

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Aim and Scope	3
1.3	Organization	4
2	Fundamentals	6
2.1	Multi-Level Energy Storage System	6
2.2	Grid-Forming Converter	8
2.3	Phasor Calculus-Based Model	9
2.3.1	Dynamic Phasor Calculus-Based Model	9
2.3.2	Quasi-Static Phasor Calculus-Based Model	10
2.4	Frequency-Adaptive Simulation of Transients	10
2.4.1	Companion Model for Instantaneous Signals	11
2.4.2	Characteristics of Analytic Signal	12
2.4.3	Companion Model and Network Construction for Multi-Scale Simulation	13
3	Virtual Capacitor Control-Based Multi-Level Energy Storage System for Mitigating Voltage Variations in DC Microgrids	16
3.1	Introduction	16
3.2	Multi-Level Energy Storage System	18
3.2.1	System Architecture	18
3.2.2	Modeling	19
3.3	Virtual Capacitor Control Based Multi-Level Energy Storage System	22

3.3.1	Concept of Virtual Capacitor Control	22
3.3.2	Implementation of Proposed Virtual Capacitor Control Based Multi-Level Energy Storage System	24
3.4	Design of PI Compensators	26
3.4.1	Transfer Function Modeling of Supercapacitor Controller	27
3.4.2	Bandwidth Selection for Control Loops	28
3.4.3	Compensator Design	29
3.5	Validation Case	32
3.5.1	DC Bus Test System	33
3.5.2	Validation of Virtual Capacitor Control for Voltage Fluctuation Mitigation	33
3.5.3	Performance Comparison with Alternative Control Methods	36
3.6	Application Case	37
3.6.1	Low-Voltage DC Distribution Network	38
3.6.2	Simulation Results Under Different Test Scenarios	39
3.7	Conclusion	40

4 Transient Modeling and Droop Controller Design of Power Electronic-Dominated Microgrids 41

4.1	Introduction	41
4.2	Modeling of Converter-Dominated Microgrid	43
4.2.1	Modeling Converter-Side Part	44
4.2.2	Modeling Grid-Side Part	48
4.3	Small Signal Modeling of Converter-Based Microgrid	49
4.4	Stability Analysis and Accuracy Comparison for DPC and QPC Based Models	49
4.4.1	Stability Analysis and Comparison for DPC and QPC Based Models	50
4.4.2	Accuracy Identification for DPC and QPC Based Models	52
4.5	Droop Controller Design Using \mathcal{H}_∞ Optimization Approach	53
4.5.1	Setup for Droop Controller Design	53
4.5.2	Construction and Solution of Objective Function	55
4.6	Validation Case	57

4.6.1	Design for Droop controllers	58
4.6.2	Validation by Simulation Results	59
4.6.3	Comparison with Empirical Droop Controllers	59
4.7	Application Case	61
4.7.1	Modified CIGRE European Low-Voltage Grid	62
4.7.2	Simulation and Verification	62
4.8	Conclusion	65
5	Multi-Scale Modeling and Simulation of Power Electronic-Dominated Microgrid	67
5.1	Introduction	67
5.2	Multi-Scale Modeling of Voltage-Sourced Converter With Grid-Forming Control	69
5.2.1	Structure of Multi-Scale Grid-Forming Converter Model	69
5.2.2	Multi-Scale Modeling of Grid-Forming Control System	70
5.2.3	Multi-Scale Modeling of Voltage-Sourced Converter	71
5.3	Interface Modeling of Grid-Forming Control System	73
5.3.1	Interfacing of Analytic to Real Signals	73
5.3.2	Interfacing of Real to Analytic Signals	76
5.4	Validation Case	76
5.4.1	Validation of Multi-Scale Grid-Forming Converter Model	77
5.4.2	Validation of Proposed Interface	82
5.5	Application Case	84
5.6	Conclusion	87
6	Conclusions	88
6.1	Contributions	88
6.2	Outlook	89
A	Small Signal State-Space Modeling	91
A.1	State-Space Representation	91
A.2	Small Signal Modeling	92

B	Modeling of Electrical Components In MLESS	94
B.1	Modeling of Battery	94
B.2	Modeling of Supercapacitor	95
B.3	Modeling of Bidirectional DC-DC Converters	96
B.4	Modeling of Short Lines	98
C	Parameters in Microgrids	100
C.1	Parameters in DC Microgrids	100
C.2	Parameters in Power Electronic Converter-Dominated Microgrids	101
D	Techniques in Modeling of Converter-Dominated microgrids	104
D.1	Details on VSC Average Modeling	104
D.2	Modeling of Grid-Forming Control System in Multi-Scale Simulation	104
	D.2.1 Modeling Power Controller	105
	D.2.2 Modeling Inner Controller	106
D.3	PWM Modulation	107
D.4	Effects of Magnitude Prediction Term	108
D.5	Imaginary Part Construction	108
E	Terminology	110
E.1	Symbols	110
	E.1.1 Upper Case Letters	110
	E.1.2 Lower Case Letters	111
	E.1.3 Greek Letters	113
	E.1.4 Additional Recurrent Subscripts and Superscripts	113
E.2	Acronyms	114
F	Bibliography	115