

J. ARRILLAGA • N. R. WATSON

COMPUTER MODELLING OF ELECTRICAL POWER SYSTEMS

Second Edition

CONTENTS

Preface	xi
1 Introduction	1
1.1 General Background	1
1.2 The New Computer Environment	2
1.3 Transmission System Developments	3
1.4 Theoretical Models and Computer Programs	3
2 Transmission Systems	5
2.1 Introduction	5
2.2 Linear Transformation Techniques	5
2.3 Basic Single-phase Modelling	7
2.3.1 Transmission lines	7
2.3.2 Transformer on nominal ratio	8
2.3.3 Off-nominal transformer tap representation	9
2.3.4 Phase-shifting representation	10
2.4 Three-phase System Analysis	11
2.4.1 Discussion of the frame of reference	11
2.4.2 The use of compound admittances	13
2.4.3 Rules for forming the admittance matrix of simple networks	17
2.4.4 Network subdivision	18
2.5 Three-phase Models of Transmission Lines	18
2.5.1 Series impedance	18
2.5.2 Shunt admittance	20
2.5.3 Equivalent π model	22
2.5.4 Mutually coupled three-phase lines	24
2.5.5 Consideration of terminal connections	26
2.5.6 Shunt elements	27
2.5.7 Series elements	28
2.5.8 Line sectionalization	28
2.6 Evaluation of Overhead Line Parameters	31
2.6.1 Earth impedance matrix $[Z_e]$	31
2.6.2 Geometrical impedance matrix $[Z_g]$ and admittance matrix $[Y_g]$	33
2.6.3 Conductor impedance matrix $[Z_C]$	34
2.6.4 Series impedance approximation for electromagnetic transients	36

2.7	Underground and Submarine Cables	36
2.8	Three-phase Models of Transformers	39
2.8.1	Primitive admittance model of three-phase transformers	40
2.8.2	Models for common transformer connections	42
2.8.3	Three-phase transformer models with independent phase tap control	47
2.8.4	Sequence components modelling of three-phase transformers	48
2.9	Formation of the System Admittance Matrix	51
2.10	References	51
3	FACTS and HVDC Transmission	53
3.1	Introduction	53
3.2	Flexible a.c. Transmission Systems	53
3.2.1	Thyristor controlled series compensator (TCSC)	54
3.2.2	Static on-load tap changing	56
3.2.3	Static phase shifter	58
3.2.4	Static VAR compensator	59
3.2.5	The static compensator (STATCOM)	60
3.2.6	Unified power flow controller (UPFC)	61
3.3	High Voltage Direct Current Transmission	62
3.3.1	The a.c.-d.c. converter	62
3.3.2	Commutation reactance	68
3.3.3	d.c. link control	69
3.3.4	Three-phase model	74
3.4	References	79
4	Load Flow	81
4.1	Introduction	81
4.2	Basic Nodal Method	82
4.3	Conditioning of Y Matrix	84
4.4	The Case Where One Voltage is Known	85
4.5	Analytical Definition of the Problem	86
4.6	Newton-Raphson Method of Solving Load Flows	87
4.6.1	Equations relating to power system load flow	89
4.7	Techniques Which Make the Newton-Raphson Method Competitive in Load Flow	94
4.7.1	Sparsity programming	94
4.7.2	Triangular factorization	95
4.7.3	Optimal ordering	95
4.7.5	Aids to convergence	96
4.8	Characteristics of the Newton-Raphson Load Flow	97
4.9	Decoupled Newton Load Flow	98
4.10	Fast Decoupled Load Flow	100
4.11	Convergence Criteria and Tests	104
4.12	Numerical Example	105
4.13	Load Flow for Stability Assessment	105
4.13.1	Post-disturbance power flows	105

4.13.2	Modelling techniques	110
4.13.3	Sensitivity analysis	110
4.14	Three-phase Load Flow	110
4.14.1	Notation	111
4.14.2	Synchronous machine modelling	111
4.14.3	Specified variables	115
4.14.4	Derivation of equations	115
4.14.5	Decoupled three-phase algorithm	117
4.14.6	Structure of the computer program	123
4.15	References	127
5	Load Flow under Power Electronic Control	129
5.1	Introduction	129
5.2	Incorporation of FACTS Devices	129
5.2.1	Static tap changing	130
5.2.2	Phase-shifting (PS)	130
5.2.3	Thyristor controlled series capacitance (TCSC)	131
5.2.4	Unified power flow controller (UPFC)	132
5.3	Incorporation of HVDC Transmission	135
5.3.1	Converter model	137
5.3.2	Solution techniques	142
5.3.3	Control of converter a.c. terminal voltage	147
5.3.4	Extension to multiple and/or multiterminal d.c. systems	149
5.3.5	d.c. convergence tolerance	151
5.3.6	Test system and results	151
5.3.7	Numerical example	155
5.4	References	158
6	Electromagnetic Transients	161
6.1	Introduction	161
6.2	Background and Definitions	162
6.3	Numerical Integrator Substitution	162
6.3.1	Resistance	163
6.3.2	Inductance	163
6.3.3	Capacitance	164
6.4	Transmission Lines and Cables	166
6.4.1	Bergeron line model	167
6.4.2	Multi-conductor transmission lines	170
6.4.3	Frequency-dependent model	173
6.5	Formulation and Solution of the System Nodal Equations	179
6.5.1	Modification for switching and varying parameters	180
6.5.2	Non-linear or time varying parameters	181
6.6	Use of Subsystems	183
6.7	Switching Discontinuities	186
6.7.1	Voltage and current chatter due to discontinuities	188
6.8	Root-matching Technique	190
6.8.1	Exponential form of difference equation	190

6.8.2	Root-matching implementation	191
6.8.3	Numerical illustration	191
6.9	a.c./d.c. Converters	192
6.10	Synchronous Machine Model	195
6.11	Transformer Model	199
6.12	The PSCAD/EMTDC Program	202
6.12.1	Structure of the program	202
6.12.2	PSCAD/EMTDC Version 3	204
6.12.3	PSCAD/EMTDC test cases	207
6.13	Real Time Digital Simulation	219
6.14	State Variable Analysis	221
6.14.1	State variable formulation	221
6.14.2	Solution procedure	222
6.14.3	Choice of state variables	224
6.15	References	225
7	System Stability	229
7.1	Introduction	229
7.1.1	The form of the equations	230
7.1.2	Frames of reference	231
7.2	Synchronous Machines—Basic Models	231
7.2.1	Mechanical equations	231
7.2.2	Electrical equations	232
7.3	Synchronous Machine Automatic Controllers	237
7.3.1	Automatic voltage regulators	237
7.3.2	Speed governors	239
7.3.3	Hydro and thermal turbines	241
7.3.4	Modelling lead-lag circuits	242
7.4	Loads	243
7.4.1	Low-voltage problems	244
7.5	The Transmission Network	245
7.6	Overall System Representation	245
7.6.1	Mesh matrix method	245
7.6.2	Nodal matrix method	246
7.6.3	Synchronous machine representation in the network	246
7.6.4	Load representation in the network	249
7.6.5	System faults and switching	249
7.7	Integration	252
7.7.1	Problems with the trapezoidal method	255
7.7.2	Programming the trapezoidal method	256
7.7.3	Application of the trapezoidal method	258
7.8	Structure of a Transient Stability Program	263
7.8.1	Overall structure	263
7.8.2	Structure of machine and network iterative solution	264
7.9	Advanced Component Models	268
7.9.1	Synchronous machine saturation	268
7.9.2	Detailed turbine model	279

7.9.3	Induction machines	284
7.9.4	Relays	289
7.9.5	Unbalanced faults	293
7.10	References	295
8	System Stability under Power Electronic Control	297
8.1	Introduction	297
8.2	Description of the Algorithm	298
8.2.1	Data flow	299
8.2.2	Modifications required to the component programs	300
8.3	TS/EMTDC Interface	300
8.3.1	Equivalent circuit components	300
8.3.2	Interface variables derivation	304
8.4	EMTDC to TS Data Transfer	306
8.5	Data Extraction from Distorted Waveforms	310
8.5.1	CFA effectiveness	313
8.6	Interface Method	313
8.7	Interface Location	315
8.8	Structure of the Hybrid Program	317
8.9	Test System and Results	322
8.9.1	Response of the individual programs	322
8.9.2	TSE hybrid response	323
8.10	Quasi Steady-state Converter Simulation	325
8.10.1	Rectifier loads	325
8.10.2	d.c. link	330
8.10.3	Representation of converters in the network	334
8.10.4	Inclusion of converters in the transient stability program	339
8.11	Static VAR Compensation Systems	339
8.11.1	Representation of SVS in the overall system	342
8.12	References	343
Appendix I	Fault Level Derivation	345
I.1	Short Circuit Analysis	345
I.1.1	System equations	346
I.1.2	Fault calculations	348
Appendix II	Numerical Integration Methods	351
II.1	Introduction	351
II.2	Properties of the Integration Methods	351
II.2.1	Accuracy	351
II.2.2	Stability	352
II.2.3	Stiffness	353
II.3	Predictor-Corrector Methods	354
II.4	Runge-Kutta Methods	356
II.5	References	357

Appendix III	Test System used in the Stability Examples	359
	III.1 Reference	362
	Index	363