An Analysis of Carrier-Based Multilevel Modulation Strategies with Different Carrier Dispositions Applied to an Open-End Winding Power Converter

Abstract: This paper presents an analysis of multilevel pulse width modulation techniques using different carrier dispositions applied to a three-level open-end-winding configuration. The structure uses a pair of two-level back-to-back converters, and the studied carrier dispositions are the Phase Shifted (PS), Level Shifted with Phase Disposition (PD) and Phase Opposition Disposition (POD). Techniques are implemented in an experimental setup and analysis are performed based on the spectral content of the resulting voltages and currents. Finally, the total harmonic distortion is calculated from the data for the entire modulation range allowing for a proper comparison between strategies, evidencing the superior performance of the Phase Disposition technique.

1 Introduction

This work presents a comparative study of modulation techniques employing distinct carrier dispositions for a three-level open-end winding (OEW) conversion system. The OEW, a multilevel configuration was introduced by [1], and consists of connecting static converters to both ends of poly-phase windings, instead of the traditional Δ/Y connection.

This topology presents the same voltage outputs as the traditional three-level systems, such as NPC and FC, but with no clamping diodes nor flying capacitors. Its main restriction, however, is the need for isolation between the converters in order to avoid common-mode circulating currents.

Choosing a suitable modulation technique can positively affect the overall behavior of the system. Multilevel configurations present redundant switching states that, when correctly used, can improve power quality, dynamics and losses distribution. Several PWM techniques have been reported over the last decades in order to achieve the best power quality and/or efficiency of the OEW configuration. Some are space vector based techniques such as the sub-hexagon in [2], others are carrier based, such as presented by [3], or hybrid, such as [4].

In this paper, carrier-based pulse width modulation (PWM) techniques are analyzed: Phase Shifted (PS-PWM), Level Shifted with Phase Disposition (PD-PWM) and Level Shifted with Phase Opposition Disposition (POD-PWM). The point of comparison is the energy quality and system performance was analyzed mainly through experimental results, with complementary simulations.

2 The Three-Level OEW Converter

The power circuit of the studied OEW system is illustrated in Fig. 1. Instead of the conventional delta or star connection, the load terminals are connected to a pair of two-level, three-phase, back-to-back converters, each one with its respective DC-link. In order to avoid the circulation of common-mode currents through the system, a transformer isolates the converters on the grid side. At the load side, the voltage output is dependent of both converters that are then treated as a single three-level converter. It is at this side that the modulation techniques under study are employed.

The experimental study is conducted using a test bench, and for sake of simplicity the load is a simple RL circuit. The grid side is used to keep the independent dc-links voltages controlled, but only the load side is analyzed here. Command and control of the system are implemented and performed by a Texas Instruments TMS320F28335 digital signal processor. Fig. 2 shows the system and its main components picture, and the table 1 the main parameters of the system. Simulation is performed using *PLECS®* with the same parameters of the test bench, allowing extrapolation of the experimental data to any condition.

Table 1: Experimental setup parameters.

Parameters	***Values***
DC-link Total Voltage	200[V]
Load Resistance	10 [Ω]
Load Inductance	4 [mH]
Load Rated Active Power	1,25 [kW]
Load Maximum RMS Current	8,8 [A]
Load Power Factor	0,99
Output Voltage Switching Frequency	1200 [Hz]

3 Modulation Techniques

The choice of the modulation strategy directly interfere in the behavior and performance of the energy converter. As a result of advances in different multilevel converters topologies, studies on modulation strategies have come into evidence. Despite the complexity associated with the greater number of semiconductor devices to be controlled, the development of different techniques is directly related to the possibility of exploring additional switching states. As a result, they allow the power converter to operate at its best performance [5, 6].

Modulation methods can be classified according to the switching frequency (Hz) and if carrier-

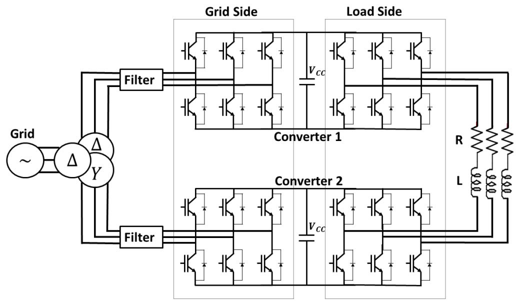

Fig. 1: Power circuit of the studied three-level OEW configuration

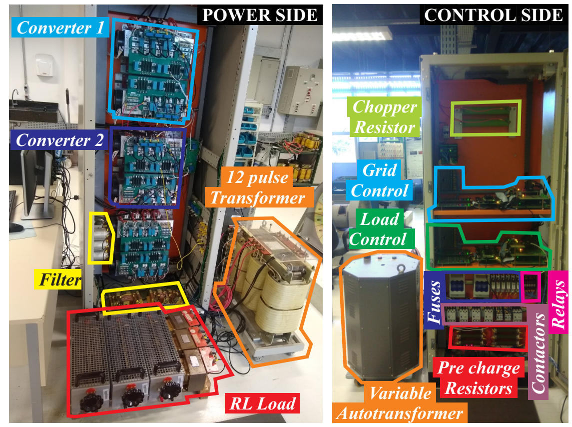

Fig. 2: Experimental setup configuration.

based, vector-based or others such as hybrid and selective harmonics elimination. Carrier-based strategies are widely used because they have a relatively simple implementation, attractive for operation with digital signal processors. Among them, two strands stand out: the first, uses phase shifted carriers (PS-PWM), and the second uses level shifted carriers (LS-PWM). The latter includes three different carrier dispositions: Phase Disposition (PD), Phase Opposition Disposition (POD) and Alternate Phase Opposition Disposition (APOD) [5, 7].

It was evidenced by [8], for two levels, and by [9], for the multilevel configuration, that the Centered Space Vector Pulse Width Modulation (CSVPWM) has similar output behavior to space vector techniques, through the addition of the correct zero sequence signal to a three-phase modulating signal. The zero sequence signal, added to the voltage reference, is obtained using equations (1)- (3) which have the three-phase referential represented by $i \in (a, b, c)$ [9].

$$v_i{}' = v_i - \frac{\max(v_a, v_b, v_c) - \min(v_a, v_b, v_c)}{2} \tag{1}$$

$$v_i{}'' = \left[v_i{}' + (n-1)\frac{v_{dc}}{2} \right] \times \bmod\ (v_{dc}) \tag{2}$$

$$v_i^* = v_i{}' + \frac{v_{dc}}{2} - \frac{\max(v_a{}'', v_b{}'', v_c{}'') - \min(v_a{}'', v_b{}'', v_c{}'')}{2} \tag{3}$$

In this study, an evaluation of the voltage output harmonic distortion was conducted for different carrier dispositions under the same circumstances, i.e., modulating signals. The analyzed strategies make use of $(n-1)$ carriers, being n the number of converter levels. In the three-level system, two carriers are compared to the three-phase modulating signals. One carrier is associated to converter 1 and the other to converter 2.

4 Testing and Results

In order to allow a proper comparison of the different carriers disposition methods, testing must be made under comparable circumstances. For all testing conditions, the RL load is fixed and the DC-links of both converters are controlled at the same level ($100V$) by their respective grid side bridges.

Also, the carrier frequencies for each technique must result in the same switching frequency in the voltage output. For that reason, the PS-PWM applies 600Hz carriers, while the level shifted strategies employ 1200Hz carriers. The first switching harmonic in the voltage output is then expected to be 1200Hz in all three analyzed strategies.

With those base conditions, the output voltages and currents were registered while the modulation index was swept over all the normal modulation range (overmodulation excepted). Since there are different expressions for the modulation index calculation, it is relevant to present the one adopted in this work: $m_i = \frac{V^*}{V_{dc}} \frac{2}{\sqrt{3}}$, being V^* the peak value of the output phase voltage, and V_{dc} the sum of both converters DC-link voltages.

As a means to evaluate the overall performance of the strategies regarding output power quality, several modulation indexes were tested in the experimental setup. The *Total Demand Distortion* (TDD) [10] was calculated from collected results and plotted as the x points in Fig. 3, along with the system simulated data, represented by the continuous lines. The analysis show that PS-PWM and POD-PWM produce similar outcomes, while PD-PWM presents the best performance for the entire modulation range.

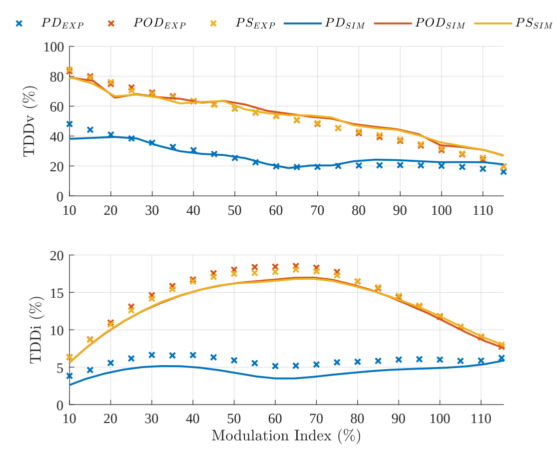

Fig. 3: Comparison of the total current demand distortion between the modulators as a function of the modulation index (experimental and simulated results).

5 Conclusion

Based on experimental tests carried out in laboratory environment, the PD-PWM modulation strategy has presented superior performance in relation to the others, regarding the output voltage quality. This work opens the path to expand future analysis of these modulation strategies applied to open-end winding topologies, including thermal losses, common-mode currents and different zero-sequence injection signals.

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