Contents

1	Intro	oduction	n	1	
	1.1	Aim ar	nd Scope of This Work	1	
	1.2	Organi	zation of This Work	3	
2	Fund	damenta	als of Modular Multilevel Converter in HVDC System	4	
	2.1	Mather	matical Model of Modular Multilevel Converter	4	
	2.2	2.2 Basic Operating Principles			
		2.2.1	Modulation Techniques of PSC-PWM and NLM	6	
		2.2.2	Operating Principle of Submodule	9	
	2.3	Calcula	ation of Ripple Voltage of Capacitor	10	
	2.4	DC Fa	ult Ride-Through Capability of Various Submodule Topologies	13	
	2.5	Half-B	ridge Submodule With Bypass Thyristor for Overcurrent Protection	15	
	2.6	Compr	ehensive Modeling Tree	15	
3	Analytical Model of Instantaneous Switching Frequency of Modular Multilevel Con-				
	verte	er		18	
	3.1	Introdu	ction	18	
	3.2	Review	v of Basic Operating Principles	19	
	3.3	Model	of Instantaneous Switching Frequency	21	
		3.3.1	Submodule State Switching Frequencies	21	
		3.3.2	Device Switching Frequencies	28	
	3.4	Instant	iation of Generic Model of Instantaneous Switching Frequencies for PSC-		
	PWM and NLM			35	
	3.5	Validat	tion	36	

		3.5.1	Test System and Operating Point	37
		3.5.2	Validation of MMC Using PSC-PWM	37
		3.5.3	Validation of MMC Using NLM	42
	3.6	Model	Predictive Switching	45
	3.7	Conclu	ision	46
4	Ana	lytical N	Model of Switching Loss of Modular Multilevel Converter	48
	4.1	Introdu	action	48
	4.2	Review	v of Basic Operating Principles and Switching Loss Characterization	49
	4.3	Analyt	ical Modeling of Switching Lasses	51
		4.3.1	Switching Loss Formulation Through Integration	51
		4.3.2	Analytical Solutions of Integrals for Steady-State Operation	54
	4.4	Valida	tion	57
		4.4.1	Test System and Operating Points	58
		4.4.2	Validation of MMC Using PSC-PWM	59
		4.4.3	Validation of MMC Using NLM	62
		4.4.4	Application for Junction Temperature Estimation of Power Electronic	
			Switching Devices of one Submodule	64
	4.5	Conclu	ision	64
5	Ana	lytical N	Modeling of MMC Under Pole-to-Pole Fault	67
	5.1	Introdu	action	67
	5.2	Stages	of Pole-to-Pole Fault and Equivalent Circuits	69
		5.2.1	Overview of Fault Scenario and Fault Stages	69
		5.2.2	System Behaviour and Equivalent Circuits of Fault Stages	70
		5.2.3	Conducting States of Switching Devices	79
	5.3	5.3 Analytical Calculation of Fault Currents of MMC Under Pole-to-Pole Fau		80
		5.3.1	Generic Equivalent Circuits	80
		5.3.2	Analytical Calculation of the AC Grid Currents	83
		5.3.3	Analytical Calculation of the Arm Currents	85
		5.3.4	Analytical Calculation of the DC Grid Current	86

	5.4	Parameter Design of Arm Inductor and Selection of Circuit Breaker Breaking Capability		87
		5.4.1	Parameter Design of Arm Inductor.	87
		5.4.2	Selection of Circuit Breaker Breaking Capability	88
	5.5	Valida	tion	89
		5.5.1	Test System and Fault Scenario	89
		5.5.2	Validation of Analytical Model of MMC Under Pole-to-Pole fault	90
		5.5.3	Validation of Parameter Design Principle of Arm Inductor	91
	5.6	Conclu	usion	93
6	Tra	nsient S	tability Assessment of AC/DC Parallel System	94
	6.1	Introdu	uction	94
	6.2	Transi	ent Stability Assessment Based on Equal Area Criterion	95
		6.2.1	Mathematical Model of AC-DC Hybrid Single Machine Infinite Bus System	96
		6.2.2	Transient Stability Assessment for AC Short-Circuit Fault	97
		6.2.3	Transient Stability Assessment for DC Short-Circuit Fault	101
	6.3	Valida	tion	103
		6.3.1	Test System and Operating Point	103
		6.3.2	Validation for Transient Stability Under AC Short-Circuit Fault	104
		6.3.3	Validation for Transient Stability Under DC Short-Circuit Fault	106
		6.3.4	Comparison for Transients of System Under AC and DC Faults	107
	6.4	Applic	ation for Assessing the Impact of Initial Power Flow on Transient Stability	108
	6.5	Conclu	usion	110
7	Con	clusions	5	112
A	Teri	ninolog	У	114
	A.1	Symbo	ols	114
		A.1.1	Upper Case Letters	114
		A.1.2	Lower Case Letters	116

		A.1.3	Greek Letters	. 119
		A.1.4	Additional Recurrent Subscripts and Superscripts	. 121
	A.2	Acrony	ms	. 121
B	Assu	imption	S	123
	B.1	Assum	ptions for Modeling of Instantaneous Switching Frequency	. 123
	B.2	Assum	ptions for Modeling of Instantaneous Switching Loss	. 123
	B.3	Assum	ptions for Modeling of MMC Under Pole-to-Pole Fault	. 124
	B.4	Assum	ptions for Transient Stability Assessment of AC-DC Hybrid System	. 124
C	Disc	rete Mo	del of Switching Frequencies in Numerical Simulation	125
	D Supplementary Calculation for Analytical Modeling of MMC Under Pole-to-Pole		_	
D	Supj	plement	ary Calculation for Analytical Modeling of MMC Under Pole-to-Po	le
D	Supj Faul	plement t	ary Calculation for Analytical Modeling of MMC Under Pole-to-Po	le 126
D	Supj Faul D.1	plement t Calcula	ary Calculation for Analytical Modeling of MMC Under Pole-to-Po	le 126 . 126
D	Supj Faul D.1 D.2	plement t Calcula Calcula	ary Calculation for Analytical Modeling of MMC Under Pole-to-Poleto-Poleto of Coefficients of AC Grid Currents	le 126 . 126 . 129
D	Supj Faul D.1 D.2 D.3	plement t Calcula Calcula Initial (ary Calculation for Analytical Modeling of MMC Under Pole-to-Po ation of Coefficients of AC Grid Currents	 126 126 129 130
D	Supj Faul D.1 D.2 D.3 D.4	plement t Calcula Calcula Initial (Arm Co	ary Calculation for Analytical Modeling of MMC Under Pole-to-Poleto-Poleto-Poleto ation of Coefficients of AC Grid Currents ation of AC Terminal Voltage of Converter Circulating Current Circulating States During Stage III	le 126 . 126 . 129 . 130 . 131
D	Supj Faul D.1 D.2 D.3 D.4 Test	t Calcula Calcula Initial (Arm Co Case Pa	ary Calculation for Analytical Modeling of MMC Under Pole-to-Poleto-Poleto of Coefficients of AC Grid Currents	le 126 . 126 . 129 . 130 . 131 133