A COMPARATIVE STUDY OF TWO MODULATION STRATEGIES APPLIED TO MULTI-LEVEL INVERTERS FOR LARGE ELECTRIC DRIVES

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Abstract – **This work briefly compares two well known modulation techniques for harmonic reduction applied to high power motor drives. The analysis consists in comparing the THD of the current drawn from the utility and the THD of the multi-level inverter output voltage and current varying the parameters of the diode clamped three-level three phase inverter, using OHSW and SPWM modulation. Simulated results show which method is desirable for a large motor drive application.**

KEYWORDS

Multi-level inverters, drive systems, harmonic reduction.

I. INTRODUCTION

The multilevel voltage source inverter is applied in many industrial applications such as ac power supplies, static VAR compensators and drive systems. The output voltage waveform of a multilevel inverter is composed by a number of voltage levels, typically obtained from capacitors.

One of the significant advantages of the multilevel configuration is the harmonic reduction in the output waveform, without increasing switching frequency or decreasing the inverter power output [1], [2], [4].

Some traditional 2-level high-frequency pulse width modulation (PWM) inverters for automotive drives can have problems associated with their high voltage change rates (dV/dt), which produces a common mode voltage across the motor windings. High frequency switching can exacerbate the problem because of the numerous times this common mode voltage is impressed upon the motor each cycle. PWM controlled inverters also require a greater amount of heat removal because of the additional switching losses [3].

Multilevel inverters solve these problems because their individual devices have a much lower dV/dt per switching, and they operate at high efficiencies because they can switch at a lower frequency than PWM-controlled inverters.

The inverter topology chosen for varying the modulation techniques is the Diode-clamped Three-level three phase for three phase traction motor drive. The diode-clamped converter is the most popular structure proposed as a transformerless voltage source inverter, and it is based on the neutral point converter. This topology will be used in train traction drive of Fortaleza Metropolitan Transportation (METROFOR). Fig. 1 shows the Diode-clamped Three-level Inverter general circuit topology.

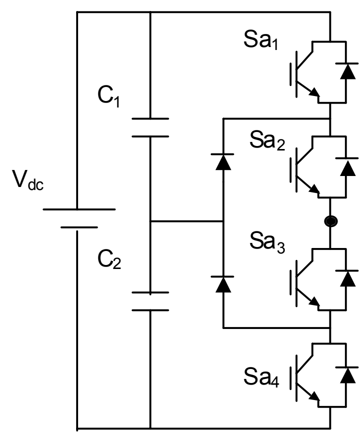

Fig. 1. A three-level diode-clamped multilevel inverter

The dc bus consists of two capacitors, and the voltage across each capacitor is Vdc/2. The voltage stress across each switching device is limited to Vdc/2 due to the clamping diodes.

Fig. 2 shows phase and line voltage waveforms for one phase of the diode clamped 3-level inverter. The line voltage V_{ab} consists of a positive phase-leg a voltage and a negative phase-leg b voltage. The resulting line voltage is a 5-level staircase waveform.

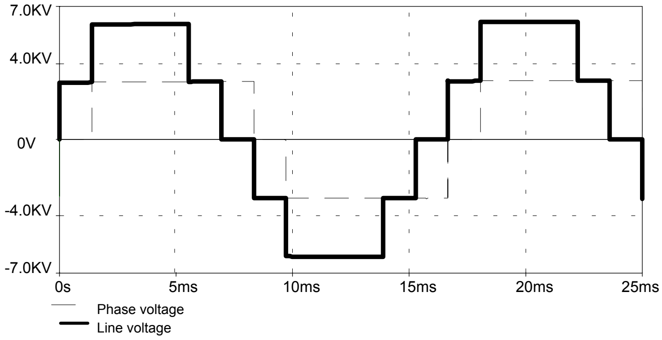

Fig. 2. Phase and line voltage waveforms for a 3-level inverter

II MODULATION STRATEGIES

This section describes the two techniques used in this work to control a three phase multilevel inverter: the step modulation [4],[5] and carrier-based PWM technique [6].

A. Optimized Harmonic Stepped-Waveform Technique

The optimized harmonic stepped-waveform technique (OHSW) is very suitable for a multilevel inverter circuit. By employing this technique, a low THD output waveform without any filter circuit is possible.

Switching devices, in addition, turn on and off only one time per period. This can reduce the switching losses, as well as EMI problems. Considering the output voltage waveform shown in Fig. 2, there are three possible optimization techniques for reducing the low-order harmonics:

1) Optimization based on equally spaced steps;

2) Optimization based on equal step heights;

3) Optimization based on both height and width of each step.

For constant input voltage, the second optimization technique is more feasible than the other two techniques. In this paper, therefore, the second optimization technique will be used. Considering equal amplitude for all dc sources, the expression of the magnitude for the harmonic components of the output voltage is given by Eq.(1):

$$H_n(\alpha) = \begin{cases} \dfrac{4E}{n\pi} \displaystyle\sum_{k=1}^{m} \cos(n\alpha_k) \rightarrow \mathit{for\,odd\,n} \\ 0 \qquad\qquad\qquad \rightarrow \mathit{for\,even\,n} \end{cases} \tag{1}$$

where E is the dc voltage supply, m is the number of dc sources and α_k the optimized harmonic switching angles[4].

In motor drive applications low-order harmonics need to be eliminated. Eq. (1) shows that m-1 odd harmonics (3rd, 5th,…) and m-1 non-triplen odd harmonics (5th, 7th,…) can be eliminated from single-phase and three-phase output waveforms respectively. Based on Eq.(1), for the three-level diode-clamped multilevel inverter the optimized harmonic switching angle found in order to eliminate most of low order harmonics was to be α_k =30° in both three phase and single phase applications.

B. Sinusoidal or "Subharmonic" Pulse Width Modulation

Carrara [6] presented multi-level subharmonic PWM (SH-PWM) as follows: for *m*-level inverter, *m-1* carriers with the same frequency f_c and same peak-to-peak amplitude A_c are disposed such that the bands they occupy are contiguous. The reference or modulation waveform has peak-to-peak amplitude A_m and frequency f_m, and it is centered at the middle of the carrier set. The reference waveform is continuously compared with each of the carrier signals. If the reference is greater than the carrier signal, then the active device corresponding to that carrier is switched on; and if the reference is smaller than the carrier signal, the active device corresponding to that carrier is switched off. In multi-level inverters, the amplitude modulation index, m_a, and the frequency ratio, m_f, are defined as:

$$m_a = \frac{A_m}{(m-1).A_c} \tag{2}$$

$$m_f = \frac{f_c}{f_m} \tag{3}$$

Carrara[6] also considered different methods of disposing the many carrier bands required in multi-level PWM inverters. The three cases he considered for an inverter with an odd number of levels were as follows:

1. Alternative phase opposition (APO) where each carrier band is shifted by 180 degrees from the adjacent bands.
2. Phase opposition (PO) where the carriers above the zero reference are in phase but shifted by 180 degrees from those carriers below the zero reference.
3. In phase disposition (PD) where all the carriers are in phase.

Fig. 3 shows a set of carriers (m_f = 10) with all of the carriers in phase for a 3-level diode clamped inverter and a sinusoidal reference voltage with m_a = 0.8. In this work is being used the carrier phase disposition (PD), which makes the line to line voltage THD to decrease. The resulting output voltage of the inverter is also shown in Fig. 3.

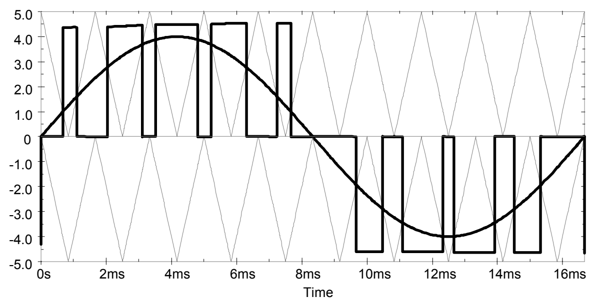

Fig. 3. Multi-level carrier-based SPWM showing carrier bands, modulation waveform, and inverter output waveform (m = 3, m_f = 10, m_a = 0.8).

In case of three phase system, there are three 120º phase-shifted modulating sinusoid to be compared with m-1 carrier signals.

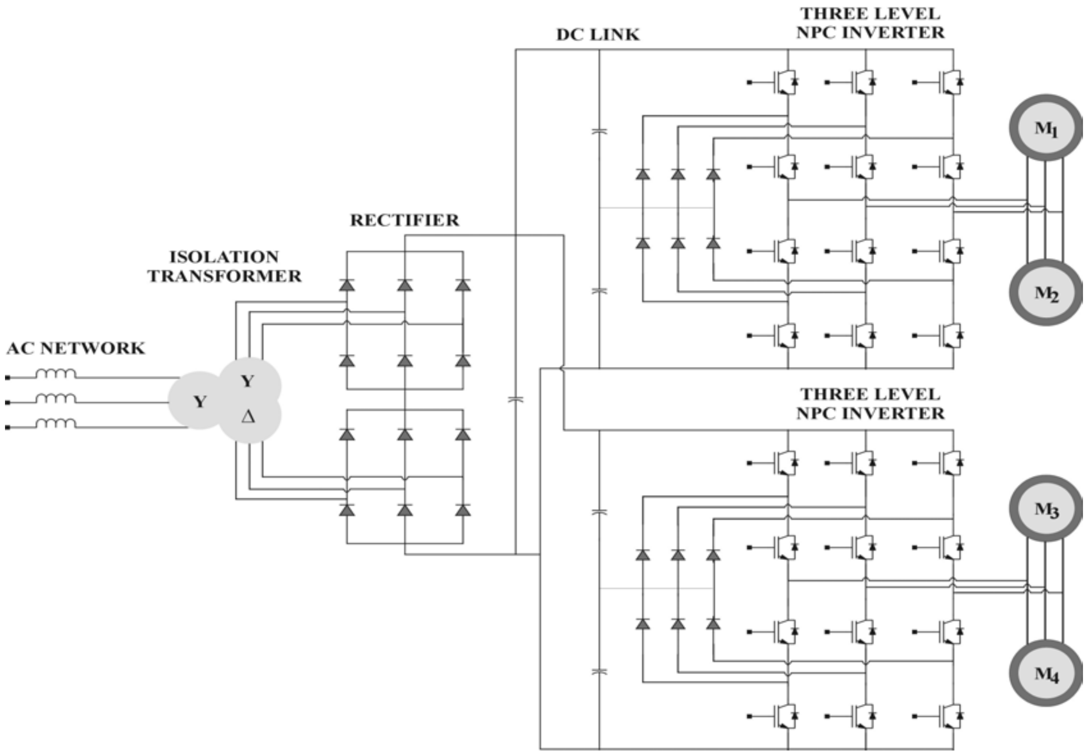

Fig. 4. Voltage Source Converter with 12-pulse rectifier, three-level inverter with IGBT's and induction motor scheme

III. CIRCUIT MODELING

The software used to simulate the two harmonic reduction strategies applied to the drive system shown in fig.04, it is required to have many features and to contain the following elements:

1. Standard R-L-C components and voltage supplies.
2. Power electronics components.
3. Coupled inductors for modeling multi-windings transformers.
4. Electrical machines.
5. Control scheme components (analog and/or digital).

A. Power circuit

The power circuit considered is represented in Fig. 4. The AC network supplies the 12-pulse diode rectifier through a 3-windings (primary Y-connection and secondary Y and Δ-connection) transformer. The DC-link is made of capacitor banks right before the 3-level inverters. Each inverter is made of 12 IGBT's and 6 NPC diodes. No additional snubber circuits are needed.

B. Motor modeling

The modeling of the three phase induction motor is based on the classical equivalent circuit diagram. Details of model used in this simulation will not be presented because it is out of this paper porpose. The ratings of the induction motor are presented in table II.

IV. SIMULATION RESULTS

A three-level three-phase multilevel converter with a 12-pulse rectifier supplying 2 inverters with 2 traction motor per inverter represented in Fig. 4 has been implemented on Orcad™ simulation tool. Table I shows systems parameters of simulation.

Table II shows the data for one motor. As seen in Fig. 4, the configuration includes 4 motors that are used in one wagon traction control. The machines are three phase squirrel cage forced-ventilated asynchronous motors.

TABLE I. System Parameters

System configuration	
Source Voltage (Line-Line)	69kV
Line Frequency	60Hz
Transformers	
Nominal Power	3.3MVA
12 Pulse Rectifier	
Nominal Power	3.3MVA
Neutral Point Clamped Inverter	
DC Link Voltage	3kV
Output Maximum Current	350A
IGBT Switching Frequency	600Hz

Table II. Motor Data

Motor Data	
Active Power Output	230kW
Voltage	2200V
Line Current	82A
Speed	1835rpm
Frequency	63Hz
Efficiency	90,9%
Power Factor	81,0%
Slip	2,9%
Poles	4

These parameters in Table I and II were based in preliminary studies of METROFOR power supply system, according to configurations of traction motor supply and control units. This configuration is used in one traction car.

The results below are presented for system operation at rated power. Startup and acceleration were not discussed in this paper.

According to Table III, the simulation results for Optimized Harmonic Stepped-Waveform Technique (OHSW) show that the diode clamped multi-inverter drew a source current with a THD of 8.14% when the displacement angle was 15º. For the same displacement angle, the THD of output line voltage and line current at the motor terminals are shown.

TABLE III. Computer Simulation Results

Modulation	*THD Source Current*	*THD Load Voltage(Line)*	*THD Load Current*
OSM angle 0º	10.97%	33.1%	17.86%
OSM angle 15º	8.14%	20.58%	19.09%
OSM angle 30º	8.66%	18.60%	17.57%
SPWM m_a =0,5	7.85%	57.94%	18.90%
SPWM m_a =0,75	11.51%	36.54%	12.82%
SPWM m_a =1	11.70%	31.21%	8.20%

For OHSW method with a 30º angle of displacement, the diode clamped multi-inverter showed a better THD value in all parameters than the first results with 15º. Figures 4 and 5 shows these three analyzed waveforms for 15º and 30º displacement respectively using OHSW technique. Figs. 6 and 7 also show the harmonic spectrum of the source current.

Considering the Sinusoidal Pulse Width Modulation (SPWM) technique, the diode clamped inverter showed a source current with a THD of 7.85% when the modulation index is 0.5. For this modulation index, the inverter output voltage at the motor terminals presented a THD of 57.94%. This result was expected due to the reduction the modulation index, decreasing the number of levels at the output waveforms. Although, for a low modulation index, m=0.5, the SPWM method presented the same THD value for the line current as the OHSW method as seen in Table III.

For SPWM method with a unity modulation index, the inverter required a source current with a THD of 11.70% and supplied output line voltage to the induction motor with a THD of 32.21%. It is important to emphasize that the load current showed a THD value of 8.20%. Which is very low as far as the motor is concern. Figures 8 and 9 shows the waveforms using SPWM with m=0.75 and unity modulation index and figure 10 and 11 shows the harmonic spectrum of the source current.

As seen in Figs. 6, 7, 10, and 11, 3rd, 5th, 7th and 9th harmonic components are eliminated. Harmonic components exist only from the eleventh harmonic.

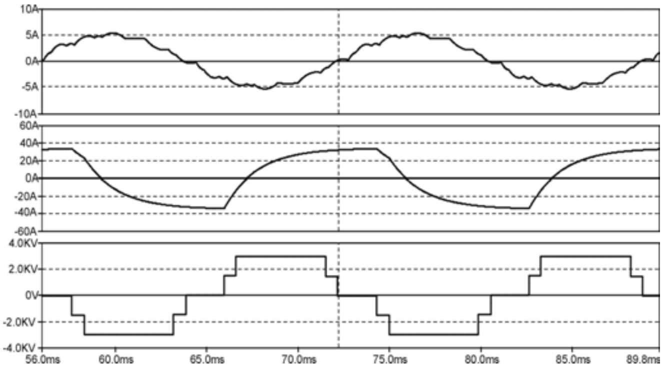

Fig. 5. Source current, line current and line voltage waveforms (OHSW => 15º)

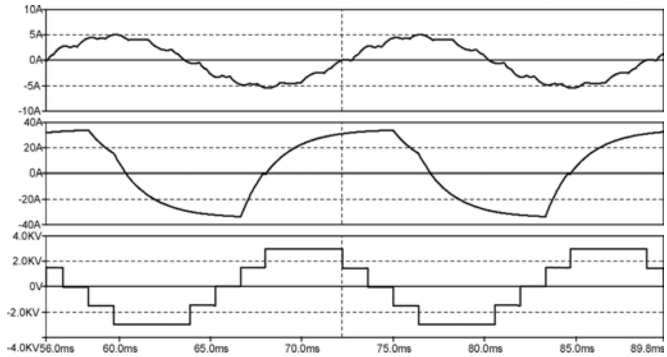

Fig. 6. Source current, line current and line voltage waveforms (OHSW => 30º)

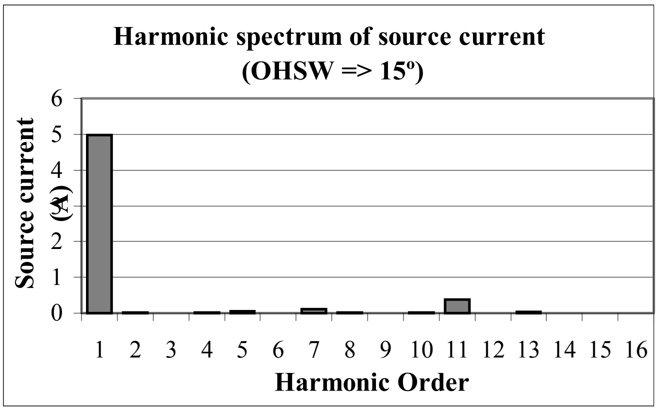

Fig. 6. Harmonic spectrum of source current (OHSW=>15º)

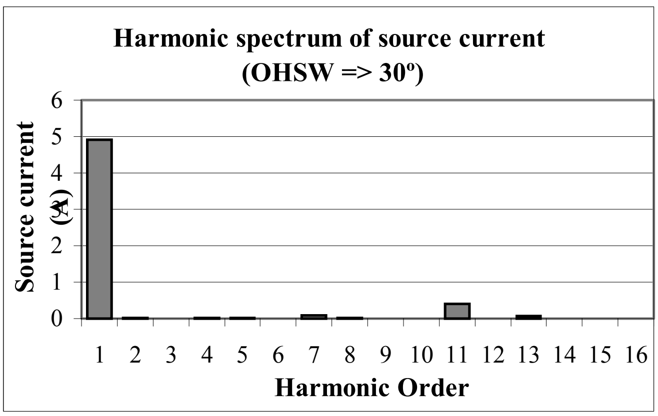

Fig. 7. Harmonic spectrum of source current (OHSW=>30º)

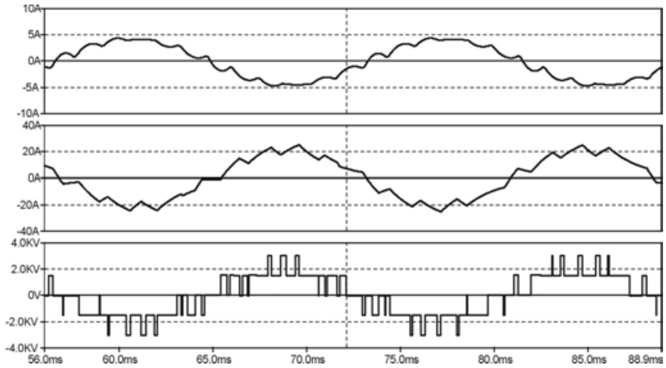

Fig. 8. Source current, line current and line voltage waveforms (SPWM => m_a=0.75)

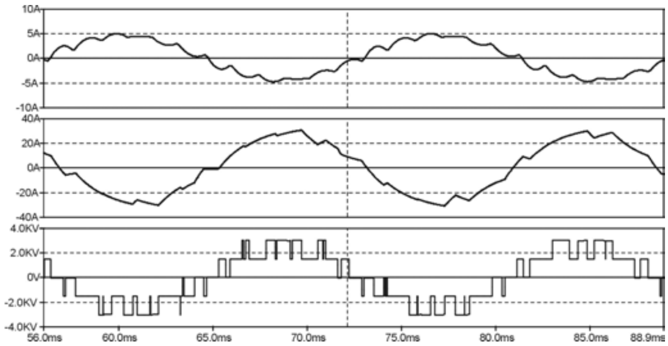

Fig. 9. Source current, line current and line voltage waveforms (SPWM => m_a=1)

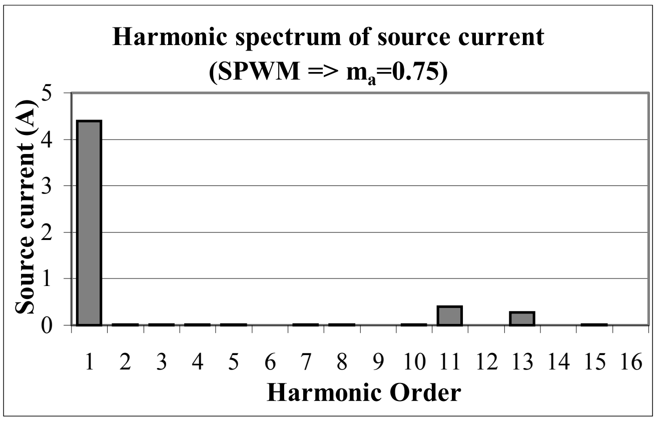

Fig. 10. Harmonic spectrum of source current (SPWM => m_a=0.75)

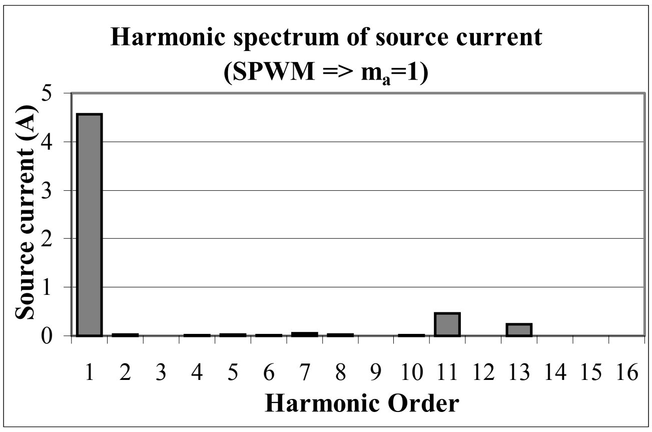

Fig. 11. Harmonic spectrum of source current (SPWM => ma=0.75)

V. CONCLUSION

A comparison between two well known modulation techniques applied to high power motor drive is presented. This analysis consisted in comparing the THD of the source current, varying the parameters of the diode clamped three-level three phase inverter, using OHSW and SPWM modulation. Additionally, simulation results also showed the output line voltage and line current harmonic analysis for the three-phase induction motor as a load. The harmonic analyzes showed that there are no 3rd, 5th, 7th and 9th harmonic components at the source current.

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