

INSTANTANEOUS POWER THEORY AND APPLICATIONS TO POWER CONDITIONING

Hirofumi Akagi

*Professor of Electrical Engineering
TIT—Tokyo Institute of Technology, Japan*

Edson Hirokazu Watanabe

*Professor of Electrical Engineering
UFRJ—Federal University of Rio de Janeiro, Brazil*

Mauricio Aredes

*Associate Professor of Electrical Engineering
UFRJ—Federal University of Rio de Janeiro, Brazil*



Mohamed E. El-Hawary, *Series Editor*

4 IEEE

IEEE PRESS

1807

©WILEY

2007

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

CONTENTS

Preface	xiii
1. Introduction	1
1.1. Concepts and Evolution of Electric Power Theory	2
1.2. Applications of the p - q Theory to Power Electronics Equipment	4
1.3. Harmonic Voltages in Power Systems	5
1.4. Identified and Unidentified Harmonic-Producing Loads	7
1.5. Harmonic Current and Voltage Sources	8
1.6. Basic Principles of Harmonic Compensation	11
1.7. Basic Principles of Power Flow Control	14
References	17
2. Electric Power Definitions: Background	19
2.1. Power Definitions Under Sinusoidal Conditions	20
2.2. Voltage and Current Phasors and the Complex Impedance	22
2.3. Complex Power and Power Factor	24
2.4. Concepts of Power Under Non-Sinusoidal Conditions— Conventional Approaches	25
2.4.1. Power Definitions by Budeanu	25
2.4.1.A. Power Tetrahedron and Distortion Factor	28
2.4.2. Power Definitions by Fryze	30
2.5. Electric Power in Three-Phase Systems	31
2.5.1. Classifications of Three-Phase Systems	31
2.5.2. Power in Balanced Three-Phase Systems	34
2.5.3. Power in Three-Phase Unbalanced Systems	36
	vii

2.6. Summary	37
References	38
3 The Instantaneous Power Theory	41
3.1. Basis of the p - q Theory	42
3.1.1. Historical Background of the p - q Theory	42
3.1.2. The Clarke Transformation	43
3.1.2. A. Calculation of Voltage and Current Vectors when Zero-Sequence Components are Excluded	45
3.1.3. Three-Phase Instantaneous Active Power in Terms of Clarke Components	47
3.1.4. The Instantaneous Powers of the p - q Theory	48
3.2. The p - q Theory in Three-Phase, Three-Wire Systems	49
3.2.1. Comparisons with the Conventional Theory	53
3.2.1.A. Example #1—Sinusoidal Voltages and Currents	53
3.2.1.B. Example #2—Balanced Voltages and Capacitive Loads	54
3.2.1.C. Example #3—Sinusoidal Balanced Voltage and Nonlinear Load	55
3.2.2. Use of the p - q Theory for Shunt Current Compensation	59
3.2.2. A. Examples of Appearance of Hidden Currents	64
3.2.2.A.1 Presence of the Fifth Harmonic in Load Current	64
3.2.2.A.2 Presence of the Seventh Harmonic in Load Current	67
3.2.3. The Dual p - q Theory	68
3.3. The p - q Theory in Three-Phase, Four-Wire Systems	71
3.3.1. The Zero-Sequence Power in a Three-Phase Sinusoidal Voltage Source	72
3.3.2. Presence of Negative-Sequence Components	74
3.3.3. General Case-Including Distortions and Imbalances in the Voltages and in the Currents	75
3.3.4. Physical Meanings of the Instantaneous Real, Imaginary, and Zero-Sequence Powers	79
3.3.5. Avoiding the Clarke Transformation in the p - q Theory	
3.3.6. Modified p - q Theory	
3.4. Instantaneous abc Theory	
3.4.1. Active and Nonactive Current Calculation by Means of a Minimization Method	
3.4.2. Generalized Fryze Currents Minimization Method	
3.5. Comparisons between the p - q Theory and the abc Theory	
3.5.1. Selection of Power Components to be Compensated	
3.6. Summary	
References	

4 Shunt Active Filters	109
4.1. General Description of Shunt Active Filters	111
4.1.1. PWM Converters for Shunt Active Filters	112
4.1.2. Active Filter Controllers	113
4.2. Three-Phase, Three-Wire Shunt Active Filters	116
4.2.1. Active Filters for Constant Power Compensation	118
4.2.2. Active Filters for Sinusoidal Current Control	134
4.2.2.A. Positive-Sequence Voltage Detector	138
4.2.2. A. 1 Main Circuit of the Voltage Detector	138
4.2.2.A.2 Phase-Locked-Loop (PLL) Circuit	141
4.2.2.B. Simulation Results	145
4.2.3. Active Filters for Current Minimization	145
4.2.4. Active Filters for Harmonic Damping	150
4.2.4.A. Shunt Active Filter Based on Voltage Detection	151
4.2.4.B. Active Filter Controller Based on Voltage Detection	152
4.2.4.C. An Application Case of Active Filter for Harmonic Damping	157
4.2.4.C.1 The Power Distribution Line for the Test Case	158
4.2.4.C.2 The Active Filter for Damping of Harmonic Propagation	159
4.2.4.C.3 Experimental Results	160
4.2.4.C.4 Adjust of the Active Filter Gain	168
4.2.5. A Digital Controller	173
4.2.5. A. System Configuration of the Digital Controller	174
4.2.5.A.1 Operating Principle of PLL and PWM Units	175
4.2.5.A.2 Sampling Operation in the A/D Unit	177
4.2.5.B. Current Control Methods	178
4.2.5.B. 1 Modeling of Digital Current Control	178
4.2.5.B.2 Proportional Control	179
4.2.5.B.3 Deadbeat Control	180
4.2.5.B.4 Frequency Response of Current Control	181
4.3. Three-Phase, Four-Wire Shunt Active Filters	182
4.3.1. Converter Topologies for Three-Phase, Four-Wire Systems	183
4.3.2. Dynamic Hysteresis-Band Current Controller	184
4.3.3. Active Filter Dc Voltage Regulator	186
4.3.4. Optimal Power Flow Conditions	187
4.3.5. Constant Instantaneous Power Control Strategy	189
4.3.6. Sinusoidal Current Control Strategy	192
4.3.7. Performance Analysis and Parameter Optimization	195
4.3.7. A. Influence of the System Parameters	195
4.3.7.B. Dynamic Response of the Shunt Active Filter	196

4.3.7.C. Economical Aspects	201
4.3.7.D. Experimental Results	203
4.4. Shunt Selective Harmonic Compensation	208
4.5. Summary	216
References	217
5 Hybrid and Series Active Filters	221
5.1. Basic Series Active Filter	221
5.2. Combined Series Active Filter and Shunt Passive Filter	223
5.2.1. Example of An Experimental System	226
5.2.1.A. Compensation Principle	226
5.2.1.A.1 Source Harmonic Current I_{Sh}	228
5.2.1.A.2 Output Voltage of Series Active Filter: V_c	229
5.2.1.A.3 Shunt Passive Filter Harmonic Voltage: V_{Fh}	229
5.2.1.B. Filtering Characteristics	230
5.2.1.B.1 Harmonic Current Flowing From the Load to the Source	230
5.2.1.B.2 Harmonic Current Flowing from the Source to the Shunt Passive Filter	231
5.2.1.C. Control Circuit	231
5.2.1.D. Filter to Suppress Switching Ripples	233
5.2.1.E. Experimental Results	234
5.2.2. Some Remarks about the Hybrid Filters	237
5.3. Series Active Filter Integrated with a Double-Series Diode Rectifier	238
5.3.1. The First-Generation Control Circuit	241
5.3.1.A. Circuit Configuration and Delay Time	241
5.3.1.B. Stability of the Active Filter	242
5.3.2. The Second-Generation Control Circuit	244
5.3.3. Stability Analysis and Characteristics Comparison	246
5.3.3.A. Transfer Function of the Control Circuits	246
5.3.3.B. Characteristics Comparisons	247
5.3.4. Design of a Switching-Ripple Filter	248
5.3.4.A. Design Principle	248
5.3.4.B. Effect on the System Stability	250
5.3.4.C. Experimental Testing	251
5.3.5. Experimental Results	252
5.4. Comparisons Between Hybrid and Pure Active Filters	253
5.4.1. Low-Voltage Transformerless Hybrid Active Filter	255
5.4.2. Low-Voltage Transformerless Pure Shunt Active Filter	258
5.4.3. Comparisons Through Simulation Results	259
5.5. Conclusions	261
References	262

6 Combined Series and Shunt Power Conditioners	265
6.1. The Unified Power Flow Controller (UPFC)	267
6.1.1. FACTS and UPFC Principles	268
6.1.1.A. Voltage Regulation Principle	269
6.1.1.B. Power Flow Control Principle	270
6.1.2. A Controller Design for the UPFC	274
6.1.3. UPFC Approach Using a Shunt Multipulse Converter	281
6.1.3.A. Six-Pulse Converter	282
6.1.3.B. Quasi 24-Pulse Converter	286
6.1.3.C. Control of Active and Reactive Power in Multipulse Converters	288
6.1.3.D. Shunt Multipulse Converter Controller	290
6.2. The Unified Power Quality Conditioner (UPQC)	293
6.2.1. General Description of the UPQC	294
6.2.2. A Three-Phase, Four-Wire UPQC	297
6.2.2.A. Power Circuit of the UPQC	297
6.2.2.B. The UPQC Controller	299
6.2.2.B.1 PWM Voltage Control with Minor Feedback Control Loop	300
6.2.2.B.2 Series Active Filter Controller	301
6.2.2.B.3 Integration of the Series and Shunt Active Filter Controllers	305
6.2.2.B.4 General Aspects	307
6.2.2.C. Analysis of the UPQC Dynamic	308
6.2.2.C.1 Optimizing the Power System Parameters	309
6.2.2.C.2 Optimizing the Parameters in the Control Systems	311
6.2.2.C.3 Simulation Results	312
6.2.2.C.4 Experimental Results	320
6.2.3. The UPQC Combined with Passive Filters (Hybrid UPQC)	326
6.2.3.A. Controller of the Hybrid UPQC	331
6.2.3.B. Experimental Results	337
6.3. The Universal Active Power Line Conditioner (UPLC)	343
6.3.1. General Description of the UPLC	344
6.3.2. The Controller of the UPLC	347
6.3.2.A. Controller for the Configuration #2 of UPLC	355
6.3.3. Performance of the UPLC	355
6.3.3.A. Normalized System Parameters	355
6.3.3.B. Simulation Results of Configuration #1 of UPLC	360
6.3.3.C. Simulation Results of Configuration #2 of UPLC	368
6.3.4. General Aspects	370
6.4. Summary	371
References	371