

Table of Contents

| | |
|---|----|
| Introduction | xv |
| Chapter 1. Carrier-Based Pulse Width Modulation for Two-level Three-phase Voltage Inverters | 1 |
| Francis LABRIQUE and Jean-Paul LOUIS | |
| 1.1. Introduction | 1 |
| 1.2. Reference voltages $v_{aref}, v_{bref}, v_{cref}$ | 4 |
| 1.3. Reference voltages $P_{aref}, P_{bref}, P_{cref}$ | 10 |
| 1.4. Link between the quantities v_a, v_b, v_c and P_a, P_b, P_c | 12 |
| 1.5. Generation of PWM signals | 13 |
| 1.5.1. Reverse sawtooth wave. | 13 |
| 1.5.2. Conventional sawtooth carrier | 17 |
| 1.5.3. Triangular carrier | 20 |
| 1.5.4. Note | 23 |
| 1.6. Determination of the reference waves $v_{arefk}, v_{brefk},$ and v_{crefk} from the reference waves $v_{arefk}, v_{brefk}, v_{crefk}$ | 24 |
| 1.6.1. “Sine” modulation. | 25 |
| 1.6.2. “Centered” modulation. | 27 |
| 1.6.3. “Sub-optimal” modulation. | 29 |
| 1.6.4. “Flat top” and “flat bottom” modulation. | 30 |
| 1.7. Conclusion | 32 |
| 1.8. Bibliography | 33 |

| | |
|--|-----|
| Chapter 2. Space Vector Modulation Strategies | 35 |
| Nicolas PATIN and Vincent LANFRANCHI | |
| 2.1. Inverters and space vector PWM | 35 |
| 2.1.1. Problem description | 35 |
| 2.1.2. Inverter model | 36 |
| 2.1.3. Space vector modulation | 40 |
| 2.2. Geometric approach to the problem | 48 |
| 2.2.1. Degrees of freedom | 48 |
| 2.2.2. Extension to the full domain | 50 |
| 2.2.3. Space vector modulation | 55 |
| 2.2.4. PWM spectrum | 56 |
| 2.3. Space vector PWM and implementation | 58 |
| 2.3.1. Implementation hardware and general structure | 58 |
| 2.3.2. Determination of working sector | 62 |
| 2.3.3. Some variants of space vector PWM | 63 |
| 2.4. Conclusion | 68 |
| 2.5. Bibliography | 69 |
| Chapter 3. Overmodulation of Three-phase Voltage Inverters | 71 |
| Nicolas PATIN and Eric MONMASSON | |
| 3.1. Background | 71 |
| 3.2. Comparison of modulation strategies | 72 |
| 3.2.1. Introduction | 72 |
| 3.2.2. “Full-wave” modulation | 73 |
| 3.2.3. Performance of standard modulation strategies | 74 |
| 3.3. Saturation of modulators | 78 |
| 3.4. Improved overmodulation | 81 |
| 3.5. Bibliography | 91 |
| Chapter 4. Computed and Optimized Pulse Width Modulation Strategies | 93 |
| Vincent LANFRANCHI, Nicolas PATIN and Daniel DEPERNET | |
| 4.1. Introduction to programmed PWM | 93 |
| 4.2. Range of valid frequencies for PWM | 95 |
| 4.3. Programmed harmonic elimination PWM | 97 |
| 4.4. Optimized PWM | 100 |
| 4.4.1. Introduction | 100 |

| | |
|--|------------|
| 4.4.2. Minimization criteria | 100 |
| 4.4.3. Applying optimization results | 103 |
| 4.4.4. Principles of real-time generation | 107 |
| 4.5. Calculated multilevel PWM | 108 |
| 4.5.1. Introduction | 108 |
| 4.5.2. Calculated three-level PWM | 108 |
| 4.5.3. Calculated PWM with independent levels. | 113 |
| 4.6. Conclusion | 114 |
| 4.7. Bibliography | 115 |
| Chapter 5. Delta-Sigma Modulation | 119 |
| Jean-Paul VILAIN and Christophe LESBROUSSART | |
| 5.1. Introduction | 119 |
| 5.2. Principle of single-phase Delta-Sigma modulation. | 120 |
| 5.2.1. Open-loop or closed-loop operation. | 122 |
| 5.2.2. Frequency characteristics | 122 |
| 5.2.3. Influence of reference amplitude on the spectrum. | 124 |
| 5.2.4. Influence of command signal frequency on spectral content. | 125 |
| 5.2.5. Absence of short pulses | 126 |
| 5.2.6. Decisional element | 126 |
| 5.2.7. Asynchronous and synchronous DSM | 126 |
| 5.3. Three-phase case: vector DSM | 128 |
| 5.3.1. Criteria for selecting the new vector | 130 |
| 5.3.2. Three level three-phase inverter | 137 |
| 5.4. Conclusion | 138 |
| 5.5. Bibliography | 139 |
| Chapter 6. Stochastic Modulation Strategies | 141 |
| Vincent LANFRANCHI and Nicolas PATIN | |
| 6.1. Introduction | 141 |
| 6.2. Spread-spectrum techniques and their applications | 142 |
| 6.3. Description of stochastic modulation techniques. | 144 |
| 6.3.1. Deterministic basis of PWM | 144 |
| 6.3.2. Variable-frequency stochastic PWM | 145 |
| 6.3.3. Random pulse position PWM. | 146 |
| 6.3.4. Stochastic PWM in three-phase inverters | 146 |
| 6.3.5. General remarks | 147 |

| | |
|--|------------|
| 6.4. Spectral analysis of stochastic modulation | 147 |
| 6.4.1. Effects on voltage spectra | 147 |
| 6.4.2. Impact on load current spectra | 149 |
| 6.4.3. Impact on DC bus current | 150 |
| 6.4.4. Impact on machine noise and vibrations | 151 |
| 6.5. Conclusion | 155 |
| 6.6. Bibliography | 156 |
| Chapter 7. Electromagnetic Compatibility of Variable Speed Drives: Impact of PWM Control Strategies | 159 |
| Bertrand REVOL | |
| 7.1. Introduction | 159 |
| 7.2. Objectives of an EMC study | 161 |
| 7.3. EMC mechanisms in static converters. | 162 |
| 7.3.1. General remarks | 162 |
| 7.3.2. EMC standards | 164 |
| 7.3.3. Standardized measurement and simulation | 165 |
| 7.4. Time-domain simulation | 167 |
| 7.5. Frequency-domain modeling: a tool for the engineer | 169 |
| 7.5.1. Objectives of modeling. | 169 |
| 7.5.2. Modeling of disturbance sources | 169 |
| 7.5.3. Frequency domain representation of the inverter | 176 |
| 7.6. PWM control. | 178 |
| 7.6.1. Carrier-based PWM. | 179 |
| 7.7. Comparison of sources for different carrier-based PWM strategies | 190 |
| 7.7.1. Sinusoidal intersective PWM. | 190 |
| 7.7.2. Harmonic injection control | 191 |
| 7.7.3. Limiting commutation rates: DeadBanded PWM control | 192 |
| 7.8. Space vector PWM. | 193 |
| 7.9. Structure for minimizing the common mode voltage | 199 |
| 7.10. Conclusion | 200 |
| 7.11. Bibliography | 200 |
| Chapter 8. Multiphase Voltage Source Inverters | 203 |
| Xavier KESTELYN and Eric SEMAIL | |
| 8.1. Introduction | 203 |
| 8.2. Vector modeling of voltage source inverters. | 204 |

| | |
|--|------------|
| 8.2.1. n-leg structure: terminology, notation, and examples. | 204 |
| 8.2.2. Mean value control: PWM | 209 |
| 8.3. Inverter as seen by the multiphase load | 221 |
| 8.3.1. Load topology and associated degrees of freedom | 223 |
| 8.3.2. Worked example: three-phase case | 227 |
| 8.3.3. Worked example: five-phase load | 232 |
| 8.4. Conclusion | 237 |
| 8.5. Bibliography | 238 |
| Chapter 9. PWM Strategies for Multilevel Converters. | 243 |
| Thierry MEYNARD and Guillaume GATEAU | |
| 9.1. Introduction to multilevel and interleaved converters | 243 |
| 9.2. Modulators | 252 |
| 9.2.1. Recap: two-level modulators | 252 |
| 9.2.2. Multilevel modulators | 255 |
| 9.3. Examples of control signal generators for various multilevel structures | 274 |
| 9.3.1. “3-point” inverters (Neutral Point Clamped Inverter) | 274 |
| 9.3.2. Flying capacitor inverters | 275 |
| 9.4. Conclusion | 280 |
| 9.5. Bibliography | 283 |
| Chapter 10. PI Current Control of a Synchronous Motor. | 287 |
| Mohamed Wissem NAOUAR, Eric MONMASSON, Ilhem SLAMA-BELKHODJA and Ahmad Ammar NAASSANI | |
| 10.1. Introduction. | 287 |
| 10.2. Model of a synchronous motor | 288 |
| 10.2.1. Model of a synchronous motor in a fixed coordinate system based on the stator | 288 |
| 10.2.2. Model of a synchronous motor in a common coordinate system (d, q) aligned with the rotor winding axis of the motor. | 294 |
| 10.2.3. Expression for electromagnetic torque | 299 |
| 10.3. Typical power delivery system for a synchronous motor | 300 |
| 10.4. PI current control of a synchronous motor in the fixed three-phase coordinate system of the stator | 303 |
| 10.4.1. Tuning of PI controllers in a fixed three-phase coordinate system aligned with the stator | 306 |
| 10.4.2. PI control structure in a fixed three-phase coordinate system aligned with the stator. | 309 |

| | |
|--|-----|
| 10.5. PI current control for a synchronous motor in a rotating coordinate system (d, q) | 311 |
| 10.5.1. Tuning of PI controllers in the (d, q) frame | 311 |
| 10.5.2. PI control structure in the (d, q) reference frame. | 314 |
| 10.6. Conclusion | 316 |
| 10.7. Bibliography | 317 |
| Chapter 11. Predictive Current Control for a Synchronous Motor. | 319 |
| Mohamed Wissem NAOUAR, Eric MONMASSON, Ilhem SLAMA-BELKHODJA and Ahmad Ammar NAASSANI | |
| 11.1. Introduction. | 319 |
| 11.2. Minimum-switching-frequency predictive control strategies | 320 |
| 11.3. Limited-switching-frequency predictive control strategies. | 321 |
| 11.4. Limited-switching-frequency predictive current control strategies for a synchronous motor. | 322 |
| 11.4.1. Predictive current control for a synchronous motor with variable, limited switching frequency | 322 |
| 11.4.2. Predictive current control with fixed switching frequency for a synchronous motor | 329 |
| 11.5. Conclusion | 333 |
| 11.6. Bibliography | 334 |
| Chapter 12. Sliding Mode Current Control for a Synchronous Motor. | 335 |
| Ahmad Ammar NAASSANI, Mohamed Wissem NAOUAR, Eric MONMASSON and Ilhem SLAMA-BELKHODJA | |
| 12.1. Introduction. | 335 |
| 12.2. Sliding mode current control for a DC motor | 336 |
| 12.2.1. Direct sliding mode current control of a DC motor | 339 |
| 12.2.2. Indirect sliding mode current control for a DC motor. | 342 |
| 12.3. Sliding mode current control of a synchronous motor | 350 |
| 12.3.1. Direct sliding mode control of the stator current vector in an induction motor | 353 |
| 12.3.2. Indirect sliding mode control of the stator current vector in an induction motor | 363 |
| 12.4. Conclusion | 369 |
| 12.5. Bibliography | 370 |

| | |
|---|-----|
| Chapter 13. Hybrid Current Controller with Large Bandwidth and Fixed Switching Frequency | 371 |
| Serge PIERFEDERICI, Farid MEIBODY-TABAR and Jean-Philippe MARTIN | |
| 13.1. Introduction. | 371 |
| 13.2. Main types of discrete-output current regulators | 374 |
| 13.2.1. Introduction | 374 |
| 13.2.2. Hysteresis regulator | 374 |
| 13.2.3. Fixed-frequency hysteresis regulator | 375 |
| 13.2.4. Turn-on triggered current regulator | 378 |
| 13.2.5. Turn-off triggered controller | 383 |
| 13.2.6. Turn-on or turn-off triggered regulator | 385 |
| 13.2.7. Principles of a hybrid modulated hysteresis regulator | 388 |
| 13.3. Tools for limit cycle analysis. | 392 |
| 13.3.1. Introduction to dynamic systems; concept of bifurcation | 392 |
| 13.3.2. Concept of bifurcation of a dynamic system | 395 |
| 13.3.3. Poincaré cross-section and bifurcation diagram | 396 |
| 13.3.4. Application to electrical engineering | 397 |
| 13.3.5. Analysis of limit cycles in nonlinear current regulators | 401 |
| 13.4. Conclusion | 414 |
| 13.5. Bibliography | 414 |
| Chapter 14. Current Control Using Self-oscillating Current Controllers | 417 |
| Jean-Claude LE CLAIRE | |
| 14.1. Introduction. | 417 |
| 14.2. Operating principle of the self-oscillating current controller | 418 |
| 14.2.1. Dual-purpose local loop | 418 |
| 14.2.2. Local control loop for switching frequency control | 419 |
| 14.2.3. Local low-frequency current control loop | 423 |
| 14.2.4. Stability of the modulator | 427 |
| 14.3. Improvements to the SOCC. | 428 |
| 14.3.1. Reducing the static error | 428 |
| 14.3.2. Controlling the switching frequency | 430 |
| 14.3.3. Variants on the initial design | 431 |
| 14.4. Characteristics of the SOCC | 432 |
| 14.4.1. Switching frequency. | 432 |
| 14.4.2. Linearity | 434 |

| | |
|---|------------|
| 14.4.3. Harmonic distortion | 435 |
| 14.5. Extensions to the SOCC concept | 435 |
| 14.5.1. Self-oscillating voltage control | 435 |
| 14.5.2. Three-phase SOCC | 441 |
| 14.5.3. Three-phase SOVC | 442 |
| 14.5.4. Emulation of high-power active loads | 444 |
| 14.5.5. Analog-to-digital converter for the measurement circuit | 444 |
| 14.6. Conclusion | 445 |
| 14.7. Bibliography | 445 |
| | |
| Chapter 15. Current and Voltage Control Strategies Using Resonant Correctors: Examples of Fixed-frequency Applications | 449 |
| Joseph PIERQUIN, Arnaud DAVIGNY and Benoît ROBYNS | |
| 15.1. Introduction | 449 |
| 15.2. Current control with resonant correctors | 451 |
| 15.2.1. Control using Kessler’s symmetric optimum | 451 |
| 15.2.2. Application to power control: example of a wind turbine | 457 |
| 15.3. Voltage control strategy | 463 |
| 15.3.1. Introduction | 463 |
| 15.3.2. Principle of power control | 465 |
| 15.3.3. Voltage control at the capacitor terminals | 468 |
| 15.3.4. Determination of reference voltages. | 472 |
| 15.3.5. Power control | 473 |
| 15.3.6. Voltage control | 476 |
| 15.3.7. Simulations | 477 |
| 15.4. Conclusion | 483 |
| 15.5. Appendix: transformer parameters | 484 |
| 15.6. Bibliography | 484 |
| | |
| Chapter 16. Current Control Strategies for Multicell Converters | 487 |
| Guillaume GATEAU and Thierry MEYNARD | |
| 16.1. Introduction | 487 |
| 16.2. Multilevel conversion topology | 488 |
| 16.2.1. Main types of multilevel structure | 489 |
| 16.2.2. Advantages and disadvantages of a multicell structure. | 492 |

| | |
|---|-----|
| 16.2.3. Evolution of high-power multicell topologies: stacked multicell converters | 494 |
| 16.3. Modeling and analysis of degrees of freedom for control. | 495 |
| 16.3.1. Instantaneous modeling. | 495 |
| 16.3.2. Mean value model | 497 |
| 16.4. Analysis of degrees of freedom available to the control algorithm | 497 |
| 16.4.1. Open-loop PWM modulation | 497 |
| 16.4.2. Degrees of freedom in the topology | 498 |
| 16.4.3. Objective of command rules. | 499 |
| 16.5. Classification of control strategies | 500 |
| 16.6. Indirect control strategy for a single-phase leg | 501 |
| 16.6.1. Principle of decoupled control | 501 |
| 16.6.2. Linearization and non-interacting control. | 502 |
| 16.6.3. Decoupling using exact input/output linearization. | 506 |
| 16.6.4. Control exploiting the phase shifts between the command signals. | 509 |
| 16.7. Direct control strategy for a single-phase leg | 513 |
| 16.7.1. Sliding mode control | 513 |
| 16.7.2. Current mode control | 517 |
| 16.8. Command strategy, three-phase approach | 521 |
| 16.8.1. Features of two-level inverters for three-phase systems | 521 |
| 16.8.2. Features of a three-phase N-level system | 522 |
| 16.8.3. Analysis of degrees of freedom made available by the use of multilevel inverters | 526 |
| 16.8.4. Examples of use of the degrees of freedom made available by using multilevel inverters | 527 |
| 16.9. Features of multicell converters: need for an observer | 530 |
| 16.10. Conclusions and outlook. | 531 |
| 16.11. Bibliography | 533 |
| List of Authors | 537 |
| Index | 541 |