

Transient Analysis of Electric Power Circuits Handbook

by

ARIEH L. SHENKMAN

*Holon Academic Institute of Technology,
Holon, Israel*



CONTENTS

FOREWORD	xiii
PREFACE	xv
CHAPTER 1	
Classical approach to transient analysis	1
1.1. Introduction	1
1.2. Appearance of transients in electrical circuits	2
1.3. Differential equations describing electrical circuits	4
1.3.1. Exponential solution of a simple differential equation	7
1.4. Natural and forced responses	11
1.5. Characteristic equation and its determination	14
1.6. Roots of the characteristic equation and different kinds of transient responses	21
1.6.1. First order characteristic equation	21
1.6.2. Second order characteristic equation	22
1.7. Independent and dependent initial conditions	26
1.7.1. Two switching laws (rules)	26
(a) First switching law (rule)	26
(b) Second switching law (rule)	27
1.7.2. Methods of finding independent initial conditions	29
1.7.3. Methods of finding dependent initial conditions	31
1.7.4. Generalized initial conditions	35
(a) Circuits containing capacitances	35
(b) Circuits containing inductances	39
1.8. Methods of finding integration constants	44
CHAPTER 2	
Transient response of basic circuits	49
2.1. Introduction	49
2.2. The five steps of solving problems in transient analysis	49

2.3. <i>RL</i> circuits	51
2.3.1. <i>RL</i> circuits under d.c. supply	51
2.3.2. <i>RL</i> circuits under a.c. supply	62
2.3.3. Applying the continuous flux linkage law to <i>L</i> -circuits	72
2.4. <i>RC</i> circuits	80
2.4.1. Discharging and charging a capacitor	80
2.4.2. <i>RC</i> circuits under d.c. supply	82
2.4.3. <i>RC</i> circuits under a.c. supply	88
2.4.4. Applying the continuous charge law to <i>C</i> -circuits	95
2.5. The application of the unit-step forcing function	101
2.6. Superposition principle in transient analysis	105
2.7. <i>RLC</i> circuits	110
2.7.1. <i>RLC</i> circuits under d.c. supply	110
(a) Series connected <i>RLC</i> circuits	113
(b) Parallel connected <i>RLC</i> circuits	118
(c) Natural response by two nonzero initial conditions	120
2.7.2. <i>RLC</i> circuits under a.c. supply	131
2.7.3. Transients in <i>RLC</i> resonant circuits	135
(a) Switching on a resonant <i>RLC</i> circuit to an a.c. source	136
(b) Resonance at the fundamental (first) harmonic	139
(c) Frequency deviation in resonant circuits	140
(d) Resonance at multiple frequencies	141
2.7.4. Switching off in <i>RLC</i> circuits	143
(a) Interruptions in a resonant circuit fed from an a.c. source	147

CHAPTER 3

Transient analyses using the Laplace transform techniques	155
3.1. Introduction	155
3.2. Definition of the Laplace transform	156
3.3. Laplace transform of some simple time functions	157
3.3.1. Unit-step function	157
3.3.2. Unit-impulse function	158
3.3.3. Exponential function	159
3.3.4. Ramp function	159
3.4. Basic theorems of the Laplace transform	159
3.4.1. Linearity theorem	160
3.4.2. Time differentiation theorem	161
3.4.3. Time integration theorem	163
3.4.4. Time-shift theorem	165
3.4.5. Complex frequency-shift property	169
3.4.6. Scaling in the frequency domain	170
3.4.7. Differentiation and integration in the frequency domain	171
3.5. The initial-value and final-value theorems	172
3.6. The convolution theorem	176
3.6.1. Duhamel's integral	179

3.7. Inverse transform and partial fraction expansions	180
3.7.1. Method of equating coefficients	182
(a) Simple poles	182
(b) Multiple poles	183
3.7.2. Heaviside's expansion theorem	184
(a) Simple poles	184
(b) Multiple poles	185
(c) Complex poles	186
3.8. Circuit analysis with the Laplace transform	188
3.8.1. Zero initial conditions	190
3.8.2. Non-zero initial conditions	193
3.8.3. Transient and steady-state responses	197
3.8.4. Response to sinusoidal functions	200
3.8.5. Thévenin and Norton equivalent circuits	203
3.8.6. The transients in magnetically coupled circuits	207

CHAPTER 4

Transient analysis using the Fourier transform	213
4.1. Introduction	213
4.2. The inter-relationship between the transient behavior of electrical circuits and their spectral properties	214
4.3. The Fourier transform	215
4.3.1. The definition of the Fourier transform	215
4.3.2. Relationship between a discrete and continuous spectra	223
4.3.3. Symmetry properties of the Fourier transform	226
(a) An even function of t	226
(b) An odd function of t	227
(c) A non-symmetrical function (neither even nor odd)	228
4.3.4. Energy characteristics of a continuous spectrum	228
4.3.5. The comparison between Fourier and Laplace transforms	231
4.4. Some properties of the Fourier transform	232
(a) Property of linearity	232
(b) Differentiation properties	232
(c) Integration properties	233
(d) Scaling properties	234
(e) Shifting properties	234
(f) Interchanging t and ω properties	235
4.5. Some important transform pairs	237
4.5.1. Unit-impulse (delta) function	238
4.5.2. Unit-step function	241
4.5.3. Decreasing sinusoid	244
4.5.4. Saw-tooth unit pulse	244
4.5.5. Periodic time function	246
4.6. Convolution integral in the time domain and its Fourier transform	247

4.7. Circuit analysis with the Fourier transform	250
4.7.1. Ohm's and Kirchhoff's laws with the Fourier transform	252
4.7.2. Inversion of the Fourier transform using the residues of complex functions	252
4.7.3. Approximate transient analysis with the Fourier transform	258
(a) Method of trapezoids	259

CHAPTER 5

Transient analysis using state variables	265
5.1. Introduction	265
5.2. The concept of state variables	266
5.3. Order of complexity of a network	270
5.4. State equations and trajectory	272
5.5. Basic considerations in writing state equations	276
5.5.1. Fundamental cut-set and loop matrixes	276
5.5.2. "Proper tree" method for writing state equations	283
5.6. A systematic method for writing a state equation based on circuit matrix representation	287
5.7. Complete solution of the state matrix equation	294
5.7.1. The natural solution	294
5.7.2. Matrix exponential	295
5.7.3. The particular solution	296
5.8. Basic considerations in determining functions of a matrix	297
5.8.1. Characteristic equation and eigenvalues	298
5.8.2. The Caley-Hamilton theorem	299
(a) Distinct eigenvalues	302
(b) Multiple eigenvalues	308
(c) Complex eigenvalues	311
5.8.3. Lagrange interpolation formula	313
5.9. Evaluating the matrix exponential by Laplace transforms	314

CHAPTER 6

Transients in three-phase systems	319
6.1. Introduction	319
6.2. Short-circuit transients in power systems	320
6.2.1. Base quantities and per-unit conversion in three-phase circuits	321
6.2.2. Equivalent circuits and their simplification	327
(a) Series and parallel connections	327
(b) Delta-star (and vice-versa) transformation	328
(c) Using symmetrical properties of a network	330
6.2.3. The superposition principle in transient analysis	330
6.3. Short-circuiting in a simple circuit	333
6.4. Switching transformers	339

6.4.1. Short-circuiting of power transformers	339
6.4.2. Current inrush by switching on transformers	345
6.5. Short-circuiting of synchronous machines	346
6.5.1. Two-axis representation of a synchronous generator	347
6.5.2. Steady-state short-circuit of synchronous machines	350
(a) Short-circuit ratio (SCR) of a synchronous generator	351
(b) Graphical solution	356
(c) Influence of the load	364
(d) Approximate solution by linearization of the OCC	365
(e) Calculation of steady-state short-circuit currents in complicated power networks	368
6.5.3. Transient performance of a synchronous generator	370
(a) Transient EMF, transient reactance and time constant	370
(b) Transient effects of the damper windings: subtransient EMF, subtransient reactance and time constant	379
(c) Transient behavior of a synchronous generator with AVR	385
(d) Peak values of a short-circuit current	387
6.6. Short-circuit analysis in interconnected (large) networks	394
6.6.1. Simple computation of short-circuit currents	399
6.6.2. Short-circuit power	400
6.7. Method of symmetrical components for unbalanced fault analysis	404
6.7.1. Principle of symmetrical components	405
(a) Positive-, negative-, and zero-sequence systems	405
(b) Sequence impedances	411
6.7.2. Using symmetrical components for unbalanced three-phase system analysis	431
6.7.3. Power in terms of symmetrical components	449
6.8. Transient overvoltages in power systems	451
6.8.1. Switching surges	452
6.8.2. Multiple oscillations	459

CHAPTER 7

Transient behavior of transmission lines	465
7.1. Introduction	465
7.2. The differential equations of TL and their solution	465
7.3. Travelling-wave property in a transmission line	469
7.4. Wave formations in TL at their connections	472
7.4.1. Connecting the TL to a d.c./a.c. voltage source	473
7.4.2. Connecting the TL to load	475
7.4.3. A common method of determining travelling waves by any kind of connection	478
7.5. Wave reflections in transmission lines	480
7.5.1. Line terminated in resistance	482
7.5.2. Open- and short-circuit line termination	485

7.5.3. Junction of two lines	486
7.5.4. Capacitance connected at the junction of two lines	487
7.6. Successive reflections of waves	493
7.6.1. Lattice diagram	494
7.6.2. Bergeron diagram	496
7.6.3. Non-linear resistive terminations	499
7.7. Laplace transform analysis of transients in transmission lines	500
7.7.1. Loss-less <i>LC</i> line	504
7.7.2. Line terminated in capacitance	504
7.7.3. A solution as a sum of delayed waves	506
7.8. Line with only <i>LG</i> or <i>CR</i> parameters	511
7.8.1. Underground cable	512
 CHAPTER 8	
Static and dynamic stability of power systems	517
8.1. Introduction	517
8.2. Definition of stability	517
8.3. Steady-state stability	518
8.3.1. Power-transfer characteristic	518
8.3.2. Swing equation and criterion of stability	524
8.4. Transient stability	529
8.4.1. Equal-area criterion	533
8.5. Reduction to a simple system	537
8.6. Stability of loads and voltage collapse	540
 APPENDIX I	
	545
 APPENDIX II	
	549
 APPENDIX III	
	551
 INDEX	
	559
 INDEX	
	559