SPREAD SPECTRUM SWITCHING: A LOW NOISE MODULATION TECHNIQUE FOR PWM INVERTER DRIVES

by

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'I wisdom dwell with prudence
and find out knowledge of witty inventions'.
Proverbs 8:12 (KJV).

ABSTRACT

Three phase AC drives controlling cage induction motors have become widely accepted in industry, but one extant problem with this technology is that of increased acoustic noise emitted from the driven motor.

This Thesis addresses the problem of the acoustic noise emitted from motors driven from voltage sourced PWM inverters and proposes a technique - Spread Spectrum Switching - for minimizing its effects. In the course of the work many other issues associated with real-time microprocessor-based PWM have also been advanced:

- efficient microprocessor based PWM waveform generation,
- harmonic analysis of generalized PWM waveforms,
- compensation for the effects of power switch timing delays, and
- compensation for the finite resolution of timers.

The Thesis uses a variety of computational and analytical methods, backed by experimental observations, to quantify the improvement gained in each of these areas.

Spread spectrum switching is a technique for eliminating the characteristically tonal structure of the acoustic noise emitted from a PWM inverter driven motor. Similar to the concept of spread spectrum communications, spread spectrum switching involves pseudo-randomly varying the instantaneous PWM switching frequency so that the energy of any PWM switching harmonics is dispersed over a wide bandwidth. This energy dispersion effectively eliminates any tonal components from the resultant motor acoustic noise while leaving the overall sound level largely unchanged; spread spectrum switching provides a significant qualitative yet minimal quantitative noise reduction.

The PWM generation paradigm used in this Thesis is the recently reported Space Vector Modulation. A novel algorithm for microprocessor based space vector PWM generation is proposed, providing a basis for fast, efficient generation, even when overmodulating - a situation where many algorithms operate significantly more slowly. Furthermore, it is shown that the space vector method inherently generates a near optimum - in terms of motor harmonic loss - PWM waveform. However, when physically realized on a practical inverter such ideal PWM waveforms are corrupted by timing errors associated with both the inverter's power switches, predominantly the lockout time, and the finite resolution of hardware

timers. Resolution corrected modulation is proposed for overcoming the problem of finite timer resolution and involves the use of integral feedback to account for any errors between ideal and physically realizable PWM switching times. This technique effectively provides 4 to 5 bits of added resolution to a given timer, allowing accurate waveform generation at low sinewave amplitudes and high switching frequencies using readily available, often microprocessor based, timers. Lockout times cause inverter output voltage errors, with consequent current zero crossing distortion, and a strategy for alleviating this problem is proposed and implemented in both a triangulation and space vector modulator.

Two harmonic analysis techniques are proposed for analyzing PWM waveforms. The first technique is suitable for the analysis of regularly sampled PWM waveforms and has been used here to obtain closed form expressions for the harmonics of both space vector and asymmetrical triangulation PWM. These expressions show that PWM harmonics occur as a series of "combs" centered on multiples of the switching frequency. A second technique - the Directional Rotational Transform - is proposed for numerical analysis of general PWM waveforms. This technique uses an equivalent space vector representation of the PWM waveform, yielding the magnitude, phase and sequence (positive or negative) of the harmonics, and is useful in situations where each of the three phase waveforms is different, as in these cases Fourier Transform analysis of a single phase or line voltage only approximates the harmonics actually seen by the motor. The spectra generated using both these techniques compare favourably with those measured experimentally and, for synchronous PWM, those evaluated from Fourier Transforms.

The culmination of modulation techniques presented in this Thesis yields a microprocessor based AC inverter drive featuring low acoustic noise emission at but a few kiloHertz switching rates and accurate PWM waveform generation using a single chip, low cost, micro-controller.

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Paul Handley
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NOMENCLATURE

Acronyms

AC	-	Alternating "Current" (denotes a sinusoidal quantity)
BJT	-	Bipolar Junction Transistor
DC	-	Direct "Current" (denotes a constant quantity)
DFT	-	Discrete Fourier Transform
DRT	-	Directional Rotational Transform
EMF	-	Electro-Motive Force (V, pu)
EPROM	-	Erasable Programable Read Only Memory
FFT	-	Fast Fourier Transform
GTO	-	Gate Turn-Off Thyristor
IGBT	-	Insulated Gate Bipolar Transistor
MCT	-	MOS Controlled Thyristor
MMF	-	Magneto-Motive Force (A-t)
MOSFET	-	Metal-Oxide-Semiconductor Field Effect Transistor
NPC	-	Neutral Point Clamped
PRBS	-	Pseudo Random Binary Sequence
PU	-	Per Unit (pu)
PWM	-	Pulse Width Modulation
QSW	-	Quasi Square Wave
RCM	-	Resolution Corrected Modulation
RMS	-	Root Mean Square
RPM	-	Revolutions Per Minute (rpm)
SCR	-	Silicon Controlled Rectifier
SPL	-	Sound Pressure Level
SSS	-	Spread Spectrum Switching
SVM	-	Space Vector Modulation
3ϕ	-	Three Phase

Symbols

a_n	-	n^{th} harmonic magnitude (pu, RMS or peak)
$A(t)$, $B(t)$, $C(t)$, $D(t)$	-	PWM pulse waveforms
B	-	instantaneous airgap flux density (T)
B_r, B_t	-	radial and tangential components respectively of B
$d(f)$	-	band-limited random dither variable (Hz, pu)

E	-	DC motor back emf or three level inverter DC bus voltage (V, pu)
e_a, e_b	-	error between ideal and realizable PWM switching times (sec)
f_c, f_m	-	PWM carrier and modulating waveform frequencies respectively (Hz)
f_1	-	fundamental frequency of modulating waveform (Hz)
f_{av}	-	average switching frequency of a SSS PWM modulator (Hz)
$J_n(x)$	-	Bessel function of first kind of order n
L	-	series inductance in DC motor equivalent circuit (H)
L_m	-	CIM equivalent circuit mutual inductance (H)
l_s, l_r	-	CIM equivalent circuit stator and rotor leakage inductances (H)
n, p, q, r	-	integers, i.e. 0,1,2,..
P_{Cu}	-	motor harmonic copper loss (W, pu)
R, Y, B, N	-	three phase waveform designators, and neutral
R_s, R_r	-	CIM equivalent circuit stator and rotor resistances (Ω)
t, t_n	-	time (sec)
δt_n	-	width of t_nth pulse (sec)
t_0, t_a, t_b, t_7	-	duration at voltage vectors $\mathbf{u}_0$, $\mathbf{u}_a$, $\mathbf{u}_b$ and $\mathbf{u}_7$ respectively during a single space vector modulation cycle (sec)
t_d	-	lockout time (sec)
T	-	single space vector modulation cycle period {i.e. half a complete PWM cycle period, $(\frac{1}{2f_c})$} in AC PWM or total PWM period in DC PWM (sec)
T_1, T_2	-	PWM pulse times for AMD9513 timing format
T_m	-	active modulation time (sec) {$T_m = t_a + t_b$}
$\mathbf{u}_S$	-	reference voltage space vector (pu)
$\mathbf{u}_a$, $\mathbf{u}_b$	-	generalized voltage space vectors; defined as the two active voltage space vectors immediately adjacent $\mathbf{u}_s$ (pu)
$\mathbf{u}_i$	-	voltage space vectors realizable with a two-level inverter, (pu), i = 0..7
V	-	voltage (V, pu)
V_{DC}	-	inverter DC bus voltage (nominally 560V for 400V 3ϕ mains) (V)
$\pm V_{DC}$	-	voltage of a a DC bus rail with respect to the bus midpoint, $\frac{V_{DC}}{2}$
α	-	intrasextant angle of $\mathbf{u}_s$ (rad)
δ	-	difference between circular and hexagonal space vector loci (pu)
$\Delta(\theta)$	-	SVM "curved" triangle distortion waveform (pu)
∂	-	duty cycle, $0 \le \partial \le 1$, (pu)

θ	-	phase angle, $\omega_m t + \phi$, (rad)
θ_i	-	i^{th} PWM switching angle, (rad)
i_n	-	n^{th} harmonic current (A, pu)
Λ	-	motor airgap permeance (Wb/A-t)
μ_o	-	permeability of free space, ($\mu_o = 4\pi * 10^{-7}$ T-m/A-t)
σ	–	harmonically weighted loss factor (pu)
σ_B	-	stress between two magnetic conductors (N/m^2)
τ	-	electrical torque (Nm, pu) or modulating waveform period (sec)
υ_n	-	n^{th} harmonic voltage (V, pu)
ϕ	-	motor flux (Wb) or phase angle offset (rad)
ω	-	angular frequency (rad/sec)
ω_c, ω_m	-	PWM carrier and modulating waveform angular frequencies respectively (rad/sec)
$\int e_a$, $\int e_b$	-	integral of timing error between ideal and realizable PWM switching times (sec)