COMPUTING and OPTIMIZATION for DC POWER SYSTEMS of ELECTRIC TRANSPORT

COMPUTING and OPTIMIZATION for DC POWER SYSTEMS of ELECTRIC TRANSPORT

Dmytro Bosyi • Oleh Sablin • Yevhen Kosariev

Dnipro National University of Railway Transport, Ukraine



Published by

World Scientific Publishing Europe Ltd.
57 Shelton Street, Covent Garden, London WC2H 9HE *Head office:* 5 Toh Tuck Link, Singapore 596224 *USA office:* 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

Library of Congress Cataloging-in-Publication Data

Names: Bosyi, Dmytro, author. | Sablin, Oleh, author. | Kosariev, Yevhen, author.

Title: Computing and optimization for DC power systems of electric transport /

Dmytro Bosyi, Oleh Sablin, Yevhen Kosariev.

Description: New Jersey : World Scientific, [2019]

Includes bibliographical references and index.

Identifiers: LCCN 2019033008 | ISBN 9781786347718 (hardcover)

Subjects: LCSH: Electric railroads -- Power supply. | Electric power systems -- Control--

Data processing. | Electric power transmission--Direct current.

Classification: LCC TF863 .B685 2019 | DDC 621.33--dc23

LC record available at https://lccn.loc.gov/2019033008

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Copyright © 2020 by World Scientific Publishing Europe Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

For any available supplementary material, please visit https://www.worldscientific.com/worldscibooks/10.1142/Q0229#t=suppl

Desk Editors: Dipasri Sardar/Jennifer Brough/Shi Ying Koe

Typeset by Stallion Press Email: enquiries@stallionpress.com

Printed in Singapore

Dedication

The book is dedicated to young scientists who, despite all the difficulties of the thorny path of science, are engaged in research and development, as well as those leaders who support their undertakings and aspirations, encourage them and do not give up on their followers in crucial moments.

The authors of this monograph express their sincere gratitude to the scientist, professor and mentor, the man who rallied young scientists around himself, inspired and supported them, and now is the embodiment of the science of railway transport — **Professor S.V. Myamlin, D.Sc.**

Preface

This monograph describes the difficulties associated with computing and optimization of traction power systems of electrified transport. An original approach is proposed for the analytical description of the processes of consumption and regeneration of electric energy, which can be used both in urban transport systems (metro, tram, trolleybus) and on electrified railways. The monograph also includes examples that show the use of several methods for optimizing power supply modes using software packages MathCAD and MatLab Simulink.

The idea of the proposed calculation method has matured for 10 years. When performing electrical calculations as well as in the process of measuring the performance indicators of traction power supply systems, the authors gained considerable experience. The combination of different approaches for solving single-type tasks, in addition to modern computational capabilities, formed the main points of the suggested method. Despite the fact that the co-authors of the monograph use it in different ways, the fundamental principles of the method did not undergo significant changes, but they only supplemented it and allowed getting a new angle on the complex processes.

A great contribution in preparing the manuscript for publication was provided by the translators, Olena Zhylenko and Tatiana Kirpa. The authors show their sincere appreciation to World Scientific Publishing and thank the staff involved in the publishing.

> D. Bosyi O. Sablin Ye. Kosariev

About the Authors



Dmytro Bosyi is a Professor in the Intelligent Power Supply Systems Department at Dnipro National University of Railway Transport. The author and co-author of more than 50 scientific articles and four monographs, he has 10 years of research experience in power supply systems for electric transport. He graduated from the Power Engineering Faculty of the Dnipro National University of Railway Transport, named after Academician V. Lazaryan in 2006. In 2011, he received

his Ph.D. degree, and in 2017, he received his D.Sc. degree. He has been involved in developing software for measuring, modeling, and analyzing the operating modes of power supply systems. His research interests include electric transport, power supply systems, energy efficiency, electromagnetic compatibility, and big data analysis. He lives and works in Dnipro, Ukraine.



Oleh Sablin is the Head of the Research Department at Dnipro National University of Railway Transport, named after Academician V. Lazaryan. In 2005, he received his master's degree and entered graduate school, where he studied the efficiency of energy consumption of electrified DC vehicles. In 2009, he received the Candidate of Sciences degree. In 2013, he started his doctoral program that dealt with increasing the efficiency of energy use for improving electrified vehicles. In

2018, he received his doctorate. His research interests include electric transport, operating modes, energy efficiency, and energy-saving technologies. He lives and works in Dnipro, Ukraine.



Yevhen Kosariev is an Associate Professor in the Intelligent Power Supply Systems Department at Dnipro National University of Railway Transport. He graduated in 2013 from the Power Engineering Faculty of the Dnipro National University of Railway Transport, named after Academician V. Lazaryan. In 2018, he received his Ph.D. degree. He has 6 years of research experience in power supply systems for electric transport. He is the co-author of more than 10 scientific and technical

reports, which include works relating to the state order. He has authored three security documents and more than 40 scientific publications. His research interests include electric transport, power supply systems, energy efficiency, and renewable energy sources. He lives and works in Dnipro, Ukraine.

Contents

Dedication	V
Preface	vii
About the Authors	ix
List of Figures	xiii
List of Tables x	xiii
Chapter 1. Introduction	1
 Application Area	$ \begin{array}{c} 1 \\ 3 \\ 7 \\ 13 \end{array} $
Chapter 2. Origin of Calculation Difficulties in Traction Power Supply System	19
 2.1. Overview of Calculation Methods	19 22 25 27 33
Chapter 3. Method Based on the Continuous Representation of the Traction Network	39
3.1. Resistance Functions3.2. Circulating Currents	39 48

Contents

3.3. Node-Potential Method for Computing the Current	
Distribution Functions	. 53
3.4. Aspects of Behavior of Electric Energy Recovery Modes	. 59
3.5. Energy Balance during the Stabilization of Traction Powe	r
by an Electric Rolling Stock	. 64
3.6. Space–Time Representation of Electrical Computing	. 80
Chapter 4. Computer-Aided Calculations of Indexes	
of the Traction Power Supply System	97
4.1. Introduction	. 97
4.2. Calculation of the Traction Power Supply System	
of the DC Railway	. 99
4.3. Calculation of the Traction Power Supply System	
for Urban Electric Transport	. 99
4.4. Calculation of the Metro Traction Power System	. 100
4.5. Efficiency of Recovery Energy	. 109
4.6. Estimation of Power Quality Distortions	. 132
Chapter 5. Optimization of Power Supply System	
Operating Modes	139
5.1. Voltage Stabilization on a Motive Load Factored	
in Traction and Recuperating Modes	. 139
5.2. Sensor Method of Searching the Voltage Weak Points	
in Traction Networks	. 148
5.3. Neuro-Fuzzy Models of Power Supply Modes Control	. 154
5.4. Estimation of Potential Electric Energy Saving under	
Implementation of the Controlled Traction Power	
Supply System	. 172
Chapter 6. Conclusions	185
	4.0-
Bibliography	187
Index	191

List of Figures

Figure 1.1.	Structure of transmission and conservation of electricity	
	for railway transport system	4
Figure 1.2.	Power losses in subsystems of electrified railways: $1 - $	
	power supply system; $2 - $ electric traction system; $3 - $	
	power supply of rail cars	5
Figure 1.3.	Timing diagrams of traction power supply and recupe-	
	ration in various types of movement (recuperation at	
	p < 0): (a) electric freight locomotives of DC; (b) sub-	
	urban electric trains; (c) trams; (d) subway	10
Figure 1.4.	Characteristics of vehicles with smooth regulation power	
	recuperation mode.	12
Figure 1.5.	Energy density vs. specific power output of energy	
	storage unit types.	15
Figure 1.6.	Modern electric buses of different manufacturers: (a)	
	Polish Urbino 12 electric, Solaris Bus & Coach S.A;	
	(b) Dutch VDL Citea SLF-120 Electric, VDL Bus &	
	Coach bv; (c) German–Turkish E-Bus S18, Sileo GmbH	
	company; (d) Belorussian Vitovt Max Electro, Belkom-	
	munmash company.	16
Figure 1.7.	Structural scheme of energy infrastructure interaction of	
	city electric transport and electrified railway	17
Figure 2.1.	Traction power supply system calculation methods	20

Figure 2.2.	Schemes of one-way (a) and two-way (b) feed of the contact network: 1 — traction substations; 2 — feeders; 3 — suction lines; 4 — contact network; 5 — rails; 6 — sectionalizing arrangement; 7 — sectional disconnector with material disconnector	
	with motor drive (normally disconnected); δ — the same	00
F ! 0.0	(normally connected).	22
Figure 2.3.	Power supply circuits for a double-track contact	
	network: (a) separate power supply of the tracks;	
	(b) nodal scheme; (c) parallel track connection. 1 —	
	traction substations; $2 - 2$ -way network of the 1st	
	track; 3 — 3-way network of the 2nd track; 4 —	
	sectionalizing arrangements; 5 — section pllar; 6 —	
	parallel connection point of the track catenary	94
E:		24
Figure 2.4.	Dependence of train recuperation excess energy from the	20
	required energy intensity of the storage device	28
Figure 2.5.	Capacitive storage replacement scheme	28
Figure 2.6.	Variations of the applied voltage function approxima-	
	tion: 1 — piecewise constant, 2 — linear. \ldots	29
Figure 2.7.	Dependence of voltage on the storage capacitive element	
	on piecewise constant (curve 1) and piecewise linear	
	(curve 2) approximations of the applied voltage	30
Figure 2.8.	Charging current of a storage device with piecewise	
	constant (curve 1) and with piecewise linear (curve 2)	
	approximations for the applied voltage	31
Figure 2.9.	Voltage on an electric train current collector (curve 1),	
	voltage on the storage (curve 2)	32
Figure 2.10.	The residual and nominal voltage ratio dependence in	
	terms of energy supplied by the storage	33
Figure 2.11.	Lines of a DC traction substation level as a	
	two-dimensional random variable	37
Figure 2.12.	Line of an AC traction substation level as a	
	two-dimensional random variable. \ldots	38
Figure 3.1.	Generalized computational scheme of traction	
	substations zone	40
Figure 3.2.	Graphical representation of functions of resistance for	
	symmetric (a) and asymmetric (b) power schemes: 1 —	
	two-way power scheme; $2 - \text{nodal}; 3 - \text{parallel}$	41

Figure 3.3.	Current distribution functions for the feeders of traction	
	substation in case of two-way power scheme	42
Figure 3.4.	Current distribution functions for the feeders of	
	the nodal power scheme: (a) symmetric and	
	(b) asymmetric.	43
Figure 3.5.	Current distribution functions for the symmetric (a) and	
0	asymmetric (b) parallel power scheme.	44
Figure 3.6.	Voltage distribution functions for the symmetric (a) and	
0	the asymmetric (b) nodal power supply scheme: 1 — on	
	the passing track; 2 — on the adjacent track	46
Figure 3.7.	Power losses for the symmetric (a) and asymmetric (b)	
0	nodal power supply scheme: 1–4 — the components	
	appropriate to the feeders of traction substations; 5 —	
	losses that account for a substation; 6 — total power	
	losses in the traction network	47
Figure 3.8.	Equivalent circuit for an electrified site replacement	49
Figure 3.9.	Scheme for an i traction substation	50
Figure 3.10.	Schematic diagram for the equivalent resistance	
-	determination.	50
Figure 3.11.	Current distribution on the i th traction substation	
	site	52
Figure 3.12.	Scheme of site for determining potentials in nodes	54
Figure 3.13.	Scheme of experimental area replacement without	
	loads	54
Figure 3.14.	Substitution scheme with load in nodes	55
Figure 3.15.	Substitution scheme with load between nodes	56
Figure 3.16.	Scheme of substitution with the "triangle-star"	
	transformation.	56
Figure 3.17.	Scheme of substitution after transformations	57
Figure 3.18.	Current distribution functions of traction substations	
	and reinforcing points.	58
Figure 3.19.	Distribution of current in the contact network	59
Figure 3.20.	Voltage mode in the contact network in the recuperation	
0	area	60
Figure 3.21.	Timing diagrams of voltage on current collector (a) and	
~	traction current (b) of DC electric trains	62
Figure 3.22.	Schematic diagram for a two-way power supply	
2	system	64

List	of	Figures
	./	

Figure 3.23.	Sets of currents for feeders with a two-way power supply by two calculation methods	67
Figure 3.24.	Relations of voltage on the electric locomotive current collectors for a two-way circuit, determined by different	01
	methods.	68
Figure 3.25.	Schematic diagram for the node-based power supply	
	scheme	68
Figure 3.26.	Set of currents on the nodal power scheme feeders by	
	two calculation methods	71
Figure 3.27.	Relations of current collector voltage on electric loco-	
	motive for a nodal scheme; defined by two methods	72
Figure 3.28.	Circuits for parallel power supply scheme	73
Figure 3.29.	Sets of currents for parallel feeders on a parallel power	
	supply circuit in accordance with two calculation	
	methods	76
Figure 3.30.	Relations of voltage on an electric locomotive current	
	collector for a parallel scheme, defined by two	
	methods	77
Figure 3.31.	Balance components at the constant power consumption	
	of $3.3 \mathrm{MW}$: 1 — load consumption; 2 — losses for two-	
	way power supply scheme; 3 — the same for the nodal	
	scheme; 4 — the same for the parallel scheme	77
Figure 3.32.	Increase of electric locomotive current in terms of the	
	basic value at a constant power consumption of 3.3 MW:	
	1 — basic current value; 2 — for the two-way layout; 3 —	-
-	for the nodal scheme; 4 — for the parallel scheme	78
Figure 3.33.	Error of voltage calculation for power schemes: 1 — two-	-
F ! 0.04	way; 2 — nodal; 3 — parallel	79
Figure 3.34 .	The structure of the space–time model of the traction	01
T: 0.05	power supply system.	81
Figure 3.35.	The train-table example for calculations.	82
Figure 3.36.	The separate catenary systems for double-track railway	
	(top) and its functions of current distribution (bottom)	
	when train is located on first track (a) or second $(1, 1)$	0.9
F: 9.97	The final and a series of the stime estimate (ter)	83
г igure 3.37.	i ne single-node power scheme of traction network (top)	
	and its functions of current distribution (bottom) when train is located on first track (a) or second	
	track (b)	Q /
	$\operatorname{uack}(D) \dots \dots$	04

	Figure 3.38
tific.com ticles.	Figure 3.39
ed from www.worldscien except for Open Access at	Figure 3.40
Download ermitted, e	Figure 3.41
ansport l ly not pe	Figure 3.42
ctric Trr is strict	Figure 3.43
ıs of Ele iribution	Figure 3.44
r Systen and dist	Figure 3.45
C Powe . Re-use	Figure 3.46
for D 01/20	
ization on 07/	Figure 4.1.
nd Optim 3.185.224	Figure 4.2. Figure 4.3.
by 195.24	Figure 4.4.
о [_]	Figure 4.5.

Figure 3.38.	The scheme of three parallel connections of the catenary between a pair of traction substations (top) and its functions of current distribution (bottom) when train is located on first track (a) or second track (b)	85
Figure 3.39.	The single-node power scheme of traction network (top) and its current distribution in contact line on the first track (bottom) when train is located on the first track before the sectioning post (a) and behind the sectioning post (b)	88
Figure 3.40.	The single-node power scheme of traction network (top) and its current distribution in contact line on the first track (bottom) when train is located on second track before the sectioning post (a) and behind the sectioning	
Figure 3.41.	post (b)	89
	distance and in the time. \ldots . \ldots . \ldots .	90
Figure 3.42.	The voltage drops distribution in the contact network along the distance.	90
Figure 3.43.	The voltage drops distribution in the contact network along the distance and in the time	93
Figure 3.44.	The instantaneous power losses curve (a) and its cumulative function (b) in the contact line	94
Figure 3.45.	The curves of the voltages at the pantographs of the cleatric rolling stocks	05
Figure 3.46.	The three-dimensional surfaces of the currents (a), voltage drops (b) and power losses (c) in the contact	90
Figure 4.1.	Initial data entering in Mathcad for DC railway power	90
Figure 4.9	Design circuit and train schedule for DC railway	100
Figure 4.2.	Besistance function and current distribution function for	101
r iguit 4.9.	DC railway line	102
Figure 4.4.	Current collector voltages of selected trains	102
Figure 4.5.	Traction substation currents of DC railway power	104
Figure 4.6.	Traction substation currents and total trains power of DC railway power system.	104
Figure 4.7.	Total traction substation power and power losses of DC railway power system.	106

Figure 4.8.	Total energy and energy losses of DC railway power	
	system	107
Figure 4.9.	Initial data entry for trolleybus power system	
	calculation	108
Figure 4.10.	Design circuit and train schedule for trolleybus line	109
Figure 4.11.	Resistance and current distribution functions for trolley-	
	bus power system.	110
Figure 4.12.	Current collector voltage of selected trolleybuses	111
Figure 4.13.	Traction substation currents of trolleybus power	
	system	112
Figure 4.14.	Total power of trains and substations for trolleybus	
-	power system.	113
Figure 4.15.	Power losses, consumed and generated energy in trolley-	
	bus power system.	114
Figure 4.16.	Energy losses in trolleybus power system	115
Figure 4.17.	Initial data entry for metro power supply system calcu-	
	lation	116
Figure 4.18.	Design circuit and train schedule for metro line	117
Figure 4.19.	Resistance and current distribution functions for metro	
	power system.	118
Figure 4.20.	Current collector voltage of selected metro trains	119
Figure 4.21.	Traction substation currents of metro power system	120
Figure 4.22.	Traction substation current and total trains power of	
	metro power system	121
Figure 4.23.	Total traction substation power and power losses in	
	metro power system	122
Figure 4.24.	Consumed and generated energy, energy losses for metro	
	power system	123
Figure 4.25 .	The diagram of the SU energy exchange control	
	mode	124
Figure 4.26.	One-track section of a traction power system (a), its	
	loading scheme (b), and its instantaneous replacement	
	scheme (c)	125
Figure 4.27.	Simulation model of the traction power system in the	
	MatLab Simulink environment	127
Figure 4.28.	Subsystem of the traction network variable resistance	
	based on the controlled voltage source. \ldots	129
Figure 4.29.	Subsystems for output data processing and correcting in	
	accordance with voltage conditions. \ldots \ldots \ldots \ldots	130

Figure 4.30.	The data input when using two-dimensional table	
	arrays	131
Figure 4.31.	Subsystem for the load current correction	132
Figure 4.32.	Subsystem of a charger-bit storage.	133
Figure 4.33.	Emission of current higher harmonics by electric traction	
	systems to the external network: (1) $3.3 \mathrm{kV}$ (6-pulse	
	scheme); (2) 27.5 kV ; (3) 3.3 kV (12-pulse circuit)	135
Figure 5.1.	The circuit of the additional power injection with the	
0	regulated reinforcement point.	139
Figure 5.2.	The result of voltage stabilization at the pantographs	
0	of the ERSs (a) and the function of the reinforcement	
	currents (b) for its achievements.	141
Figure 5.3	The circuit of the additional power injection with the	
1 igure 0.0.	regulated reinforcement point	142
Figure 5.4	Voltages on current collector of EBS (a) and currents of	
1 18410 0.11	reinforcement point (b) in voltage stabilization mode for	
	various restrictions of minimum voltage value	143
Figure 5.5	Voltages on current collector (a) of EBS and currents	1 10
1 igure 5.5.	of reinforcement point (b) in current limiting mode for	
	various restrictions of maximum reinforcement	
	current	144
Figure 5.6	Concept of voltage monitoring system in a contact	111
1 igure 5.0.	network	145
Figure 5.7	Basic block diagram of distributed traction power	140
i iguite 0.1.	system with PV sources and ESS	146
Figure 5.8	ESS-level diagram	140
Figure 5.0.	Cage section of the Pridneprovska railway	1/18
Figure 5.10	Congreted current of each ESS	1/10
Figure 5.11	Calculation area of a real electrified section of the	140
1 iguit 0.11.	railway	150
Figuro 5 19	Schedule of trains at an area: (a) train schedule No. 1:	100
Figure 5.12.	(b) train schedule No. 2: (c) train schedule No. 3:	
	(d) train schedule No. 2, (c) train schedule No. 3,	151
Figure 5.12	Voltage change corrider for train schedule: (a) train	101
rigure 5.15.	schedule No. 1. (b) train schedule No. 2. (c) train	
	schedule No. 3; (d) train schedule No. 2; (c) train	159
Figure 5.14	Structurel diagram of the regularization area	157
Figure 5.14.	Model of distribution of the recuperation element in the	107
r igure 5.15.	inoder of distribution of the recuperation current in the	150
	traction and external power supply system	199

Figure 5.16.	Functions of the input parameter — the traction load in the recuperation area I_{rec1} (a) and the output parameter — component of the recuperation current I_{rec2} utilized in the brake rheostats (b)	162
Figure 5.17.	Fuzzy model of the distribution of recuperation energy within a traction substation.	163
Figure 5.18.	Decision-making area.	167
Figure 5.19.	Examples of output from modeling	167
Figure 5.20.	Neural network based on fuzzy conclusion on the distribution of excessive energy recovery.	169
Figure 5.21.	Output function of the input parameter $U_1(t)$	171
Figure 5.22.	The initial membership function of the parameter $U_1(t)$, changed to fit the training set	171
Eimung E 92	Changed to fit the training set	171
Figure 5.25.	Schedule of trains on the site.	172
Figure 5.24.	Output charts of train sument consumption	170
Figure 5.26.	Options of the substation structural scheme: (a) a rectifier without an SU; (b) an inverter without an SU; (c) a rectifier with an unmanaged SU; (d) an inverter with an uncontrolled SU; (e) a rectifier with a controlled SU; (f) an inverter with a controlled SU	173
Figure 5.27.	General view of the voltage–current characteristics of a charger-bit converter.	174
Figure 5.28.	Current collector voltages of electric locomotives in different operation modes of the traction substation equipment: (a) a rectifier without an SU; (b) an inverter without an SU; (c) a rectifier with an uncontrolled SU; (d) an inverter with a uncontrolled SU; (e) a rectifier with a controlled SU; (f) an inverter with a	
	controlled SU	176
Figure 5.29.	Electric locomotive currents in different operation modes of the traction substation equipment: (a) a rectifier without an SU; (b) an inverter without an SU; (c) a rectifier with an unmanaged SU; (d) an inverter with an uncontrolled SU; (e) a rectifier with a controlled SU; (f) an inverter with a controlled SU	178
		110

Computing and Optimization for DC Power Systems of Electric Transport Downloaded from www.worldscientific.com by 195.248.185.224 on 07/01/20. Re-use and distribution is strictly not permitted, except for Open Access articles.

Figure 5.30.	Voltages on the buses of the traction substation (1) ,	
	currents of substation (2), currents of SU (3) in dif-	
	ferent operation modes: (a) a rectifier without an SU;	
	(b) an inverter without an SU; (c) a rectifier with an	
	unmanaged SU; (d) an inverter with an uncontrolled SU;	
	(e) a rectifier with a controlled SU; (f) an inverter with a	
	controlled SU.	180
Figure 5.31.	The SU charge level in different operation modes of the	
	traction substation equipment: a — a rectifier without	
	an SU; b — an inverter without an SU; c — a rectifier	
	with an uncontrolled SU; d — an inverter with an	
	uncontrolled SU; e — a rectifier with a controlled SU;	
	f — an inverter with a controlled SU. \ldots . \ldots .	182
Figure 5.32.	Electricity consumption in different operation modes	
	of the traction substation equipment: a — a rectifier $% \left({{{\left[{{\left[{\left({{\left[{\left({{\left[{\left({{\left[{\left({{\left[{\left({{\left[{\left({{\left({$	
	without an SU; b — an inverter without an SU; c — a	
	rectifier with an uncontrolled SU; d — an inverter with	
	an uncontrolled SU; e — a rectifier with a controlled SU;	
	f — an inverter with a controlled SU. \ldots . \ldots .	182
Figure 5.33.	Electricity-consumption savings at different variants of	
	substation assembly	183

List of Tables

Table 1.1 .	Typical structural schemes classification of vehicles on the	
	possibility of recuperation.	11
Table 1.2.	Energy and discharge rates of different storage unit	
	types	15
Table 3.1.	Standard values of voltage on the tires of traction	
	substation and electric rolling stocks current collectors of	
	the different systems of electric traction	61
Table 4.1.	The comparison of current and voltage higher harmonics	
	in the traction substations primary network	135
Table 4.2.	Comparative table of current and voltage higher	
	harmonics	136
Table 5.1 .	Sensor nodes of the calculation area	154
Table 5.2 .	Input data and their ranges	161
Table 5.3 .	Control parameters and their ranges	162
Table 5.4.	Membership function of the traction load in the	
	recuperation area	163
Table 5.5 .	Membership function of the component of the recupera-	
	tion current, which is utilized in the braking devices	163
Table 5.6 .	The contents of fuzzy model blocks	164
Table 5.7 .	Structure of fuzzy model blocks	165
Table 5.8 .	Indicators of the reliability measure of rules	165
Table 5.9.	Results of the electricity consumption calculation	183