



# Transients in Power Systems

Lou van der Sluis

# Contents

Preface	xi
<b>1 Basic Concepts and Simple Switching Transients</b>	<b>1</b>
1.1 Switching an LR Circuit	3
1.2 Switching an LC Circuit	6
1.3 Switching an RLC Circuit	9
1.4 References for Further Reading	13
<b>2 Transient Analysis of Three-Phase Power Systems</b>	<b>15</b>
2.1 Symmetrical Components in Three-Phase Systems	16
2.2 Sequence Components for Unbalanced Network Impedances	17
2.3 The Sequence Networks	20
2.4 The Analysis of Unsymmetrical Three-Phase Faults	22
2.4.1 The Single Line-to-Ground Fault	22
2.4.2 The Three-Phase-to-Ground Fault	24
2.5 References for Further Reading	30
<b>3 Travelling Waves</b>	<b>31</b>
3.1 Velocity of Travelling Waves and Characteristic Impedance	32
3.2 Energy Contents of Travelling Waves	34
3.3 Attenuation and Distortion of Electromagnetic Waves	36
3.4 The Telegraph Equations	38
3.4.1 The Lossless Line	40
3.4.2 The Distortionless Line	42
3.5 Reflection and Refraction of Travelling Waves	42

3.6	Reflection of Travelling Waves against Transformer- and Generator-Windings	45
3.7	The Origin of Transient Recovery Voltages	49
3.8	The Lattice Diagram	52
3.9	References for Further Reading	56
<b>4</b>	<b>Circuit Breakers</b>	<b>57</b>
4.1	The Switching Arc	58
4.2	Oil Circuit Breakers	63
4.3	Air-Blast Circuit Breakers	64
4.4	SF <sub>6</sub> Circuit Breakers	64
4.5	Vacuum Circuit Breakers	66
4.6	Modelling of the Switching Arc	68
4.7	Arc-Circuit Interaction	74
4.8	References for Further Reading	80
<b>5</b>	<b>Switching Transients</b>	<b>83</b>
5.1	Interrupting Capacitive Currents	84
5.2	Capacitive Inrush Currents	91
5.3	Interrupting Small Inductive Currents	93
5.4	Transformer Inrush Currents	95
5.5	The Short-Line Fault	97
5.6	References for Further Reading	105
<b>6</b>	<b>Power System Transient Recovery Voltages</b>	<b>107</b>
6.1	Characteristics of the Transient Recovery Voltage	110
6.1.1	Short-Circuit Test Duties based on IEC 60056 (1987)	111
6.1.2	Short-Circuit Test Duties based on ANSI/IEEE Standards	115
6.1.3	The Harmonisation between IEC and ANSI/IEEE Standards with Respect to Short-Circuit Test Duties	115
6.2	The Transient Recovery Voltage for Different Types of Faults	116
6.3	References	119
<b>7</b>	<b>Lightning-Induced Transients</b>	<b>121</b>
7.1	The Mechanism of Lightning	122
7.2	Waveshape of the Lightning Current	124

7.3	Direct Lightning Stroke to Transmission Line Towers	125
7.4	Direct Lightning Stroke to a Line	127
7.5	References for Further Reading	134
<b>8</b>	<b>Numerical Simulation of Electrical Transients</b>	<b>135</b>
8.1	The Electromagnetic Transient Program	137
8.2	The MNA Program	142
8.3	The Xtrans Program	145
8.4	The MATLAB Power System Blockset	152
8.5	References for Further Reading	156
<b>9</b>	<b>Insulation Coordination, Standardisation Bodies, and Standards</b>	<b>159</b>
9.1	The International Electrotechnical Commission – IEC	160
9.2	The American National Standards Institute – ANSI	162
9.3	The Conférence Internationale des Grands Réseaux Electriques à Haute Tension – CIGRÉ	162
9.4	The Short-Circuit Testing Liaison – STL	163
9.5	Standards Related to High-Voltage Electrical Power Equipment	164
9.6	References for Further Reading	168
<b>10</b>	<b>Testing of Circuit Breakers</b>	<b>169</b>
10.1	The High-Power Laboratory	170
10.2	The Historical Development of Circuit Breaker Testing	172
10.3	Direct Test Circuits	174
10.4	Synthetic Test Circuits	180
10.5	Short-Line Fault Testing	186
10.6	Measuring Transient Currents and Voltages	189
10.6.1	Transducers for Current Measurements	191
10.6.2	Transducers for Voltage Measurements	196
10.7	Measurement Setup for Transient Voltage and Current Measurements	199
10.8	References for Further Reading	203
	<b>Index</b>	<b>205</b>