MODULATION AND CONTROL OF THREE-PHASE PWM MULTILEVEL CONVERTERS

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(ABSTRACT)

Three-phase diode-clamped multilevel topologies are studied in this dissertation. These static converters can generate three or more voltage levels in each output phase, and are generally applied to high-power applications because of their ability to operate with larger voltages than the classical two-level converter. The analysis is mainly focused on the three-level topology, although there are also some contributions for converters with a larger number of levels. The main objectives are to propose new computationally efficient space-vector PWM modulation algorithms, to analyze the imbalances in the DC-link capacitors and the compensation for their effects, and to study advanced control loops. The results are obtained from different models in order to guarantee conclusion reliability. Furthermore, most of the results have been checked experimentally. The main contributions are summarized in the following.

A new space-vector PWM scheme is presented. This algorithm takes advantage of symmetry in the space-vector diagram in order to reduce processing time. The low-frequency oscillation that appears in the neutral point of the three-level converter for some operating conditions is analyzed and quantified. The information provided will help for the calculation of the DC-link capacitors in a given specific application.

The modulation algorithm is extended to converters with more than three levels. DC current components appear in the mid points of the DC-link capacitors for some operating conditions that make the system unstable. The unstable operating area of the four-level converter is revealed.

A novel and efficient space-vector PWM feedforward algorithm in the three-level converter is presented. This modulation strategy can achieve balanced AC output voltages despite any imbalance in the neutral point.

The negative effects of unbalanced linear loads and nonlinear loads on the neutral-point voltage balance are analyzed. A direct sequence of fourth-order harmonics in the AC currents can produce instability. The maximum allowed amplitude of these harmonics is shown.

Significant voltage-balancing improvements can be obtained when two converters are connected back-to-back. The limits in which the low-frequency neutral-point oscillation in the three-level converter can be removed are revealed. A practical example of this connection is the AC/DC/AC conversion used in motor drive applications able to operate with unity power factor.

Finally, an optimal multivariable control loop is applied to a three-level boost rectifier. Since the task of balancing voltages of the DC-link capacitors is assigned to the modulator stage, the linear quadratic regulator has been simplified.

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A la meva dona Montse,
pel seu suport i comprensió.

To my wife Montse,
for her support and understanding.

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List of Abbreviations and Acronyms

A/D: analog-to-digital (converter)
AC: alternating current
AVG: average
CLK: clock
CPES: Center for Power Electronics Systems
CMOS: complementary metal-oxide-silicon (transistor)
D/A: digital-to-analog (converter)
DC: direct current
DEE: Department of Electronic Engineering
DSP: digital signal processor
EMI: electromagnetic interference
EPE: European conference on Power Electronics and applications
EPLD: erasable and programmable logic device
GTO: gate turn-off thyristor
HVDC: high-voltage direct current
IEEE: Institute of Electrical and Electronics Engineers
IGBT: insulated gate bipolar transistor
IRQ: interrupt request
LQR: linear quadratic regulator
MAX: maximum
MIN: minimum
MIMO: multi-input multi-output (system)
MIPS: million of instructions per second
MP: mid point
MSPS: million of samples per second
MUX: multiplexor
NP: neutral point
NPC: neutral-point-clamped (converter)
NTV: nearest-three-vector (modulation)
PEBB: power electronics building block
PEDS: Power Electronics and Drive Systems
PEMC: Power Electronics and Motion Control
PESC: Power Electronics Specialists Conference
PF: power factor
PH: phase
PI: proportional integral
PIEMC: Power Electronics and Motion Control conference
PLL: phase-locked loop
PROM: programmable read only memory
PWM: pulsewidth modulation

RMS: root mean square
SAAEI: Seminario Anual de Automática, Electrónica industrial e Instrumentación
S/H: sample and hold
SMES: superconducting magnetic energy storage
SPWM: sinusoidal pulsewidth modulation
SV: space vector
SVM: space-vector modulation
SV-PWM: space-vector pulsewidth modulation
UPC: Universitat Politècnica de Catalunya
UPS: uninterruptible power system
USA: United States of America
VA: Virginia
VAR: volt-ampere reactive
VSI: voltage-source inverter
ZCT: zero-current transition

Terminology

Glossary of Generic Terms

d_x: duty cycle

$\hat{I}_{hx}$: current amplitude of the x-order harmonic

i_{Cx}: current thought a capacitor

$Im(\vec{x})$: imaginary part of $\vec{x}$

i_x: mid current in the x-point of an n-level converter (x={1, 2, 3, … , n-1})

$\vec{p}_x$: vector projection

$Re(\vec{x})$: real part of $\vec{x}$

$\mathbf{U}_x = [1 \quad 1 \quad 1 \quad \cdots \quad 1]^{\mathrm{T}}$; in which x is the number of ones

v_{Cx}: voltage of a DC-link capacitor (x={1, 2, 3, … , n-1})

$\vec{x}$: generic vector

$|\vec{x}|$, x : vector norm or length of vector $\vec{x}$

x_i: input variables of the back-to-back connection

x_o: output variables of the back-to-back connection

$\bar{x}$: local-averaged variable

$\tilde{x}$: small-signal variable

$\hat{\mathbf{X}}$: vector (or matrices) of a state-space-formulated system that includes the control loop

$\mathbf{X}^{-1}$: inverse of square matrix **X**

$\mathbf{X}^{\mathrm{T}}$: transpose of matrix **X**

$\mathbf{X}_{\{i,j\}}$: i x j matrix

X^* : reference value

$\hat{X}$: amplitude of a sinusoidal variable

X_{RMS} : RMS value of a periodic waveform

$x_{(k)}$: sampled variable at period k

$\mathbf{x}_{(k)}$: sampled vector at period k

$x_{(t)}$: time-dependent variable

$\mathbf{x}_{(t)}$: time-dependent vector

x_{ss} : steady-state value of a variable

$\mathbf{x}_r$: rotating coordinate variables

$\mathbf{X}_r$: rotating coordinate matrices

$[X_1, X_2]$: closed interval $X_1 \le x \le X_2$

θ : angle

Glossary of Particular Terms and Definitions

$\vec{a} = e^{j\frac{2\pi}{3}}$

A, **B**, **C** and **D**: matrices of the linear state-space representation of a system

$\mathbf{A}_d$, $\mathbf{B}_d$, $\mathbf{C}_d$ and $\mathbf{D}_d$: matrices of the discrete state-space representation of a system

C: capacitor

C_f: floating capacitor

e_a, e_b and e_c: utility phase voltages

e_d, e_q and e_o: dq transformed utility phase voltages

$\mathbf{e}_{ph} = [e_a \quad e_b \quad e_c]^{\mathrm{T}}$

$\mathbf{e}_{LL} = [e_{ab} \quad e_{bc} \quad e_{ca}]^{\mathrm{T}} = [e_a - e_b \quad e_b - e_c \quad e_c - e_a]^{\mathrm{T}}$

E_L: RMS line-to-line utility voltage

f: line frequency

f_m: modulation frequency

f_s: sample frequency and switching frequency

$f_{s\ mean}$: mean switching frequency. Complete turn-on and turn-off cycles in the total switches of the NPC divided by 12.

G: parameter related to the quadratic error of the voltages in the DC-link capacitors

I: unit matrix

i_a, i_b and i_c: phase currents in the AC side of a converter

i_{ap}, i_{bp} and i_{cp}: positive sequence of currents

i_{an}, i_{bn} and i_{cn}: negative sequence of currents

i_{ao}, i_{bo} and i_{co}: zero sequence of currents

$\mathbf{i}_{ph} = [i_a \quad i_b \quad i_c]^{\mathrm{T}}$

$\mathbf{i}_{LL} = [i_{ab} \quad i_{bc} \quad i_{ca}]^{\mathrm{T}} = [i_a - i_b \quad i_b - i_c \quad i_c - i_a]^{\mathrm{T}}$

i_d, i_q and i_o: dq transformed phase currents

$\mathbf{i}_{dq} = [i_d \quad i_q]^{\mathrm{T}}$

$\bar{\mathbf{i}}_{MP} = [\bar{i}_{n-2} \quad \bar{i}_{n-3} \quad \cdots \quad \bar{i}_1]^{\mathrm{T}}$; local-averaged mid-point currents

$\bar{i}_{1\min}$: minimum local-averaged NP current

$\bar{i}_{1avg}$: average NP current over a line period

$\hat{I}$: current amplitude (fundamental)

I_{RMS}: RMS value of the phase currents of the converter (fundamentals)

J: LQR quadratic performance index

K: LQR optimal solution matrix

L: inductance

m: modulation index (in the case of linear modulation $m = \hat{V}_{LL} / V_{DC}$ and $0 \le m \le 1$)

(m_g, m_h): normalized components of the reference vector in the non-orthogonal gh axes

(m_1, m_2): normalized components of the equivalent reference vector in the first sextant in the non-orthogonal gh axes

(m'_1, m'_2): components of the equivalent reference vector in the first sextant in the non-orthogonal gh axes

(m_{OV1}, m_{OV2}): normalized components of the equivalent reference vector in the first sextant in the non-orthogonal gh axes for overmodulation mode

$m_{12} = 2 - m_1 - m_2$

$\vec{m}$: reference vector

$\vec{m}_n$: normalized reference vector

$m_n = \frac{\sqrt{3}}{2}(n-1)m$; amplitude of the normalized reference vector

$\mathbf{M}$, $\mathbf{Q}$ and $\mathbf{R}$: hermitic weighting matrices positively defined for evaluation of the parameter J in the LQR

n: number of available voltage levels in each leg of a multilevel converter. This number typifies an n-level converter

N: neutral-point of a three-phase star-connected load. Also, last sample of a discrete sequence in the definition of the parameter J in the LQR

p: instantaneous power

R: electrical resistance

s_{ij}: switching function, $s_{ij} = \begin{cases} 1 & \text{if } i \text{ is connected to } j, \text{ and} \\ 0 & \text{otherwise.} \end{cases}$

s_x: sextant function, $s_x = \begin{cases} 1 & \text{if the reference vector lies in sextant } x, \text{ and} \\ 0 & \text{otherwise.} \end{cases}$

$\mathbf{S}$: interchanging matrix that depends on sextant functions

$\mathbf{S}_T = \mathbf{T}_{dq}\mathbf{S}^{\mathrm{T}}$; transformed interchanging matrix that depends on sextant functions

t: time

T: line period

T_m: modulation period

$\mathbf{T}_{dq}$: dq transformation or park transformation

$\mathbf{u}$: input vector or control variables in the state-space representation

v_{a0}, v_{b0} and v_{c0}: output voltages of a multilevel converter refereed to the lower DC-link voltage

$\mathbf{v}_{ph} = [v_{a0} \quad v_{b0} \quad v_{c0}]^{\mathrm{T}}$

$\mathbf{v}_C = [v_{C(n-1)} \quad v_{C(n-2)} \quad \cdots \quad v_{C1}]^{\mathrm{T}}$

$\mathbf{v}_{C3L} = [v_{C2} \quad v_{C1}]^{\mathrm{T}}$

v_{DC}: total DC-link voltage as a variable (in modeling and controlling sections)

V_{DC}: constant or rated total DC-link voltage

V_{DC1}: voltage source applied to the lower DC-link capacitor

V_{DC2}: voltage source applied to the upper DC-link capacitor

$\hat{V}_{LL}$: line-to-line voltage amplitude

v_{N0}: neutral voltage of a star-connected load refereed to the lower DC-link level

x: state vector in the state-space representation

y: output vector in the state-space representation

α, β: orthogonal axes in a two-dimensional representation

$\beta = \frac{I_{RMS}}{fCV_{DC}}$; nondimensional balancing parameter

$\gamma_1 = \frac{v_{C1}}{V_{DC}/2}$; parameter for the imbalance in the lower DC-link capacitor

$\gamma_2 = \frac{v_{C2}}{V_{DC}/2}$; parameter for the imbalance in the upper DC-link capacitor

$\Delta p_C = \frac{d\varepsilon_C}{dt}$; total instantaneous power in the DC-link capacitors

$\Delta v_C = v_C - \frac{V_{DC}}{n-1}$; voltage error in a DC-link capacitor

Δv_{NP} : low-frequency peak-to-peak NP voltage ripple

$\Delta v_{NPn} = \frac{\Delta v_{NP}}{I_{RMS}/fC}$; normalized low-frequency peak-to-peak NP-voltage ripple

ε_C : total electric energy stored in the DC-link capacitors

θ_n : angle of the normalized reference vector (first sextant)

θ_o : initial angle

θ_r : rotating coordinated angle of the dq transformation

η : efficiency

φ, φ_1 : current phase angle refereed to the voltage phase angle (fundamentals)

$\omega = 2\pi f$; angular frequency