Assessment of operation performance of power converters with low frequency PWM drive issues and field weakening

Marcos Paulo Brito Gomes
Electrical Engeneering Department
CEFET-MG
Belo Horizonte, Brazil
marcospbgomes@gmail.com

Alex-Sander Amável Luiz
Electrical Engeneering Department
CEFET-MG
Belo Horizonte, Brazil
asal@des.cefetmg.br

Marcelo Martins Stopa
Electrical Engeneering Department
CEFET-MG
Belo Horizonte, Brazil
marcelo@des.cefetmg.br

***Abstract* - This paper addresses a study of a low pulsation PWM modulation technique performance, applied on frequency inverters and electric drive systems of medium to high power induction motors such as in the mining and steel industries. The main goal of using this technique is to minimize maintenance in applications with reliability and accessibility concerns. This paper focuses on modulation techniques with reduced dv/dt, and harmonics mitigation in energy conversion process, mainly those that give higher losses to the drives, being the 5^{th} and 7^{th} harmonics. The dv/dt reduction implies minimizing problems on motors windings, damaged insulation and electrostatic currents on the viscous fluid of bearings that cause motors degradation. Another concern is the need to avoid currents asymmetries that can induce pulsating torques in the machine, undesired DC voltages per phase and displacement of neutral voltage on three-phase loads, which in turn can influence common-mode current flows. The PD-PWM, POD-PWM modulation techniques and the selective harmonic elimination, SHE-PWM, are presented and evaluated, then compared through simulations and experimental results.**

I. INTRODUCTION

At an industrial manufacturing environment there are frequency inverters drives for a large power range, from kVA to tens of MVA. In steel bars and wires manufacturing, systems such as enrollers of machine wire carriages, grit blasting machines for externally corroded steel pickling, as well as grit collector belt drives from the container to the blasting system, can have their drive systems optimized. Added to these examples are general industrial drives such as hydraulic system pressurizer, load-carrying engines, conveyor arms, conveyor belts and overhead cranes that may have their motors preserved by improving the power quality driven to the machinery. The electric power quality and the search for energy efficiency have been two of the biggest concerns in the world's energy environment. Electric utilities demand regularity of power factor, decrease in operating power for unbalanced potentials, reactive power consumption limitation, and low harmonic distortion rates, THD, of industrial plants.

From the point of view of harmonic content, several international norms have addressed this concern. An example is IEEE 519-2014, which addresses the need to include higher order harmonics for THD calculation, addresses standard procedures for measurement and sampling harmonious signals in accordance with the European standard IEC 61000-4-7, indicating the $THDv$ limit of voltages and $THDi$ limit of currents in the PCC (Common network coupling point). The standard points a concern to limit individual current harmonics because they are more harmful, taking into account the ratio between the maximum short-circuit current and at nominal load I_{SC}/I_{RL}. The IEEE 1459-2010 standard indicates procedures for non-sinusoidal regime measurements and demonstrates that harmonics interfere with power factor measurement and also drain active and reactive power from electrical systems. The IEEE 519-2014 standard does not make limitations on individual plant equipment. From the grid side, individual consumers harmonics diversity implies cancellation phenomena on common coupling point, which is beneficial. In addition each consumer can use filtering systems or phase shifting transformers that mitigate harmonics of industrial plants individually, [1,2].

The drive by power converters has provided the mining and steel industry with applications in wide ranges of speed and torque, as happens in iron mills and steel mills, but the different techniques of PWM modulation imply different harmonic spectra intrinsic of the process of energy conversion AC/DC/AC on VSIs and CSIs, constituting a much discussed problem during power electronics projects. From the industrial loads side, harmonics are avoided because they cause decrease on efficiency, increase of heating, vibrations and sound noises in equipment and losses in ferromagnetic materials of transformers and electric motors, such as eddy currents and harmonics hysteresis sub-cycles. THD also becomes a concern for high efficiency drives [3,4,5,6]. Recent works have indicated that the harmonic presence can also be harmful to control systems, especially those of trajectory tracking using observer techniques. Some controls require the machine

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parameters estimation and the harmonics alter magnetization and leakage inductances, apparent rotor and stator resistances due to skin effect, and these problems tend to worsen at high operating frequencies [7, 8, 9, 10].

The problems caused by individual harmonics are difficult to establish, but it is expected that mainly the low order ones are responsible, and the 5^{th}, 7^{th} and 11^{th} harmonics being the most responsible for vibrations and pulsating torques on electric motors, especially at low speeds, when they are more noticeable, [3,11]. Modulation techniques with selective harmonic elimination, SHE-PWM, came up with the objective of eliminating specific harmonics for the entire modulation index range [12,13,14]. Furthermore, active and passive harmonic filters are important to improve the quality of synthesized voltage, being quite effective, [14,15,16].

Renowned researchers have investigated the THD of PWM modulation from its more classical forms comparing with sawtooth and triangular carriers with natural and regular sampling, and considering DSP sampling effects. Mathematical theories are often employed to calculate the Fourier series coefficients analytically, which includes approximation by Bessel's series and Jacobi-Anger's expansion, [19]. Fig. 1 shows a plot of $TDHv$ of phase voltage to neutral point V_{a0}, by natural sampling, typically expected as a function of the variation of mi and m_f. Where mi is the modulation index, and m_f is the frequency modulation index (relation between the carrier frequency f_c and the modulating voltage frequency f_m, ($m_f = f_c / f_m$).

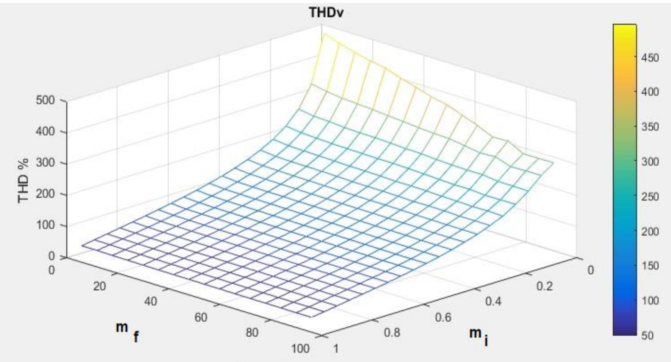

Fig. 1. Phase V_{a0} $THDv$, from a 3-level NPC inverter from symmetrical PWMs with synchronous modulating carriers and natural sampling.

Analyzing Fig. 1 it is possible to infer that for low mi the $THDv$ is always larger, but the increase of mf contributes decreasing $THDv$, but in contrapart, it is necessary to yield a greater number of pulsations to the drive dv/dts. For higher mi, $mi > 0.6$, this exchange becomes less impacting and does not significantly decrease $THDv$ and $THDi$. Even though high mf values put the harmonic content at higher frequencies, in lateral bands around the carrier wave frequency and its multiple, which facilitates filtration, but certainly in some industrial applications the reduced pulsation rate would be beneficial.

An even greater concern arises when it comes to high rates of voltage variation, dv/dts, for industrial load drives. The dv/dts are primarily responsible for the bearings degradation and electric motors damage by electrostatic discharges, increased heating and insulation damage, which reduce the machine's life causing industrial production stops for maintenance and financial losses. In addition, they cause electromagnetic emission that interfere in surrounding control circuits, as well as increased losses by switching in the inverter semiconductors [6,17,18]. For medium and high voltage drives, multilevel VSIs were consolidated as better options for switches configuration, [13,14,19,20,21].

The reduced pulsation index would reduce losses in the switching of medium and high power converters and minimize problems related to motor degradation due dv/dt. This article aims to investigate an adequate conciliation between harmonic distortion and pulsation index, considering that harmonics bring losses in the ferromagnetic material but dv/dts causes damage, being worse. In medium and high power motors and therefore more robust, the inductors act as great harmonic filters for the currents, and the $THDi$ is always smaller than the $THDv$. For low pulsation index, selective harmonic elimination can still mitigate the most harmful harmonics, being the 5^{th} and 7^{th}, decreasing the filter needs, as will be demonstrated.

II. Drive System Description

The simulation and experimental tests address an open-loop drive to investigate the impacts of three different converter modulations on the synthesized voltage quality in terms of harmonic content and dv/dts. The Fig 2. following represents the topology of three-phase three-level NPC frequency inverter.

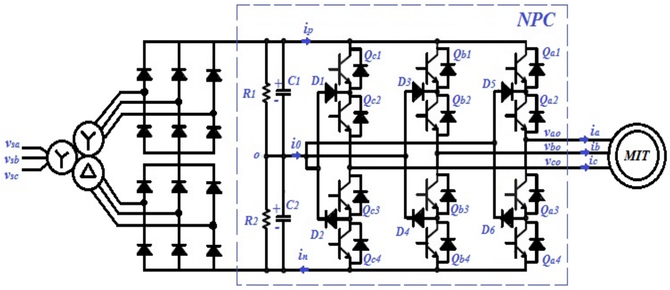

Fig. 2. Three-phase three-level NPC Inverter.

Table 1 below indicates the nominal parameters for the WEG W22 Premium 160M 15cv motor and the equivalent circuit parameters obtained by testing. These parameters were used to observe the dynamic behavior of motor currents and speeds.

TABLE I. PARAMETERS OF THE WEG W22 PEMIUM 15CV

Parameters - MIT - W22 Premium WEG 160M 15cv			
Nominal Power	**11kW(15cv)**	*Rs*	**429.0531 mΩ**
Nominal Voltage	**220/380 Vrms**	*Rr'*	**236.8330 mΩ**
Nominal Current	**38.4/22.2 Arms**	*Lls*	**1.96467 mH**
Nominal Frequency	**60 Hz**	*Llr'*	**1.96467 mH**
Nominal Speed	**1765 rpm**	*Lm*	**51.3310 mH**
Nominal Efficiency	**92.7%**	*J*	**0.1843 kgm²**
Pole Numbers	**4**	*b*	**0.00219 Nms**
Insulation Class	**F**	-	-
Temp. of Insul. Class	**80K (80°C)**	-	-
Regime Duty	**S1**	-	-

The characteristics of the modulations were analyzed for a low power converter, as a simplified testing at low currents and voltages. However the effects of the modulations as $THDv$ and number of dv/dts are independent of the power range and it is possible to estimate the impacts on more robust asset systems.

III. THE SELECTIVE HARMONIC MODULATION (SHE-PWM)

The selective harmonic elimination techniques have been studied in the last 40 years, used for converters with 2 and 3 levels, [13,14]. SHE-PWM modulation is a harmonic elimination technique that is based on a pre-programmed pulse drive. The number and angular position of the cuts in the synthesized waveform is directly related to the specific harmonics eliminated and the general decrease of the synthesized $THDv$.

The M value is related to the number of angles established within 90° ($\pi/2\ rad$), where semiconductors are switched to specific values, synthesizing the waveform. The angles are then mirrored for the remainder of waveform, given a sinusoid quarter-wave symmetry. According to [14], in order to control the amplitude of the fundamental component it is necessary to solve the following set of nonlinear and transcendental equations, which allow the elimination of $(M-1)$ harmonics. Solving this matrix of equations eliminates $(M-1)$ odd harmonics and the fundamental component is left. The last harmonic eliminated is $n_i = (3M-1)$ for M even, $n_i = (3M-2)$ for odd M. For $M = 3$, it is eliminated until the 7^{th} harmonic in the synthesis of the wave and for M = 4, eliminates until the 11°. The angles to be found are all within the range $0 < \alpha_1 < \alpha_2 \ ... \ \alpha_M < \pi/2\ rad$.

The system presented does not have an analytical solution but multiple solutions can be found numerically, so they are called trancedental equations. Based on Newton Raphson's iterative method, the system of equations can be written as:

$$\begin{bmatrix} \cos(\alpha_1) & -\cos(\alpha_2)+ & \dots & (-1)^{M+1}\cos(\alpha_M)-\frac{\pi}{4}m_i \\ \cos(5\alpha_1) & -\cos(5\alpha_2)+ & \dots & (-1)^{M+1}\cos(5\alpha_M) \\ \vdots & \vdots & & \vdots \\ \cos(n_i\alpha_1) & -\cos(n_i\alpha_2)+ & \dots & (-1)^{M+1}\cos(n_i\alpha_M) \end{bmatrix} = \begin{bmatrix} f_{1k} \\ f_{2k} \\ \vdots \\ f_{Mk} \end{bmatrix} \quad (1)$$

The switching angles vector $\overline{\alpha_k}$ and the coefficients of $f(\overline{\alpha_k})$ of the M equations at a time instant k are defined as:

$$\overline{\alpha_k} = [\alpha_{1k} \quad \alpha_{2k} \quad \dots \quad \alpha_{Mk}\ ]^T \quad (2)$$

$$f(\overline{\alpha_k}) = [f_{1k} \quad f_{2k} \quad \dots \quad f_{Mk}\ ]^T \quad (3)$$

For the system of equations (1) the Jacobian's matrix with the partial derivatives is calculated:

$$J(\overline{\alpha_k}) = \left.\frac{\partial f(\overline{\alpha})}{\partial \overline{\alpha}}\right|_{\overline{\alpha_k}} = \begin{bmatrix} \frac{\partial f_1}{\partial \alpha_1} & \frac{\partial f_1}{\partial \alpha_2} & \dots & \frac{\partial f_1}{\partial \alpha_M} \\ \frac{\partial f_2}{\partial \alpha_1} & \frac{\partial f_2}{\partial \alpha_2} & \dots & \frac{\partial f_2}{\partial \alpha_M} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_M}{\partial \alpha_1} & \frac{\partial f_M}{\partial \alpha_1} & \dots & \frac{\partial f_M}{\partial \alpha_M} \end{bmatrix} \quad (4)$$

Because it is a trigonometric function, the Jacobian's matrix becomes:

$$J(\overline{\alpha_k}) = -\begin{bmatrix} \sin(\alpha_1) & -\sin(\alpha_2) & \dots & +(-1)^{M+1}\sin(\alpha_M) \\ 5\sin(5\alpha_1) & -5\sin(5\alpha_2) & \dots & +(-1)^{M+1}5\sin(5\alpha_M) \\ \vdots & \vdots & \ddots & \vdots \\ n_i\sin(n_i\alpha_1) & -n_i\sin(n_i\alpha_2) & \dots & +(-1)^{M+1}n_i\sin(n_i\alpha_M) \end{bmatrix} \quad (5)$$

Returning to equation (2) we notice that the goal is to zero the vector $f(\overline{\alpha_k})$, thus:

$$f(\overline{\alpha_k}) = [0 \quad 0 \quad \dots \ 0\ ]^T \quad (6)$$

According to [14], to reach this goal the algorithm implemented by Newton's Method must follow a sequence of steps:

1. Generate the value of $\overline{\alpha_k}$ to for the vector of switching angles, $(k = 0)$;
2. Algorithm evaluates the coefficient vector $f(\overline{\alpha_k})$ of equation (2) for the $\overline{\alpha_k}$ values.
3. From a certain precision condition ε, check that the values found for $f(\overline{\alpha_k})$ satisfy $|f_{ik}| \leq \varepsilon\ \forall i\ \in \{1,2..M\}$;
4. In the affirmative case, if the $\overline{\alpha_k}$ are between interval $0 < \alpha_1 < \alpha_2 \ ... \ \alpha_M < \pi/2$, this is the answer.
5. If no, the system shall be linearized at the point $\overline{\alpha_k}$ in such a way that $f(\overline{\alpha_k}) + J(\overline{\alpha_k})\Delta\overline{\alpha_k} = 0$;
6. Resolution of $\Delta\overline{\alpha_k}$ such that $\Delta\overline{\alpha_k} = -J^{-1}(\overline{\alpha_k}).f(\overline{\alpha_k})$;
7. Update the switching angles as $\overline{\alpha}_{k+1} = \overline{\alpha_k}+\Delta\overline{\alpha_k}$;
8. Return to the second step by repeating from the eighth step until the desired precision is obtained for the coefficients $f(\overline{\alpha_k})$ and the condition of the 4^{th} step is satisfied.

For modulation index between $0 < mi < 1.19$, the switching angle curves versus modulation index are generated. In general, for the curves generated there is a linear behavior in the graphs for $mi < 0.6$, also in general, the beginning of each curve of the switching angles $\alpha_1, \alpha_2, \alpha_3 \ ... \ \alpha_M$, have positive and negative inclination alternating. The resulting curve for $M = 3$ eliminates the 5^{th} and 7^{th} harmonics. Given the switching angle, it is possible to implement an inverter modulation in order to comply with a constant V/f drive by "sweeping" the graph from left to right, as the machine is accelerated by increasing the frequency and mi over time, as demonstrated in Fig. 3. Eventually, for situations above the nominal speed, the modulation index is kept constant ($t = 5s$) and only the synthesized voltage frequency is increased (field weakenig region).

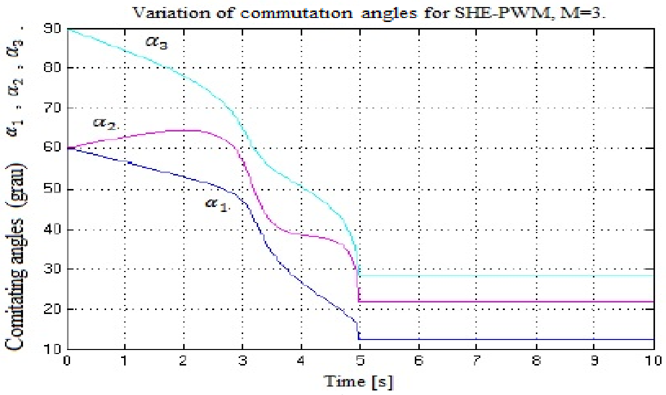

Fig. 3. Commutation angles for SHE-PWM, *versus* time.

IV. Operation at Low Frequency Modulation and Minimized Pulsation Rate.

In order to investigate the behavior of the modulations described for low mf, defending the possibility of a low pulsation index drive, this section will present the details investigated in simulations. This analysis will be performed for PD-PWM and POD-PWM for $mf = 6$ and for SHE-PWM $M = 3$, which also equals 6 pulses per fundamental voltage period.

A. PD-PWM Modulation

It can be seen from Fig. 4 that the Phase Disposition Pulse Width Modulation (PD-PWM) has switching problems because of low mf ($mf < 21$). For $mf = 6$ and $mi = 1$, the negative half-time has only one voltage draw, for $mi = 0.9$ the negative half-period would have two voltage degrees and the phase voltage waveform V_a and V_b would remain asymmetric. This reflects on the symmetry of the line waveforms V_{ab} and V_{bc} and the currents I_a ($T_L = 0$), I_a ($T_L = 1pu$) which are also asymmetric.

The current waveform of the PD-PWM for $mf = 6$ is quite distorted when there is no load torque, as demonstrated in Fig. 5. Analyzing the harmonic spectra of Fig. 6, for I_a ($T_L = 0$) the $THDi = 114.40\%$ which is extremely high. But when there is a load torque, $THDi$ lowers, because the harmonics get smaller compared to the fundamental value, for I_a ($T_L = 1pu$) a $THDi = 16.12\%$. For line voltages at $THDv = 35.29\%$.

It is worth mentioning that in these conditions there is a very low pulsation rate per fundamental period. And the increase in THD is being changed in favor of a decrease of dv/dts. To improve the symmetry of the waveforms the POD-PWM is proposed for pulse equivalence in the two half-period of voltage waveform and synthetization of symmetrical voltage wave.

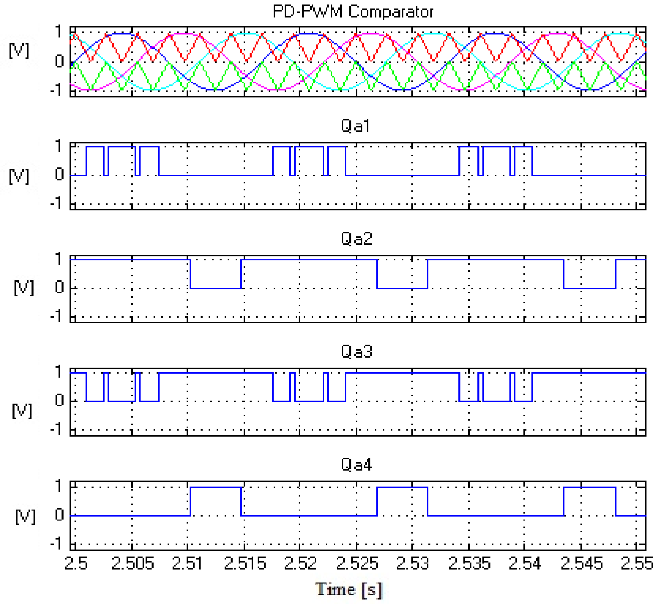

Fig. 4. PD-PWM modulation, phase a gate pulses, $mf = 6$ e $mi = 1.0$.

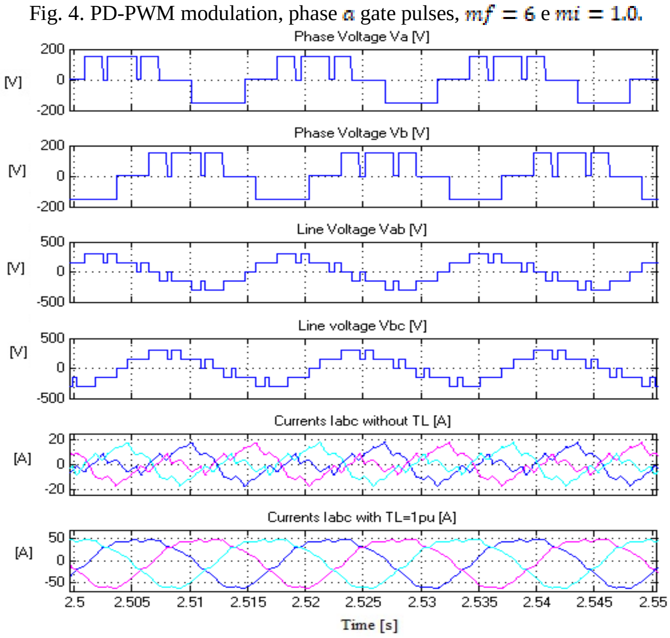

Fig. 5. PD-PWM, $mf = 6$ e $mi = 1.0$. V_a, V_b, V_{ab}, V_{bc}, I_a ($T_L = 0$), I_a ($T_L = 1.0pu$) waveforms.

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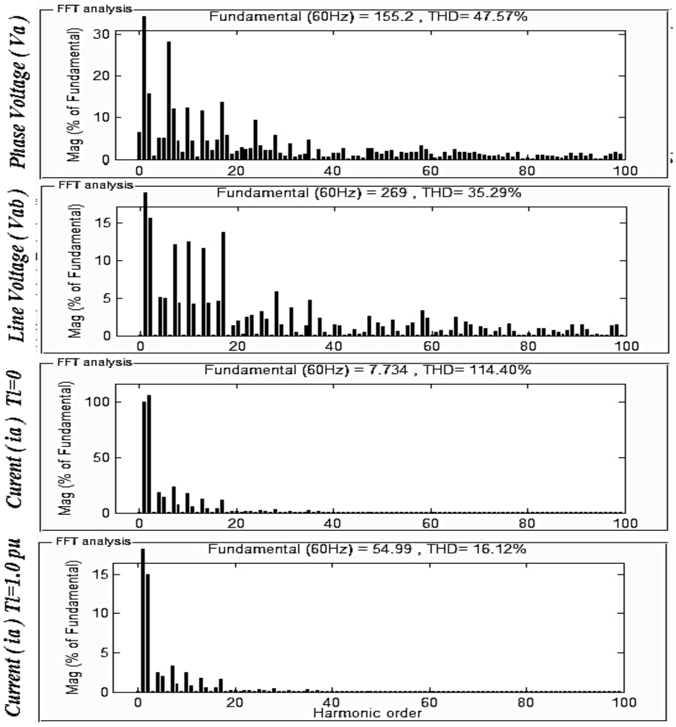

Fig. 6. PD-PWM, $mf = 6$ e $mi = 1.0$. V_a, V_{ab}, $I_a\,(T_L = 0)$, $I_a\,(T_L = 1.0pu)$ Harmonic spectrum.

B. *POD-PWM Modulation*

For the Phase Opposition Disposition Pulse Width Modulation (POD-PWM) of $mf = 6$ and $mi = 1{,}0$ there is symmetry in the gates commands, as demonstrated in Fig. 7. The waveforms of the phase voltages V_a and V_b are symmetric, and the line voltages V_{ab} and V_{bc} are also symmetrical, as demonstrated in Fig. 8.

There is an interesting harmonic cancellation phenomenon, because for PD-PWM the $THDv$ for line and phase voltages are smaller than for POD-PWM, although the latter has semi-period symmetry. Analyzing Fig. 9, for POD-PWM, V_a has $THDv = 53.43\%$ and V_{ab} has $THDv = 44.45\%$. (For PD-PWM, the corresponding values are $THDv = 47.57\%$ and $THDv = 35.29\%$, being smaller).

However the $THDi$ for the POD-PWM is always smaller than for the PD-PWM, as can be observed comparing Fig. 6 and Fig. 9. And this is interesting because current harmonics are more worrying than voltage harmonics. Without load torque, for I_a $(T_L = 0)$ the POD-PWM has $THDi = 69.73\%$ and for I_a $(T_L = 1pu)$ the current distortion is $THDi = 11.02\%$. (For PD-PWM, the corresponding values are $THDi = 114.40\%$ and $THDi = 16.12\%$, being higher).

Although this work does not address vector modulation, which is a newer technology compared to the classical modulations, but it is expected similar results to those found for POD-PWM, in reference to a synthesized voltage whose reference has a zero sequence. Then SHE-PWM for $M = 3$, based on pre-calculated pulses for harmonic optimization, will be discussed.

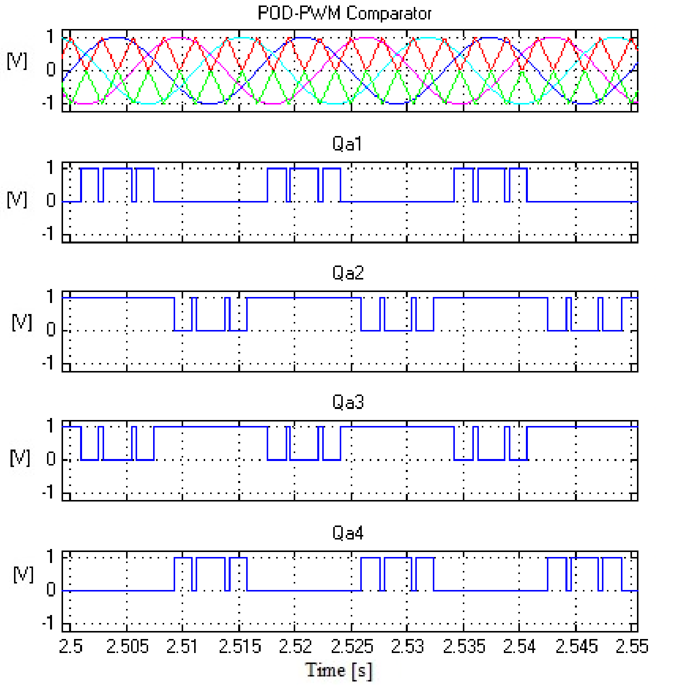

Fig. 7. POD-PWM modulation, phase a gate pulses, $mf = 6$ e $mi = 1.0$.

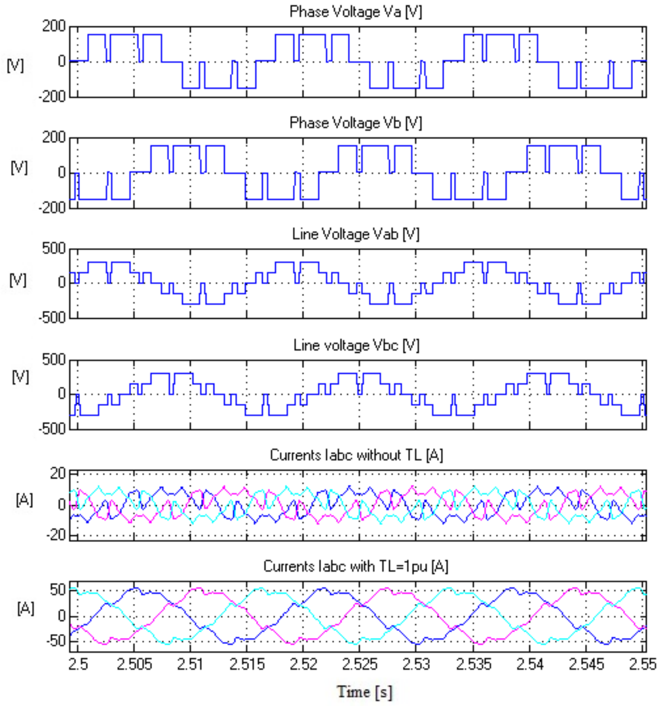

Fig. 8. POD-PWM, $mf = 6$ e $mi = 1.0$. V_a, V_b, V_{ab}, V_{bc}, $I_a\,(T_L = 0)$, $I_a\,(T_L = 1.0pu)$ waveforms.

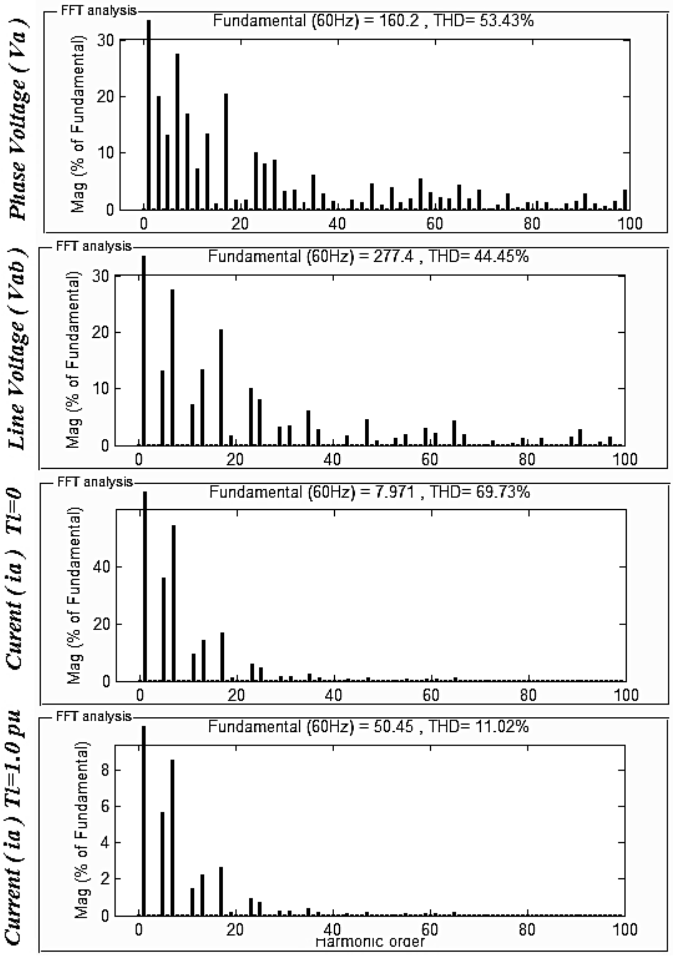

Fig. 9. POD-PWM, $mf = 6$ and $mi = 1.0$.
V_a, V_{ab}, $I_a\,(T_L = 0)$, $I_a\,(T_L = 1.0pu)$ Harmonic spectrums.

C. SHE-PWM Modulation

The SHE-PWM $M = 3$ pulses are indicated in Fig. 10 below and are always symmetrical similar to that of POD-PWM, but have different shifting. These switching angles were pre-calculated to eliminate the 5^{th} and 7^{th} harmonics of voltage and current, as can be observed in Fig. 11. These harmonics are the most damaging according to the literature [3,11]. For SHE-PWM the angle values for $mi = 1$ are $\alpha_1 = 24.4201\,°$, $\alpha_2 = 38.2065\,°$, $\alpha_3 = 48.6503\,°$.

As the pulse command is symmetrical the phase voltages V_a and V_b, line voltages V_{ab} and V_{bc}, and currents I_a $(T_L = 0)$, I_a $(T_L = 1.0pu)$ are also symmetrical. Comparing Fig. 10 with Fig. 7 it is possible to note that SHE-PWM has lower harmonic content for all voltages and currents, which is beneficial for the drive.

The SHE-PWM $M = 3$ has a $THDv = 47.75\%$ for V_a at $THDv = 32.57\%$. The current for the uncharged motor I_a $(T_L = 0)$ has $THDi = 29.43\%$ and for I_a $(T_L = 1.0pu)$ a $THDi = 4.10\%$.

The $THDi$ obtained for the motor with load is quite low, in front of the extremely low pulsation rate. For SHE-PWM of $M = 3$, the semiconductors switching frequency is $f_c = 360Hz$. SHE-PWM would be beneficial for large motors with power above 300kVA for which switching frequencies of up to only $f_c = 1kHz$ are allowed. Comparing with the parameters of the motor considered in simulation, whose power is 14kVA, for more robust motors it is expected lower currents harmonic content, since its series-inductances are greater.

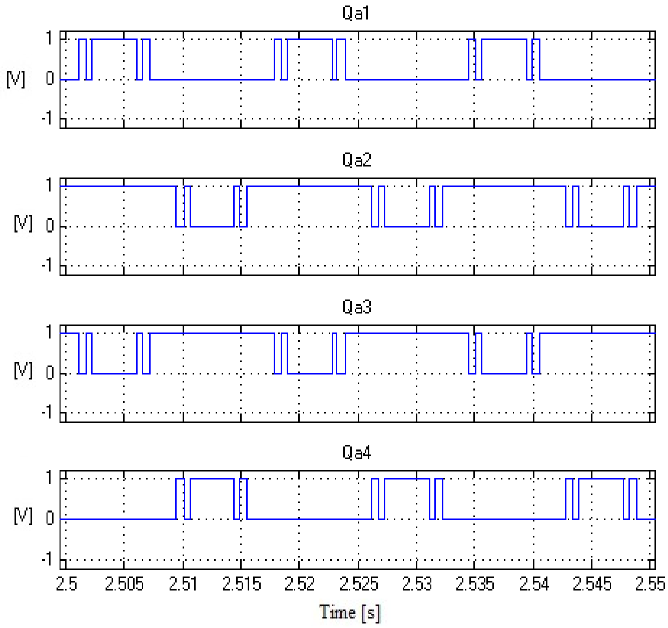

Fig. 10. SHE-PWM modulation, phase a gate pulses, $M = 3$ e $mi = 1.0$.

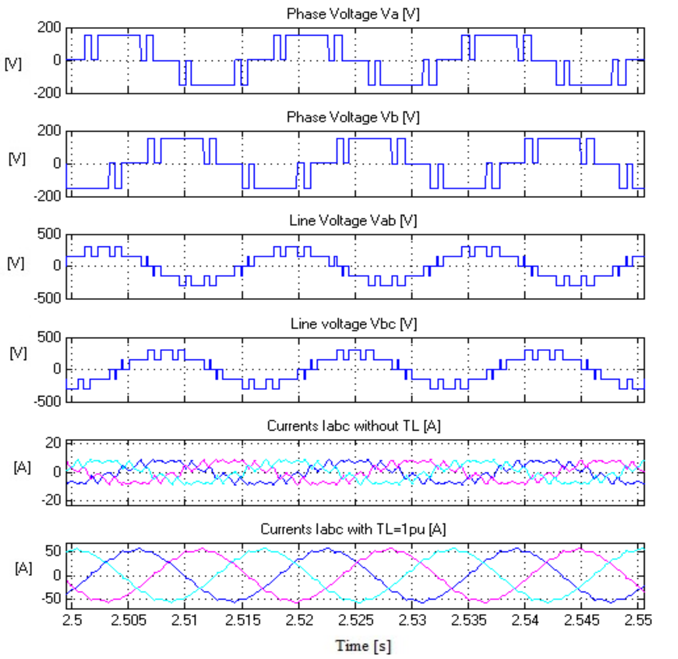

Fig. 11. SHE-PWM, $mf = 6$ e $mi = 1.0$.
V_a, V_b, V_{ab}, V_{bc}, $I_a\,(T_L = 0)$, $I_a\,(T_L = 1.0pu)$ waveforms.

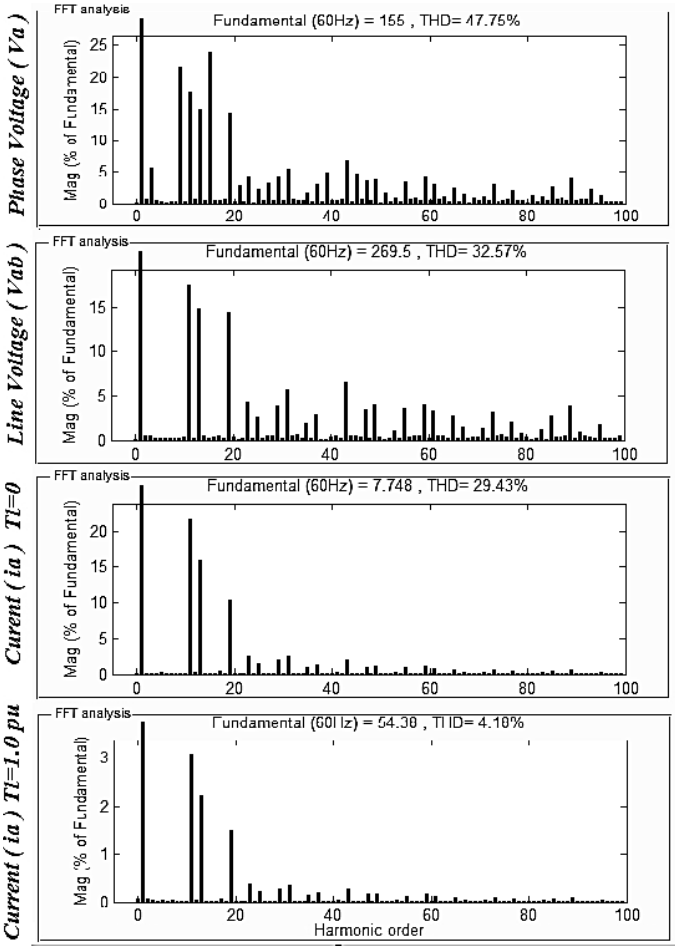

Fig. 12. SHE-PWM, $M = 3$ and $mi = 1.0$.
V_a, V_{ab}, $I_a\,(T_L = 0)$, $I_a\,(T_L = 1.0pu)$ Harmonic spectrums.

V. EXPERIMENTAL RESULTS

The experimental part consists of laboratory stand tests, Fig. 15. The selective harmonic modulation, SHE-PWM of $M = 3$, was implemented. The algorithm containing the pre-calculated pulses was implemented in a DSP signal processor. The signal processor was used to control two gate drive boards, each commanding six IGBTs of the semiconductor block, Fig. 15.

From an oscilloscope, two voltage differential probes and two ammeters, it was possible to demonstrate the two voltage signals V_a, line V_b and two-phase currents I_a and I_b for the WEG W22 Premium 15cv motor, Fig. 15, driven by the three-level frequency inverter, NPC. The voltage waveforms and currents were saved from the oscilloscope and are arranged in Fig. 13. The CSV sampled points of the signals were saved and the $THDv$ and $THDi$ acquired, as shown in Fig.14.

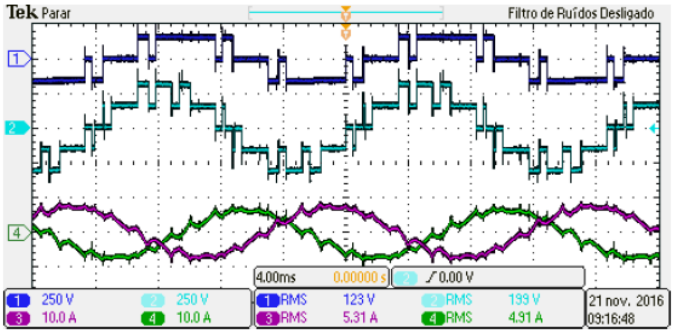

Fig. 13. Experimental SHE-PWM, $M = 3$ e $mi = 1.0$.
V_a, V_{ab}, I_a e I_b $(T_L = 0)$, waveforms.

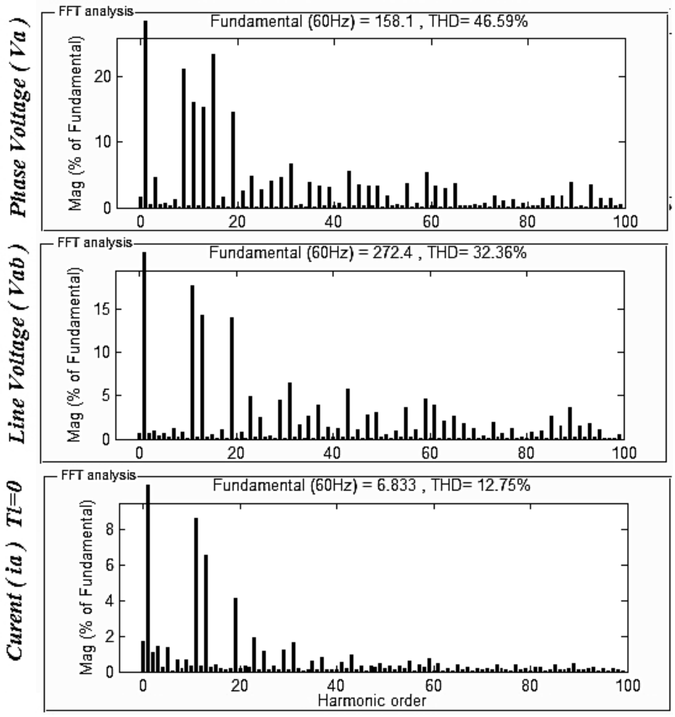

Fig. 14. Experimental SHE-PWM, $M = 3$ e $mi = 1.0$.
V_a, V_{ab}, I_a $(T_L = 0)$, Harmonic spectrums.

Fig. 15. Experimental Setup. The-level Three-phase NPC inverter and motor drive.

Fig. 13 shows the waveforms V_a, V_{ab}, I_a and I_b for SHE-PWM $M = 3$ and motor without load torque, at which time the currents $THDi$ is the maximum predicted. Experimental $THDi$ is better than simulated, comparing Fig. 12 and Fig. 14, which indicates that the experimental distortion for current is even smaller for motor with load. Engine drive designs have major concerns about temperature rise. Several issues are considered as ambient temperature, atmospheric altitude pressure and air rarity, working regime, service factor, and insulation class. The application of an unconventional modulation with reduced dv/dt also raises concerns about issues of machine overheating by possible increase of $THDi$.

The WEG W22 Premium 15 cv motor has F insulation class, class temperature $\Delta t = 80K$ for S1 working regime. As described in manual, the motor can have a maximum temperature of 155 ° C at any point and work up to 3600rpm in field weakening region. Three Pt-100 sensors were installed in the stator windings to aid in insulation protection, with the terminals available for measurement. The temperature in the ferromagnetic core and the bearings were also measured, as shown in Fig. 16.

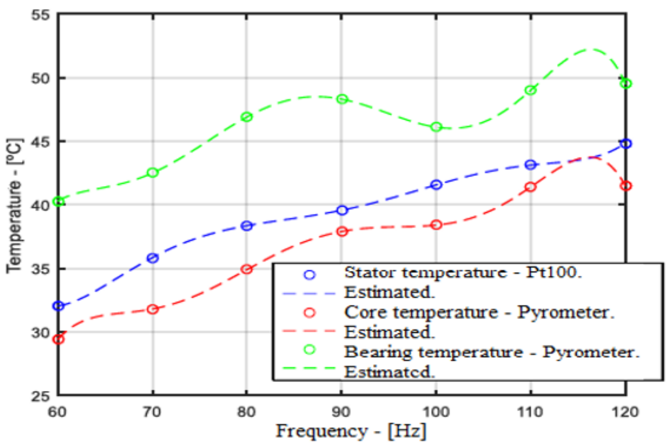

Fig. 16. Temperature measured in WEG W22 Premium 15cv motor fed by SHE-PWM modulation. 1800rpm (60Hz) to 1600rpm (120Hz).

These measurements indicate a small temperature rise, which account for the effects of harmonics, but mainly by heating the bearings by mechanical friction at high frequencies. It is possible to infer that the motor can raise the temperature by more than 110 ° C, with load coupled, without insulation damage. The low pulsation index, dv/dt, will preserve parts of the drive system, such as motor bearings and switching losses on IGBTs. Probably a long-term test will indicate for an increase in the useful life of these parts.

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