

Index

active power, see power, real	chance constraint, 185
acyclic, see radial	change of variables, 58, 88
admittance, 27, 30, 45, 122	Cholesky decomposition, 52, 65
matrix, 47	competitive equilibrium, 140
shunt, 30	complementary slackness, 138-139
affine function, 6, 88, 134	conductance, 30
ampacity, see transmission current capacity	cone
ancillary services, 145, 159	convex, 10
approximation, 3-4	programming, 9–13
arbitrage, see load shifting	congestion
arborescence, 102	Internet, 133
auction	rent, 151
discriminatory and uniform price, 176	transmission, 149, 151, 155, 160-164, 175-176
transmission right, 161	transportation, 106
automatic generation control, 90, 186	constant instantaneous power, 32
	constraint qualification, 134
balanced	contract
budget, 151, 155, 156, 161, 164	bilateral, 145
operation, 31–34	path, 161
Bertrand competition, 143–144, 171	control
Bertrand-Edgeworth competition, see capacitated	decentralized, 186
price competition	model predictive, 89-90, 159
bilateral	policy, 82–83, 87–90, 95, 159
contract, 145	trajectory, 82–84
trading, 161	convex, 2, 5–8
bilinear nonconvexity, 122, 123, 126	function, 5
binary variable, 23, 25, 96–107, 117, 124–125	optimization problem, 6
blackout, 90, 93, 132	set, 6
Borůvka, Otakar, 121	cost
bounded rationality, 141	curve, 35, 46, 97
Braess's paradox, 106	nonconvex, 46, 72–74
branch flow, see power flow, branch	generation, 45, 106
branch-and-bound, 17	startup and shutdown, 97, 167
budget	costate, 159
balanced, 151, 155, 156, 161, 164	Cournot competition, 143, 171, 172
constraint, 114, 119	CQCP, see quadratically constrained programming,
equation, 151, 155-156, 161, 163, 165	convex
	current
California Electricity Crisis, 132	alternating, 1, 28–34, 43
capacitance, 30	direct, 29, 43, 70–71
capacitated price competition, 173-176	sinusoid, 28
capacitor bank, see reactive power source	cutting planes, 17
cascading failure, 93	
certainty equivalence, 95, 159	DC power flow, see power flow, linearized



194 Index

demand	flowgate right, 161–164
curve, 36, 147	frequency, see voltage frequency
response, 1, 36, 84	instability, see dynamic instability
deregulation, 132-133, 148	FTR, see financial transmission right
determinant, see principal minor	fuel
differential-algebraic system, 92	curve, see cost curve
discrete, see mixed-integer	multiple sources, 72
disjunctive constraint, 16, 96–100, 103–104, 113, 122	Fundamental Theorems of Welfare Economics, 140
DistFlow, see branch flow	game
distributed	single-shot, 176
generation, 116	strategic form, 142
optimization, 186–188	theory, 141–144, 168–176
distribution system, 81, 86–87, 101–107, 118	algorithmic, 144, 189
dual	dynamic, 188–189
function, 134–136	two-stage, 173
multiplier, 134, 140, 186	Gauss-Seidel, 67
matrix, 136, 156	generator, 35
sensitivity interpretation, 139	placement, 116
vector, 136, 153, 156	scheduling, see unit commitment
problem, 134	synchronous, 29
duality, 133–141	third order approximation, 91–92
strong, 134–136, 140	three-phase, 32
weak, 134	trip, 90
duopoly, 142–144, 171	graph
dynamic	Laplacian, 69
constraint, 82	theory, 24–25
instability, 90–93	Great Depression, 132
pricing, 157–160	greedy algorithm, 24, 114, 128
programming, 87–89	
. 1 147 107	Hermitian, 11, 22, 52
economic dispatch, 147, 187	Hessian, 5
Edison, Thomas, 43, 132	hyperbolic constraint, 23, 54, 63, 125
efficiency loss, 169, 172	:
eigenvalue, 11, 69	impedance, 30, 45, 123
optimization, 11–12	incentive compatible, 190
elasticity, 147, 171	independent power producer, 132
electricity	inductance, 30 matrix, 69, 93
market, 35, 144–148	induction motor, 35
pool, 147 energy storage, 84–89, 154, 167, 173, 176, 188	infeasibility, 19–20, 65–66, 128–129
placement, 120	infinite bus approximation, 64
scheduling, 87–89	Insull, Samuel, 132
Enron scandal, 132	integer, see mixed-integer
equilibrium	interior point method, 2, 9, 10, 17, 47
competitive, 140	primal-dual, 53, 133
dominant strategy, 190	inventory control, 87–89
Nash, 142, 189	invisible hand of the market, 140
expected utility hypothesis, 144	mvisible hand of the market, 140
expected utility hypothesis, 144	Karmarkar, Narendra, 2, 9
fault, 90	Karush-Kuhn-Tucker conditions, 139, 172
feasible	Kirchhoff's law, 28
point, xiv, 6, 114	knapsack problem, 116
set, xiv, 7	Kron reduction, 93
strictly, 134	Kuramoto oscillator, 93
FGR, see flowgate right	Turamoto oscinator, 75
financial transmission right 161–164	Lagrange multiplier see dual multiplier



Index

195

Lagrangian, 133, 149	fuel sources, 72
relaxation, 137	periods, 81-90, 96-101, 157-159, 188
Laplacian matrix, 69	scenarios, 118-120
Lay, Kenneth, 132	myopic algorithm, see greedy algorithm
linear	
complementarity problem, 172	Nash
constraint, 6	equilibrium, 189
matrix inequality, see semidefinite programming	mixed strategy, 142
programming, 1, 8–9, 17	pure strategy, 142
duality, 135	negative externality, 160
standard form, 9	network
quadratic regulator, 83, 94-96, 159-160	design, 120
relaxation, see relaxation, lift-and-project	flow, 1, 50–51, 105–106, 150
time-invariant system, 94	neutral line, 31
linearization, 18, 49, 55, 151	Newton's method, 9, 47
load, 28, 32, 35–36, 92	Newton-Raphson, 67
balancing, 104	nonlinear
duration curve, 119	dynamics, 91–93
flow, 37, 67–70	programming, 1, 47–48, 128
linearized, 69–70	NP-hard, 1, 7, 9, 13, 16, 18, 24, 47
over-satisfaction, 57	
serving entity, 147	Ohm's law, 28, 31, 36, 49, 62
shifting, 88, 168–170	opportunity cost of reactive power, 35, 71, 154
uncertainty, 90	orthogonal matrix, 58
ZIP model, 35, 54–55	
locational marginal price, see price, nodal	Pareto efficient, 140
loop flow, 161	per unit, 27, 36–37
loss	PhaseLift, 69
charges, 155, 156	phasor, 29–31
flowgate right, 163–164	measurement unit, see synchrophasor
resistive, 31, 44, 45, 51, 60, 104, 119	physical transmission right, 161
storage, 85, 87	PNE, see Nash equilibrium, pure strategy
LP, see linear programming	polynomial-time, 2, 7, 9, 10, 18, 24, 57
lumpiness, 166	polytope, 9
r	power
make-whole payment, 166	apparent, 44
market	balance, 1, 51, 69, 99, 145, 170, 187
clearing price, 145–147, 168	electronics, 43, 70, 117
electricity, 35, 144–148	converter, 85, 129, 154
operator, 147	factor, 30
power, 141, 167–176, 188	flow
spot, 145–147	arriving and departing, 31, 44
Max-Cut, 25	branch, 62–65, 86, 125–126, 152–155
mechanism design, 189–190	decoupled, 49–50
metaheuristic, 1, 26–27	direct current, 70
microgrid, 43, 70	linearized, 48–49, 84, 93, 100–101, 106–107
mileage payment, 159	117, 123–125, 148–151
mixed-integer, 15–17, 166–167	nonconvex, 46, 52
linear programming, 17, 18, 117, 123–125, 128	second-order cone, 53–54, 107, 128
quadratic programming, 17, 18, 117, 123–123, 128	semidefinite, 52–53, 126–127, 155–156
	instantaneous, 29
second-order cone programming, 17, 18, 104,	constant, 32
119, 125–126, 128	reactive, 29, 44
semidefinite programming, 18, 126–127	capability curve, 71–72, 86, 154
MNE, see Nash equilibrium, mixed strategy	opportunity cost, 35, 154
model predictive control, 89–90, 159	pricing, 153–155
multiple	source, 85, 90, 117–118



196 Index

real, 29, 44	moment-based, 21
three-phase, 31–34	polyhedral, 50, 74–75, 128
PPAD-complete, 144	second-order cone, 23, 53-54, 71, 128
price, 139–141	semidefinite, 21-22, 25, 52-53, 68, 71, 136-138
dynamic, 157–160	Shor, 22
market clearing, 145-147, 168	sums-of-squares, 21
nodal, 85, 120, 145, 148-156	renewable energy, 81, 84, 87, 90, 96, 118, 167
regulation, 160	reservation utility, 173
of anarchy, see efficiency loss	reserves, 84, 90, 145
policy, 159	resistance, 30
shadow, 140, 149	restructured power system, 148
taker, 141, 168	revenue adequate, 151, 162
trajectory, 158	Riccati equation, 95
primal problem, 133	risk-limiting dispatch, 83
principal minor, 11, 14, 23, 53	robust optimization, 99, 185-186
proportional sharing rule, 165–166	
pseudoinverse, 69, 137	Schur complement, 12-13, 137
Public Utility	Schweppe, Fred, 133, 159
Holding Company Act (1935), 132	SDP, see semidefinite programming
Regulatory Policies Act (1978), 132	second-order cone
	power flow, see power flow, second-order cone
QCP, see quadratically constrained programming	programming, 2, 10–11, 18, 23, 74–75
QP, see quadratic programming	duality, 135–136
quadratic	standard form, 11
equality constraint, 28, 45, 47, 64	relaxation, see relaxation, second-order cone
programming, 8-9, 17, 95, 172	semidefinite
standard form, 8	matrix, 9, 11
quadratically constrained programming, 13–15, 17,	power flow, see power flow, semidefinite
18, 21–22, 46	programming, 2, 11–13, 18, 22
convex, 10, 14, 64	duality, 53, 135–136
quasiconvex, 142, 147	standard form, 13
	relaxation, see relaxation, semidefinite
radial, 24, 50, 55–57, 81, 86, 101–107, 118	Shor relaxation, 22
ramp constraint, 83–84, 86–87, 100, 157–158	shortest path, 108, 124, 187
rank, 8	
constraint, 52	simplex algorithm, 8, 17
minimization, 68	single-phase approximation, 1, 3, 27, 32
rational agent, 144	single-shot game, 176
Rayleigh quotient, 12	singular system, <i>see</i> differential-algebraic system
reactance, 30	Slater's condition, 134
reactive power, see power, reactive	Smith, Adam, 140
real power, see power, real	social welfare, 140
real-time price, see price, dynamic	SOCP, see second-order cone programming
receding horizon control, see model predictive	sparsity, 53
control	speed governor, 90, 92, 186
reconfiguration, 101-106	state
regulation, 84, 90, 145	dynamic, 82
frequency, 90, 95–96	of charge, 85
pricing, 159–160	static VAR compensator, see reactive power source
voltage, 90	stationarity, 134
relaxation, 18-26, 51-66	conditions, 149, 153, 156
bound, 19, 66	steady-state, 1, 3, 27, 29, 47
branch flow, 125–126	stochastic programming, 184–185
continuous, 15, 112, 122, 129	strategic form game, 142
exactness, 19, 55–57, 86, 103, 107, 118	supply function, 35, 46, 147
Lagrangian, 137	equilibrium, 170–172
lift-and-project, 20–23, 52, 123–127	susceptance, 30



Index

197

swing bus, 37, 67, 70 equation, 90-96 synchrophasor, 95 Tesla, Nicola, 43 three-phase power, 31-34 torque balance, 91, 96 tracing, 165-166 transformer, 36-37, 43 transmission current capacity, 44, 59 high-voltage direct current, 29, 43, 70 planning, 120-129 power capacity, 44, 100-101, 122 right auction, 161 financial, 161-164 flowgate, 161-164 physical, 161 switching, 106-107 transportation model, see network flow tree, see radial two-stage game, 173

problem with recourse, 184 uncertainty disturbance, 82, 90 Gaussian, 94-96, 159, 185 load, 35, 87 unit commitment, 51, 96-101, 166-167 uplift payment, 166 valid inequality, 21 valve-point loading, 72 Vickrey-Clarke-Groves mechanism, 189-190 voltage angle, 48, 65, 70 collapse, see dynamic instability frequency, 28, 90, 93, 95-96 magnitude, 28, 44, 48, 54, 59, 72 polar coordinates, 48-50, 60-61 rectangular coordinates, 61-62, 68 sinusoid, 28 Walrasian equilibrium, 140 War of the Currents, 43 Westinghouse, George, 43 wide area measurement, 95