

---

# Contents

---

<b>Preface</b>	<b>xiii</b>
<b>1 Power system stability overview</b>	<b>1</b>
1.1 General	1
1.2 Understanding power system stability	1
1.3 Classification of power system stability	3
1.3.1 Small signal stability	3
1.3.2 Transient stability	6
1.4 Need for modelling	8
1.5 Stability margin increase	9
References	10
<b>Part I Modelling</b>	<b>11</b>
<b>2 Modelling of the synchronous machine</b>	<b>13</b>
2.1 Introduction	13
2.2 Synchronous machine equations	14
2.2.1 Flux linkage equations	14
2.2.2 Voltage equations	15
2.2.3 Torque equation	16
2.3 Park's transformation	17
2.4 Transformation of synchronous machine equations	18
2.4.1 Transformation of flux linkage equations	18
2.4.2 Transformation of stator voltage equations	19
2.4.3 Transformation of the torque equation	25
2.5 Machine parameters in per unit values	26
2.5.1 Torque and power equations	30
2.6 Synchronous machine equivalent circuits	32
2.7 Flux linkage state space model	34
2.7.1 Modelling without saturation	34
2.7.2 Modelling with saturation	40
2.8 The current state space model	42
References	44
<b>3 Synchronous machine connected to a power system</b>	<b>47</b>
3.1 Synchronous machine connected to an infinite bus	47
3.1.1 Flux linkage state space model	49
3.1.2 Current state space model	55

3.2	Synchronous machine connected to an integrated power system	57
3.3	Synchronous machine parameters in different operating modes	58
3.4	Synchronous machine-simplified models	62
3.4.1	The classical model	62
3.4.2	The $E'_q$ model	64
3.5	Excitation system	67
3.5.1	Excitation system modelling	68
3.6	Modelling of prime mover control system	74
3.6.1	Hydraulic turbines	75
3.6.2	Steam turbines	77
	References	79
<b>4</b>	<b>Modelling of transformers, transmission lines and loads</b>	<b>81</b>
4.1	Transformers	81
4.1.1	Modelling of two-winding transformers	81
4.1.2	Modelling of phase-shifting transformers	91
4.2	Transmission lines	93
4.2.1	Voltage and current relationship of a line	94
4.2.2	Modelling of transmission lines	95
4.3	Loads	97
4.3.1	Static load models	99
4.3.2	Dynamic load models	101
4.4	Remarks on load modelling for stability and power flow studies	103
	References	104
	<b>Part II Power flow</b>	<b>107</b>
<b>5</b>	<b>Power flow analysis</b>	<b>109</b>
5.1	General concepts	109
5.2	Newton–Raphson method	111
5.2.1	Power flow solution with polar coordinate system	113
5.2.2	Power flow solution with rectangular coordinate system	114
5.3	Gauss–Seidel method	121
5.4	Decoupling method	123
5.4.1	Fast-decoupled method	125
	References	129
<b>6</b>	<b>Optimal power flow</b>	<b>131</b>
6.1	Problem formulation	131
6.2	Problem solution	132
6.3	OPF with dynamic security constraint	137
	References	142

<b>Part III Stability analysis</b>	<b>145</b>
<b>7 Small signal stability</b>	<b>147</b>
7.1 Basic concepts	147
7.1.1 Equilibrium points	149
7.1.2 Stability of equilibrium point	150
7.1.3 Phasor diagrams of synchronous machines	152
7.2 Small signal stability	154
7.2.1 Forced state variable equation	162
7.3 Linearised current state space model of a synchronous generator	164
7.4 Linearised flux linkage state space model of a synchronous generator	172
7.5 Small signal stability of multi-machine systems	177
References	183
<b>8 Transient stability</b>	<b>185</b>
8.1 Synchronous machine model	186
8.2 Numerical integration techniques	192
8.3 Transient stability assessment of a simple power system	193
8.4 Transient stability analysis of a multi-machine power system	201
References	218
<b>9 Transient energy function methods</b>	<b>221</b>
9.1 Definitions of stability concepts	221
9.1.1 Positive definite function	222
9.1.2 Negative definite function	222
9.1.3 Lemma	222
9.1.4 Stability regions	223
9.1.5 Lyapunov function theorem	223
9.2 Stability of single-machine infinite-bus system	225
9.3 Stability of multi-machine power system	234
9.3.1 Energy balance approach	235
9.3.2 TEF method	241
References	250
<b>Part IV Stability enhancement and control</b>	<b>251</b>
<b>10 Artificial intelligence techniques</b>	<b>253</b>
10.1 Artificial neural networks	253
10.2 Neural network topologies	255
10.2.1 Single-layer feed-forward architecture	255
10.2.2 Multi-layer feed-forward architecture	255
10.2.3 Recurrent networks	256
10.2.4 Back-propagation learning algorithm	256
10.3 Fuzzy logic systems	259

10.3.1 Fuzzy set theory	260
10.3.2 Linguistic variables	261
10.3.3 Fuzzy IF–THEN rules	261
10.3.4 Structure of an FL system	261
10.4 Neuro-fuzzy systems	263
10.4.1 Adaptive neuro-fuzzy inference system	263
10.4.2 Structure of the NFC	265
10.4.3 Online adaptation technique	267
10.5 Adaptive simplified NFC	269
10.5.1 Simplification of the rule-base structure	269
10.6 Control system design of the proposed ASNFC	272
References	274
<b>11 Power system stabiliser</b>	<b>277</b>
11.1 Conventional PSS	278
11.1.1 Configuration of common PSS	278
11.1.2 PSS input signals	279
11.1.3 Characteristics of common PSS	280
11.2 Adaptive control-based PSS	281
11.2.1 Direct adaptive control	282
11.2.2 Indirect adaptive control	283
11.2.3 Indirect adaptive control strategies	286
11.3 PS control-based APSS	287
11.3.1 Self-adjusting PS control strategy	287
11.3.2 Performance studies with pole-shifting control PSS	290
11.4 AI-based APSS	291
11.4.1 APSS with NN predictor and NN controller	292
11.4.2 Adaptive network-based FLC	293
11.5 Amalgamated analytical and AI-based PSS	297
11.5.1 APSS with neuro identifier and PS control	297
11.5.2 APSS with fuzzy logic identifier and PS controller	299
11.5.3 APSS with RLS identifier and fuzzy logic control	301
11.6 APSS based on recurrent adaptive control	301
11.7 Concluding Remarks	307
References	307
<b>12 Series compensation</b>	<b>311</b>
12.1 Definitions of transmission line parameters	311
12.2 Compensation of lossless transmission line	313
12.2.1 Determination of amount of series compensation	313
12.2.2 Transient stability improvement for lossless compensated line	316
12.3 Long transmission lines	319
12.3.1 Series compensation for long transmission lines	321
12.4 Enhancement of multi-machine power system transient stability	329

12.5	Investigation of transmission power transfer capacity	333
12.6	Improvement of small signal stability	335
12.7	Sub-synchronous resonance	340
12.7.1	The mechanical system	341
12.7.2	The electrical network	343
	References	348
<b>13</b>	<b>Shunt compensation</b>	<b>351</b>
13.1	Shunt compensation of lossless transmission lines	351
13.1.1	Shunt-compensated line parameters	351
13.1.2	Transient stability enhancement for shunt-compensated lossless lines	353
13.2	Long transmission lines	357
13.3	Static var compensators	360
13.3.1	Characteristics of FC-TCR compensators	362
13.3.2	Modelling of FC-TCR compensators	362
13.4	Static synchronous compensator (STATCOM)	369
13.5	Application of ASNFC to shunt-compensated power systems	374
13.5.1	Simulation studies	375
13.5.2	Three-phase to ground short circuit test	376
	References	377
<b>14</b>	<b>Compensation devices</b>	<b>379</b>
14.1	Introduction	379
14.2	Flexible AC transmission system	380
14.2.1	Thyristor-controlled series capacitor	380
14.2.2	Static synchronous series compensator	382
14.2.3	Static var compensator	384
14.2.4	Static synchronous compensator	387
14.2.5	Phase-shifting transformer	389
14.2.6	Unified power flow controller	389
	References	392
<b>15</b>	<b>Recent technologies</b>	<b>395</b>
15.1	Energy storage systems	395
15.1.1	Chemical energy storage systems (batteries)	397
15.1.2	Flywheel energy storage	397
15.1.3	Compressed air energy storage	397
15.1.4	Pumped hydroelectric energy storage	398
15.1.5	Super capacitors	400
15.1.6	Superconducting energy storage	400
15.2	Superconductivity applications	409
15.2.1	Superconducting synchronous generators	409
15.2.2	Superconducting transmission cables	411
15.2.3	Superconducting transformers	411
15.2.4	Superconducting fault current limiters	412

15.2.5	SMES applications	416
15.2.6	Features of storage systems	418
15.3	Phasor measurement units	420
15.3.1	Structure of WAMS	420
15.3.2	Benefits of WAMS	421
15.3.3	Case studies	422
	References	423

<b>Appendix I</b>	<b>Calculation of synchronous machine parameters in per unit/normalised form</b>	<b>427</b>
<b>Appendix II</b>	<b>Nine-bus test system</b>	<b>437</b>
<b>Appendix III</b>	<b>Numerical integration techniques</b>	<b>439</b>
<b>Appendix IV</b>	<b>15-bus, 4-generator system data</b>	<b>445</b>
<b>Index</b>		<b>449</b>