

Contents

Part I Theoretical Framework

1	Introduction to Switched Circuits	3
1.1	Simple Examples of Switched Circuits	3
1.1.1	Diode Modeling	3
1.1.2	An RCD Circuit	5
1.1.3	An RLZD Circuit	7
1.1.4	An RCZD Circuit	10
1.1.5	An RLD Circuit	12
1.1.6	More Examples: Order-Two and Order-Three Circuits	19
1.1.7	A Circuit with an Ideal Switch	23
1.2	A Unified Dynamical Framework: Lur’e Dynamical Systems	26
1.3	An Aside on Nonsmooth Mechanics: The Bouncing Ball	27
1.4	Conclusions	29
1.5	Historical Summary	30
2	Mathematical Background	33
2.1	Basics from Convex and Nonsmooth Analysis	33
2.1.1	Convex Sets and Functions	33
2.1.2	Multivalued Functions	46
2.2	Non Convex Sets	51
2.3	Basics from Complementarity Theory	51
2.3.1	Definitions	51
2.3.2	Complementarity Problems: Existence and Uniqueness of Solutions	53
2.3.3	Links with Inclusions into Normal Cones	56
2.3.4	Links with Variational Inequalities	57
2.3.5	Links with Optimization	58
2.4	Mathematical Formalisms	59
2.4.1	Moreau’s Sweeping Process, Measure Differential Inclusions	60
2.4.2	Dynamical Variational Inequalities	65
2.4.3	Complementarity Dynamical Systems	66

2.4.4	Filippov's Inclusions	73
2.4.5	Maximal Monotone Inclusions, Unilateral Differential Inclusions	81
2.4.6	Equivalences Between the Formalisms	82
2.5	The Dynamics of the Simple Circuits	84
2.5.1	The Ideal Diode Voltage/Current Law	85
2.5.2	The Piecewise-Linear Diode Voltage/Current Law	85
2.5.3	A Mixed Nonlinear/Unilateral Diode	85
2.5.4	From Smooth to Nonsmooth Electrical Powers	86
2.5.5	The RLD Circuit in (1.16)	88
2.5.6	The RCD Circuit in (1.3)	90
2.5.7	The RLZD Circuit in (1.7)	91
2.5.8	Coulomb's Friction and Zener Diodes	91
2.5.9	The RCZD Circuit in (1.11)	93
2.5.10	The Circuit in (1.41)	94
2.5.11	The Switched Circuit in (1.52)	96
2.5.12	Well-Posedness of the OSNSP in (1.45)	97
2.5.13	The Bouncing Ball	98
2.6	Time-Discretization Schemes	99
2.6.1	Maximal Monotone Differential Inclusions	100
2.6.2	Linear Complementarity Systems	100
2.6.3	Moreau's Sweeping Process	102
2.7	Conclusions and Recapitulation	104

Part II Dynamics Generation and Numerical Algorithms

3	Conventional Circuit Equation Formulation and Simulation	109
3.1	Circuit Topology and Kirchhoff's Laws	109
3.1.1	The Circuit Network as a Connected Oriented Graph	109
3.1.2	The Incidence Matrix A and Kirchhoff's Current Laws	110
3.1.3	The Loop Matrix B and Kirchhoff's Voltage Laws	111
3.1.4	KVL in Terms of Nodes Voltages	111
3.2	The Sparse Tableau Analysis (STA)	112
3.3	The Modified Nodal Analysis	112
3.3.1	Classification of the Branches	113
3.3.2	Standard Resistive, Capacitive and Inductive Branches	113
3.4	The Charge/Flux Oriented MNA	115
3.5	Standard DAEs Stemming from the MNA	115
3.5.1	Various Forms of DAEs	116
3.5.2	Index and Solvability	118
3.6	Semi-Explicit DAE Forms	124
3.6.1	A First Naive Attempt	124
3.6.2	A Second Attempt	126
3.6.3	The Proposed Solution	129
3.7	Basics on Standard Circuit Simulation	131
3.7.1	Computation of the Initial Conditions	131

3.7.2	Time-Discretization of the MNA	132
3.7.3	Solving Nonlinear Systems	132
3.7.4	Implementation Details and the Stamping Method	134
4	Nonsmooth Modeling of Electrical Components	137
4.1	General Nonsmooth Electrical Element	137
4.2	Nonsmooth Elements as Inclusions into the Subdifferential of Convex Functions and Variational Inequality (VI)	138
4.3	Nonsmooth Elements as Inclusions into Normal Cones and Variational Inequalities	140
4.4	Complementarity Problems	141
4.5	The Linear Input/Output Relation Case	142
4.5.1	Some Instances of Linear Nonsmooth Components	142
4.6	Generic Piecewise-Linear Components	143
4.6.1	The First Model Description of van Bokhoven	143
4.6.2	The Second Model Description of van Bokhoven	144
4.7	Special Instances of Nonsmooth Components	145
4.7.1	Ideal Diode	145
4.7.2	Zener Diode	145
4.7.3	Ideal Switch	146
4.7.4	Explicit Ideal Switch. Glocker's Model	147
4.7.5	MOSFET Transistor	148
4.7.6	Nonlinear and Nonsmooth MOS Transistor	152
4.7.7	Comparator Component	153
5	Time-Stepping Schemes and One Step Solvers	155
5.1	Summary of the Mathematical Formalisms	155
5.1.1	Nonsmooth DAE Formulation. Differential Generalized Equation (DGE)	155
5.1.2	The Semi-Explicit Nonsmooth DAE: Semi-Explicit DGE	157
5.2	Principles of the Numerical Time-Integration Scheme	158
5.2.1	Time-Stepping Solutions for a Solution of Class C^1	160
5.2.2	Time-Stepping Schemes for an Absolutely Continuous Solution	161
5.2.3	Time-Stepping Solutions for a Solution of Bounded Variations	166
5.2.4	Illustrations of Wrong Discretizations	170
5.2.5	How to Choose a Scheme in Practice?	173
5.2.6	Newton's Method for the Nonlinear Dynamics	177
5.3	Time-Discretization of the General Cases	179
5.4	One-Step NonSmooth Problems (OSNSP) Solvers	180
5.4.1	K is a Finite Representable Convex Set	181
5.4.2	K is a Generalized Box	181

Part III Numerical Simulations

6	The Automatic Circuit Equations Formulation (ACEF) Module and the SICONOS Software	185
6.1	An Insight into SICONOS	185
6.1.1	Step 1. Building a Nonsmooth Dynamical System	186
6.1.2	Step 2. Simulation Strategy Definition	189
6.2	SICONOS Software	190
6.2.1	General Principles of Modeling and Simulation	190
6.2.2	NSDS Related Components	193
6.2.3	Simulation-Related Components	195
6.2.4	SICONOS software design	196
6.3	The ACEF Module and Algorithms	198
6.3.1	A Module Able to Read a Circuit File: A Parser	200
6.3.2	Build the Vector of Unknowns I_{NS}	201
6.3.3	An Algorithm to Choose the Unknowns	201
6.3.4	Building the System $N(x, t)\dot{x} = f(x, z, t)$ of (3.70)	202
6.3.5	Building the Relation $0 = g(x, z, t)$ of (3.70)	203
6.3.6	The Stamp Method for Nonsmooth Components	204
6.3.7	Some Stamp Examples	205
6.3.8	The ACEF Global Execution Algorithm	206
6.3.9	An Example of the Stamp Method with Nonsmooth Component	206
7	Simple Circuits	215
7.1	Maffezzoni's Example	215
7.1.1	The Dynamical Model	216
7.1.2	Simulation Results: Failure of the Newton-Raphson Algorithm	217
7.1.3	Numerical Results with SICONOS	219
7.1.4	Numerical Results with ELDO	219
7.2	A First Diode-Bridge Wave Rectifier	221
7.2.1	Dynamical Equations	221
7.2.2	Simulation Results	222
7.3	A Second Diode-Bridge Wave Rectifier	224
7.4	The Ćuk Converter	225
7.5	A Circuit Exhibiting Sliding Modes	231
7.5.1	Models and Dynamical System	234
7.5.2	Simulation and Comparisons	235
8	Buck and Delta-Sigma Converters	239
8.1	The Buck Converter with Load Resistor	239
8.1.1	Dynamical Equations	240
8.1.2	Numerical Results with SICONOS	241
8.1.3	Comparisons and Discussions	244

8.2	The Buck Converter Loaded by a Resistor and an Inverter Chain . .	253
8.2.1	Simulation as a Nonsmooth Dynamical System with SICONOS	253
8.2.2	Simulation with PLECS	254
8.3	The Delta-Sigma Converter	254
8.3.1	Dynamical Equations	259
8.3.2	Numerical Results with SICONOS	264
8.3.3	Comparisons and Discussions	265
8.4	Conclusions	265
Appendix A Some Facts in Real Analysis		267
A.1	Absolutely Continuous Functions and Sets	267
A.2	Lipschitz Continuous Functions and Sets	268
A.3	Functions of Bounded Variations in Time	268
A.4	Multifunctions of Bounded Variation in Time	270
A.5	Differential Measures	270
A.6	Measure Differential Inclusion (MDI)	271
References		273
Index		281

Nonsmooth Modeling and Simulation for Switched
Circuits

Acary, V.; Bonnefon, O.; Brogliato, B.

2011, XXIII, 284 p., Hardcover

ISBN: 978-90-481-9680-7