Energy Efficiency Optimization through THD and Switching Losses Reduction in Continuous and Discontinuous Digital Modulation Techniques

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Abstract: This paper analyzes the way to increase the energy efficiency of three phase converters applied to control AC motor drives, through the reduction of the total harmonic distortion (THD) of the output voltage and the reduction in the switching losses in the PWM inverter. The aim is to develop a system which selects the most adequate modulation technique required to simultaneously optimize the harmonic distortion and the commutation losses in the electronic switches that constitute the power converter. The developed modulation techniques are the sinusoidal pulse width modulation (SPWM), the sinusoidal pulse width modulation with the injection of a third harmonic of zero sequence (THIPWM), the space vector pulse width modulation (SVPWM) and different discontinuous modulation techniques (DPWM2, DPWMMAX and PWMMIN). The validation of the proposed method has been carried out on an experimental system based on the digital signal processor DSP56F807 from the commercial firm Motorola.

Key-Words: Digital PWM Modulation, Energy Optimization, Switching Losses, THD Reduction

1 Introduction
In the last few years, Voltage Controlled PWM inverters have been extensively used in the industrial world, mainly in AC driver applications, although this energy conversion has resulted in a remarkably high harmonic distortion grade in the voltage wave of the power grid. Different PWM modulation techniques have been studied in order to improve the following issues: linear modulation range, output power, total harmonic distortion (THD), switching losses and software integration simplicity. These aspects are all related to the energy efficiency optimization and so with both power factor and power quality [5].

On the other hand, the control circuit architecture of the electronic switches of the power converter has an important effect in the AC drive performance. The substitution of power supplies with transformers with multiple secondary outputs by bootstrap circuits has played an important role in the internal consumption of energy in the equipment and also in its size, weigh and cost.

These integrated circuits are developed in non-punch through (NPT) technology of high voltage, and it is possible to directly connect the digital signal processor to it. A flyback power supply and three capacitors are the only external components [7].

The carrier-based PWM methods based in analogical components have been used for years in voltage source inverters (VSI) because of their implementation simplicity and the possibility of using a very high commutation frequency that increases the power continuity in the load. The limitation of switching frequency exists due to the switching losses that are produced in the electronic converter [2].

The development of digital signal processors (DSP) and digital signal controllers (DSC) has allowed the digital modulation methods to become the most important PWM methods for three-phase converters. And the space vector modulation (SVPWM) with the extensive use of vector control schemes became the most important technique in the last decade. In this method the possibility of controlling the commutation sequence allows for the so called discontinuous methods (DPWM) that improve the energy efficiency in certain circumstances [3] [6].

The experimental prototypes presented here are a consequence of a co-design scene, in which digital processors especially designed to be used in electronic power conversion, integrated devices to control the electronic switches with capacitive insulation and high voltage instrumentation are employed, along with software that provides the optimization of highly specialized functions. Based
on all this, a vector control scheme that includes techniques of continuous and discontinuous modulation that can be used individually or in combination has been developed. The total harmonic distortion (THD) generated and the switching losses in the electronic conversion are simultaneously studied looking for the best combination for increasing the efficiency of the energy transformation.

### 2 New Electronic Power Switches Control Techniques

The communication between the power system and the control system is one of the main issues in the power electronic design. Fig. 1 shows the different functions that an AC driver has to incorporate to control an induction motor and allows to be observed the necessity for electric isolation between the processor, the instrumentation system and the gate drive functions [7].

![Fig. 1 Functions in AC motor drives](image)

The search for solutions has lead to different hardware design strategies: two level voltage architecture, one level voltage architecture and hybrid architecture.

By means of the experimental analysis of the three architectures it can be concluded that the one voltage level scheme allows an important reduction of the converter internal consumptions and the diminution of its size, weight and cost, since the number and dimension of the necessary supply sources in the operation are dramatically reduced. These characteristics will allow its growth in low and middle power systems.

The circuit to control gates shown in the Fig. 2 is designed based on the capacitive isolation obtained through the so called circuit “bootstrap” and that is formed by the capacitor $C_{bstr}$ and the ultrafast diode $D_{bstr}$. The operation is based on the charge of this capacitor with the energy obtained by a remote power supply when the power transistor $T4$ is turned-on. When this transistor is blocked and supposing that the capacitor is charged, the diode $D_{bstr}$ is blocked and isolates the power supply from the voltage applied to the $A$ motor phase. The energy charged in the capacitor $C_{bstr}$ will suppose the control of the converter when the command system imposes the transistor $T1$ to be turned-on. The bootstrap capacitor is designed from equation (1).

![Fig. 2 Bootstrap circuit](image)

$$C = 15 \times \left[ \frac{2Q_g + \frac{I_{gh(max)}}{f} + Q_h + \frac{I_{Ch(leak)}}{f}}{V_{cc} - V_f - V_{LS}} \right]$$

where $Q_g$ is the upper transistor gate load, $I_{Ch(leak)}$ is the leak current of the isolation capacitor, $V_f$ is the direct voltage of the bootstrap diode, $Q_h$ is the load displacement by cycle required (5nC for IC-600V or 20nC for IC-1200V), $f$ is the frequency of operation, $I_{gh(max)}$ is the gate current, and $V_{LS}$ is the lower switch direct voltage.

### 3 Digital Signals Modulation and System Losses

In three phase power inverters for AC motor drives, the concept of modulation is related to the DC/AC energy transformation in the best conditions. Many studies and research have been carried out on the way to obtain a quality modulated wave [3] [5] [6].

The factors that define this concept of quality are maximum output power from the DC voltage to obtain the greatest amplitude of AC voltage, the generation of minimum number of harmonics that affect to the machine and to the grid, and finally, the decrease in the losses in the electronic converter.

A useful figure of merit employed in the study of power converters is the distortion factor $d$ that is defined by the equation (2). This parameter relates the rms value of the distortion current for the modulated system, equation (3), to the rms value of the harmonic current of the converter modulated in a six-step technique [5].

$$d = \frac{I_h \text{ rms}}{I_h \text{ rms six-step}}$$

$$I_h \text{ rms} = \sqrt{\frac{1}{T} \int_0^T [i(t) - i_1(t)]^2 \, dt}$$
The index of maximum modulation $M_i$, equation (4), is the figure of merit that indicates the level of power in the AC-DC-AC transformation from the direct voltage to the ac voltage obtained in the inverter output:

$$M_i = \frac{V_1}{V_{1 \text{ six-step}}}$$  

being:

$$V_{1 \text{ six-step}} = \frac{2}{\pi} U_{dc}$$  

where $V_1$ is the amplitude of the fundamental harmonic of the modulated wave in the motor phase and $V_{1 \text{ six-step}}$ represents the amplitude of the fundamental harmonic for the six-step modulation technique.

The evaluation of the losses that are produced in the system is complex since it depends on different factors such as the level of load on the motor, the commutation frequency $f_s$, or the modulation technique.

The losses in the power semiconductors can be classified in two categories: the losses by conduction, equation (6), and the commutation losses that can also be classified in turn-on and turn-off transitions in each period of commutation. It is possible to approximate the average switching power loss from equation (7).

$$P_{on} = V_{Son} I_{dc} \frac{t_{on}}{T_s}$$  

$$P_{comm} = \frac{1}{2} U_{dc} I_{dc} \left( t_{on} + t_{off} \right)$$  

where $V_{Son}$, $t_{on}$, $t_{on}$, and $t_{off}$ are the conduction voltage, the conduction time, and the turn-on and turn-off transition time respectively. $U_{dc}$, $I_{dc}$ and $T_s$ are the DC voltage, the DC load current and the transition time.

Fig. 3 shows the scheme of a high performance vector control AC drive, and the parameters that are included in it. It is possible to obtain the losses in the machine through these parameters [1].

The losses in AC machines can be divided into four basic categories: copper losses $P_{\text{cor}}$, core losses $P_{\text{copper}}$, mechanical losses, and stray load losses.

The electrical or copper losses are the resistive heating losses that occur in the stator and rotor winding of the machine, equation (8). The rotor copper losses are produced by the rotor current that is established by electromotive force produced by slip frequency $\omega_s$ and rotor flux $\psi_r$, equation (9).

$$P_{\text{copper}} = k \left[ R_s |i_s|^2 + \left( i_{sq} \frac{L_n}{L_m} \right)^2 R_r \right]$$  

being:

$$\omega_s \psi_r = i_{sq} \frac{L_n}{L_m} R_r$$  

where $R_s$, $R_r$, $L_n$, and $L_m$ are the resistances and inductances of the induction motor, $i_s$ is the stator current vector and $i_{sq}$ is its component over the q axis.

As the motor winding resistances vary with the different harmonic components of the current modulated wave, due to the skin and lateral effects, it is possible to calculate the copper losses produced by them as follows:

$$P_{\text{copper}} = 3 I_{\text{rms}}^2 (R_s + R_r)$$  

The core losses are the hysteresis and eddy current losses occurring in the metal of the motor. These losses vary with the square of the flux density and with the rotation speed of the magnetic field. These losses can be described as:

$$P_{\text{cor}} = k \left[ k_h |\omega_s|^2 + k_e \omega_e^2 \right]$$  

where $k_h$, $k_e$ and $k$ are the hysteresis, eddy and Clarke design coefficient, $\omega_s$ and $\omega_e$ are electromagnetic flux and its speed respectively. On the other hand, the rotor core losses have not been taken into account due to low slip value [2].

As conclusion, it can be seen on the one hand, the influence that the distortion factor has on the motor losses and on the other hand, the influence that the level of current, voltage and the number of commutations have in the power converter losses. An improvement in these parameters by the adaptation of the modulation technique to the conditions of the machine can reduce the losses level and therefore can improve the efficiency of the system.

4 Digital Pulse Width Modulation (PWM)

Two main implementation techniques exist in the pulse width modulation (PWM): the per-carried-based PWM method and the space-vector PWM method. The first one compares a triangular high
frequency signal with a modulation reference signal, being the commutation times the cross points of both signals. The SVPWM method is based in vector control schemes [5].

The star wire connexion in AC machines and the absence of the neutral current path to the co-phased harmonic to be returned provide a degree of freedom in the digital implementation of both methods: the injection of zero sequence signals in per-carried-based PWM and the control of zero vectors in the space vector modulation. The last one provides different techniques of discontinuous pulse width modulation.

4.1 SPWM

In digital SPWM modulations a sinusoidal wave is digitised in a board in the memory of the processor, with as many values as the precision of the modulation and the maximum frequency of commutation that the converter requires. Later, by means of a routine of the application program, the values of the board are read in such a way that the signal modulated in width is synthesized to obtain an adequate value of the fundamental harmonic and the necessary frequency for a correct speed control of the AC machine.

The carrier signal is a high frequency triangular signal and the modulating signal is the sinusoidal reference wave. The modulated output voltage of the PWM inverter becomes:

\[ V_{AN} = \frac{1}{2} m U_{dc} \sin(\omega t) + HF \text{ Components} \]  

where \( m \) represents the modulation index between the peak value of the sinusoidal modulating signal and the peak value of the high frequency carrier signal, \( \omega \) the fundamental frequency in rad/s and the high frequency terms are proportional to the frequency of the carrier signal \( \omega_c \).

While the maximum value of the modulating signal is lower than the triangular signal, the modulation is linear and its index is smaller than one. When the amplitude of the sinusoidal signal exceeds that of the triangular signal the modulation is not linear and enters the so called overmodulation zone in which the output modulator signal tends to a six step modulation [4].

A way to increase the AC output voltage level and therefore to increase the total modulation index \( M \), is the zero sequence signals addition in the modulators. The injection of a third harmonic with different amplitude leads to the THIPWM modulation.

4.2 SVPWM

The space vector modulation is related to the vector control of AC motor drives (Fig 3). This modulation transforms directly the components of the stator voltage vector in a stationary reference system into the duty cycles of the power switches of the three phase inverter [3][5].

Fig. 4 shows a SVPWM modulation that permits eight possible states: six conduction states and two non conduction states. The six conduction or active vectors are called \( U_0, U_{60}, U_{120}, U_{180}, U_{240}, U_{300} \) and the two zero or non active vectors \( U_{000} \) and \( U_{111} \), all defined in an orthogonal stationary system of co ordinates d-q.

In this kind of digital modulation the active vectors divide the space in the six regions (I-VI) in which the output voltage vector can be situated, and in each of these regions the stationary components of this vector should be projected on the active vectors that limit the region. On the other hand, the different distributions of the zero vectors give rise to different space vector modulation techniques.

As shown in the Fig. 4 the reference voltage vector \( v_s \) is formed by its two orthogonal static components \( v_{ds} \) and \( v_{qs} \), that are originated in the vector control output. These orthogonal components, as can be observed in the diagram, are projected on the active vectors \( U_0, U_{60} \). This sequence of projections in the stationary axes d-q and in the active vectors \( U \) will be repeated for each position of the
output stator voltage $v^*_s$, in each of the six possible regions.

The equation (13) represents the Clarke transformation that relates the three phase stator voltages and the two phase d-q components of the stationary orthogonal co ordinates system, equation (14).

\[
\begin{pmatrix}
v_{ds} \\
v_{qs}
\end{pmatrix} = \frac{2}{3} \begin{pmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{pmatrix} \begin{pmatrix}
v_{av} \\
v_{bs} \\
v_{cs}
\end{pmatrix}
\]

(13)

\[v^*_s = v_{ds} + jv_{qs}\]  

(14)

In one sampling interval the output voltage vector can be written as:

\[v^*_s = \frac{T_0}{T_s} U_0 + \frac{T_{60}}{T_s} U_{60} + \ldots + \frac{T_{300}}{T_s} U_{300}\]  

(15)

where $T_0$, $T_{60}$, ..., $T_{300}$ are the turn-on time of the vectors $U_0$, $U_{60}$, ..., $U_{300}$. The total of these time intervals is the sampling time. This expression permits to evaluate the output voltage vector in infinite possibilities, the usual one is to use the two adjacent vectors and the zero vectors.

Finally, when voltage vector $v^*_s$ has been represented in the stationary orthogonal reference frame by its components, these components can be calculated on the active vectors depending on the sector ($n = I...IV$) where they are located projecting them on these vectors, according to the equations (16) and (17). Each active vector application time is obtained from these equations and, with the definite sampling time for the modulation period, allows the calculation of the application time of the zero vectors according to the equation (18):

\[T_0 U_0 = \frac{2}{\sqrt{3}} v^*_s \sin(n \frac{\pi}{3} - \alpha)\]  

(16)

\[T_{60} U_{60} = \frac{2}{\sqrt{3}} v^*_s \sin(\alpha - (n-1))\]  

(17)

\[T_s = T_0 + T_{60} + T_{(000)} + T_{(111)}\]  

(18)

For the sector I, $U_0$ and $U_{60}$ are the adjacent active vectors corresponding to this sector, $T_0$ and $T_{60}$ are the each active vector application times, $T_{(000)}$ and $T_{(111)}$ are the zero vectors application times, and finally $T_s$ is the sampling time.

The possibility of controlling the zero vectors in the SVPWM becomes it into a method to arise the discontinuous modulations DPWM. The DPWM2 modulation alternates the zero vectors, the vector $U_{(111)}$ in odd sectors and the vector $U_{(000)}$ in even sectors. The DPMMMAX modulation utilizes only the null vector $U_{(111)}$ what supposes that $T_{(000)}=0$ in the equation (18). Finally, the DPWMMIN modulation will utilize only the null vector $U_{(000)}$ which supposes that $T_{(111)}=0$ in the equation (18).

5 Comparative Analysis and Study of Commutation Performance

The converter which has been designed and developed for the analysis of different continuous and discontinuous modulation techniques is shown in Fig. 5. These techniques have been implemented, in some cases, in an independent way and in others, combining them to achieve an optimization of the converter efficiency.

![Fig. 5 Experimental converter](image)

The characteristics of different techniques have been experimentally studied on an IGBT based inverter driving a three phase 1/2 hp and a three phase 7 hp induction motors. In both studies similar results have been achieved.

In the following figures 6-11 the experimental modulations can be observed. In each figure, the first graphic shows the continuous voltage level in the intermediate circuit (green) and the modulated voltage by phase on the output of the digital modulator (red) and in the second one a harmonic voltage phase motor analysis is presented.

The SVPWM method shows its superior performance characteristics over the SPWM technique providing a better use of inverter voltage utilization. Moreover Fig. 12 shows a smaller content of high frequency harmonic. Taking into account these considerations it can be said that the SVPWM technique improves its impact in the performance system.

When the modulation index is growing the digital modulators reduce the harmonic distortion, fundamentally in the DPWM2 at low velocity and the DPWMMIN at high speed. These reductions added to a lower number of commutations, that impact on the switching losses, dramatically improving the efficiency.
Fig. 6 Sinusoidal modulation (SPWM)

Fig. 7 Space vector modulation (SVPWM)

Fig. 8 Sinusoidal modulation with injection of a third harmonic (THIPWM)

Fig. 9 Digital modulation DPWM2

Fig. 10 Digital modulation DPWMMAX

Fig. 11 Digital modulation DPWMMIN
Fig. 12 Index of total harmonic distortion (THD) for three different velocities

Fig. 12 shows the graphic that compare the total harmonic distortion index for the modulation techniques that have been developed and implemented by the software. In this figure the measurement at low speed, at base speed and finally in the field weakening zone is carried out.

Fig. 13 and Fig. 14 show the resulting measurements of temperature variation obtained in the induction motor and in the three phase power block head sink. This component has a temperature sensor that provides a method to evaluate the changes on this parameter. Current and voltage measurement at the power switch terminal is difficult because access to the switch is not always practicable.

It is possible to estimate the total losses in commutation for the proposed modulations by the analysis of the different temperature range reached. In Fig. 13 and Fig 14 the graphics compare the temperature for the studied modulation techniques. In the first graphic the measurement at nominal speed without load is carried out and in the second graphic the measurement at low speed and total load is carried out.

When a high efficiency in the modulation performance is required it is possible to combine these techniques, by means of algorithms that seek to optimize the distortion factor of the signal at the output, the losses in the commutation of the electronic switches or both. Fig. 15 shows the on-line decision algorithm.
However a notable effect produced in the digital modulations DPWM2 and DPMMAX is the strong audible noise in stator wounding to zero frequency, a lot more noticeable than in the other implemented modulations.

6 Conclusion
The introduction of new hybrid microprocessors with power converter oriented components has made possible the development of digital continuous and discontinuous modulation techniques in the AC drivers that can improve the energy efficiency in AC-DC-AC transformations.

The converter presented in this paper utilises a software algorithm that selects the optimal modulation based on the induction motor speed, on the mechanical load level and on the temperature of three phase power converter. The reduction on the motor losses has been estimated to be between 10% and 25% and the reduction on switching losses to be between 10% and 40%. These variations depend on speed, load and temperature conditions.

It can also be further stated that improvements in the AC drive internal energy efficiency can be obtained by new designs of electronic systems to control the gates of power switches.

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