
Contents

FOREWORD	xi
INTRODUCTION	xiii
CHAPTER 1. ISSUES IN ELECTRICAL ENERGY STORAGE	1
1.1. Difficulties of storing electrical energy	1
1.2. Why store electrical energy?	3
1.3. Value enhancement of storage in electrical grids	6
1.4. Storage management	9
1.5. Bibliography.	13
CHAPTER 2. RECENT DEVELOPMENTS IN ENERGY STORAGE	17
2.1. Introduction	17
2.2. Storage technologies	17
2.3. Characteristics of a storage system	19
2.3.1. Energy storage capacity.	19
2.3.2. Maximum power and time constant.	20
2.3.3. Energy losses and efficiency.	20
2.3.4. Aging	21
2.3.5. Costs	21
2.3.6. Energy and specific power	22
2.3.7. Response time	23
2.3.8. Gray energy.	24
2.3.9. State of energy	24

2.3.10. Other characteristics	25
2.4. Hydraulic storage	26
2.4.1. Principle of hydraulic storage	26
2.4.2. Exercise: Lac Noir station	27
2.5. Compressed-air storage	32
2.5.1. Principle of compressed-air storage.	32
2.5.2. First- and second-generation compressed-air storage	33
2.5.3. Adiabatic compressed-air storage	34
2.5.4. Air storage	35
2.5.5. Hydropneumatic storage	36
2.6. Thermal storage	38
2.6.1. Sensitive-heat storage	38
2.6.2. Latent-heat storage.	39
2.7. Chemical storage	40
2.7.1. Electrochemical storage.	40
2.7.2. Hydrogen storage	45
2.8. Kinetic storage	47
2.9. Electrostatic storage	48
2.10. Electromagnetic storage	49
2.11. Compared performances of storage technologies	51
2.12. Bibliography	52
CHAPTER 3. APPLICATIONS AND VALUES OF ENERGY STORAGE IN POWER SYSTEMS	55
3.1. Introduction	55
3.2. Introduction to power systems and their operation	59
3.2.1. Generation plants	60
3.2.2. Electric grids	65
3.2.3. Demand	68
3.2.4. Some basics of the operation of power systems	69
3.3. Services that can be provided by storage	84
3.3.1. Introduction	84
3.3.2. Services required for connection to the transmission grid.	85
3.3.3. Potential additional services provided to a transmission system operator	88

3.3.4. Potential services provided by storage to a distribution system operator	91
3.3.5. Services for a centralized generation owner	107
3.3.6. Services for a renewable decentralized producer	108
3.3.7. Services for consumers	118
3.3.8. Benefits from market activities	124
3.4. Example of the contribution of storage to the treatment of congestion events	127
3.4.1. Indicator of state of charge of grid	127
3.4.2. Evolution scenario for electric grid	128
3.4.3. Treatment of congestion events in Brittany	128
3.5. Example of contribution of storage to dynamic support of frequency control in an island grid.	131
3.5.1. Context and potential interest of this service.	131
3.5.2. What is under-frequency load shedding?	131
3.5.3. Technical specifications of dynamic support	132
3.5.4. Method used for detailed study of dynamic support	135
3.5.5. Stage 1: theoretical approach	135
3.5.6. Stage 2: dynamic simulations	141
3.5.7. Stage 3: experimental laboratory implementation.	142
3.5.8. Economic value making	144
3.5.9. Conclusion	145
3.6. General conclusion	145
3.7. Bibliography.	146

CHAPTER 4. INTRODUCTION TO FUZZY LOGIC AND APPLICATION TO THE MANAGEMENT OF KINETIC ENERGY STORAGE IN A HYBRID WIND-DIESEL SYSTEM. 153

4.1. Introduction	153
4.2. Introduction to fuzzy logic	154
4.2.1. Principle of fuzzy reasoning	154
4.2.2. Fuzzy logic and Boolean logic.	155

4.2.3. Stages of a fuzzy supervisor	160
4.2.4. Example of fuzzy reasoning	164
4.3. Wind-kinetic energy storage combination on an isolated site with a diesel generator	168
4.3.1. Introduction	168
4.3.2. Energy management strategy	170
4.3.3. Fuzzy logic supervisor	171
4.3.4. Results of simulation with fuzzy supervisor	174
4.3.5. Results of simulation with simple filtering	176
4.4. Conclusion	179
4.5. Bibliography	179
 CHAPTER 5. SUPERVISOR CONSTRUCTION METHODOLOGY FOR A WINDPOWER SOURCE COMBINED WITH STORAGE.	
	181
5.1. Introduction	181
5.2. Energetic system studied	182
5.3. Supervisor development methodology	183
5.4. Specifications	184
5.4.1. Objectives	184
5.4.2. Limitations	184
5.4.3. Means of action	185
5.5. Supervisor structure	186
5.5.1. Input values	186
5.5.2. Output values	187
5.5.3. Supervisor development tools	187
5.6. Identification of various operating states: functional graph	191
5.6.1. Graph of level N1	192
5.6.2. Graph of level N1.1	193
5.6.3. Graph of level N1.2	194
5.6.4. Graph of level N1.3	194
5.7. Membership functions	195
5.8. Operational graph	199
5.8.1. Graph of level N1	200
5.8.2. Graph of level N1.1	200
5.8.3. Graph of level N1.2	201
5.8.4. Graph of level N1.3	201
5.9. Fuzzy rules	202

5.10. Experimental validation	203
5.10.1. Implantation of supervisor	203
5.10.2. Experimental configuration.	204
5.10.3. Results and analyses	207
5.11. Conclusion	212
5.12. Bibliography	212
CHAPTER 6. DESIGN OF A HYBRID MULTISOURCE/MULTISTORAGE SUPERVISOR	215
6.1. Introduction	215
6.2. Methodology for the construction of a supervisor for a hybrid source incorporating windpower	217
6.2.1. Determination of system specifications	218
6.2.2. Structure of supervisor	220
6.2.3. Determination of functional graphs	223
6.2.4. Determination of membership functions.	227
6.2.5. Determination of operational graphs	231
6.2.6. Extraction of fuzzy laws	233
6.3. Compared performance of different variants of hybrid source	234
6.3.1. Characteristics of simulated system.	234
6.3.2. Simulations of different hybrid source variants.	237
6.3.3. Comparison of performance of different hybrid sources by means of indicators	248
6.4. Conclusion.	249
6.5. Appendices	249
6.5.1. Range of output value variations	249
6.5.2. Fuzzy rules	251
6.6. Bibliography.	253
CHAPTER 7. MANAGEMENT AND ECONOMIC ENHANCEMENT OF ADIABATIC COMPRESSED-AIR ENERGY STORAGE INCORPORATED INTO A POWER GRID	255
7.1. Introduction	255
7.2. Services provided by storage	257
7.2.1. Storage planning	257
7.2.2. Frequency control	257

7.2.3. Congestion management	258
7.2.4. Guarantee of variable renewable production	258
7.3. Supervision strategy	259
7.3.1. Methodology	259
7.3.2. Objectives, constraints and means of actions	260
7.3.3. Supervisor structure	260
7.3.4. Determination of functional graphs	262
7.3.5. Determination of membership functions	267
7.3.6. Determination of operational graphs	270
7.3.7. Extraction of fuzzy rules	270
7.3.8. Indicators	270
7.4. Economic value of services	271
7.4.1. Purchase/sale action	272
7.4.2. Frequency control billing	273
7.4.3. Billing of additional services	273
7.5. Application	274
7.5.1. Test grid	274
7.5.2. Interest of the contribution of storage to ancillary services	275
7.5.3. Interest of fuzzy supervisor compared to a Boolean supervisor	279
7.6. Conclusion	281
7.7. Acknowledgments	282
7.8. Bibliography	282
INDEX	285