

Contents

1 Introduction	1
References	6
2 Dynamics of Electromechanical Systems.....	9
2.1 Mechanical Systems	9
2.1.1 Basic Concepts	9
2.1.2 Constraints, Classification of Constraints and Effects of Their Imposition	12
2.1.3 Examples of Constraints	13
2.1.4 External Forces and Reaction Forces; d'Alembert Principle	15
2.1.4.1 External Forces and Reaction Forces	15
2.1.4.2 Virtual Displacements	16
2.1.4.3 Perfect Constraints	17
2.1.4.4 d'Alembert Principle	17
2.1.5 Number of Degrees of Freedom and Generalized Coordinates.....	20
2.1.6 Lagrange's Equations.....	23
2.1.7 Potential Mechanical Energy	26
2.1.8 Generalized Forces, Exchange of Energy with Environment.....	28
2.1.9 Examples of Application of Lagrange's Equations Method for Complex Systems with Particles	30
2.1.10 Motion of a Rigid Body	36
2.1.10.1 Fundamental Notions	36
2.1.10.2 Motion of a Mass Point on a Rigid Body	37
2.1.10.3 Kinetic Energy of a Rigid Body	39
2.1.10.4 Motion of a Rigid Body around an Axis	43
2.1.10.5 Rigid Body's Imbalance in Motion around a Constant Axis	43
2.1.11 Examples of Applying Lagrange's Equations for Motion of Rigid Bodies.....	46
2.1.12 General Properties of Lagrange's Equations.....	52
2.1.12.1 Laws of Conservation.....	52
2.1.12.2 Characteristics of Lagrange's Functions and Equations.....	54
2.2 Electromechanical Systems	59
2.2.1 Principle of Least Action: Nonlinear Systems	59

2.2.1.1	Electrically Uncharged Particle in Relativistic Mechanics	61
2.2.1.2	Electrically Charged Particle in Electromagnetic Field	64
2.2.2	Lagrange's Equations for Electromechanical Systems in the Notion of Variance	66
2.2.2.1	Electric Variables	68
2.2.2.2	Virtual Work of an Electrical Network	69
2.2.3	Co-energy and Kinetic Energy in Magnetic Field Converters	72
2.2.3.1	Case of Single Nonlinear Inductor	72
2.2.3.2	The Case of a System of Inductors with Magnetic Field Linkage	75
2.2.4	Potential Energy in Electric Field Converters	77
2.2.5	Magnetic and Electric Terms of Lagrange's Function: Electromechanical Coupling	78
2.2.6	Examples of Application of Lagrange's Equations with Regard to Electromechanical Systems	80
References		106
3	Induction Machine in Electric Drives	109
3.1	Mathematical Models of Induction Machines	109
3.1.1	Introduction	109
3.1.2	Construction and Types of Induction Motors	110
3.1.3	Fundamentals of Mathematical Modeling	114
3.1.3.1	Types of Models of Induction Machines	114
3.1.3.2	Number of Degrees of Freedom in an Induction Motor	117
3.1.4	Mathematical Models of an Induction Motor with Linear Characteristics of Core Magnetization	121
3.1.4.1	Coefficients of Windings Inductance	121
3.1.4.2	Model with Linear Characteristics of Magnetization in Natural (phase) Coordinates	123
3.1.4.3	Transformation of Co-ordinate Systems	125
3.1.5	Transformed Models of Induction Motor with Linear Characteristics of Core Magnetization	128
3.1.5.1	Model in Current Coordinates	128
3.1.5.2	Models in Mixed Coordinates	130
3.1.5.3	Model in Flux Coordinates	133
3.1.5.4	Special Cases of Selecting Axial Systems ' u, v '	133
3.1.6	Mathematical Models of Induction Motor with Untransformed Variables of the Stator/Rotor Windings	136
3.1.6.1	Model with Untransformed Variables in the Electric Circuit of the Stator	137
3.1.6.2	Model with Untransformed Variables of Electric Circuit of the Rotor	140

3.2	Dynamic and Static Characteristics of Induction Machine Drives	143
3.2.1	Standardized Equations of Motion for Induction Motor Drive	143
3.2.2	Typical Dynamic States of an Induction Machine Drive – Examples of Trajectories of Motion.....	147
3.2.2.1	Start-Up during Direct Connection to Network	147
3.2.2.2	Reconnection of an Induction Motor.....	151
3.2.2.3	Drive Reversal.....	153
3.2.2.4	Cyclic Load of an Induction Motor.....	154
3.2.2.5	Soft-Start of an Induction Motor for Non-Simultaneous Connection of Stator's Windings to the Network.....	155
3.2.2.6	DC Braking of an Induction Motor	159
3.2.3	Reduction of a Mathematical Model to an Equivalent Circuit Diagram.....	164
3.2.4	Static Characteristics of an Induction Motor.....	168
3.3	Methods and Devices for Forming Characteristics of an Induction Motor	175
3.3.1	Control of Supply Voltage	176
3.3.2	Slip Control	180
3.3.2.1	Additional Resistance in the Rotor Circuit.....	180
3.3.2.2	Scherbius Drive.....	181
3.3.3	Supply Frequency f_s Control	188
3.3.3.1	Direct Frequency Converter–Cycloconverter.....	188
3.3.3.2	Two-Level Voltage Source Inverter	194
3.3.3.3	Induction Motor Supplied from 2-Level Voltage Inverter	213
3.3.3.4	Three-Level Diode Neutral Point Clamped VSI Inverter	220
3.3.3.5	Current Source Inverter with Pulse Width Modulation (PWM).....	230
3.4	Control of Induction Machine Drive.....	236
3.4.1	Vector Control.....	236
3.4.1.1	Mathematical Model of Vector Control	238
3.4.1.2	Realization of the Model of Vector Control.....	239
3.4.1.3	Formalized Models of Vector Control	241
3.4.2	Direct Torque Control (DTC)	247
3.4.2.1	Description of the Method.....	247
3.4.2.2	Examples of Direct Torque Control (DTC) on the Basis of a Mathematical Model.....	251
3.4.3	Observers in an Induction Machine.....	264
3.4.3.1	Rotor Flux Observer in Coordinates α, β	265
3.4.3.2	Rotor Field Observer in Ψ_r, ρ Coordinates.....	266
3.4.3.3	Rotor Field Observer in x, y Coordinates with Speed Measurement	268

3.4.3.4	Observer of Induction Motor Speed Based on the Measurement of Rotor's Position Angle	270
3.3.2.5	Flux, Torque and Load Torque Observer in x, y Coordinates	271
3.4.3.6	Stator Flux Observer Ψ_r with Given Rate of Error Damping.....	273
References		275
4	Brushless DC Motor Drives (BLDC)	281
4.1	Introduction	281
4.2	Permanent Magnet – Basic Description in the Mathematical Model.....	283
4.3	Mathematical Model of BLDC Machine with Permanent Magnets	294
4.3.1	Transformed Model Type $d-q$	297
4.3.2	Untransformed Model of BLDC Machine with Electronic Commutation.....	300
4.3.3	Electronic Commutation of BLDC Motors	302
4.3.3.1	Supply Voltages of BLDC Motor in Transformed Model u_q, u_d	304
4.3.3.2	Modeling of Commutation in an Untransformed Model of BLDC.....	305
4.4	Characteristics of BLDC Machine Drives	309
4.4.1	Start-Up and Reversal of a Drive	310
4.4.1.1	Drive Start-Up	310
4.4.1.2	Reversing DC Motor.....	317
4.4.2	Characteristics of BLDC Machine Drive	321
4.4.3	Control of Rotational Speed in BLDC Motors.....	332
4.5	Control of BLDC Motor Drives.....	338
4.5.1	Control Using PID Regulator.....	338
4.5.2	Control with a Given Speed Profile	346
4.5.3	Control for a Given Position Profile.....	351
4.5.4	Formal Linearization of BLDC Motor Drive	366
4.5.5	Regulation of BLDC Motor with Inverse Dynamics.....	369
References		378
5	Switched Reluctance Motor Drives	381
5.1	Introduction	381
5.2	Operating Principle and Supply Systems of SRM Motors.....	384
5.3	Magnetization Characteristics and Torque Producing in SRM Motor	390
5.4	Mathematical Model of SRM Motor	393
5.4.1	Foundations and Assumptions of the Mathematical Model	393
5.4.2	Equations of Motion for the Motor	395
5.4.3	Function of Winding Inductance.....	396
5.5	Dynamic Characteristics of SRM Drives.....	400
5.5.1	Exemplary Motors for Simulation and Tests	400

- 5.5.2 Starting of SRM Drive401
 - 5.5.2.1 Start-Up Control for Switched Reluctance Motor
by Pulse Sequence402
 - 5.5.2.2 Current Delimitation during Direct Motor Starting410
- 5.5.3 Braking and Generating by SRM411
- 5.6 Characteristics of SRM Machines420
 - 5.6.1 Control Signals and Typical Steady-State Characteristics420
 - 5.6.2 Efficiency and Torque Ripple Level of SRM.....422
 - 5.6.3 Shapes of Current Waves of SRS427
- 5.7 Control of SRM Drives431
 - 5.7.1 Variable Structure – Sliding Mode Control of SRM431
 - 5.7.2 Current Control of SRM Drive.....432
 - 5.7.3 Direct Torque Control (DTC) for SRM Drive439
 - 5.7.4 Sensor- and Sensorless Control of SRM Drive442
 - 5.7.5 State Observer Application for Sensorless Control of SRM444
- References446**
- Index449**