Predictive Direct Power Control of MV-Grid-connected Two-Level and Three-Level NPC Converters: Experimental Results

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Keywords

Three-phase system, Voltage Source Converter (VSC), Direct Power Control, Predictive Control, Multilevel converters

Abstract

This paper deals with the Predictive Direct Power Control of MV-grid-connected two-level and three-level NPC converters. The well-known direct power control is combined with a predictive selection of a voltage-vectors sequence, obtaining both high transient dynamic and constant switching frequency on high-power converters. The initial Predictive Direct Power Control proposal explored only the basic formulation based on simple vector-sequences applied to two-level converters. Later on, the same approach was extended to the family of three-level NPC converters, including the predictive direct control of neural voltage. In the same way, an advanced hybrid Predictive Direct Power Control was presented, providing only simulated data. The work presented in this paper provides experimental results of the hybrid Predictive Direct Power Control applied to two-level and three-level NPC converters. These results show that the P-DPC approach is an attractive solution to MV grid-connected applications.

Introduction

The three-phase two-level VSI configuration is the most habitual topology employed in many applications because of its simplicity, reliability and robustness [1-2]. Over a number of years they have frequently been employed in the wide market of electrical drives, becoming very popular in the industrial sector. Generally, almost all of the high-power VSI units used under medium voltage applications have been based on thyristors and GTOs. Nowadays, improvements in the new semiconductors such as the increase of tolerable voltage around some kV, the capability of high currents and fast switching performances allow us to make an efficient design of VSI for many grid-connected MV applications [1].

The multi-level structures appear in order to increase the power of VSI by means of adding voltage levels in such a way that the voltage in each semiconductor is reduced. Generally, a larger number of voltage levels applied to a given grid-filter make it decrease the harmonic range of the current, obtaining a high power quality in the converter's AC-side. The augmentation on voltage levels can be obtained increasing the number of switches, which leads to complex structures and, as a consequence, makes the control difficult [3-6]. The features of these topologies and especially the three-level NPC VSI are very attractive for many applications, involving the sector of VSI for medium voltage and high-power levels in particular [2-4].

The control techniques which are commonly used in grid connected converter systems could be classified as direct or indirect control strategies [7]. The indirect control is characterized by a modulator (Pulse Wide Modulation PWM or other) that computes the turn-on/turn-off times of converter's switches along a switching period through the evaluation of the voltage reference. This voltage reference is issued by the controller, which idealizes the converter as a dependent continuous voltage source. On the other hand, direct control techniques establish a direct relation between the behavior of the controlled variable and the state of the converter's switches. Generally, the main advantage of indirect control techniques resides in the resulting constant switching frequency, whereas the direct control techniques offers faster transients.

In this framework, a new approach called Predictive Direct Power Control (P-DPC) was proposed in [8]. P-DPC combines the direct power control strategy with a predictive vector sequence selection, obtaining both high transient dynamic and constant switching frequency. The initial P-DPC proposal [8] explored only the basic formulation based on simple vector-sequences applied to two-level VSI (2L-VSI). Only simulation results were provided. Later on, in [7], complementary experimental results validated the approach. Next, in [9], the same approach was extended to the family of three-level neural-point-clamped VSI (3L-NPC VSI), including the predictive direct control of neural voltage. In the same paper [9], an advanced hybrid P-DPC was proposed, and all the results were validated by simulation.

Finally, this paper provides experimental results of the hybrid P-DPC applied to 2L and 3L-NPC VSIs.

Power System's Description

The basic scheme of a grid-connected 2L-VSI with an L-type filter is shown in Fig.1. The structure of the converter consists of six switching cells (based on IGBTs, IGCTs, GTOs, or others) in such a way that eight possible configurations of the switches are available, leading to seven possible voltage states at the output of the converter. The per-phase output is connected to the negative (-) or positive (+) point of the DC-link when the state of the switch Sx is equal to '0' or '1', establishing a current way between the DC-side and AC-side.

Equation (1) computes the available voltage vectors in the complex space. Six of them are classified as active vectors (the combination of the converter's switches leads to a non-zero voltage in the AC-side) whereas the other two vectors are null vectors (all phases are connected to the same point). The graphical representation is shown in Fig.2.

$$
\begin{cases}
v_{kn} = \dfrac{2}{3} v_{DC} e^{j(n-1)\frac{p}{3}} & n = 1,..,6 \\
v_{k0} = v_{k7} = 0
\end{cases}
\tag{1}
$$

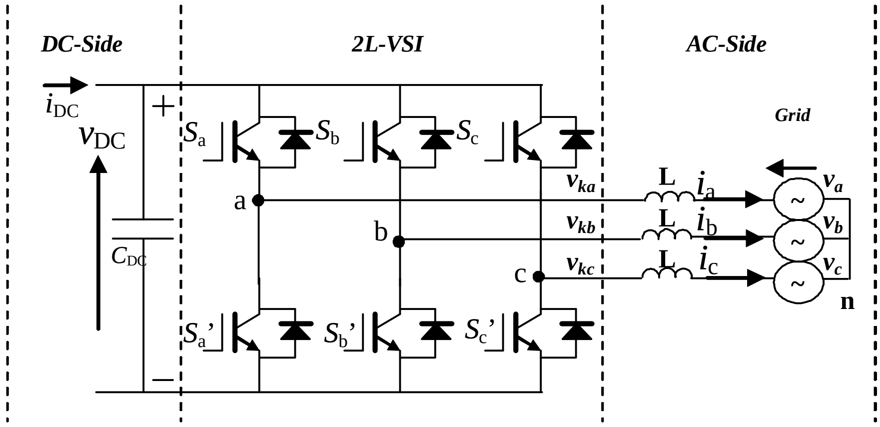


Fig. 1: Grid-connection of a three-phase 2L-VSI with an L-type filter

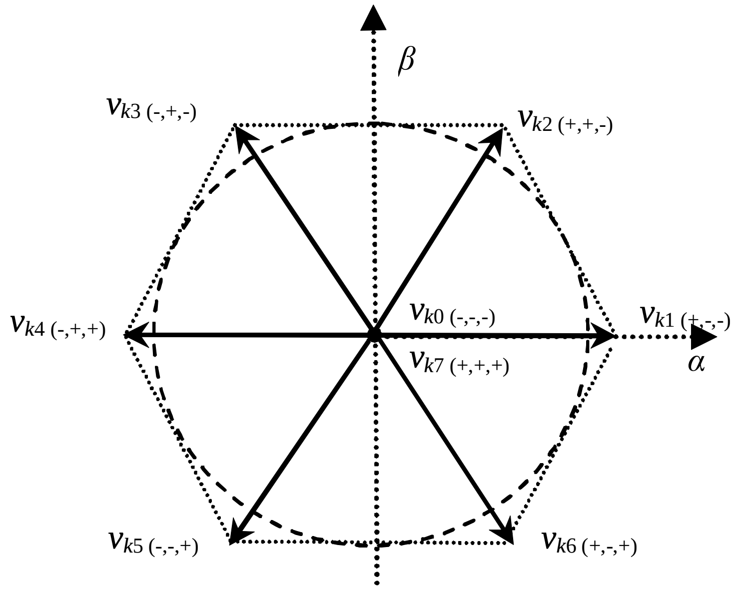


Fig. 2: Space vector representation of different voltage vectors available at the converter's AC-side in a 2L-VSI

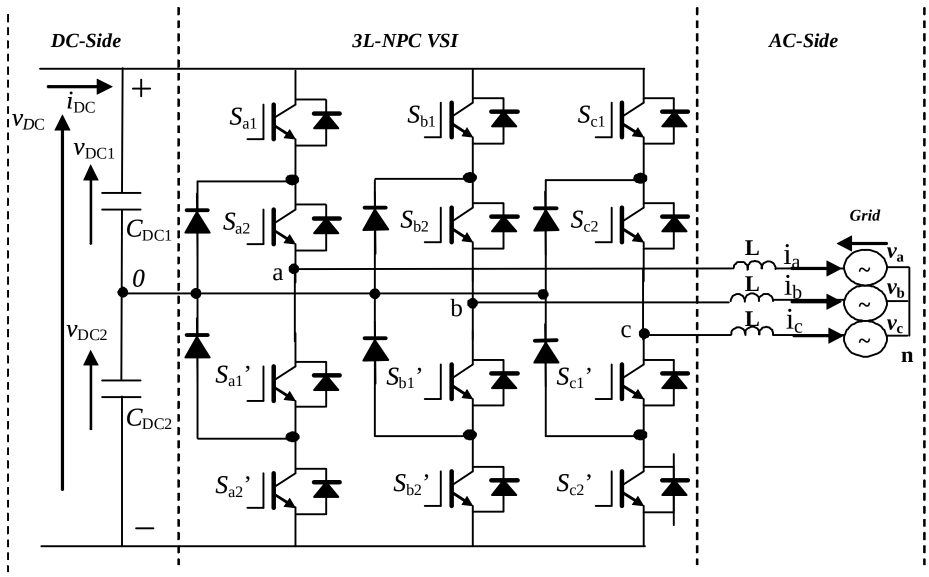


Fig. 3: Grid-connection of a three-phase 3L-NPC VSI with an L-type filter

Fig.3 shows the scheme of a grid-connected 3L-NPC VSI with an L-type filter. The converter consists of twelve switching cells and six clamp diodes, leading twenty seven non-destructive different combinations of the states of the switches. Any given output phases of the converter can be connected to negative (Sa1=0, Sa2=0), neutral (Sa1=0, Sa2=1) or positive (Sa1=1, Sa2=1) points of the DC-link, which results in different current paths between the DC-side and AC-side.

The twenty-seven switching states of the 3L-NPC VSI generate nineteen different voltage vectors at the converter's AC-side (eighteen active vectors and one null vector). The availability of redundancies in different states provides extra degrees of freedom. Equation (2) computes the vector representation in the complex space where the sub-index l,m,s are related to large, medium and small vectors .The graphical representation is shown in Fig.4.

$$\begin{cases} v_{kn\_l} = \frac{2}{3} v_{DC} e^{j(n-1)\frac{p}{3}} \\ v_{kn\_m} = \frac{1}{\sqrt{3}} v_{DC} e^{jn\frac{p}{6}} \qquad n = 1,..,6 \\ v_{kn\_s} = \frac{1}{3} v_{DC} e^{j(n-1)\frac{p}{3}} \\ v_{k0} = v_{k1} = v_{k2} = 0 \end{cases} \tag{2}$$

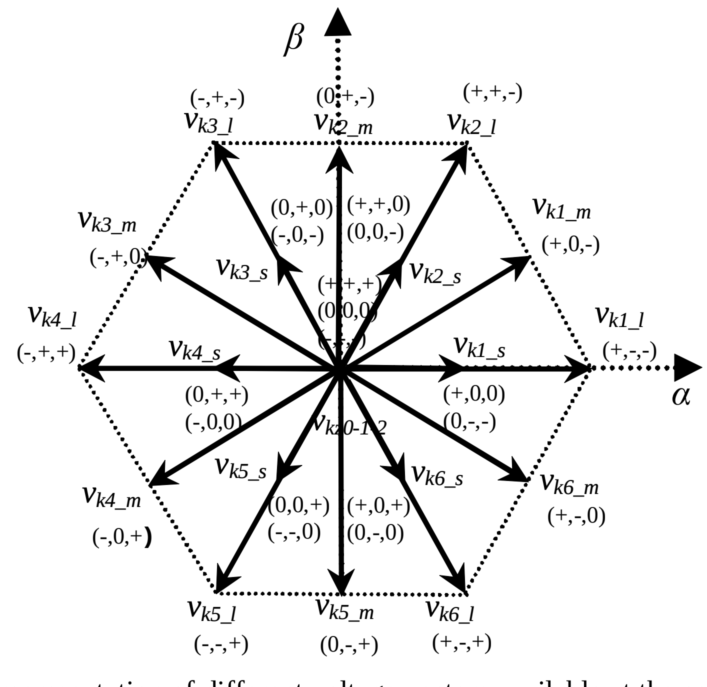


Fig. 4: Space vector representation of different voltage vectors available at the converter's AC-side in a 3L-NPC VSI

Control System's Configurations based on P-DPC

The P-DPC selects the best voltage-vectors' sequences and computes their application times in order to control the power flow through the VSI under constant switching frequency operation. This strategy requires a predictive model of the instantaneous power behavior, which has been explained in [7-9] along with several possible control approaches. Here, possible P-PPC-based control system configurations for the 2L and 3L-NPC VSI are described, see Fig.5 and Fig.6.

Generally, initial line-voltage and current values are required in order to compute initial active and reactive powers [P0, Q0]. The control algorithm evaluates this information and the reference-power values, selects the appropriate sequence and computes the application times which minimize the final tracking errors. In addition, the 3L-NPC VSI configuration considers the DC-link voltage dynamics in order to keep the required voltage-balanced in the DC-link capacitors, see Fig.6.

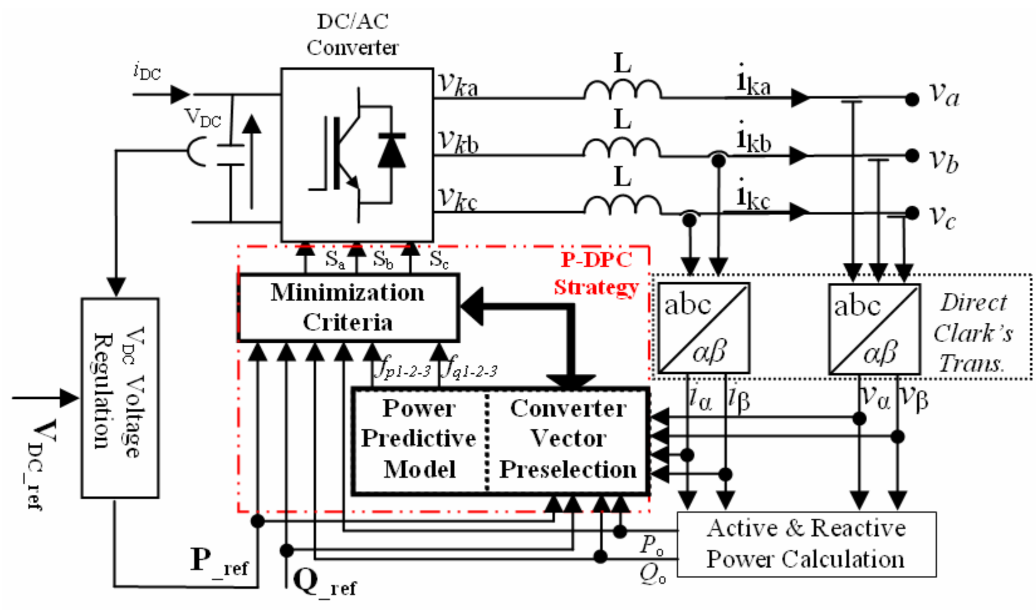


Fig. 5:P-DPC system's block diagram of 2L-VSI

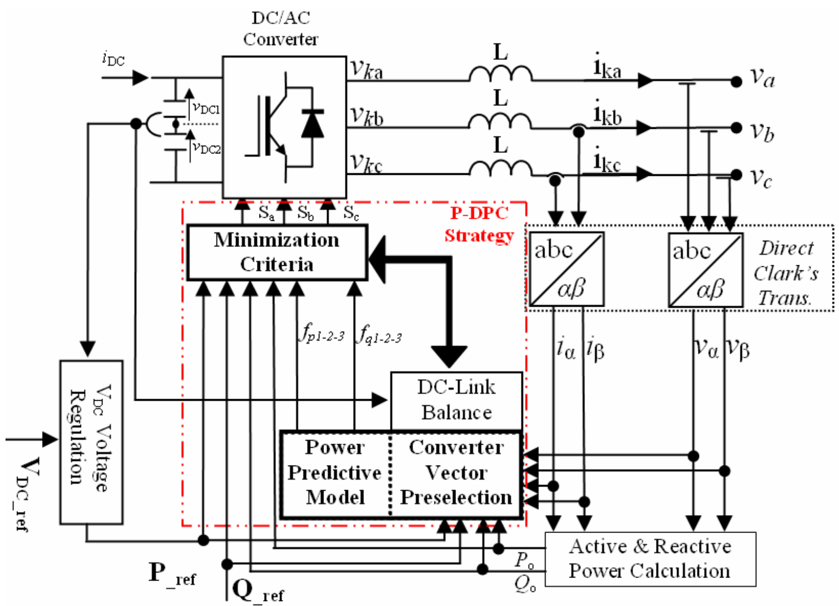
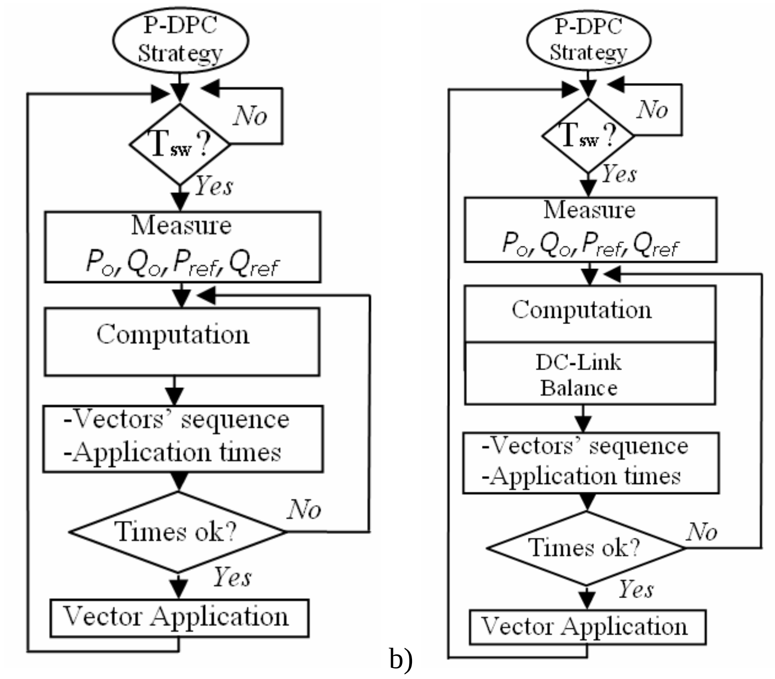


Fig. 6:P-DPC system's block diagram of 3L-NPC VSI

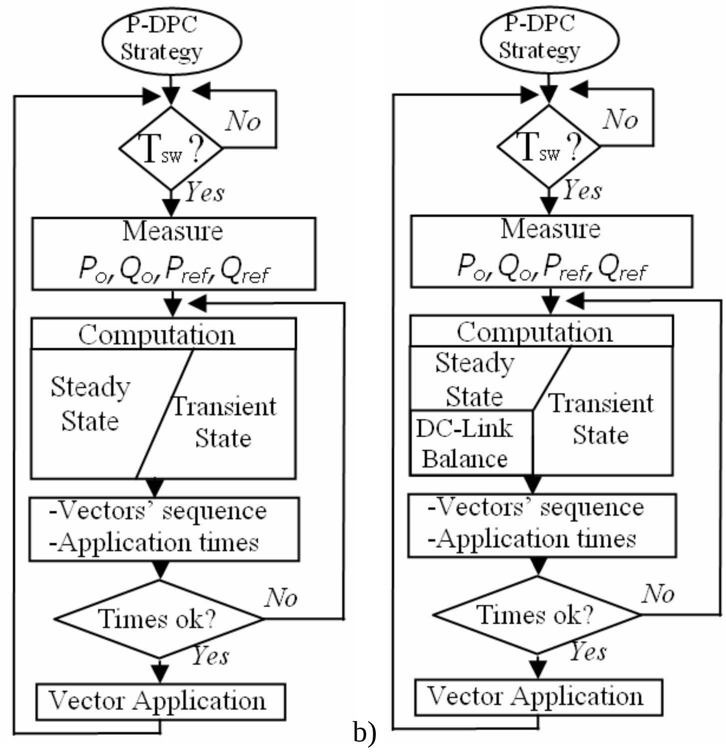
Fig.7 shows four flowcharts summarizing the main P-DPC strategies. All of them can exploit any of the simple P-DPC strategies explained in previous works [7-10], such as the asymmetrical P-DPC based on 2 or 3 voltage-vectors' sequence or the P-DPC based on symmetrical 2+2 or 3+3 voltage-vectors' sequences.

Basically, in the beginning of each control period the active and reactive-powers are computed using instantaneous current and voltage measures. Then, the P-DPC algorithm selects the optimum voltage vectors' sequence and the related application times (using any of the P-DPC versions), taking into account the power tracking requirements and the DC-link balance (3L-NPC VSI case). The selected voltage-vectors are applied during the computed application times, completing the control period.



a) b)

Fig. 7: Simple P-DPC-based flowcharts: a) 2L-VSI b) 3L-NPC VSI



a) b)

Fig. 8: Hybrid P-DPC-based flowcharts: a) 2L-VSI b) 3L-NPC VSI

Hybrid P-DPC strategies could be also proposed [8,10], see Fig.8. The main idea here is to make use of a large set of concatenated-voltage vectors only in steady state operation, improving efficiency and current ripple. The advantages of a simple set of two concatenated-voltage vectors are exploited in transients. The steady-state strategy employs the nearest active voltage-vectors improving the steady-state performance. Obviously this is not the best strategy for transients, where other far active voltage-vectors would provide faster responses. Because of this, for transients, the voltage sequence must be built by the voltage vector which generates the fastest evolution on the desired direction, i.e., the best-oriented larger active vector, followed by a null vector.

In the 2L-VSI, all active vectors are evaluated whereas in the 3L-NPC VSI case only large vectors are considered. The proposed hybrid configuration will need few μs to identify whether a transient is required or not, select the best voltage-vectors' sequence and compute the application times. Finally, the voltage-vectors will be applied during the computed application times within the control period.

However, they are other considerations related to the robustness against parameter drifts of line disturbances which it should be taken into account [10]. The P-DPC is a model based control method, so its mathematical approach is based on the knowledge of the system's parameters becoming more sensitive than VOC against any drift on the value of the filter's inductance. In addition, the P-DPC algorithm could be considerably affected by typical disturbances as line voltage harmonics and voltage sags. It should be also noted, that the reference power evolutions must be always conditioned to the maximum available current value (especially under distorted operation conditions) in such a way that non-predicted behaviors are avoided.

Experimental Results

Several experimental tests have been carried out in order to validate the proposed P-DPC algorithm. The experimental platform consists of a commercial three-phase 2L and 3L-NPC VSIs located at Faculty of Engineering of the University of Mondragon. The main specifications of power and control systems are listed in Table I. On one hand, the symmetrical 3+3 vectors' sequence version of the P-DPC is evaluated under the 2L-VSI operating at 400V-15kVA. On the other hand, a hybrid P-DPC version has been proposed in a 3L-NPC VSI under same operation conditions.

Table I: Specifications and Parameters of Power and Control System

	2L-VSI	**3L-NPC VSI**
Rated Power	15[kW]	
Line-to-line Voltage (RMS)	400[V]	
Filter	L=10[mH]	
DC-Link (C_{DCx})	C_{DC}=5[mF]/700V	C_{DC}=1.16[mF]/700V
P-DPC version	Symmetrical 3+3 switching pattern	Hybrid
Switching frequency (max)	f_{SW}=2000Hz	

The control algorithms run under the SIMULINK/MATLAB environment in a dSPACE ds1103 real-time platform and the measurement system is based on a YOKOGAWA PZ4000 with a sample time of 2.5MS/s and Tektronix TPS 2024 200MHz. In order to generate the switching patterns, the standard PWM tools of dSPACE are 'codec' using combinatory logic circuits under the 2L-VSI whereas the FPGA platform SPARTAN 3 is employed in the 3L-NPC VSI.

Fig.9. compares the experimental per-phase switching signals and normalized line-current of the P-DPC based on symmetrical 3+3 voltage vectors' sequence and the hybrid P-DPC strategy under the 2L and 3L-NPC VSIs. As can be observed there are no switching actions along the maximum of the line current, therefore the overall switching losses are minimized in both strategies. The steady state is evaluated by THD measurements, see Fig.10. The P-DPC based on symmetrical switching pattern presents current THD levels near 4.8% in the 2L-VSI whereas in the hybrid version is of around 2.4%. Nevertheless, both strategies meet the IEEE Std 519-1992 recommendation.

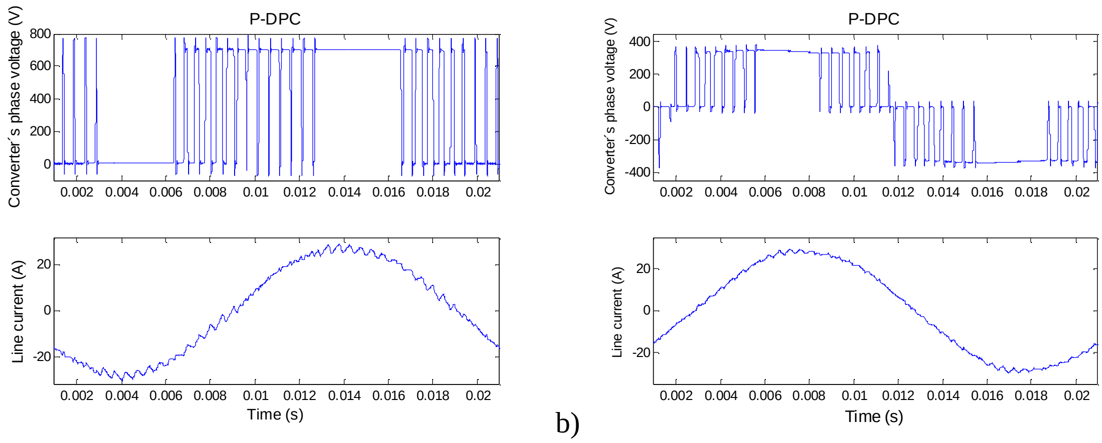


Fig. 9: a) Converter's per-phase voltage and line current: a)P-DPC based on symmetrical 3+3 voltage vectors' sequence (2L-VSI) b) Hybrid P-DPC (3L-NPC VSI)

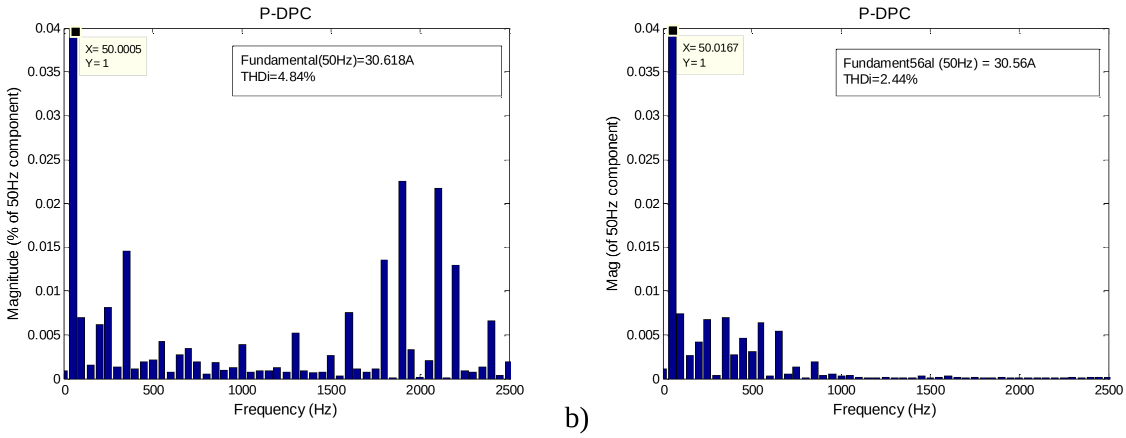


Fig. 10: Experimental current spectrum: a)P-DPC based on symmetrical 3+3 voltage vectors' sequence (2L-VSI) b) Hybrid P-DPC (3L-NPC VSI)

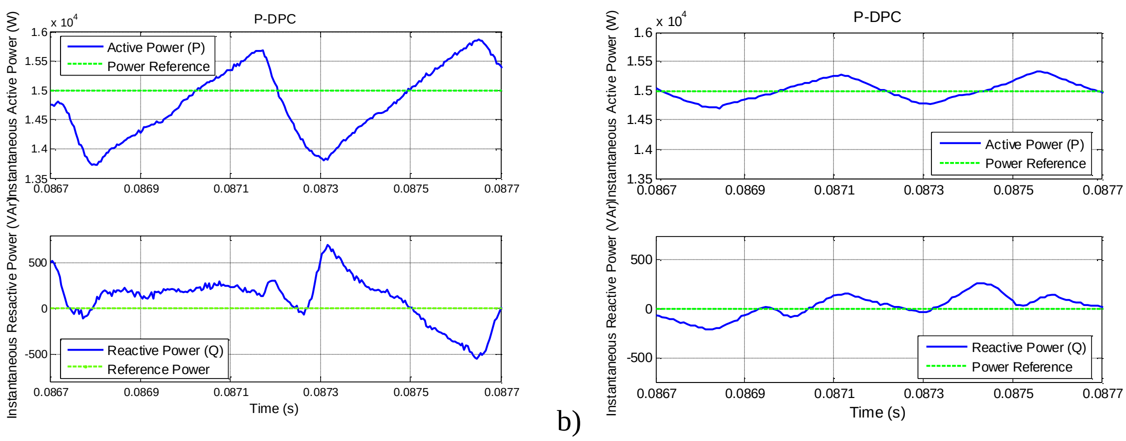


Fig. 11: Experimental detailed power trajectories: a)P-DPC based on symmetrical 3+3 voltage vectors' sequence (2L-VSI) b) Hybrid P-DPC (3L-NPC VSI)

The P-DPCs behaviors along two control periods are shown in Fig.11. As can be observed, quasi-linear trajectories evolve around the reference values in both cases, with a ripple below 5% under the 2L-VSI and 3% in the 3L-NPC VSI. Fig.12 shows the evolution of the DC-link voltages and line currents in the 3L-NPC VSI under P-DPC operation when several active reference steps from 5kW to 10kW are applied. It should be noted that the low frequency harmonic of around 5Hz under the DC-link voltages is related to the DC supply which has been used in the experimentation.

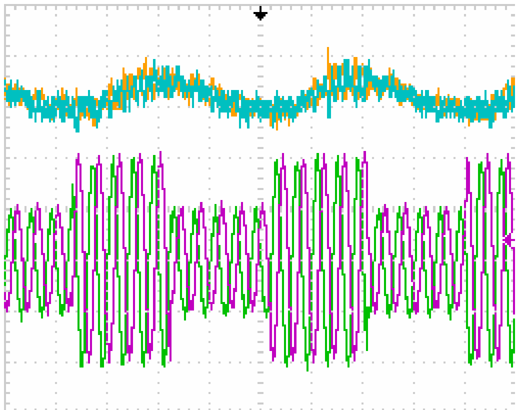
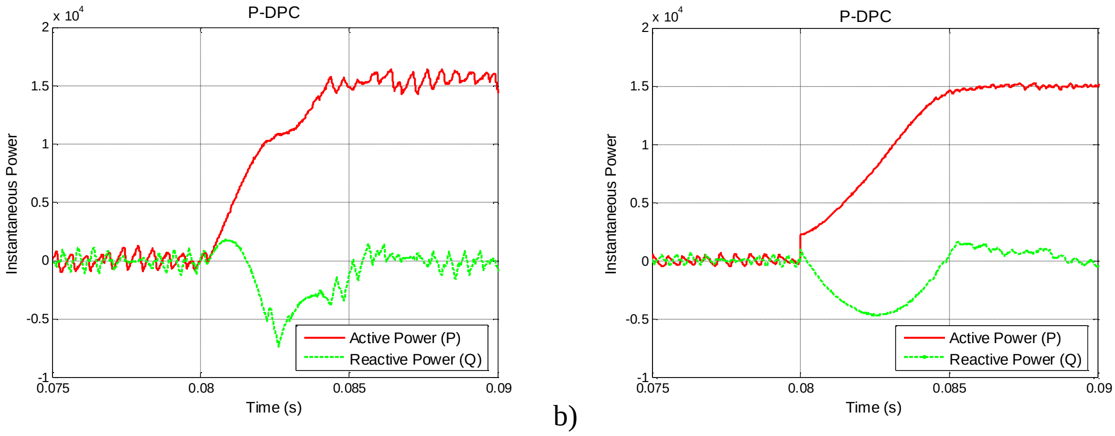


Fig. 12: Experimental results of DC-link capacitors' voltage ripples and line currents under several active power reference steps

Finally, experimental results of the active power transient behavior under a large reference step from 0kW to 15kW are shown in the following figure, As can be observed both P-DPC strategies shows an very good transient behavior, obtaining a fast dynamic response below 5ms without any overshoot.



a) b)

Fig. 13: Experimental instantaneous power behavior during active power reference steps: a)P-DPC based on symmetrical 3+3 voltage vectors' sequence (2L-VSI) b) Hybrid P-DPC (3L-NPC VSI)

Conclusions

The P-DPC approach has been proposed for high power MV grid-connected 2L and 3L-NPC VSI configurations. Several P-DPC algorithms have been described, involving basic and complex control approaches such as the P-DPC based on symmetrical 3+3 voltage-vectors' sequence and hybrid versions. In order to verify the behavior of the proposed control strategies several experimental test have been carried out in different laboratory platforms under 400V-15kW operation conditions. The experimental results show that the P-DPC approach is able to get very good results both in steady-state and transients, becoming a good solution to MV grid-connected converters.

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