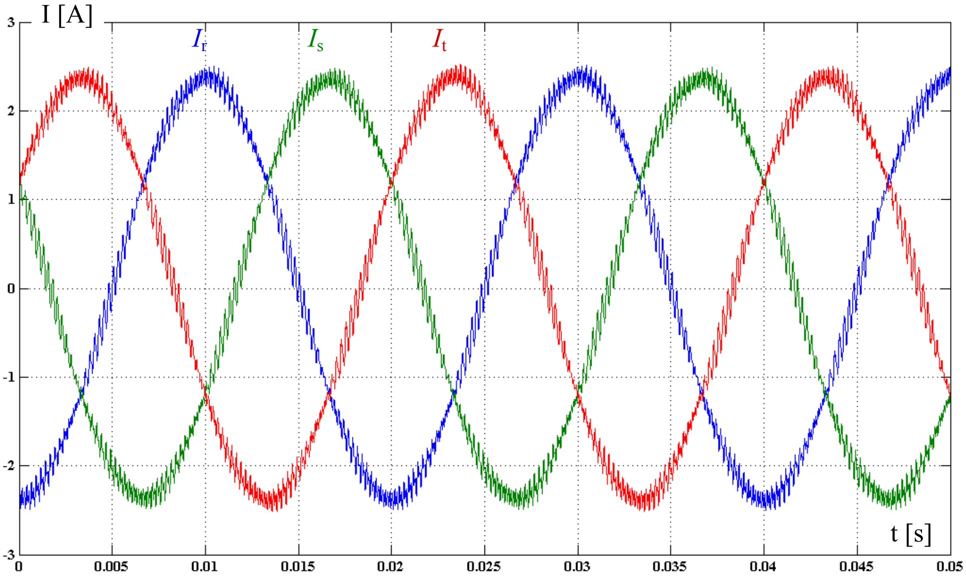

Fig. 8: Simulated grid injected phase currents.

Experimental results

The parameters and general operation conditions in the experimental tests of the system are the same as in the previous section.

As shown in Fig. 9, the control of the rotational speed (ω_{PMSM}) of the wind emulator provides a three-phase voltage at the output of the PMSG (V_{uv}, V_{vw}, and V_{wu}). As said in the previous section, the amplitude and frequency (V_{PMSG} and f_{PMSG}) of the voltages varies proportionally with the rotational speed.

The overall system performance can be observed in Fig. 10. The signals shown in Fig. 10 (a) are: V_{uv}, line-to-line generator voltage; I_u, extracted generator current; V_{rs}, line-to-line grid voltage; and I_r, injected grid current. As can be seen in Fig. 11, under the conditions simulated before, both the generator and the grid operate at unity power factor (V_{uv}, line-to-line generator voltage; I_u, extracted generator current; V_{rs}, line-to-line grid voltage; and I_r, injected grid current).

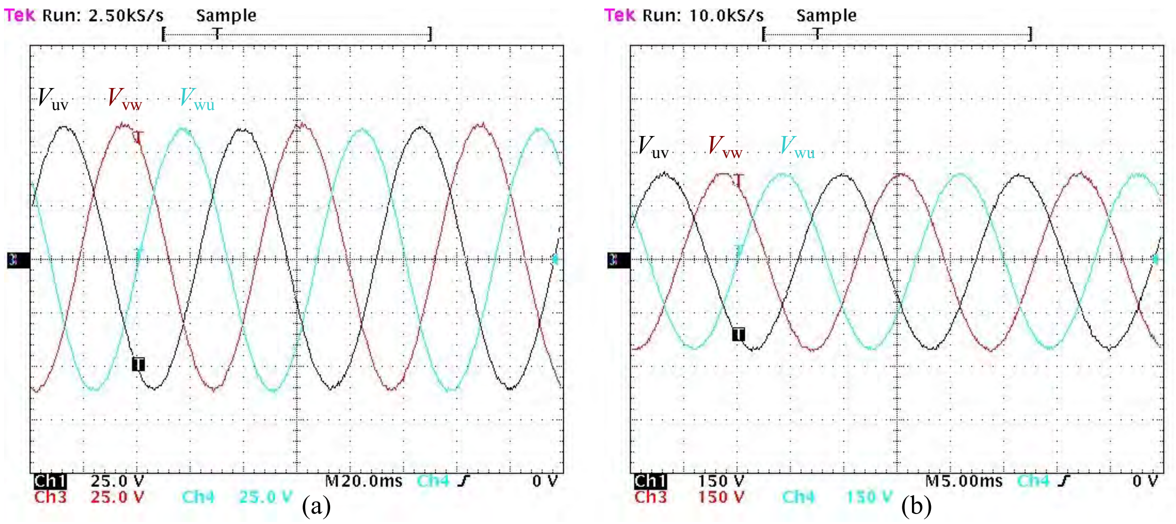

Fig. 9: PMSG voltages (a) ω_{PMSM}= 225 rpm. (b) ω_{PMSM}= 900 rpm.

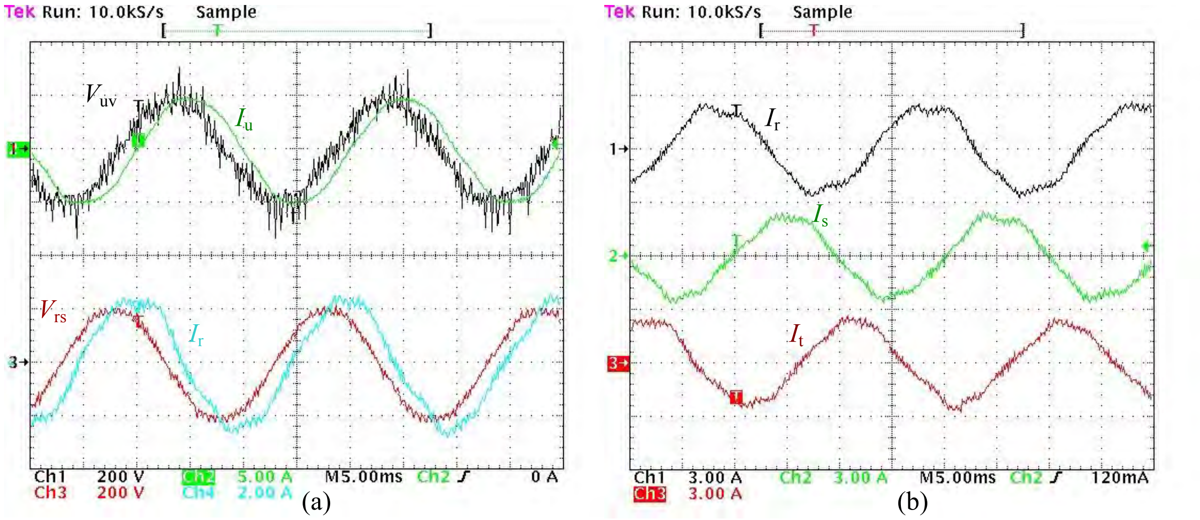

Fig. 10: (a) Overall system performance. (b) Grid currents.

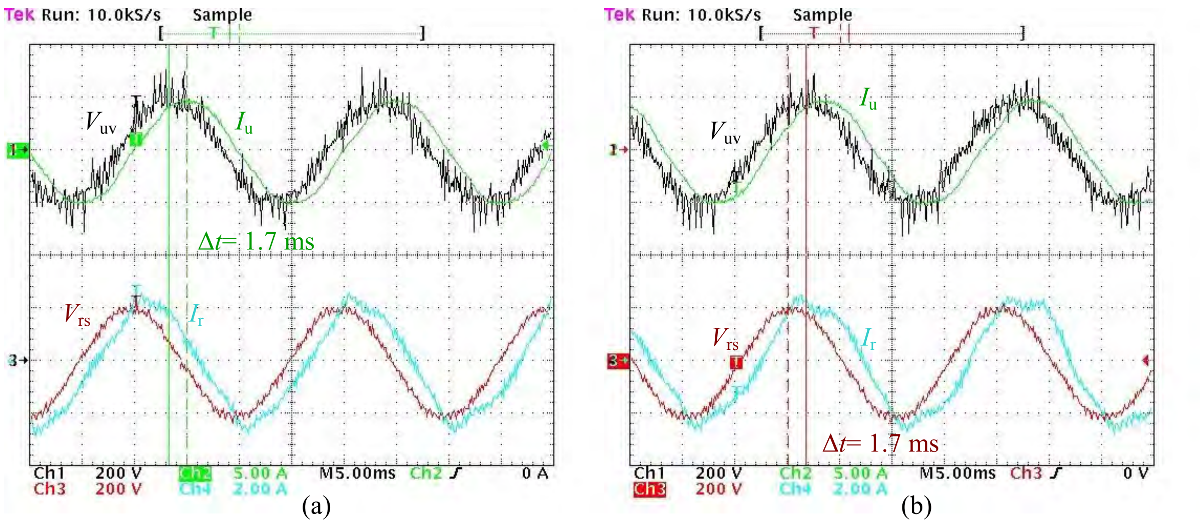

Fig. 11: Unity power factor operation. (a) Generator phase lag 30º. (b) Grid phase lag 30º.

The five different line-to-line voltage levels typical of the three-level NPC converters ($V_{uv,\text{ not filtered}}$ and $V_{rs,\text{ not filtered}}$) and the DC-link capacitor voltage balance (voltage of both capacitors; V_{po} and V_{on}; and DC-link voltage V_{pn}) are shown in Fig. 12.

The system performance has been tested under different rotational speeds; see Fig. 13, giving good results in all cases (V_{uv}, line-to-line generator voltage; I_u, extracted generator current; V_{rs}, line-to-line grid voltage; and I_r, injected grid current).

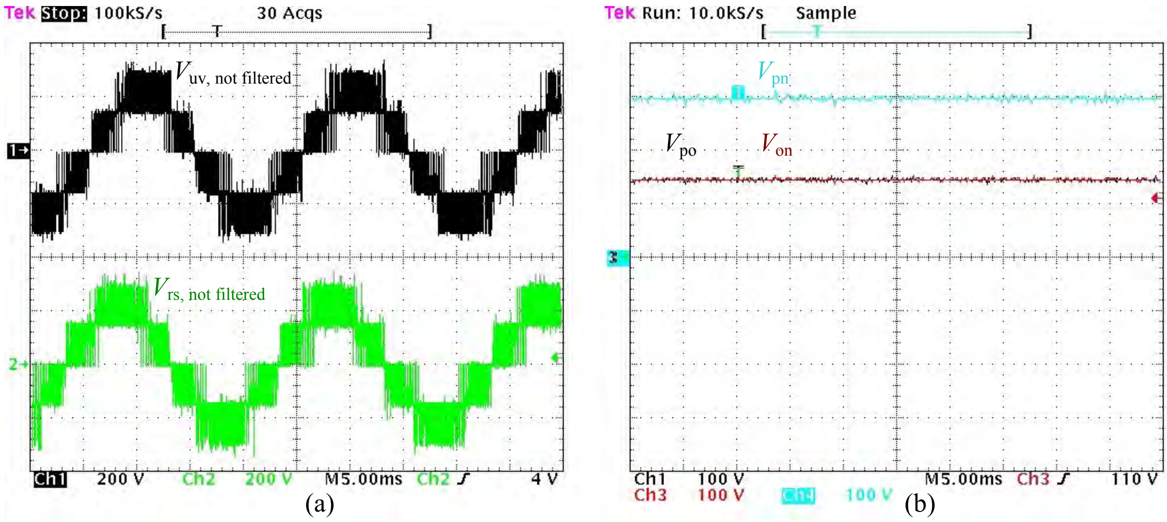

Fig. 12: (a) Rectifier and inverter five-level line-to-line voltage. (b) DC-link voltage balance.

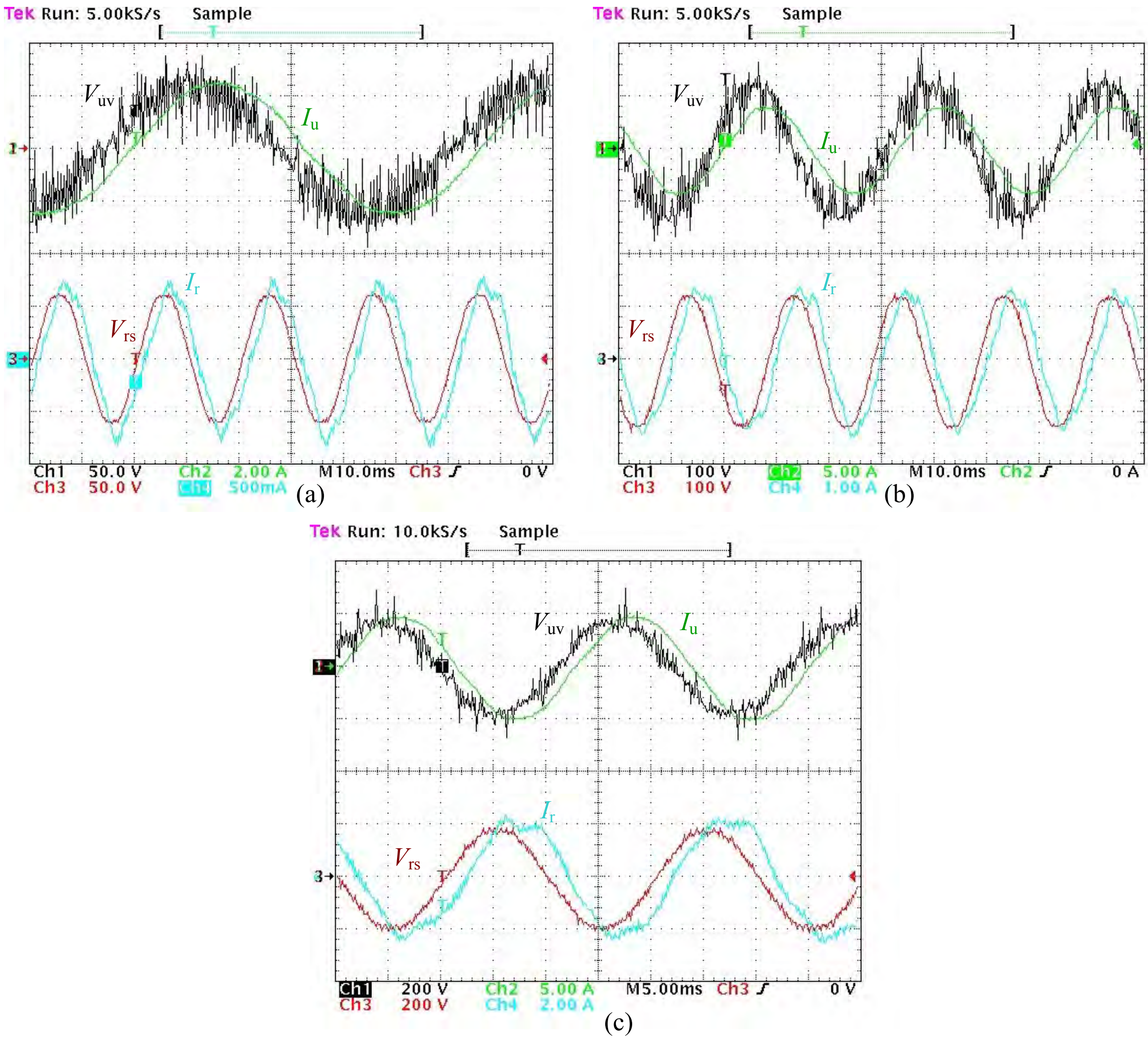

Fig. 13: Different rotational speeds. (a) ω_{PMSM}= 225 rpm. (b) ω_{PMSM}= 450 rpm. (c) ω_{PMSM}= 675 rpm.

Conclusion

A back-to-back converter implemented by two three-level three-phase neutral-point-clamped converters has been presented. This converter is applied to transfer the energy produced in a wind generation system to the grid. The role of the windmill has been played by a wind emulator with a permanent magnet synchronous generator connected to the back-to-back converter.

The control strategy of the converters guarantees unity power factor on both generator and grid sides to transfer the maximum amount of active power. The system operates correctly regardless the generator's rotor speed. The modulation strategy guarantees DC-link capacitor voltage balance of the back-to-back converter.

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