

# Contents

<b>Abstract</b>	<b>ii</b>
<b>Acknowledgements</b>	<b>iii</b>
<b>1 The fast and safe charge of Li-ion batteries: An introduction</b>	<b>1</b>
1.1 Fast and safe charge of a single cell: a complexity challenge . . . . .	5
1.2 From the single cell to a battery pack: an equalization challenge . . . . .	8
1.3 Objectives of this thesis: The reduction of the computational intensiveness . .	10
1.4 Summary and Overview of this thesis . . . . .	11
<b>2 Model, estimation, and operating admissible region of Li-ion battery cells</b>	<b>12</b>
2.1 The Equivalent Hydraulic Model . . . . .	12
2.2 Estimation of electrochemical states through an Extended Kalman Filter . . .	15
2.3 Estimating the EHM parameters for a commercial Li-ion battery cell . . . . .	17
2.3.1 Selecting a model for the equilibrium potentials of the electrodes . . .	18
2.3.2 Fitting procedure to identify the kinetic parameters of the EHM . . . .	20
2.4 Formalization of the admissible regions for the safe charge of single Li-ion cells	24
2.5 Summary . . . . .	26
<b>3 Constrained-control charging strategies for the fast and safe charge of a single battery cell</b>	<b>28</b>
3.1 Model Predictive Control . . . . .	28
3.1.1 Time-invariant convexification . . . . .	29
3.1.2 Time-varying convex embedding of a concave set . . . . .	30
3.2 Charging protocols based on Reference Governors . . . . .	31
3.2.1 State feedback . . . . .	32
3.2.2 Reference Governors . . . . .	33
Scalar Reference Governor with or-operators . . . . .	33
3.3 Explicit Reference Governor . . . . .	38
3.4 Summary . . . . .	42
<b>4 Experimental Validations of charging policies for single cells</b>	<b>44</b>
4.1 Charging strategies . . . . .	44
4.1.1 Experimental Test Bench . . . . .	46
4.1.2 Experimental protocol . . . . .	46
4.2 Experimental results on commercial LCO battery cells . . . . .	47
4.3 Summary . . . . .	52
<b>5 Constrained-control algorithms for the fast charge and balance of a string of Li-ion battery cells</b>	<b>56</b>
5.1 A max-min sub-optimal algorithm to solver the mixed-integer nonlinear MPC	58

5.2	A Pulse Width Modulation approach for the shunting switches. . . . .	58
5.2.1	Development of a charging and equalizing strategy based on Reference Governors . . . . .	61
5.3	Summary . . . . .	61
<b>6</b>	<b>Numerical validations of algorithms for the fast charge and balance of a string of LCO-graphite battery cells</b>	<b>63</b>
6.1	Characteristics of the numerical validations . . . . .	63
6.1.1	Case of study . . . . .	63
6.2	Numerical Results . . . . .	64
6.3	Summary . . . . .	68
<b>7</b>	<b>Concluding remarks</b>	<b>72</b>
7.1	Closing remarks . . . . .	72
7.1.1	The single cell case . . . . .	72
7.1.2	The multi-cells case . . . . .	73
7.2	Future research opportunities . . . . .	73
7.2.1	The lifespan tests . . . . .	74
7.2.2	The extension with thermal effects . . . . .	74
	<b>Bibliography</b>	<b>76</b>
<b>A</b>	<b>Comparison of estimation methods used in Battery Management Systems</b>	<b>85</b>
<b>B</b>	<b>Equilibrium Potentials Models for LCO battery cells available in the literature</b>	<b>89</b>
<b>C</b>	<b>Selection of an equilibrium model for Beez2B Lipo (LCO) battery cells</b>	<b>91</b>
<b>D</b>	<b>Cross-validation of for the fitting of the EHM parameters</b>	<b>92</b>
<b>E</b>	<b>Sequential charge of a string of battery cells with a PWM approach</b>	<b>93</b>
<b>F</b>	<b>Fast charge of a single cell considering decoupled electrochemical and thermal models</b>	<b>95</b>

# List of Figures

1.1	Scheme of a Li-ion battery cell where “Y” can be any transition metal or an Iron-Phosphate . . . . .	3
1.2	The Constant Current-Constant Voltage protocol (CCCV) . . . . .	4
1.3	Effects of the CCCV tuning parameters on the charging time of a Li-ion battery cell . . . . .	5
1.4	An Equivalent Circuit Model [29] . . . . .	6
1.5	Scheme of a passive balancing grid . . . . .	8
1.6	Scheme of an active balancing grid . . . . .	9
2.1	Hydraulic description of the EHM . . . . .	14
2.2	Selection of the equilibrium potentials model for Turnigy battery cells . . . . .	21
2.3	Profiles for the EHM parameters identification for Turnigy nanotech battery cells of 160mAh . . . . .	23
2.4	Admissible region for the fast and safe charge of LCO-graphite batteries . . . . .	26
3.1	Time-invariant convex set resulting after convexification . . . . .	30
3.2	Effects of the selection of the linear constraint to convexify the admissible set . . . . .	30
3.3	A convex set is generated by embedding the concave constraint with the half-plane tangent to $m(\text{CSC}(k)) = 0$ . . . . .	31
3.4	Charging control scheme based on Reference Governors . . . . .	32
3.5	Examples of the union of linear constraints to approximate the non-convex admissible region . . . . .	35
4.1	Peltier cell with an on/off dead-band control action to regulate the ambient temperature of each test . . . . .	46
4.2	Custom-built experimental setup, where 1) Li-ion battery coupled with a thermal sensor (surface of the battery), 2) thermal sensor for the temperature inside of the box, 3) current and voltage sensors, 4) acquisition board, 5) and 6) temperature transmitters, 7) power supply and 8) security relay . . . . .	47
4.3	Performance of the charging strategies within the admissible region at 10°C . . . . .	48
4.4	Experimental validations at $T_{amb} = 10^\circ\text{C}$ . . . . .	48
4.5	Experimental validations at $T_{amb} = 20^\circ\text{C}$ . . . . .	49
4.6	Experimental validations at $T_{amb} = 30^\circ\text{C}$ . . . . .	50
4.7	Experimental validations at $T_{amb} = 40^\circ\text{C}$ . . . . .	51
5.1	Theoretical balancing grid . . . . .	56
6.1	Numerical validation of the max-min mixed-integer MPC (Algorithm 5.1) with a reconfiguration time of 1s . . . . .	65
6.2	Numerical validation of the max-min mixed-integer MPC (Algorithm 5.1) with a reconfiguration time of 60s . . . . .	66
6.3	Numerical validation of a nonlinear MPC-based policy that considers PWM . . . . .	67

6.4	Numerical validation on the DFN of a ratio-based MPC-based algorithm that considers PWM (Algorithm 5.2) . . . . .	68
6.5	Numerical validation on the DFN of a ratio-based PWM-based ERG algorithm (Algorithm 5.3) . . . . .	69
6.6	Effects on the charging time of increasing the number of battery cells within the string . . . . .	69
6.7	Effects on the computational time of increasing the number of battery cells within the string . . . . .	70
6.8	Numerical validation on the DFN of a ratio-based MPC-based algorithm that considers PWM and if-operators (Algorithm E.1) . . . . .	70
C.1	OCV selection for Beez2B battery cells . . . . .	91
F.1	Numerical validation on the DFN of the 2-level constrained policy for the fast and safe charge of a battery cell accounting for thermal constraints . . . . .	96