THESIS ON POWER ENGINEERING, ELECTRICAL
ENGINEERING, MINING ENGINEERING D25

MICROPROCESSOR CONTROL SYSTEMS OF LIGHT RAIL VEHICLE TRACTION DRIVES

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Declaration: Hereby I declare that this doctoral thesis is my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any degree or examination.

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PREFACE

This work relates to a long-term research experience at the department of Electrical Drives and Power Electronics in the field of drives in electrical transport. I would like to thank all of my colleagues who were involved in the research or development work of electrical drives in 1998-2006. I would like to thank in particular my supervisor professor Juhan Laugis and colleague Jüri Joller who faced the main difficulties at project start-up and helped to solve practical problems encountered in the application of results on trams.

The application of the drive with a new and original power circuit was possible thanks to support from Mr. Juri Savitski, former chief executive, Mr. Peeter Maspanov, former head of the board of Tallinn Tram and Trolleybus Company, Estonian chartered engineer Mr. Uno Heinvere, former head of tram fleet, chief engineer Mr. Aare Rebane, and Mr. Matti Koore, head of tram depot.

Applied research into traction drives began in 1998 under the leadership of professor Juhan Laugis by experimental research of operational parameters of drives in Tallinn traffic conditions.

Former master student Andres Arukivi and doctoral student Jüri Joller were engaged in the experiments. Energy consumption, losses and their main sources were investigated. Technical drawbacks of existing tram drives were investigated and technical assignments were specified.

The modernization of trams required the development of a new traction drive to be applied on trams of ČKD Tatra KT4 type. Concerning hardware development of the traction drive, technical solutions implemented in several European cities (Riga, Prague, Plzen, Cottbus, Chemnitz, Bremen, Frankfurt and Hannover) were investigated. Professors of Tallinn University of Technology Juhan Laugis and Tõnu Lehtla and associate professor Jaan Tomson provided useful recommendations on the preliminary study of original separately magnetized traction drive and on the development of its control methods. The author of this thesis was involved in the research, product development and application of traction control systems. The author developed hardware and software of the control unit. The first prototype was tested in traffic in August 2000.

The original solution of the power stack was registered as Estonian utility model. Authors of this invention are: former colleague Jüri Joller, author of this thesis Madis Lehtla, professor Juhan Laugis, and former head of Tram Fleet, Estonian Chartered Engineer Uno Heinvere. Also, the engineer of tram fleet Mr. Hillar Saarse was involved in mechanical design. The representative of Semikron OY Mr. Hannu Madekivi assisted developers on the design of the converter.

Electricians Mr. Tõnu Jakobson, Mr. Leonid Boltov, Mr. Endel Rae, Mr. Peeter Paasik, Mr. Meelis Mõis, etc. led by Mr. Valentin Kodi helped to assemble power circuits. Mr. Tiit Klotsmann, Mr. Peeter Kallas and Mr. Andres Arukivi installed the control units developed by the author on the vehicles.

Printed circuit boards for traction controller units were designed by the author of the thesis and produced in company Brandner PCB in Tallinn. The author prepared testing methods for the assembled units. Students Oleksandr Kiritsenko and Pavel Sidelnikov and researcher Dmitri Vinnikov assisted in the assembly of the units.

The experiments with the new traction drive started in the laboratory of Tallinn University of Technology in 1999. Experiments were also carried out in the traction motor test bench of tram fleet by the author together with Jüri Joller and master student Andres Arukivi. As a result, proper control methods and preliminary software design were selected. Many tram-drivers were participating in load tests in the traffic conditions. Quality engineer Mr. Paul Kukk was participating in the acceptance tests of braking systems.

To verify electromagnetic compatibility, specialists of the department of Communication used a bus equipped for radio frequency interference measurements. Project manager Mr. Andres Arukivi carried out measurements of low-frequency magnetic fields.

Low-temperature tests were carried out in Tallinn University of Technology using liquid nitrogen. Several changes were implemented in control system hardware to improve temperature stability and compatibility with low-floor sections and their braking systems from Hanning&Kahl. Control systems with improved functionality and electrical parameters were installed on trams with low-floor sections according to the instructions of Mittenwalde Gerätebau. Student Kristjan Ojala and Jüri Joller developed the new in-gearbox pulse sensors in 2003. The author developed all the needed software.

The mentioned control system has been installed on 28 tramcars. Experiments, software development and improvement of documentation have continued up to now.

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INTRODUCTION

Background

The development of transport systems is a priority field in national strategic programs as well in the EU research frameworks. The 6-th framework subprogram *Sustainable Development, Global Change and Ecosystems* includes the topic *Sustainable Surface Transport*. The 6-th framework contained subjects related to the efficient use of energy, like *New Energy Storage Technologies, More Efficient Energy Consumption*. These topics are also connected with transport, because transport is one of the fields of human activity with highest energy needs.

The **topic** of this thesis is multi-motor traction drives of light rail vehicles and their microprocessor control systems. Light-rail vehicles are mainly vehicles with light- weight intended for use in short distances. Trams are light-rail vehicles that are intended to be used on tramways in city streets. Trams usually consist of one to three tramcars. Light-rail vehicles usually have multiple traction motors that are connected as one drive system. Different drive configurations are used on different types of rail vehicles. These traction drive configurations and control systems should fulfil all the needed functions with required response and accuracy, function correctly in all modes of operations and environment conditions and should also be reliable, disturbance insensitive, stable, with suitable construction, easily testable, maintainable, repairable and reasonably low-priced. Mainly, such modern control systems are implemented using software-based control on microprocessor control systems. The processing performance, amount, type, construction and operation principle of inputs and outputs depend on the control object – a light-rail vehicle. The current thesis investigates light-rail vehicle problems based on the example of a tram.

The **research object** of the thesis is software-based control methods and technical applications of these methods on new and renovated drives and development methods used in different stages of drive system design.

The thesis deals with a novel solution of traction drive and its control software that was developed by the author's participation at Tallinn University of Technology and which was granted the Estonian utility model. In August 2000, the first tram with a new-type traction drive was implemented, which contained a microprocessor control system and software developed by the author. Solution of technical problems led to several theoretical problems arising because of the novel technical solution. Theoretical investigation, problem solving and improvement of the drive system continued in the next years. The thesis investigates technical solutions of traction drives experimentally and with the use of computer simulations. Microprocessor control system has been developed for traction drive, comprising stages operation principle up to implementation on the tram, including developments for serial production and control and supervision software. The thesis also studies the systems that are directly involved in traction drive, like driver interfaces and control structures and algorithms of auxiliary systems.

Actuality of the topic

Topicality of the research problem is based on the practical needs and possibilities (opportunities). The development of energy efficient transportation systems is a priority field in strategic programs. Trams are one of the most efficient transportation vehicles in cities. The requirements for public transportation include energy efficiency, environment saving, comfort, safety, attraction and reliability. This is a specific field where transportation of each city is a unique system that is described with technical parameters: specific width of tramway, type of supply voltage, type of overhead contact line and current collection devices, certain vehicle and wagon types and traditionally formed traffic conception. Tram operators and depots of each city are a tram building enterprises in a sense, because trams need regular maintenance, repair and modernization. According to data from several European tram-operators, the lifetime of rolling stock is 30...40 years. In this period, 3...4 overhauls are made, in which electrical systems and other technical devices are modernized. Thus, during a lifecycle, a tram needs several modernizations.

The requirements mentioned have become possible due to new developments in technology. Power-semiconductor technology and information technology are particularly fast advancing fields. The application of power converters will cause changes in the construction of electric drives and control principles. The advances of power electronics are improved controllability of systems, reproducibility and accuracy of processes, reduced losses and energy consumption, reduced size and weight of equipment, reduced amount of pollution (incl. noise, etc.) and other by-products. Today's power-semiconductor converters are controlled by microprocessors. Microprocessor-systems implement control, regulation, measurement, protection, supervision, signalization communication, and other algorithms. Software-based methods allow excellent flexibility compared to hardware-based control methods. These technologies allow reduction of energy consumption of light-rail vehicles, improvement of reliability and control quality. New fibre-optic connections and new sensors have extended these possibilities.

Topic selection was drawn from practical needs and from cooperation between Tallinn University of Technology and Tallinn Tram and Trolleybus Company that started in 1998. The main reason of the modernization project was poor technical condition of electrical equipment that needed serious repair. Additionally, modernization allows updating of vehicle on-board systems and improvement of reliability and following more strict environment requirements, including reduction of hazardous materials (cadmium, asbestos, etc.) usage as well as reduction of energy consumption. The results of initial analysis show that the energy consumption of most vehicles was abnormally high, much higher than a technically reasonable level for a light-rail vehicle. The use of obsolete technical solutions leads to a high level of energy losses. These circumstances resulted in rapidly increasing expenditures in conditions of increasing energy price. The energy consumption of rheostat-controlled traction drive is very high due to high losses in resistances in acceleration, braking and freewheeling.

Grounds of the topic selection

The application research of new and modernized tram development is going on in many companies and research institutions. Because of specific systems, the tram systems of many cities are unique and require unique technical solutions. Large tram manufacturers (Bombardier, AD-trans, Siemens, Škoda, Ansaldo, Alstom) are continuously developing new vehicles. The development cycle of a tram is relatively long (5...10 years), thus in term of application time the technology applied on trams in not the newest. Interests for modernization are connected to certain projects and technical solutions used in new vehicles are not always usable for old vehicle reconstruction. Because of that, modernizations are implemented by tram operators and tram depots in cities. Technical solutions of modernization applied are often very specific, thus prospective technical level of trams and sustainable development of tram traffic are not ensured.

The design of power electronic converters is especially important on special-purpose solutions, because by large there is no suitable mass-production converters available and their control software is application-specific.

The topic of the thesis was selected, based on the demands of reconstruction of trams in Tallinn, topicality of electric transport development in Estonia, Europe and Tallinn University of Technology and existing competence and infrastructure for research and development. This topic was a challenge in the field of research and development that allowed importing and creating very important know-how in the field of technology of energy and drives.

Objectives

The main objectives of thesis are as follows.

To **analyze** different tram systems and traction drives used on trams and to evaluate their technical properties on the basis of possibilities available in modern technology.

Theoretical and experimental **study** of operation modes of traction drives using experiments and computer simulations. To compose computer models of control system components and their verification via comparison of experiment results with simulation results. The existence of models about system components allows one to significantly reduce the amount of experiments needed for system tuning and testing and to avoid dangerous damages.

To **create** a new type of electric drive based on recent technology suitable for the reconstruction of trams in Tallinn that can be flexibly reconfigured and enhanced in the future.

To **develop** the principles of microprocessor control for traction drive and supply converter, system structure, technical solutions for circuits and construction and methods for their design. To develop hardware and software of traction drive suitable for software-based and model-based control.

To **develop** a modular and sustainable traction drive concept that does not require redesign of the whole system for the modernization of its components. It must be possible to integrate the control of traction drives to the control system of a tram and through it to the general traffic control and supervision system, etc.

To **develop** technological principles with hardware and software-based principles needed for series production of electronic units. Testing methods for series production of these converters and drive systems were developed, including troubleshooting algorithms for fault location and algorithms for operation, maintenance and repair.

To **analyze** possible sources and cases of failures and faults needed for supervision diagnostic and protection algorithm development.

Problems of multi-motor traction drives that require research and solution

1. A problem in motor torque-speed operation ranges in different multi-motor drives. For stability and controllability of the multi-motor drive system in the field-weakening range it is necessary to set the rules for field weakening according to the motor speed, motor current, maximal value of supply voltage and the voltage regulation reserve. The problem is how to ensure smooth acceleration in the changeover from nominal-field operation to the field-weakening operation in all traction motors.
2. Traction force distribution problems. For balanced distribution of the traction force between different bogies and different traction motors, it is necessary to solve the speed and torque balancing between different traction motors. Mechanical characteristics of traction motors and wheel diameters are always somehow different. Unequally distributed traction forces cause different wearing of wheels, instability in driving especially on slip-tramway, for example, on the existence of ice or leaves.
3. Bends (turns) pass problems. For smooth and stable passing of bends it is necessary to assure stable traction force of wheels on different speeds. The essences of the problem depend on the mechanical construction of the bogie.

The solutions of this problem are different in through-axle bogies and separate wheel bogies.

4. Dynamics of the traction drive. To assure a good controllability and stability, it is necessary to adapt the characteristics of a traction drive with dynamical characteristics of control pedals, buttons and levers and tram driver's response times. The fast torque control loop can cause fast transitions and shocks in the case of wrong adjustment. This problem is especially important at low speeds.
5. Off-line operation problems. At low speeds, when regeneration to contact line network is not possible, the converter may operate in off-line mode. Because in this mode, there is no supply from contact network, the magnetization of the drive depends only on the regenerated power. On the instability and slip conditions, when wheels can lock for longer periods, the braking stability problems occur on the wrong control or adjustment of motor magnetization. The deceleration causes a reduction of stability. The oscillations of the magnetization cause braking torque to fluctuate (vacillate, oscillate) in a wide amplitude range that also causes oscillations in the voltage of converter direct-current bus-bars.
6. Transitions between different braking modes, including switching from regenerative to dynamic and combining problems of different electrical brakes that cause torque chocks and electric arc on contactor contacts. To solve these problems, it is necessary to find optimal switching algorithms for input contactors and control algorithms for the braking resistor.
7. Over-voltage problems on traction converter direct current bus bars. Unsuitable switching will cause over-current in input circuit that further causes an over-voltage on the direct current link. The oscillations of RLC input circuit can occur within one tram, between trams and also between trams and substation. To solve this problem, it is necessary to damp over-voltages and to avoid over-currents. These problems can be partially solved by optimal switching algorithms of the input contactors.
8. Problems with combining of different braking systems. It is necessary to create optimal control algorithms for control of different mechanical brakes (electromagnetic track brakes, solenoid spring-brakes and electro-hydraulic brakes of the middle part) and their combinations. It is necessary to create optimal control algorithms to assure smooth braking and avoid spaces in transition to mechanical brakes at the end of the dynamic braking mode and when parking brakes are applied. It is necessary to optimally control both electrical braking of the traction drive and mechanical brake systems at the end of dynamic braking for a stable, smooth and space-less deceleration.

It is necessary to solve these problems for the development of traction drives. These solutions are implemented in control system software of the traction drive. Important theoretical problems involved in implementation are described in the thesis.

Research methods

The following methods have been used in this research – analysis of scientific literature, computer simulation models of the described systems, laboratory experiments and industrial experiments.

Investigated literature includes main scientific journals covering electrical drives and main international conference proceedings, especially publications from conferences of EPE, EPE-PEMC and IEEE. The patent search was also done for the application of the utility model of the traction converter and the patent application of the traction drive.

To solve theoretical and technical problems, modelling and computer simulation packages were used, such as MATLAB Simulink and PSpice. Modelling and simulation of traction drive component dynamic processes was carried out using MATLAB Simulink modelling tools. Electrical processes in the traction converter were studied using computer simulation package PSpice and digital oscilloscopes Tektronix TDS series. The programming language C and microcontroller programming and debugging tools were used in the software development process. Electronic Design Automation packages were used in printed circuit design. All the missing component libraries were made according to component datasheets and measured data.

The magnetization curves and mechanical characteristics of traction motors were specified and compared with laboratory experiment results. Experiments were partially carried out in the laboratory of Electrical Drives at Tallinn University of Technology and partially at test-bench of the Tram Fleet. First operation tests were carried out on the traction motor test-bench of the Tram Fleet and final tuning was carried out in the pilot tram. The first experiments with control principles were made in the Laboratory of Electrical Drives at Tallinn University of Technology on the electrical model of traction drive with reduced power. These tests continued on the traction motor test bench in the Tram Fleet. Final tuning was done on the pilot-tram. At the same time, the load tests of traction drive were carried out with 11.3 tons of steel rails loaded onto the vehicle. To start a series production, temperature tests were carried out on the developed control units, for both low and high operation temperatures. Liquid nitrogen was used on low-temperature experiments. The experiments and tuning of the antilock braking system was carried out on lubricated rails. Further developments include experiments on the control system with active traction control of axles. After the first pilot tram came into operation, energy consumption of its traction drive was measured and compared to energy consumption of former traction drive systems.

Source information

The research and design took into account the standards, scientific publications (references), patents, existing documentation and research reports about similar devices and systems. New and improved product development requires also negative information and information about drawbacks of existing products. Information about system drawbacks can be acquired from users of these products via unofficial interviews.

Sources of information used in circuit design

1. Technical specifications and data about new systems including technical documentation and commercial information
2. Technical specifications and documentation about competitive systems
3. Information collected via visits of companies and unofficial interviews.

Sources of information used in software development

1. Test and measurement results
2. Manuals of new software tools
3. Datasheets, manuals and application notes of electronic components
4. Analyzed and specified user opinions, requirements and practical needs

Scientific novelty

Theoretically novel aspects introduced in the thesis are as follows:

1. The modular structure of multi-motor traction drive and its MatLAB SIMULINK model have been studied. The structure consists of modules from component model groups. Using these components it is possible to describe all dependencies of effects and reactions.
2. The new control principle of multi-motor drive with merged (common) magnetization circuit has been introduced. This control principle uses a model of traction motor electromotive force that is based on mathematically described magnetization curves.
3. Control algorithm for anti-lock braking control of a multi-motor traction drive. The purpose of this system is to equalize wearing of wheel surfaces.
4. The operation modes in the novel traction drive with separately controllable magnetization have been investigated and modelled. The models developed allow detailed investigation of possible fault modes and malfunctioning in a new drive system.
5. Research of reconstruction possibilities in tram traction drives. Explanations and recommendations were given to choose control principles on the traction drive reconstruction. Suitable choice of power and control circuits in the traction drive reconstruction allows improvements in the quality of motor control.

6. A general-purpose converter unit for direct current and alternating current drives has been proposed. This improves flexibility in the reconstruction and operation process. The same converter unit is usable with direct current motors and at completion of motor lifetime adaptable to other bogies and other traction motor types.

Practical significance

The practical value of this doctoral work and thesis is stated as follows.

1. The microprocessor control system and electronic units for a novel traction drive system have been developed.
2. The data for computer-aided manufacturing (CAM) of printed circuit boards (PCB) for electronic units with testing principles, equipment and instructions for cards assembly and testing have been developed. Printer circuit boards for series of all 28 tram's control systems were industrially manufactured on the basis of computer-aided manufacturing data developed by the author of the thesis.
3. The software for the traction control system has been developed and applied (programmed) on 28 reconstructed trams in Tallinn.
4. A new and flexible power unit of a traction converter has been developed. Utility model "Traction converter for electric vehicles" approved on 15.10.2002 by Estonian Patent Office under EE00332U1. Authors of this utility model are Jüri Joller, Madis Lehtla, Juhan Laugis, and Uno Heinvere.
5. Controller area network based diagnostic interface has been developed that allows supervision of traction drive from board computer or from portable diagnostic PC (laptop).
6. Traction drive diagnosis- and user interfaces have been developed and programmed by the author of the thesis.

Dissemination of results

During the doctoral study the author of the thesis have published 16 international publications, 5 publications are accessible via international database *Inspec* and 1 via *ISI web of Science Proceedings*. During doctoral research the author has presented results on several international conferences – *European Power Electronics* (EPE), *Power Electronics and Motion Control Conferences* (EPE-PEMC), *Baltic Electronics Conference* (BEC), *Compatibility in Power Electronics* (CPE), *IEE Power Electronics and Variable Speed Drives Conference*, etc.

The developed products have been introduced on fairs in Estonia *Tehnoloogiamess 2004*, *Tallinna Ettevõtluspäev 2005* (Entrepreneurship Day of Tallinn 2005) and also abroad on EPE-PEMC 2004 in Riga and on EPE 2005 in Dresden. The designed traction converter and auxiliary converter are patented as Estonian utility models:

1. Joller, J., Lehtla, M., Laugis, J., Heinvere, U. *Elektrisõiduki veomuundur* (Traction converter for electric vehicles) approved 15.10.2002 by Estonian Patent Office as EE00332U1.
2. Vinnikov, D., Joller, J., Lehtla, M., Kiritsenko, O., Laugis, J. *Elektrisõiduki kõrgsageduslik abitoiteallikas* (High-frequency auxiliary power supply for Electric Vehicles) approved 15.10.2002 by Estonian Patent Office as EE00331U1.

These systems introduced in this thesis have been produced and applied on 28 trams in Tallinn Tram Fleet. The development work (contract 245F) of the Department of Electrical Drives and Power Electronics received award from Tallinn Enterprise Board and an award of applied scientific research at Tallinn University of Technology.

Outline of the thesis

Chapter 1 describes recent trends in the field of DC supplied traction drive systems, including configurations of traction converters, different systems as perspective development and application areas.

Chapter 2 covers new mathematical and computer simulation models developed by the author.

Chapter 3 discusses a new structure of the control system and its software developed by the author.

Recommendations for end users and for further development are given before the conclusion.

Abbreviations

ABS	Anti Blocking System
AC	Alternating Current
ADC	Analogue-Digital Converter
C/C++	Standardized (ANSI, ISO/IEC 14882) Programming languages
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAN	Controller Area Network, ISO 11898-1
CANopen	Communication protocol for Control Area Network (CAN)
CPLD	Complex Programmable Logic Device
CPU	Central Processing Unit
CSV	Comma Separated Values
DC	Direct Current
DSP	Digital Signal Processor
DTC	Direct Torque Control (ABB)
EDLC	Electrolytic Double-Layer Capacitor
EMC	Electromagnetic Compatibility
EMF	Electromotive Force
EMI	Electromagnetic Interference
EMS	Energy Management System
EMU	Electric Multiple Unit
FLASH	Electrically re-programmable, non-volatile memory
FMEA	Fault Mode and Effect Analysis
FTC	Fault Tolerant Control
GPS	Global Positioning System
GTO	Gate turn-off thyristor
HMI	Human Machine Interface
I2C	Inter-IC (integrated circuit) serial computer bus (invented by Philips).
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
JavaScript	Programming language standardized using ECMA- 262 and ECMA- 357
LED	Light Emitting Diode
LRV	Light Rail Vehicle
MatLAB	Matrix Laboratory ®
MC	Micro-controller
NVRAM	Non-Volatile Random Access Memory
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
RCT	Reverse Conducting Thyristor
RFI	Radio Frequency Interference
RISC	Reduced Instruction Set Computer
RS232	Standardized (TIA 232 formerly EIA RS-232) serial interface. A similar ITU-T standard is V.24.
RS-485	Standard physical layer electrical specification of serial connection
RTC	Real-Time Clock
SCR	Silicon controlled rectifiers
SDRAM, SRAM	Synchronous Dynamic Random Access Memory
Simulink®	Simulink is a block library tool for modelling, simulating and analysing dynamic systems.
SMD	Surface Mounted Device
SOA	Safe Operating Area
TCN	Train Communication Network
TCP/IP	Transmission Control Protocol / Internet Protocol
VDC	Voltage of Direct Current

Symbols

μ_p	peak friction coefficient
λ	wheel slip
μ, \nu	friction coefficient
v, v_t, vt	vehicle linear speed
v_r, vr, v_{bogie}	linear velocity of the wheel traction surface
λ_v	slip at peak adhesion coefficient μ_p
T_e	electrical output torque without mechanical losses
ω, \omega	angular speed of motor shaft, rad/s
ω_r	angular frequency of wheel or axle
I_{a*}	reference value of armature current
I_a, i_a	armature current
emf, e_{a1}, e_{a2}	electromotive force of DC traction motor
EMF, E, e_Σ	sum of electromotive force of series connected DC traction motors
\Phi, Φ', φ	relative flux of separately magnetized motor
F_n, N	normal wheel-rail contact force, N
F_d	force of traction effort
$F_{contact}$	contact force
F_r	resistance force per axle or motor
m_n, mn	axle weight
M, m	vehicle weight
r, r_w	wheel radius
g	acceleration of gravity
a	acceleration (of vehicle)
F_a	air resistance force
T_{loss}	mechanical losses of transmission converted to resistance torque of motor shaft
T_m	machine output torque
J	moment of inertia
K_m	electromechanical torque coefficient
U_{dc}	DC-link voltage
I_{dc}, I_dc	load current
U_{line}	line voltage
I_{line}	line current
I_f	magnetization current
U_f	magnetization voltage
U_a	armature voltage
u_{chop}	instantaneous output voltage of switch-mode converter
R_{choke}	internal resistance of input choke
R_a	resistance of series connected armature windings and interpoles
R_{a1}, R_{a2}	resistances of armature windings
L_{a1}, L_{a2}	inductances of armature windings
k_{bogie}	transfer ratio of a bogie
k	exponent
k_a	air resistance coefficient (air drag)
k_s	coefficient of air resistance surface
S	air resistance surface
H	vehicle height
W	vehicle width
b	mass centre height from rails
l	distance between axles (bogies)
l_e	mass centre from first axle (bogie)
v_s	speed difference between wheel surface and vehicle
v_{ref}	vehicle speed calculated as minimum of wheel surface linear speeds
z	tooth number on pulse sensor on axle
p	number of series connected motors
n_t	time interval measured using discrete timer
n	transmission coefficient

1. DEVELOPMENTS IN ELECTRIC TRACTION

1.1. Overview

1.1.1. Construction

The purpose of the electric traction drive is to provide energy exchange between the energy source (contact network) and the wheels. The required motion properties, such as speed control, acceleration and deceleration, including braking of vehicles, have to be ensured via proper control of energy flows. Single motor drives are used on smaller rail vehicles and trolleybuses, trains and trams mostly have multi-motor traction drives.

Electric drives can have different constructions. Amount of components, types depend on the main electric circuit. The structure of traction drive for a DC supply network is given in Figure 1.1. Control signals and energy flows are shown as arrows.

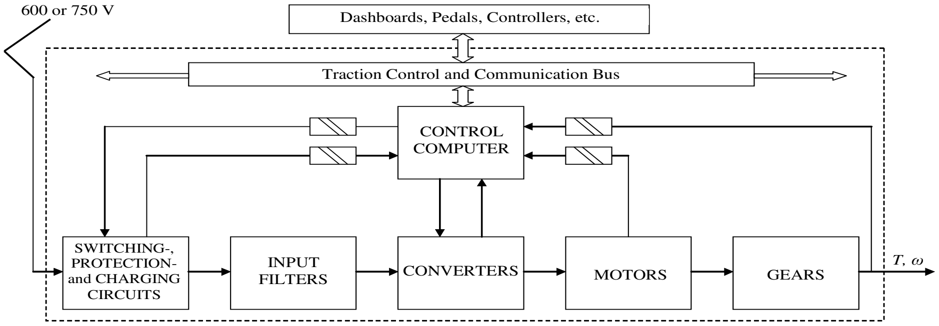


Fig. 1.1 Structure of an electric traction drive

Electric traction drive consists of one or more traction motors, mechanical transmission, control and protection systems. Control and protection circuits include a traction converter with a controlled braking chopper and braking resistor or an energy storage device, switched mode converter with sensors and control circuits, including its control system and auxiliary circuits (resistors, rheostats, contactors, sensors, etc.). These systems also contain protection circuits, filters, circuit-brakers, fuses, over-voltage protection varistors etc.

The input circuits of the vehicle are also connected with the traction drive. These include switching, protection and capacitor charging, input filters and sensors for input current parameter measurements. Several mechanical systems of a vehicle, e.g. some braking systems are not part of the traction drive, but their control has to be made compatible with the traction drive control.

1.1.2. Development Trends

The attention of developers is focused on the improvement of the efficiency of traction drives and reduction of losses. This leads to a decrease in energy consumption that generally helps to improve environmental conditions and sustainable development.

On the other hand, more strict requirements are forced to operation and control quality. This is related to required safety and needed comfort of passengers, but also to environmental requirements, like reduction of electromagnetic emission and noise.

Three main development stages or generations can be distinguished during the last 100 years in the development of electric drives.

1. First generation drives used rheostat control of series-magnetized DC motors, where switching operations were performed using control relays and contactor apparatus.
2. The drives of the second generation were applied after the invention of power semiconductor switches like thyristors. The speed and torque began to control using pulse width modulation via supply voltage regulators. These systems enabled active control of currents in traction motors.
3. Third generation drives are characterized by microprocessor control systems and application of information technology. Software-based control has significantly enlarged control possibilities. Further development of power semiconductor technology enabled the application of flexibly controlled GTOs, IGCTs and IGBTs. Flexible control facilitates required technical properties in torque-speed-power space using a different motor, a different converter and other component types. Thus, developers of traction drives were provided significantly more choices than in earlier years. Model-based control methods will be used more widely. At same time, technical requirements for passenger and environment safety and reliability have become stricter.

Numerous inventions in the field of energy management and storage have been published in recent years. The software and computing possibilities for research of traction drives via computer models have improved significantly. This allows the application of exact models in the design and diagnosis of traction drives. New ergonomic and intelligent control devices allow improving traffic safety and controlling quality, which leads to improvements in driving and usage convenience. The amount of available electronically commutated motors is enlarged. Important technologies in electric traction [SEK05] and their development stages are shown in Fig. 1.2.

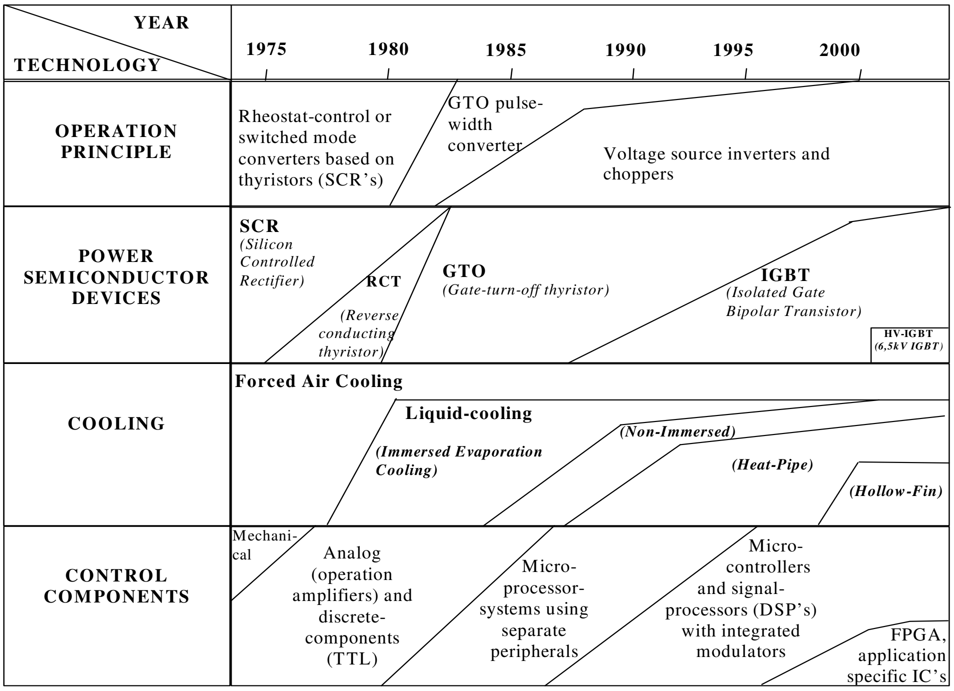


Fig. 1.2 Developments in electric traction drives

Problems are connected with sustainable development, because new technologies lead to compatibility problems. Producers are often not economically interested on the redevelopment of old vehicles.

1.1.3. Classification

Traction drives of light rail vehicles can be classified by external properties such as supply voltage type and level, output power, vehicle speed and also by the structure of the drive system [JOL01] such as the amount and type of motors, type of supply converter and control device and motor control methods [JOL02], energy management methods and user interface type, including additional functions. Important properties of electric traction drives are given in Table 1.1.

Table 1.1 External properties and inner structure of traction drives

Property	**Used configurations**
Amount and type of traction motors	Rail-vehicles use mostly multiple motors. New drive systems are using mainly AC motors without mechanical commutators due to lower price and maintenance costs.
Structure	Individual-, shared (common) or combined drive
Nominal supply voltage level and frequency	DC supplied, AC supplied or multi-system drives

Property	**Used configurations**
Operation mode of traction motors	One, two or four quadrant control
Control system	Mechanical controllers (pneumatic controllers), relay-contactor control, rheostat servo-control, analogue or digital electronic and microprocessor control
Type of converter or starter	Bridge rectifier, switch-mode converter, inverter, acceleration rheostat, rheostat controller, motor regrouping controller, etc.
Elements of converter and controller	Semiconductor switches: SCR, GTO, IGCT, IGBT and contactor-switching apparatus or contact-controllers (acceleration, braking, reversing). Switched-mode converters of modern tram drives are using IGBT half-bridge modules on DC voltages 600 V and 750 V
Electrical system	Isolated (for trolleybuses, 4 rail systems etc.) or connected to vehicle body (earth)
Indication	Signal lamps, LED’s, displays, etc.
Control interfaces	Buttons, keyboard, touch-screen, pedals, levers
Energy storage possibilities of drive and vehicle	For driving using stored energy, energy storage for higher power usage in regenerative braking and acceleration, low energy storage for maneuvers in depot, energy storage for supply of auxiliary devices, or without energy storage
Communications between traction drive groups	Communication and control via pneumatic systems (trains), digital set-point and reference via separate electrical signals (relay control), analog control, control of torque and speed set-points via computer network
Reversing	Full reversibility or partial reversibility with reduced speed in reverse direction
Redundancy	Possibilities to allow partial operation in the case of failures of traction motors control or supply system using reserving
Control possibilities of electrical braking modes	Independent control of electrical braking or combined control of regenerative or dynamic braking and mechanical brakes
Possibilities of speed and traction force control	Speed-torque characteristics, maximal power at different speeds and different modes of operation, etc.
Possibilities of control of consumed and regenerated power and energy management possibilities	Control possibilities for feeding energy back to network, including regenerative braking combined with electro-dynamic braking, energy management, etc. or only electro-dynamic braking with heat usage

In addition to external properties given in Table 1.1, the structure of the power circuit (main circuit) depends on the control object – the vehicle including its traction motors (one or more) and components of power and control circuits and control software.

1.1.4. Control methods and dynamics

Usable control methods depend directly on circuit structure and components. Modes of operation like electrical braking, regeneration and their properties (speed and power range, etc.) and functions depend on the construction of traction drive and the vehicle.

The dynamical operation of multi-motor traction drive is a complicated process where loads of wheels and motors are continuously changing, thus there is a continuous danger of different oscillations and traction force instability. The disparity and differences of technical properties of traction motors and control circuits, unequal wearing of wheels, different slip on rails, different loads on different parts of vehicle and other effects cause unequal power distribution and unequal torque distribution between wheels. Unequal speeds and torques of wheels lead to wearing and aggravate operation quality of traction drive.

Electrically and mechanically stable operation of traction drive is especially important on braking. The minimal deceleration and maximal braking distance is arranged with regulations [BOStrab] [RTL641] for ensuring traffic safety. It is complicated to fulfil these requirements on greasy track caused by ice, oil or leaves. The anti-slip control system is needed to avoid wheel sliding on braking and traction control for acceleration and constant speed operation. The speed difference of wheels can also occur on tramway-bend passing and can lead to turning problems of a bogie.

1.1.5. Voltage and Current Conversion for Traction Motors

Voltage control possibilities depend on the used supply system. Traction drives supplied only from single-phase AC contact network are rarely used on light rail vehicles and are beyond of the scope of the thesis. Multi-system light-rail vehicles that have direct current intermediate circuit and use medium voltage AC supply additionally to 600V or 750 V DC supply will be applied more widely. Different voltage control methods used for different motor types are shown in Fig. 1.3. Modern switch-mode controlled DC or vector controlled AC drives are mainly based on voltage source transistor converters with DC intermediate circuit.

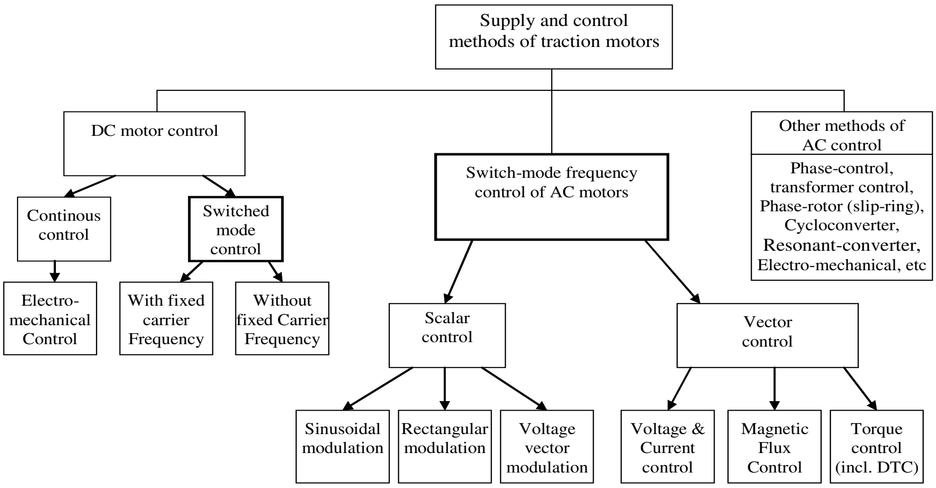


Fig. 1.3 Voltage control possibilities in electric traction drives

Recent traction drives are using AC or DC motors in DC contact network. For DC traction motors the transformer control and (phase-controlled) rectifiers are applicable only in AC systems. In the DC continuous control (electromechanical control), using contactors and resistors or acceleration rheostat, has low efficiency on dynamic operation due do losses on resistances. It is neither not applicable on AC traction motor control.

First switch-mode converters for tram traction drives were implemented using single-operation thyristors [KAR95]. Similar circuits are still used in many vehicles, including trains that are using 3 kV supply and DC traction motors.

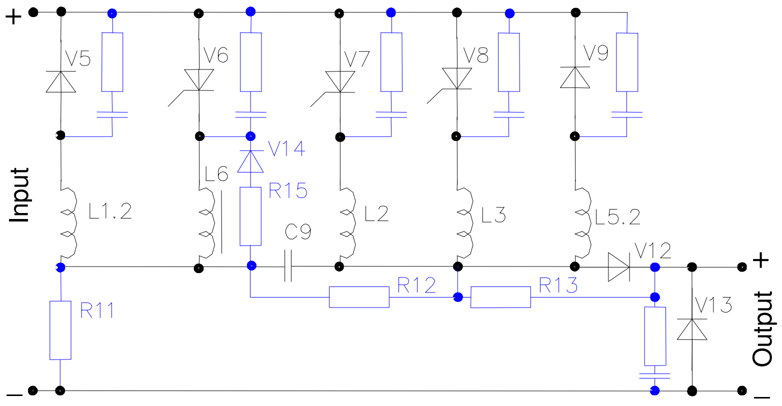


Fig. 1.4 Common power circuit of a thyristor chopper

The thyristor-based chopper circuit (from trolleybus Škoda 14tr) shown in Fig. 1.4 has the following drawbacks:

1. Parallel connection of multiple slow thyristors is complicated and requires additional filter circuits L2, L3, L5.2 that cause energy losses.
2. RC circuits used for over-voltage damping cause additional losses.
3. Closing commutation of main circuit thyristors V7, V8 requires additional commutation circuit with thyristor V6, capacitor C9, freewheeling diode V5, and resistor R11. The existence of commutation components does not allow high switching frequencies that lead to bigger and more complicated filters. The voltage ripple on motors causes additional problems. Control, protection and separation of commutation circuit signals require complicated firing circuits.
4. Freewheeling diode V9 and separate freewheeling diodes in load circuit V13. Recent semiconductor switches have integrated freewheeling diodes RCTs, IGBTs, etc.)

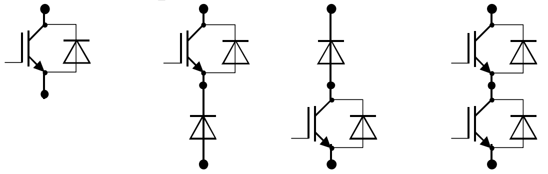
Circuits described in Fig. 1.4 are not used in modern traction converters because of availability of compact, fast and efficient transistor modules. Pulse width modulation and vector control are widely used in converters, including in controlled rectifiers and drives because of availability of fast power semiconductor devices and better output voltage quality. Bridge-circuit based inverters are widely used for the supply of AC traction motors. Power stacks of traction converters are mostly assembled using power semiconductor devices produced in large series (Fig. 1.5) or using intelligent power modules. The same power stack enables usage of different output voltages, different control methods of AC voltage or voltage vector modulation.

Problems that require further research are:

1. Problems that arise with increasing switching frequency, including 3D circuit design, EMC and long cable problems. The described hardware problems should be reduced by software, including by choice of suitable modulation, frequencies and control methods.
2. Protection of converter transistors and traction motors on failures and malfunctioning.
3. EMI immunity of feedback and measurement circuits.
4. Design of flexible and efficient converters that can be used for control of different traction motor types.
5. EMC problems are tightly bound with the control methods of traction converter, e.g. modulation, allowed switching patterns and switching delays.
6. Application of new power-semiconductor devices in traction converters, such as 6.5 kV IGBTs, SiC-based ultra fast freewheeling diodes, etc.

1.1.6. Wide-Spread Circuits of Power-Semiconductor Modules

Modules (in series production) containing several parallel transistors and anti-parallel freewheeling diodes are used in inverters and choppers in high-power drives, including tram traction drives (Fig. 1.5). This allows one to make the power stack more compact and to simplify construction of DC busbars. To achieve the required output current, these modules [TUR01] are built from several elements connected in parallel.



a) M1C
switch with
reverse diode

b) M1F
switches with
freewheeling diode

c) M2C
half-bridge

Fig. 1.5 Power module circuits used in recent switch-mode converters of tram traction drives

High-power full-bridge converter circuits used in AC and DC drives also contain half-bridge power modules. For conversion between different levels of DC voltage, step-up and step-down converters can be used.

To limit voltage on DC busbars, the braking chopper in M1F (middle point circuit with one controlled switch and freewheeling diode) circuit is used with braking resistor circuits. M1F circuit is suitable for choppers with unidirectional energy flow and for loads that do not need reversing.

The M2C (middle-point circuit with two controlled switches) in Fig. 1.5.c can be used as buck-boost circuit, which is suitable for bidirectional energy flow control, e.g. for control of energy storage devices. This circuit is also suitable for loads with unidirectional energy flows that require reversing, e.g. for control of supply of motor magnetization windings. High-power three-phase bridge circuits B6CI can be also made of three half-bridge circuits M2C.

Bridge circuits are suitable for the supply of DC or AC motors, but require a suitable control unit and a driver circuit. For Push-pull controlled half-bridges, the control and adjustment of interlock dead time and protections are important. Use of half-bridge circuits in multi-output DC/DC converters requires driver circuit suitable for independent control of semiconductor switches. In intelligent power modules (Fig. 1.6) of Semikron SKiiP-series [TUR01], several IGBT half-bridges are connected in parallel to achieve required output current. The common driver circuit is used for control and protection of parallel-connected half-bridges.

Intelligent driver circuit assures galvanic isolation, isolated supply for secondary driver circuits and sensors and protects power modules against short-circuit or overload. To protect parallel-connected power modules, both collector-emitter voltage monitoring and current monitoring in parallel branches is used. Output current feedback signal for the microprocessor is formed as a sum of measured current values of parallel branches. Use of over-current protection (OCP) allows the protection of transistor module, independent of switching characteristics and temperature.

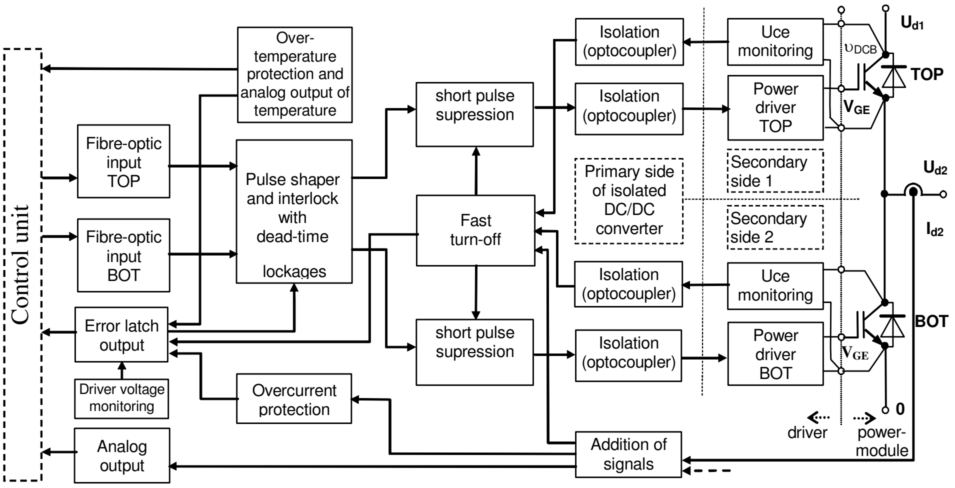


Fig. 1.6 Half-bridge intelligent power module

The driver (Fig. 1.6) has additional protection against wrong control patterns with dead-time interlock and short (< 750 ns) pulse suppression for the reduction of switching losses. Intelligent power modules also contain following protection and monitoring circuits.

1. Monitoring of driver supply voltage and protection against under-voltage.
2. Over-temperature protection with integrated temperature sensors.
3. Short-circuit protection using current sensors and monitoring of transistor voltages.
4. Over-current protection via current monitoring.

Switch-mode converters use active control and limiting of current using controllers with fast feedback signals. Nowadays, this is more reliable and cheaper than use of passive components (resistors, rheostats) for current limiting. Switch-mode control requires motors with improved isolation properties, but allows better control quality, including accurate control and limiting of currents.

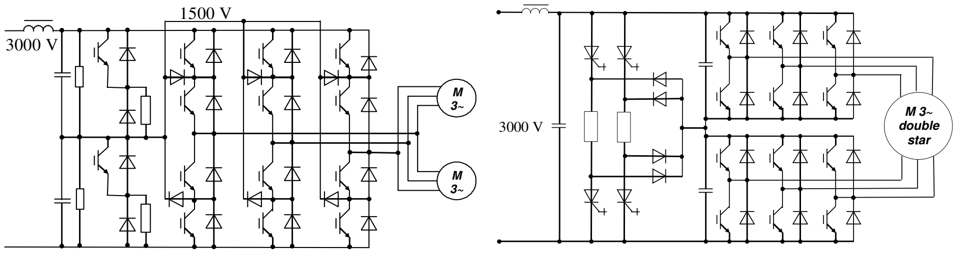
Half-bridge circuits allow developing converters usable for AC or DC supply and AC or DC motors.

1.1.7. Medium-Voltage Drive Circuits

The operating voltage is a critical parameter for transistors and capacitors. Although the switching characteristics of IGBTs are better, the medium voltage circuits often use GTOs or series connection of components. The disadvantages of series connection are large amount of components, complicated voltage balancing and reduction of reliability because of large amount of components.

Medium voltage traction systems have been in use for over 100 years. First 1.5 kV electric traction networks were built the early 1900s and first 3 kV networks in the 1930s. Line voltage was too high for auxiliary devices, thus equipment was bulky and heavy [HIL94] [KEM89]. Systems used in higher voltage networks still have many technical problems.

On voltages up to 1500 V, IGBT-based auxiliary and traction converters are used. On higher voltages, series connection with voltage balancing circuits is used [BOD99] with special traction motors. New 6.5 kV IGBT modules could become applicable in traction systems in the near future [BOD01]. High voltage converters also need high voltage capacitors banks, protection devices and other electronic components. Because the technical properties of power circuit components have continuously improved the development of transistor-based converter units for traction systems with 3 kV DC can soon be expanded. Multi-level bridge circuits can be used on 1.5 kV or higher DC voltages to reduce amplitude and voltage transients (dU/dt) in motor windings (Fig. 1.7, a).



a) Centre-tapped multi-level converter
Onix 3000, Alstom 1998

b) Series connection of converters for
Double-star motor supply on
Škoda Electric Multiple Unit 471

Fig. 1.7 IGBT inverters applicable on higher supply voltages

Multi level converters (Fig. 1.7, a) allow more than two voltage levels at phase outputs and thus enable better output voltage quality. Double-star motors have multiple stator windings (Fig. 1.7, b) and that allows the reduction of voltage and current amplitude on windings. The control of this special circuit requires special control drivers and a common voltage modulator for all series connected converters with DC voltage balancing in driving and braking. Challenges for further research in the future could be control of multi-level converters, voltage-balancing in series connected converter circuits and determination of optimal usage areas of soft-switching and hard-switching converters. Soft switching converters allow high switching-frequencies but their disadvantages are complexity of usage and possible losses in additional components.

1.2. Supply Systems of Traction Drives

Different standards exist for different traction supply systems. Three main traction supply systems are used in light-rail vehicles: AC supply via overhead contact line, DC supply via overhead contact line or contact rails and supply from on-board diesel-generator of the vehicle. Supply circuit components on drives with traction converters for different supply systems are shown in Fig. 1.8.

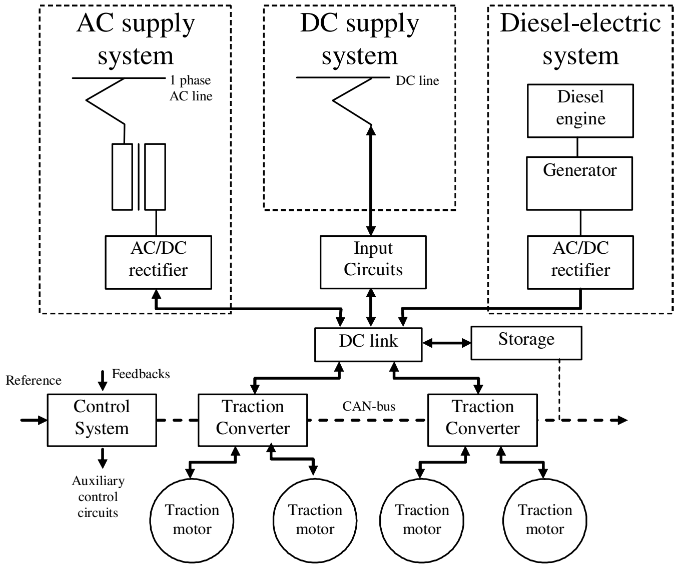


Fig. 1.8 Units of converter supplied traction drives for different supply systems

The type of the converter depends on the supply system. Modern voltage-source converters have DC-link, thus rectifiers are needed for connection to AC systems or diesel generators. The voltage is rectified on-board of AC supplied vehicles or in substations of the DC traction system. DC-link voltage is selected according to the required voltages (and power) of a traction motors. DC systems allow flexible control of energy flows and storage. For bi-directional energy exchange between AC networks, bi-directional traction substations are also available [TSE98]. Best results can be achieved by combining regeneration with storage possibilities.

The adaptation of drive supply for different contact networks with multiple voltages is becoming more important. Flexibility requirements expand to hardware used in traction drives and converters that should become usable with different motor types. Original traction converter hardware has been developed in the current thesis, which can be used on trams with different motor types. This original converter was registered as a utility model [EE332U].

Further research problems related to supply systems could be the output voltage of the traction converter and the optimal power control on regenerative braking.

1.2.1. Direct Current Supply Systems

In DC supplied vehicles, traction converters have no input converter and converter DC-link is connected to the network via the input filter. The DC-link voltage control and drive control according to voltage fluctuations in contact line is complicated. Old DC vehicles used direct supply of low voltage traction motors from contact network. This is simple, but requires contact wires with a larger diameter and higher density of substations. Higher voltage systems allow one to improve efficiency, increase transmitted power, reduce losses and increase the distance between substations.

Medium AC voltage systems used on railways require heavy low-frequency transformers, expensive switched mode rectifiers [BER00] or special motors with high insulation of windings or multiple stator windings [STE99]. The usage of higher voltage also leads to needs of auxiliary equipment with higher voltage and auxiliary converters, because vehicles also have systems with low voltage, safety low voltage and uninterruptible supply. New vehicles are using DC/DC converters for the supply of auxiliary in-vehicle systems. Requirements for power electronics and converters for rail-vehicles are described in standard [EN 50207]. This standard is also for trailer-cars of trams and trains and for other electric vehicles, such as trolleybuses. Voltage systems used in European traction systems are defined in standard [EN 50163]. This applies to line voltages of traction systems under normal operating conditions and limits. The DC supply systems are widely used in cities (see Table 1.2).

Table 1.2 DC traction systems used on LRVs including trams

Nominal voltage	Vehicles	Main properties and areas of application
600 V	trams and metros	This is widely used in tram and trolleybus systems. Choppers are used for DC drives and inverters for AC drives. Old 600 V DC drives use directly connected motors with rheostat control. Voltage is significantly higher in regenerative braking mode up to 720V. Short-term overvoltages are allowed up to 800 V. IGBT modules with voltage range 1200 V are well suitable for these systems with 400V electrolytic capacitors connected in pair wise series.
750 V	trams and metros	This is widely used in new tram systems. These new systems are using mainly new vehicles with inverter control of AC motors. The maximal allowed voltage is 950 V. Thus, 1200V IGBTs are also suitable for this voltage system with pair wise series connections of electrolytic capacitors with 475 V or higher voltage rating.
1200 V	common railways, metros, LRVs	This is used in Spain (Sóller railway), Cuba and Germany (on contact rails of Hamburg S-bahn). The historic 1200 V system in less spread today, but this was also used in Estonian electric railway between 1924-1941 and 1946-1958 [LÕH04].
1500 V	common railways, LRVs	This is used on railways of France, Netherlands, Spain, Switzerland, Portugal and Japan. Comparative analyses of this system to 750V [AÇI04] and 1200V or 3000V [PHA00] systems can be found in literature.
3000 V	common railways, LRVs	This DC system is used in Belgium, Italy, Spain, Poland, Czech Republic, Slovakia, Serbia, Croatia, Slovenia, Russia, Ukraine, and in Estonia and Latvia. In addition to Europe, this is also used in South Africa, Brazil, Chile and India. The maximal allowed DC voltage is 3900 V (was 4200 V in the former USSR). Up to today, thyristors and special converters were used in these systems. The challenge for future is application of new 6.5 kV IGBTs in these systems.

Different voltages can be used in different voltages. For example, lower voltage can be used for safety reasons inside depot buildings. Lower voltages (110V) are used in special industrial applications, for example, for trains in underground mining railways.

Multi-system traction drives are used in vehicles those have to be used on railways with different voltage systems. These systems can be re-switched to different voltages, but electronic components should be capable of operating at higher voltage levels that leads to their excessive price.

1.2.2. Alternating Current Supply Systems

In addition to DC voltages used in vehicles, also medium-voltage AC systems are used. Compatibility with AC systems is also important in new multi-system trams to allow usage of railway tracks with AC supply. Systems that use low-frequency transformers are generally simple and allow usage of cheaper power semiconductor devices. Medium voltage AC traction systems have many disadvantages, including higher EMI emissions to environment, heavy weight of transformers, unequally loaded phases, lack of suitable semiconductor-based converters, etc.

Very-low frequency AC supply systems allow the supply of AC commutator-motors or universal collector motors without rectifiers. It is possible to supply commutator motors, including series-magnetized DC traction motors from AC network, because alternation of currents in both stator and rotor does not change the torque direction of the machine. Lower frequency than commonly used in electric networks was applied to improve operation and reduce of mechanical stresses in commutator motors. Many European countries applied the 15 kV (earlier 6 kV and 7.5 kV) AC system with frequency 16⅔Hz (20 Hz in USA, accordingly). Traction motors were supplied from transformers with switchable windings. Transformer control had higher efficiency than rheostat control used in DC traction systems. On-board auxiliary systems are supplied from auxiliary windings of the main transformer, thus auxiliary equipment is compact and low-weighed compared to equipment in old 1.5 kV and 3 kV DC traction vehicles. Very-low frequency 16⅔Hz AC supply system is used in Germany, Austria, Switzerland, Denmark, Norway, and Sweden.

First experiments to use a single-phase 50 Hz standard frequency contact network were made in the 1930s in Hungary. This system started to spread more widely after the invention of suitable rectifiers in the 1950s. Transformers with rectifiers were applied in locomotives to allow the control of low-voltage DC (pulsating current) for traction motors. First mercury-arc rectifiers were used and later power semiconductor based rectifiers. Traction motors were controlled via switching of transformer windings. The most important disadvantages of this system are unequally loaded phases of electric network and high EMI emission. 25 kV 50 Hz single-phase traction systems is used in France, Great Britain, Finland, Russia, Lithuania, Czech Republic, Hungary, Slovakia, Slovenia, and Japan. Development of power semiconductor devices and converters may allow soon to apply 30 kV DC voltage in existing 25 kV AC contact networks [ÖST92]. The heavy weight of the transformer has been the problem of LRVs with medium-voltage supply. In the future, the soft-switched high-frequency DC converters that use very compact medium-voltage transformers can be used [BER00]. In addition, circuit topologies without transformers for the control of special motors with multiple isolated stator windings can be found in literature [STE99].

1.2.3. Multi-System Rail Vehicles

Often rail vehicles are needed that could use differently electrified railway tracks. Multi-system rail vehicles can travel on different supply systems with a different voltage type or levels without stopping. Four-system railway locomotives (DC 1.5 kV, DC 3 kV, AC 15 kV 16⅔ Hz, AC 25 kV 50 Hz) have been used in Europe. These locomotives are important on international cargo transportation when changing of locomotives on changing to a different railway track is not usable [GEL95].

In addition to locomotives, there are multi-system light rail vehicles used in Europe, including light low-floor multi-system trams that are capable of operating on railway tracks. Tram-trains allow connecting outskirts and rural areas to the city transportation system using existing railway and tramway tracks. Multi-system tram-trains allow using of lower voltage (600 V or 750 V) on city streets and medium-voltage supply on outskirts or rural areas. An overview of multi-system trams and their electrical systems is given in Table 1.3.

Table 1.3 Electrical systems of multi-system trams (2005)

Company, product or project	**Supply voltages**	**Description**
Siemens *Avanto*	600/750/ 1500/3000 VDC	Low-floor light rail vehicle with multi-system supply [BRI03]
Kraków project	600/3000 VDC	Application research of dual-system DC tram [KOW01]
ALSTOM *Regio CITADIS*	15 kV AC/ 750 VDC	Multi-system DC and AC tram-train
Kiepe electrical system for 2-system tram	15 kV AC/ 750 VDC	Electrical system for 2-system tram of the Stadtbahn Saar (Germany)
Saar-Lor-Lux project of tramlines	25 kV AC 15kV AC 750 VDC	Tram for region of Saarland (Germany), Lorraine (France) and Luxembourg [MEY03]

The electrical power circuits of traction drive should be capable of operating on the required nominal- and over-voltage levels according to voltage standards. Thus, motor isolation should endure existing voltages including over-voltages. Step-down converters with filters have been introduced to supply lower voltage drives with existing motors from higher voltage contact networks. Analysis and equipment description for the usage of existing 600V DC tram drives in 3kV DC networks can be found in literature [KOW01]. Theoretical problems that require further research are safe and reliable operation of protection and switching algorithms, transient over-voltage suppression in windings of medium voltage traction motors using hardware- and software-based methods and control of supply converters of multi-system vehicles. This thesis investigates low-voltage DC tram traction drives that are more widely used in cities.

1.3. Traction Motors and Gears

The main motor type used in electric traction drives has been series-magnetized DC motor with mechanical commutator, mainly because of suitable speed-torque characteristics. The main disadvantage of these motors is a mechanical commutator, which requires regular maintenance. The construction of such motors is more complicated compared to asynchronous induction and reluctance motors that lead to higher price.

Latest developments in the field of control systems have lead to further development and a wide application of motors without mechanical commutators in electric traction. These developments have also lead to an increase in overall efficiency and power density, reduction of operation and maintenance costs and improvement of reliability. The initial cost of semiconductor-commutated drives has been reduced. Spreading of semiconductor converters in new traction drives have led to the application of new motor types instead of series excited DC motors, e.g. squirrel cage induction motors. Classification of motors [CHA97] is shown in Figure 1.9, widely applied traction motors are shown with bold lines.

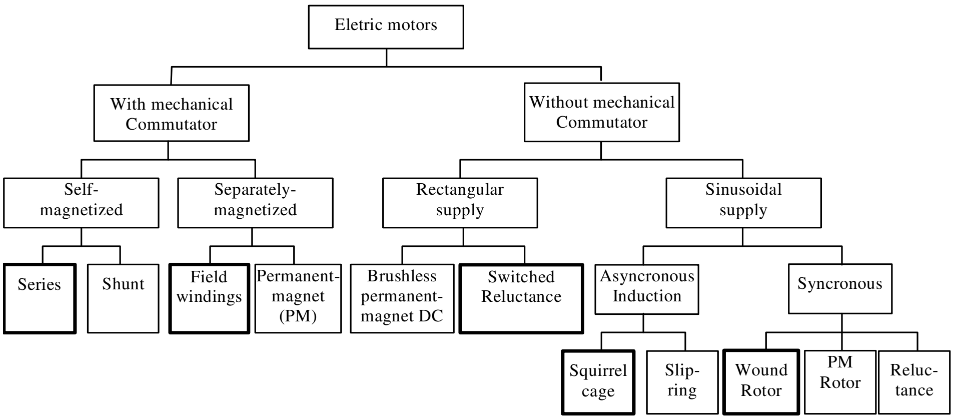


Fig. 1.9 Motors used in electric traction

Most widely used motors on light rail vehicles (LRVs) are series excited DC motors with mechanical commutators and AC asynchronous motors, especially of squirrel-cage type. DC motors have long lifetime, but require periodical maintenance. These systems are renovated and reconstructed after an 8...10-year period, because these need also a technically improved control system and higher control quality.

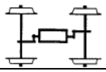
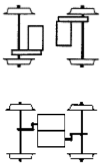
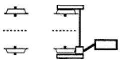
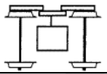
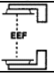
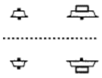
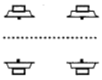
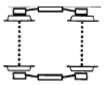
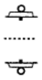
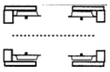
Mainly maintenance-free motors without mechanical commutators and brush-contacts are applied in traction drives of new vehicles, e.g. asynchronous induction motors and semiconductor-commutated DC motors. Other motor types are also used in special cases, e.g. synchronous motors, because of higher efficiency on high power heavy traction vehicles. **Synchronous motors** were chosen for French TGV high-speed trains and applied in 1993 [JAH01]. After that, mainly **asynchronous induction motors** have been applied in locomotive and tram traction drives. The advantages of **reluctance motors** (reactive synchronous motors) are simple construction, low maintenance cost and suitable torque-speed characteristics [RAH98]. The reluctance traction motors are a type of variable reluctance stepping motors from operation principle [CHA97] and can be used with vector control methods similar to other AC motors. The advantages of **permanent magnet motors** (PM) are higher efficiency and power density [JOC04]. The brushless DC traction motors e.g. DC motors with semiconductor commutator have wide application [CHU01] on light off-road electric vehicles.

The conclusions are as follows. Asynchronous and brushless DC motors are preferred due to their lower initial cost and lower maintenance expenses. New low-floor vehicles need motors with small dimensions that could efficiently operate in braking. Separate control on bogie axles is preferred in electric vehicles to allow better control of traction forces on variable wheel slip conditions. Separately motorized wheels [CHE02] are often used on low-floor light-rail vehicles.

Power-gear is a component of electric drive. Different transmission and motor-wheel configurations [OKA98] are used depending on the rail-vehicle type, operation speed, floor height, rail gauge and many other technical properties of bogies, like hinges (joints) and articulation. Drives with in wheel-hub gears and with cardan shaft transmission are used.

Completely low-floor bogies cannot have through axles, thus separate motors drive wheels on the left and right sides. Variable ratio gearboxes are commonly not used on rail-vehicles. Different wheel arrangements and wheel-motor configurations [TCR95] are shown in Table 1.4.

Table 1.4 power-gear types and wheel-motor configurations of LRVs

Symbol, drawing	Description
M1 	Conventional traversal wheel-set 'B' of mono-motor bogie, where both axles and all wheels are connected to one traction motor.
M2 	Conventional wheel-set 'Bo' bogie with two motors placed traversal or longitudinal. Most vehicles have two motorized bogies with four independent axles and traction motors (wheel-set Bo' Bo'). ČKD Tatra T3, T4 and KT4 trams (in Tallinn, Riga, Cottbus, etc.) have motor shafts placed longitudinally in the movement direction. Electric trains RVR ER1 and ER2 have gearboxes with transverse mounted motors. These configurations are not suitable for completely low-floor vehicles due to through-axles.
M3 	Bogie with a pair of driven and a pair of freewheeling wheels.
M4 	Transverse-mounted drives, both axles are connected through parallel gears and cardan shafts to one motor.
M5 	Motored electrically self-steering wheel-set without guiding wheels. Patented configuration [BIS98].
M6 	Articulated truck frame with two large hub-motor driven wheels and two small guiding wheels (steering by guiding wheels).
M7 	Four independent hub-motor driven wheels. This is used on Duewag/Siemens R3.1 (Frankfurt), ABB (Henschell) Variotram (Chemnitz, Helsinki) and BN tram 2000'1 (Brussels). Water-cooled AC motors are mounted into independently rotating wheel hubs. Wheels are driven via planetary gearboxes that are in the same body with the hub-motor.
M8 	Traction motors are on sides via cardan shafts. This was used on Schindler COBRA (VBZ Zürich, Switzerland) prototype tram. Traction motors are mounted on the vehicle body frame under floor. Motor drives an independent pair of wheels on the single side of the vehicle via a cardan shaft. Each wheel has right-angle bevel gearing.
M9 	Vertically mounted motors are driving independent wheels built into the articulation portal. This was used on Siemens SGP ULF 197 tram (Vienna, Austria). Each separately steered wheel drive has right-angle bevel gearing and a water-cooled induction motor.
M10 	Independent wheels mounted on radial-arm axle-boxes driven by motor via parallel gears. This was used on motorized bogies of ABB Eurotram Strasbourg. Each of the independent wheels on the axle boxes is driven via gearbox, using separately mounted 3-phase water-cooled induction motors.

Increasingly more electronic equipment is placed into bogies, including different sensors. The reliability of sensors located outdoors is often problematic.

Compact bogies with high power density require an effective cooling system to ensure homogeneous temperature and long lifetime.

Problems that require further investigation are bogies with multiple separately driven motors, equalizing of motor torques between different axles, optimal control of traction motors in a wide speed range, control of motor voltage and motor protection in the case of failures. The above problems were investigated using computer models for the development of traction drive with good dynamic properties and described in chapter 2 of the thesis. The developed control system is described in chapter 3.

1.4. Control Systems

1.4.1. Software and its Functions in a Traction Drive

Traction motors and converter with different sensors and additional devices form a traction drive. Different methods are used for control of this system, including field weakening, voltage control in the converter DC-link, including control of capacitor bank charging, voltage limiting etc. An overview of the auxiliary control systems of traction drive is given in Fig. 1.10. Modern information technology and model-based control methods are applied for control of all the described systems.

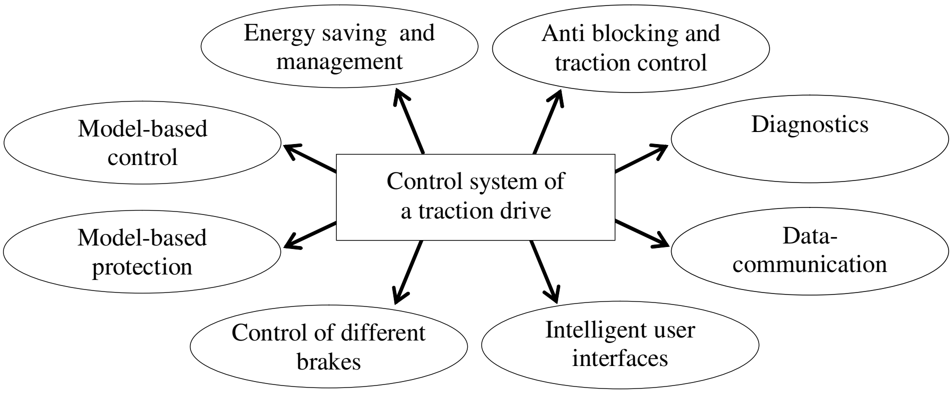


Fig. 1.10 Systems used in third generation traction drives

In addition to basic function like speed, traction and braking force control, third generation drive controllers integrate several additional systems and functions.

From **model-based control methods**, the model-based control of magnetization is used by the author. It would be possible to use flux-vector control methods on AC supplied motors. **Anti-slip control systems** include traction control with limiting of traction force on driving and braking systems with limiting of braking force by the anti-blocking system (ABS).

Intelligent electromechanical brakes allow flexible control of the braking force of different braking systems from the traction drive controller. Control of electromechanical brakes is close-knit with energy management including automatic control of regenerative and electro-dynamic braking of traction drive. Electro-mechanical parking and stopping brakes are controlled according to drive operation. In addition, other electro-mechanical anti-slip systems, e.g. sanding systems, are controlled according to traction drive and braking systems.

Model-based protection system includes software-based protection algorithms and component models in addition to common protection apparatus. Protection system and drive circuits allow **redundant control** of traction drive and brakes on the braking mode. **Diagnostic system** and its software uses models for analyzing of fault symptoms and is linked to the protection system, user interfaces and data communication.

Intelligent user-interfaces, including intelligent controls, allow methods for improved driving safety and efficiency. Haptic force feedbacks to controls, e.g. pedals, levers allows driver to improve cognition of vehicle's behaviour, thus improving controllability of the vehicle. Drive-assisting systems, including road condition indication, allow selection of proper speed and acceleration profiles for different conditions. Control of locks on the auxiliary systems - doors, road points, ramps, traffic lights, etc. allows increased efficiency and improved safety of auxiliary systems.

Communication networks (CAN, Ethernet, etc.) are used because systems are in-vehicle distributed. Communication networks allow traction drive synchronization in hooked-up cars and wagons and feedback. Feedback and control includes signalization and control of indication, including braking-lights, warning-bells etc. Intelligent solid-state relays with load feedback allow condition monitoring of auxiliary devices, e.g. identifying and diagnosis of a broken lamp on-line without stopping.

Energy management and saving systems include methods for efficient regeneration of braking energy to contact network, such as combining of regenerative and electro-dynamic braking with the control of loads for efficient use of braking energy. Energy storage devices are tested on pilot prototype vehicles to study energy flow control with intelligent energy management systems. This enables control of chemically (batteries), electrically (electrolytic capacitors) and mechanically (flywheels) stored energy including control of vehicle's heating.

Traffic control system could enable continuous control of power limits of vehicles and synchronization of accelerating and braking processes. This leads to flexible power control and loss reduction in supply lines.

1.4.2. Control Methods of Traction Drives with DC motors

Series excitation was widely spread on drives with DC traction motors. Such traction drives have suitable speed-torque characteristics without a control system. Resistors of rheostat are current limiting devices that were used in drives as an open-loop control system without feedback circuits. Recent drive systems are using switch-mode converters with closed-loop control. Relays and contactors are used in combined systems for expanding the control range of voltage and current - for current limitation, load reconfiguration from series to parallel connection and vice versa, reconfiguration of motor windings, equalization of currents in different parts of circuit via series connection and for equalization of voltages in different circuit parts via parallel connection. Drawbacks of relay-contactor control are additional switching elements - relays and contactors that increase complexity of control and reduce reliability. Disadvantages of such mechanical and electro-mechanical switches are slow response and electric arc on the commutation of currents.

Pulse width (switch-mode) control is used for converter voltage, current and motor speed control. Systems that do not contain passive components for current limiting, apply active closed-loop control methods with feedback circuits. Current control used on DC motors has good dynamic properties, but causes wheel-slip problems due to stiff characteristics. The anti-slip control is ineluctable in these systems. Combined control of speed on current (or torque) gives better dynamic properties and allows smooth acceleration ramps, but in some operation modes could cause slip and oscillation between different traction axes of the vehicle. Thus, this control method requires conjunct control of all axes and speed sensors. In addition to the abovementioned methods, a combined control can be used in different operation ranges and modes. Many obsolete drives are using one single converter for supply of entire traction drive instead of a separated control systems. The drawbacks of such systems are higher price of power semiconductor devices, absence of flexible slip control and absence of redundancy.

1.4.3. Field or Excitation Control

The limitation of converter output voltage is the main reason for usage of field-weakening [CHA03] in modern traction drives. Voltage-source inverters and step-down DC converters lack step-up capabilities, thus maximal value of output voltages of traction converters is bound to supply voltage. Traction drives of light-rail vehicles do not use gears with a variable ratio. Thus, motors have to operate in a wide speed range with limited power. This can be achieved via control of field in both AC induction or DC motors. The field-weakening is one of the possibilities for output power limitation on speeds over nominal speed and allows one to increase speed without increasing winding currents. Field weakening can be implemented using model-based control of magnetization in DC motors and field-vector control or voltage-frequency scalar control in AC motors. The field weakening can be avoided for the simplification of drive systems, if output voltage of a traction converter is sufficient for operation over nominal speed. Short-term overloading should also be taken into consideration on motor selection.

Shunting of field winding using contactors and resistors or power semiconductor switches, regrouping of circuits from parallel to series connection and vice versa, separate control of magnetization with a switch-mode converter and mechanical turning of permanent magnets can be used for field weakening. The latter is not used due to its complexity. Possibilities of excitation from voltage-less state and regenerative braking capabilities depend on the electrical circuits and control methods.

1.4.4. Control Methods Used in Drives with AC Motors

Traction drives with AC motors with transistor-inverters allow flexible control without electro-mechanical contactors in output circuits. Scalar control ($U/\sqrt{f} = const$) has high losses during transients. Thus, to achieve the required torque on acceleration and braking, motors have to be selected with significantly higher power than DC motors with the same traction properties. Scalar control is relatively simply applicable for the control of multiple parallel-connected traction motors.

Flux-vector control with the torque control of a motor allows achieving of good static and dynamic properties and high efficiency. Scalar and vector control can be combined in different operation ranges. Flux-vector control methods are wide spread in modern drives. Mainly direct torque control (DTC) is used to control asynchronous induction motors but appropriate vector control methods have been developed for other motor types, including switched reluctance traction motors.

Application of the vector control on a vehicle with a multi-motor drive appears to be a complicated problem. The equalizing of traction torques and speeds of wheels in multi-motor vector-controlled drive is a complicated assignment the implementation of which is not always successful in practice. This results in increased and unequal wearing of wheels and problems on vehicle control. Control method of parallel-connected traction motors is reported in literature [BOI04]. Flexible control of multiple AC motors requires separate supply converters [HEI95]. The first experimental tram (no. 11) with speed sensorless direct torque control was implemented in Helsinki in 1995 by ABB [HEI95]. The experimental tram has through-axles and good dynamic properties. Low-floor trams developed later are without through-axles (Adtrans Variotram), thus have independent control of wheels. These problematic vehicles were returned after experimental usage to the factory for improvements to be made in control systems. Analyses of problems connected to the control of separately driven wheels can be found in literature [CHE02].

Some multi-system vehicles with AC motors [KET97] include contactors at the output circuits of converters for reconfiguring of traction motors between star and delta connection [FUC99]. Control of multiple AC motors from single traction converter also requires independent protection circuits and circuits for redundant control during faults and failures. Switches and contactors on output circuits are also required for the implementation of various maintenance functions like abrading of wheels. Flexible traction converters should be usable with different output circuits and motor types.

1.5. Energy-Saving Control Methods

Electric traction drive is the system that has the highest energy consumption and power in the vehicle and can be a source of electrical energy on the braking mode. Operation modes of traction drive assign power flow between the drive and the network. Vehicles and their drive systems can be classified according to the possibilities of energy flow control.

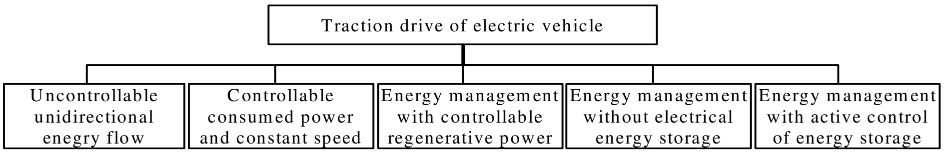


Fig. 1.11 Classification of control properties of different electric traction drives

Obsolete trams and trolleybuses are without constant speed and have only uncontrollable unidirectional energy flow. Only maximal consumed power is limited. Manual coordination of power limitation is used on traffic-jams when many vehicles start-up concurrently because the output power of the substation is not sufficient for the needed power for all vehicles in line section. Power limitation in the automatic energy management system enables use of time-based or priority-based control. Priority- or time-based power and driving speed limitation in traffic enables energy saving and improved voltage quality in systems where traction drives allow operation at constant speed. Braking energy can be regenerated to contact network. The need for the control of regenerated power is bound to voltage quality requirements. Different braking systems and modes are combined because regenerative braking is not usable at all driving speeds.

Energy management without electrical energy storage uses storage capabilities of other in-vehicle systems, e.g. active control of heating power and regenerative braking power. Storage devices of electrical energy allow flexible control of energy flows for the reduction of losses in the contact network. Control of energy flows and energy management is an important development trend of vehicles and transport companies.

Choice of methods and feasibility depends on the duration and requirements of acceleration and braking processes in traffic conditions. Operation modes and control methods should undergo a feasibility study because these depend on traffic conditions. The regenerative braking is more important on congested traffic conditions, thus driving-cycle measurement are carried out in real traffic conditions and adequate load.

1.5.1. Control of Braking Energy Transfer

For the use of electrical braking the energy should be the directed to braking resistor (electrodynamic braking) or back to the network or storage (regenerative braking). Most of modern traction drives have a **combined electrical braking** that allows flexible concurrent control of electrodynamic and regenerative braking. Electrical braking circuits often cannot be separated from other drive circuits. This applies to most of modern drives with AC traction motors. Braking methods used on LRVs can be divided as follows: mechanical braking without electrodynamic or regenerative braking, electrodynamic braking without energy regeneration, partial regenerative braking without a boost converter, regenerative braking with a boost converter, regenerative braking with current control using fast power semiconductors, and regenerative braking with energy management of storage. The DC braking of AC motors that is widely used in industrial applications is generally not used in vehicles.

Electrical traction drives are designed to work in the nominal voltage range. Voltage of the contact line on regenerative braking mode is significantly higher than on acceleration or freewheeling. The upper limit of line voltage is set via brake-chopper voltage settings (e.g. voltage limit on 600V nominal voltage can be 720V). Voltage standard [EN 50163] allows short-term over-voltages up to 800V on 600V nominal line voltage. Operating voltage levels of traction converters are set according to the nominal voltage of the contact network, but voltage levels on different vehicles should be equalized for control of regenerative braking.

Fast input switches that include both electromechanical switch and semiconductor switching circuits against electric arc [MEY00] can be used in input circuits of traction drives for flexible switching and protection. The braking energy can be stored in energy storage devices [TAK03] [JOL0422] for improved reuse of energy or directed to heating elements. Fast semiconductor switching circuits and input converters allow flexible control of regenerated power.

1.5.2. Autonomous Energy Management

Energy management systems allow improved control of consumed energy and flexible reuse of regenerated power in a vehicle. Different control methods are used on drives with different main-circuit configurations, including different energy management methods. More complicated energy management methods are used in autonomous electric vehicles with very limited energy storage possibilities. Efficient energy usage and monitoring of stored energy [CHA97] are main problems for achieving reasonable performance of autonomous electric vehicles. Structure of an energy management system adapted to contact-line connected vehicles is shown in Fig. 1.12.

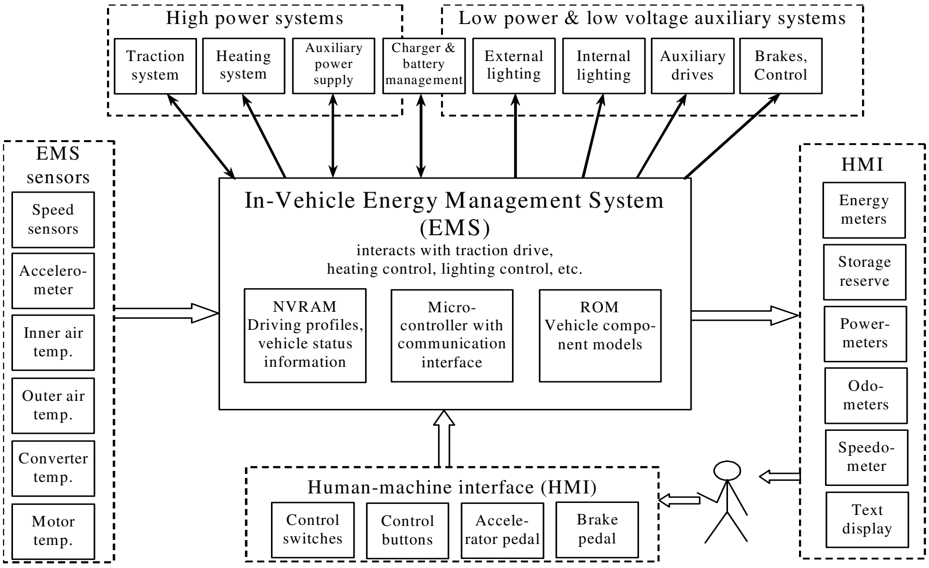


Fig. 1.12 Structure of energy management system for line-supplied vehicles

The energy management system described in Fig. 1.12 uses information from sensors located in vehicle subsystems. This shows stored energy, possible autonomous driving distance using the stored energy, controls energy use of vehicle subsystems, recommends a driving style with lower energy consumption and redirects braking energy to storage devices (batteries and ultra-capacitors), selects a charge algorithm for a battery according to state-of-charge and cycle-life-history, controls air-conditioning and lighting intensity according to weather conditions. The control of on-board vehicle subsystems is implemented via the control bus (computer network). The control bus allows collecting information from subsystem sensors and transfer of control signals. A multi-master Controller Area Network (CAN-bus) is the most widely spread in-vehicle network. Energy management system can be linked with navigation systems of autonomous vehicles. This allows selections of energy-efficient routes and efficient placement of storage and charging equipment on longer routes. This also enables change of route predictions and prediction of a possible driving ranges in real-time according to traffic and weather conditions. The power and speed limitation can be used to reduce energy consumption.

1.5.3. On-line Energy Management

Energy management methods are also applicable on light-rail vehicles including trams. Reviews of energy efficient technologies on railways [NOL03] can be found in literature. Application of energy management with energy storage devices [GAY02], such as flywheels, e.g. storage units from company Beacon Power and ultra-capacitors, e.g. storage stations Siemens SITRAS SES [SIE05], allow increased overall efficiency of the system [RUF03]. The energy storage devices can be installed on substations or into vehicles, e.g. tram traction drive [STE04] from company Bombardier and hybrid drive for trams and busses [LOH04] from company Vossloh Kiepe GmbH. Fly-wheel storage can also be placed onto rail-vehicle bogie [PAR03]. Possible technical view of DC supplied rail vehicles with storage can be found in literature [TAK03]. Tallinn University of Technology has applied for patent [PET0424] for on-line energy management system of line-connected vehicles, such as trams, trains or trolleybuses. Wireless communication channel between multiple vehicles in the same line section is needed for real-time control and management of energy transfer.

1.6. Slip Control on Light-Rail Vehicles

The traction and braking force depend on the adhesion between a rail and a wheel. When the traction or braking force is applied, it always causes some slip between the wheel and the rail. High traction and braking forces can be achieved due to very high forces in wheel-rail contact point, but even molecular amount of contaminants significantly decreases adhesion. These effects are very random and cannot be determined or precisely modelled, but each traction drive system should operate in these conditions. Main contaminants that have effect on the rail-wheel adhesion coefficient are water, ice, oil, trash, etc. Modern traction control systems correct reference signals of a driver automatically in real-time and determine the peak adhesion. This enables better acceleration and braking.

1.6.1. Sensors for Slip Detection

Most systems are using speed sensors to achieve better performance of slip control. Traction drives with separately driven AC motors and wheels enable the estimation of speed via vector models. The speed difference method [YAS97] is using slip velocity v_s

$$v_s = \omega_r \cdot r - v_{ref}\ , \tag{1.1}$$

where: ω_r – angular speed, r – radius of wheel, v_{ref} – vehicle speed estimated from the minimum of the angular wheel velocities. The more wheels are used to determine the minimum velocity, the higher the accuracy of the reference speed will be.

There are other methods [GUS95] that can be used in other vehicles: velocity differences on a driven and a non-driven wheel, vehicle dynamic behaviour analyze, surface reflections observation in the front of the vehicle via optical sensors, wheel sound analyze via acoustic sensors, and mechanical strain sensors in the wheels. With separately controlled AC motors, speed estimation via motor current differences [WAT02] is applicable. A separately magnetized DC drive system with separately controllable motor groups allows detection via motor electromotive force differences.

1.6.2. Traction Control on Wheel Slip

On the operation of slip control in light-rail vehicles, different operation ranges can be distinguished: stable traction without significant slip, large slip, slip on the balance of output torque and adhesion force, reduction of torque for reduction of slip, retrieval of output torque to estimated limit and retrieval of output torque to set-point (according to pedal position). The adhesion retrieval methods used for vector-controlled AC motors are described in literature [HOR99] and creep control methods for ABB Variotram (Helsinki) [SCH97].

The following methods can be used to control the traction force according to slip-conditions [FRY03]:

1. Neural Networks for estimating the parameters that cannot be measured on-line [GAD97]
2. Diagnostic Algorithms [GUS98] as Pattern Control Method [PAR01], for example thresholds (of slip) that will trigger the control process when exceeded
3. Detection via Motor Current Differences of AC drives [WAT02]
4. Model-Based Controllers [OHI00]
5. Hybrid Slip Control Method [PAR01]
6. Steepest Gradient Method [OHI98]
7. Fuzzy Logic Based Slip Control [PAL94][HIL97]

Methods used for slip, antilock and re-adhesion control are shown in Fig. 1.13.

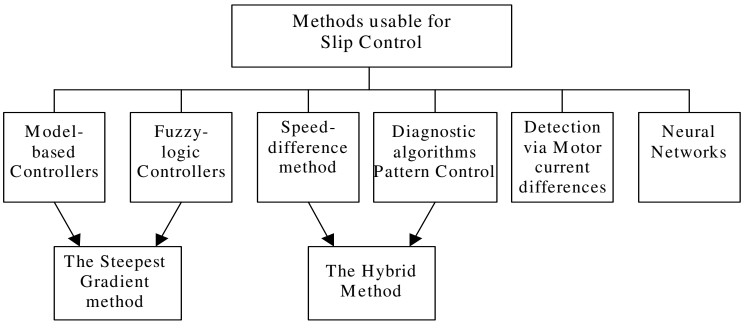


Fig. 1.13 Methods used for slip, antilock and re-adhesion control

Some ABS algorithms for passenger cars [DAY02] can also be adapted and applied to light-rail vehicles. Different mechanical and electro-mechanical anti-slip systems and anti-blocking brakes are used in LRVs. The following systems are used on trams:

1. application of separate mechanical brakes or track-braking magnets in the case of blocked wheels
2. equalization of braking forces via flexible antilock control of separate bogies
3. electrically controlled sand-systems for the improvement of adhesion during braking and acceleration.

1.6.3. Slip Detection in Multi-Motor Traction Drive

Mainly wheel speed comparison is used in multi-motor traction drive systems for slip detection. Speed signals can be measured via sensors or estimated from motor models using the measured current and voltages values. The comparison of measured speeds or comparison of values that are indirectly proportional to speeds can be used for slip detection. Direct comparison of speeds requires speed sensors in all axles. This is a good solution, as the feedback quality does not depend on the condition of motors and other components of the drive system.

The indirect comparison of speeds uses speed values estimated from the models of separately controlled motors. This can be applied for speed comparison between separately supplied under-carriages (bogies).

Instead of model-based methods, slip can be also detected via direct comparison electrical parameters. Comparison of electromotive forces can be used for DC traction motors. A bridge circuit can be used for back-electromotive force comparison. Traction drive system with series connected DC motors (trams ČKD Tatra KT4 and T3/T4, trains RVR ER1, ER2, etc.) is using the bridge circuit shown in Fig. 1.14. This simple bridge circuit does not detect slip if the slip is equal on both axles.

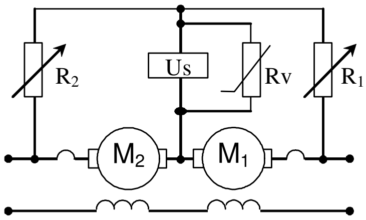


Fig. 1.14 Circuit diagram of DC traction motor slip detection system

An isolated voltage sensor U_s, voltage level relay with higher winding voltage or semiconductor relay with optocoupler is used for voltage detection. A sensor or a relay gives a signal if back-electromotive forces of traction motors are not equal. A parallel-connected metal-oxide varistor R_v increases a delay and reduces the influence of high-frequency disturbances caused by chopper supply and commutators. An analysis of the load distribution in series connected DC traction drive system [BOU03] can be found in literature.

1.6.4. Control of Anti-Lock Braking

The aim of the adhesion sensing and slip control in light-rail vehicles is to improve of overall stability and thus reduction of overall braking distance in traffic conditions. These systems also help to equalize wheel wearing and loads of different braking systems. The measured slip/spin signals allow the vehicle driver receive information about rail-wheel adhesion conditions. These can be also used for multi-motor drive system diagnostics. In addition to control of motor braking, these signals can be used together with sand systems and rail-braking magnets. This is different in comparison to road vehicles where the main aim of the ABS systems is to maintain steering control.

An overview of antilock control methodologies and parameters on road vehicles can be found in literature [DAY02] and can be adapted to light-rail vehicles. The parameters of the systems developed by the author of the thesis are shown in Table 1.5. Antilock braking systems of separately controlled axis should operate in accordance with other systems to maintain the stability of the drive system.

Table 1.5 Parameters of anti-lock brakes in electric traction drive

Parameter	**Description**
Cycle Rate	Required time (maximal time) to complete cycle for stable braking force
Threshold ABS velocity	Minimal vehicle velocity for anti-lock system activation
ABS threshold DC-link voltage	Drive and converter parameter that determines the possibility of anti-slip control usage
Apply Delay	Time delay for controlled output current increase
Release Delay	Time delay for controlled output current decrease
Input signal threshold	The difference of speeds required for ABS activation (implemented via electromotive force comparison of different DC motors)
Application Output Ramp Rate for Braking force (torque)	Ramp for smooth increase of braking force
Threshold Output Current Percentage	Minimum output current percentage from reference value for anti-lock system activation

1.7. Vehicle Controls and User Interfaces

1.7.1. Reference Controls for Traction and Braking

Controls that are used for setting of traction and braking force can be divided as manual or pedal controls. The entire drive workplace is designed according to the type of controls (hand-controller or pedals), including all positions of buttons, levers, pedals etc.

Pedal control is widely applicable on busses and trolleybuses where driver's hands are used for steering. Older trams, including ČKD Tatra, are using mainly pedal control. Manual control uses only one lever for acceleration and brake that is in most cases placed for left hand control. In new light-rail vehicles, the manual control is preferred because of lower initial cost. Combined traction and braking pedal [NIL00] can be found in literature, where traction and braking are controlled using single pedal without releasing foot. Combined acceleration-braking pedals have multiple sensors and thus more complicated construction than single-function pedals. Light-rail vehicles have safety dead-man-control pedals or dead-man buttons in addition to traction and braking controls. New dead-man controls are introduced in new vehicles. Those are designed for periodical pressing and have warning signals instead of continuously held pedals or buttons.

Systems that are directly bound with traction drive control are emergency brake, sanding systems, park-brakes and indications like stop lights, reverse-direction lights and warning bells. Additional panel controls and reverse control panel located the rear end of the vehicle are used for moving vehicle in the depot and in the reverse direction.

1.7.2. Construction of Controls

Contact-less position sensors are used in modern vehicles for traction and braking force referencing (instead of potentiometers or contact controllers). This allows improving reliability and increasing lifetime. Additional contacts for emergency and extra braking are only included to enable safe, reliable, independent and redundant operation of braking systems. In addition, signalization systems, like braking lights and signal-bells, are tightly bound with braking systems and their controls. Obsolete contact controllers do not allow smooth set-point adjustment, thus control has steps for different traction torques. The resolution of set-point adjuster with potentiometers or contact-less position sensors is more than hundred times as compared to contact controllers, thus a driver does not notice different reference value steps. Modern systems enable the use of pulse or position sensors instead of potentiometers or contact controllers.

1.7.3. Redesign Problems of Driver Workplace

The redesign of traction drives leads to the redesign of driver workplace. This leads to additional re-instruction of staff.

The use of manual control instead of pedal control is also connected with the redesign of driver panel to enable operations (like switching of lights, bells, turn controls etc.) to be performed with one hand. This leads to changes in many auxiliary, indication and signalization systems bound with traction drive. The design of driver workplace is also connected with traffic safety, thus different investigations have been carried out for redesign, e.g. tram-driver's workplace [KAI05] redesign in Vienna (Austria) and harmonization of control panels used in international cross-border railway traffic [SOR01].

Changes of control methods in traction drive are unavoidable on changing of the traction drive type, e.g. in applications of switch-mode converters. Principles of energy-efficient control of switch-mode drives differ from those of rheostat-controlled drives. Redesign will cause changes in the control of acceleration and braking processes. Lower energy consumption in a rheostat-controlled vehicle can be achieved if the use of rheostat is minimized, thus with short acceleration at high power. This is different from switch-mode control where losses are lower on smooth acceleration and constant speed is applicable. Differences in control are also important on the changing of drive control, e.g. changing of the excitation principle or current control methods. Differences exist between series-magnetized and independent-magnetized drives. The efficiency of series-magnetized drive is lower on magnetization currents than on nominal or higher currents when poles are saturated. The control system of independently magnetized drive enables keeping magnetization current constant on optimal value that allows better efficiency at lower speeds. Smooth acceleration on the switch-mode system can be achieved by smooth speed and torque control via smooth pressing of controls (pedal or hand-controller).

1.7.4. Panel Indication and Signalization

The different drive control systems require different signalization on driver panels. Light emitting diodes (LEDs), digital- or graphical displays are used for signalization in new designs. Older or obsolete systems also include electromechanical displays, e.g. speedometers and odometer. The mechanical position of the switch is often also a state-indicator and mechanical memory that does not need additional indication. For warnings information, voice signals are often used in addition to visible indication. Indication and displays that are directly connected with driving are classified as primary displays and displays of auxiliary systems (heating, radio communication, meters etc.) as secondary displays. Positions and properties of displays and indicators of vehicles, including for contact line supplied vehicles according to requirements and recommendations [GUI04] [BEA98] are shown in Table 1.6 and 1.7.

Table 1.6 Primary displays of electric vehicles

Display	Description
Speedometer	Speedometer should be an easily visible display, which allows convenient limitation of speed according to limitations and traffic conditions. This display is placed directly ahead of the vehicle driver.
Warning indicators	Most important signalization devices are located directly in front of the vehicle driver. These include important state and error indicators of the braking system and traction drive (input switch, error signals, and magnetization of motors). Park-brake indicators are using indicators with red color. Audible warning signals are used together with visible indicators.
Electrical system displays and indicators	These displays allow condition monitoring (battery, motors, etc.) that allow expedite fault location and repair.
Turn indicators	These indicate state of turning lamps.
Indicator of high-beam of driving lamps	This usually blue-colored indicator shows state of high-beam lamps.
Park-brake indicator	These indicators show state of parking brakes and other braking systems condition.
Line voltage indicator	This indicator shows the state of line-voltage, additional indicators are used for drive supply. These are needed to indicate availability of regenerative braking mode and state of drive and converter and supply voltage for driving mode.
Power-meter of traction drive	Instrument that shows direction of power, including power that is consumed or redirected to the brake resistor or regenerated to the line. If exact level is not important only ammeter is used, which does not give accurate results on variable line voltage.
Wheel slip indicators	Indicator for condition monitoring of wheel surface adhesion and operation of anti-slip or antilock system.

Table 1.7 Auxiliary displays of electric vehicles

Display	Description
Electricity meters	Voltage and current sensors that are located at the input of traction drive allow metering of both consumed and regenerated energy.
Odometer	The distance integration (counting or summing) is performed using signals from pulse sensors that are also used for drive control.
Indicator of regenerative braking	Regenerative braking indicators allow selection of energy efficient braking, including possibilities of regenerative braking in current track slip and line voltage and mechanical brake conditions.
Thermometers	Thermometers show inner, outer and equipment temperature and allow keeping lower equipment temperature in the case of failures.

1.7.5. Haptic Controls with Force Feedback

Tactual or haptic feedback of force allows improvement of controllability of a vehicle by driver cognition of forces and vehicle behaviour. This back force actuator allows driver (vehicle operator) to sense the forces measured by the drive control system [HUS99]. Force feedback can describe different reactions −wheel slip, failures, dangerous traffic conditions, too short distance etc.

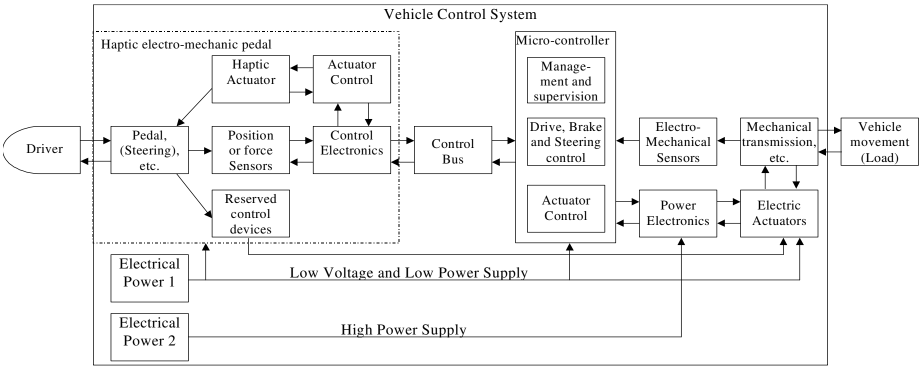


Fig. 1.15 Main signal flows in drive-by-wire system with haptic feedbacks

Driving assistance systems have been developed for cars and rail vehicles, such as Active Distance Support (company Continental Temic, Germany) and Integrated Longitudinal Support (company BMW, Germany) [SCH00]. Vibrating haptic pedal is activated by help of sensors and warns the driver of dangerous situations on the track or street. The main aim of such systems is to avoid collisions.

Haptic force feedback is also applicable for driver assistance on wheel-slip control on braking. Sensors of antilock systems feed signals to the driver panel, but these signals can be sent to the driver tactually for improving of operation. General requirements for controls of rail vehicles and control interfaces of brakes are described in standards [IEEE 1475]. Control panels and displays are described in standard [SAEJ1138] (SAE 1998f). The problem is assuring safety and compatibility of new devices and drives systems with existing controls or control principles.

1.8. On-board Supply and Communication

1.8.1. Supply of Traction Control and Auxiliary Circuits

The purpose of the on-board in-vehicle supply network is to supply low voltage current to on-board systems. Safety-critical systems, like traction drives and brakes, require uninterruptible supply of their control circuits. Redundancy for supply and control circuits is required for braking in the case of failure. Thus, these safety-critical systems have separate actuators, separate protection and separate wiring. In addition, electromechanical brakes have separate wiring and protection for redundancy of braking systems. The battery is used for uninterruptible supply of brakes and their control systems, including traction control system. The battery is charged from the contact line via an auxiliary converter. Safety low-voltage (voltages 24V, 48V, 72V or 110V DC) is used for the supply of in-vehicle equipment. Mainly separate auxiliary converters are used between line and battery voltage conversion, but these converters can be integrated into one single unit with a traction converter [MES01].

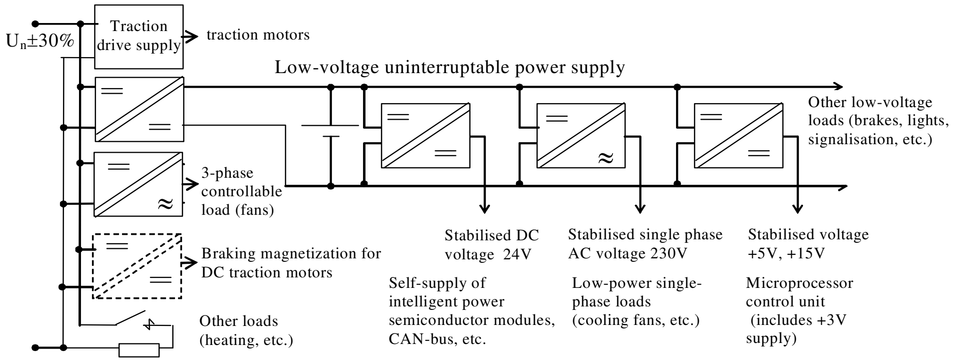


Fig. 1.16 Supply systems of traction drive and its auxiliary circuits

Protection circuits are designed to allow separate protection and redundant operation of auxiliary systems. Separate wiring is also used for brakes, doors, control circuits, and emergency lighting.

1.8.2. Communication for Drives and Auxiliary Systems

According to different requirements, different multiplexing-networks with different characters are needed. Communication networks with different functions, protocol mechanism, area, and data transfer rate, data packet size, fault-tolerance or other different parameters are used in vehicles.

In-vehicle (on-board) multiplexing network systems [HAD00] can be divided according to different requirements as follows:

1. power-train network is for control systems management of drives, brakes, ABS systems, static-converters, auxiliary systems, etc.
2. body network is for control systems management of door, climate control, lighting etc.
3. multimedia network is a network for navigation systems, cameras, audio and video systems, audio receivers, amplifiers, passenger information panels, mobile phones etc. multimedia systems. Multimedia network completes control, monitoring and diagnostic systems.
4. X-by-wire systems and drive-by-wire network are separate networks, which are used for vehicle primary controls for safety reasons. This connects control systems of controls like pedals, traction drive, brake, etc.

All these network systems can have so-called sub-networks that operate only inside one system. These sub-networks are commonly using a simple master-slave configuration. Drive-by-wire systems used for vehicle primary controls (pedals, hand-controls) need reliable high-speed communication. Networks like high-speed CAN, Time-Triggered protocol or Train Communication Network (TCN) can be used for drive-by-wire systems. The purpose of TCN is communication between cars (wagons) in a train while CAN is used inside one wagon or tramcar. Main properties of networks [HAD00] are the data transfer rate, protocol mechanism, reliability, fault-tolerance, and price. In-vehicle network design adds requirements for network circuits and used protocols [LEE02], these are:

1. System integrity means that probability of an undetected error must be negligible for the life span of the vehicle.
2. Bounded determinism of information system sets a guaranteed upper threshold on message latency time for control problems.
3. EMC compliance requirements set both emitted radiation levels and the tolerated absorption levels.
4. Requirements of compactness, reliability and compatibility of connectors are more important on rail vehicles compared to domestic electronics because of very rough operating conditions.
5. Modularity and composability requirements allow replacing, expanding and variations of components without changing the overall structure of the network. This is also important for compatibility and after-market use.

Properties that are often required for traction drive systems are high computation performance, compatibility, endurance to rough environmental conditions etc. Special purpose micro-controllers and standardized programming languages, e.g. C (ISO, ANSI standards) are mainly used for traction converter control and data communication. Hardware-based implementation of CAN 2 protocol allows a significant simplification of software and protocol stack design.

Profibus, Ethernet, CAN-bus, CANopen, Interbus are industrially spread automation and control networks. Advantages of CAN usage in electric vehicles [HAD00] can be stated as follows: mature standard, because the CAN protocol was introduced already in 1986. There are now numerous CAN products and tools available on the open market. Hardware implementation of the protocol makes it possible to combine the excellent error handling and fault confinement facilities with a high transmission speed. It has simple transmission medium, such as a twisted pair of wires. A CAN system can also work with just one wire with a common ground. The electrical isolation possibilities via optocouplers or fibre-optics and supply voltage with additional wire-pair are practical advantages. Besides advantages, it has some disadvantages. Disadvantages are that a precise time when a message will be received is not specified, worst-case transmission time and jitter are not known and the design of priority-based systems is complex. Message transmission is priority-based and error correction is hardware-based, thus it is static and cannot be changed during message transmission. Thus, messages with high priority should be used for critical functions.

Some companies have developed multifunctional communication systems. One such is on-board information and control system (Bordinformations- und Steuer-System) Kiepe BISS [8NGTW], which connects control units of vehicle subsystems with integrated diagnosis and fault indication. Second generation Kiepe BISS is based on internationally standardized CANopen protocol and allows data transfer between vehicles operating in trains consisting of up to 4 vehicles (Fig. 1.17).

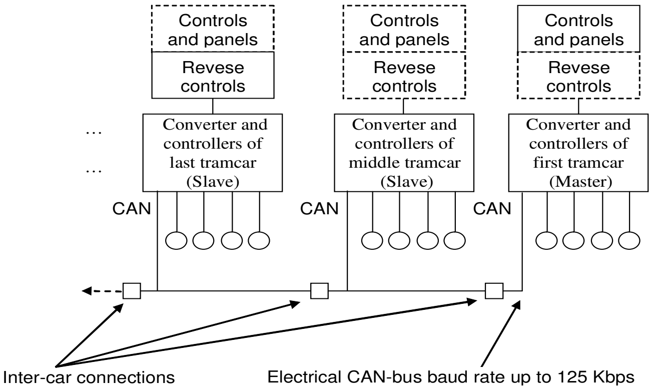


Fig. 1.17 Network for control of train-connected tramcars

The given structure is used for control of traction drive operation, including accordance of torques and speeds on different wheels or axles of different motorized cars. This also enables condition monitoring and error feedback from traction drive sub-modules to driver panel. The physical connection between traction drive sub-modules in different cars or wagons in tram tram-train or electric multiple unit depends on the type and construction of communication interfaces.

CAN-bus is usually based on twisted-pair or electrical wires, but the fibre-optic system or repeater-based and optocoupler separated electrical system is also possible. Electrically controlled braking systems can have multiple control wiring, including for relay-based control to assure redundant operation in fault conditions. Optocoupler separated connection can be used for inter-car connections with wire-jumpers or contact-buffer pins. Infrared (optocoupler), transformer separated connections or radio communication is usable. The galvanic separation modules can be supplied from existing supply voltages of the in-vehicle CAN-bus.

2. MODELLING

2.1. Overview

Modern computers allow the application of **simulation models** to study complex dynamic systems. Simulation models are functional, behavioural or structural abstraction of the simulated object. The purpose and functions of models are shown in fig. 2.1.

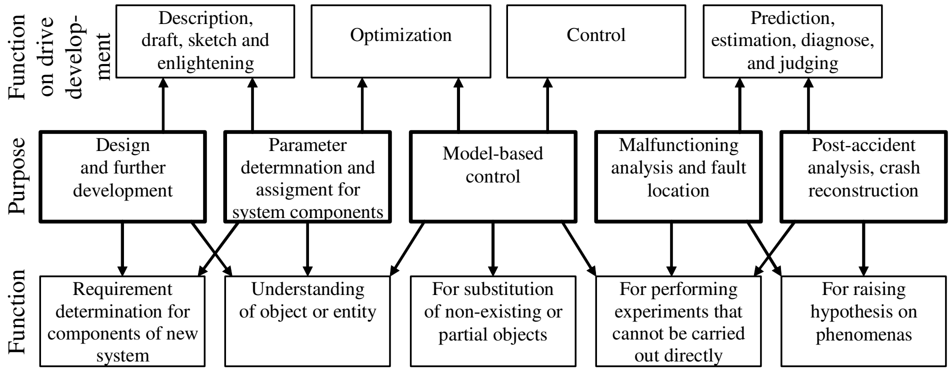


Fig. 2.1 Purpose and Functions of Models

Steady-state models are usable only for steady-state analysis, but analysis of dynamic processes requires **dynamic models**. Dynamic models can be divided according to their representation and implementation as follows:

1. formal (mathematical equations)
2. continuous simulation models that can be analogue electrical models (analog computers)
3. discrete simulation models that can be numerically implemented models, including software-based simulation models.

A **simulation model** should be simplified as much as possible because of energetic, technical and time restrictions. A model is always a simplification of reality for a certain purpose. Simulation models can be divided to behavioural models of an object (input and state functions) and structural models of objects (describing object structure and construction). A model describes phenomena or different aspects of an object selectively, thus some properties are not included knowingly or are included only partially. A model can be **fictitious** if the object with the given properties does not exist in reality. This is common practice for describing environmental conditions, like adhesion of the track. Such models can be regulated according to experimental results acquired in certain environmental conditions to achieve a realistic model applicable in the design process. The existence of empirically imperfect models is preferable from the user's point of view to a non-existing model.

Several dynamic models of rail vehicles can be found from literature [HIL96]. In addition to rail vehicles, several dynamic models of electric vehicles can be found in literature [HOR98]. General principles for modelling of electromechanical systems are described in the paper about the group control of DC motors [BOU03] and in another about the modelling of traction drive [WIP99]. Practical samples about the modelling of power-electronic converters using MatLAB SIMULINK [FLI97] and the complete model of a simplified rail vehicle [MAT95] can be found in literature.

Data flow structure diagram based software (such as MatLAB SIMULINK) is well suitable for dynamic models used in computer simulations. The **parameter evaluation** and determination is important in modelling. Measurement results and their evaluation results are used to determine the parameters. The exception is fictitious wheel-rail adhesion characteristics, that is based on the integration of data given in different sources and thus does not match exact road conditions.

Purposes for composing of models differ in research, design, control, and monitoring. The main purpose of the control object and load modelling is a virtual testing of control methods, thus simplification of the development process. A model was used to study of dynamic properties of drives, including speed-torque characteristics in dynamic operation modes and to check suitability of control methods. Models allow the verification of control methods and software in different operation modes, mode-altering conditions and different braking modes. This also allows tuning of current controllers and stability verification, including with non-linear feedback and integration circuits.

Models are used for tuning of control circuits of traction converter DC-link and evaluation of their properties in offline and emergency modes. Models were used for model-based control of magnetization of motors described in this thesis. Models are also applicable to tuning of antilock systems on different surface conditions (dry steel, grease steel, drench steel or steel with sand) and different angles and inclinations with different losses and reaction forces. Models allow the location of faults and accident analysis according to the information recorded (stored in) to the fault log. By dislodging the control object (hardware model) from the Simulink model remains a part that is usable as graphical development environment of control system software. By adding peripheral driver blocks with program code, a suitable model is formed for software design that can be converted to machine code according to the instruction set of the processor (*code generation and compilation*). Simulink diagrams can also be used to generate hardware design language (HDL) code used for programming of programmable logic chips (FPGA, CPLD, etc.).

2.2. *Modular Model Structure of Multi-Motor Vehicle*

Energetic macro models [VUL01] [SER02] of components are used for composing of dynamic models of traction drives. These are models described using transfer functions for both effects and reactions. System components in energetic macro models are grouped by physical content, thus energy sources, conversion elements, and storage elements are described using different symbols and blocks. As different from the described approach, the author of the thesis recommends grouping of these blocks according to system structure not physical content. Component grouping only on physical content reduces flexibility, because changes in the system structure lead to changes of the physical content and replacement of numerous symbols. MatLAB SIMULINK simulation model has a hierarchical structure and each block can be flexibly composed from configurable sub-blocks. The grouping of the block should take into account different configurations of drive hardware, such as different motor-wheel configurations, different compositions of supply converters, motors etc. This simplifies the comparison of properties (parameters) on different drive configurations. Inputs and outputs of model blocks should be comparable with the values measured from the real system. This allows checking of each block separately and its comparison with a real system component.

Electrical subsystems described using transfer functions have input with the instantaneous value of voltage and reaction is calculated as the instantaneous value of current. Mechanical subsystems can have input with linear or angular speed and reaction calculated as force or torque. These inputs and outputs can be exchanged. To describe an interaction a pair of two variables should be always used. One variable is an input and describes the effect and another is a result and feedback as a reaction. The instantaneous power can be calculated from this variable pair. Using all of important interactions (voltage and current, torque and angular speed and force and velocity), a transferred power can be calculated from component macro model inputs and outputs. For model verification and comparison with the real system, it should be divided into subsystems described using subsystem macro models. These subsystem macro models can be also divided to subsystem and component models. The model of the mechanical part and control circuits together form a model of a control object that includes models of load, electromagnetic part of motors, electrical part, electronic part of the converter, hardware of the control part and feedbacks. In addition, control principles (methods) are an important component needed for modelling. Most of modern systems are based on a microprocessor control system, thus a dynamic model should also contain descriptions of software based controllers, control algorithms, including torque controllers, speed controllers or reference integrators, ramp-functions, anti-slip systems (ABS, creep control), control of field weakening, control of operation mode, control of braking chopper and control input switches.

A model should be simple because of energetic, technical, time limitations and limitations of usable computer hardware, but should include important properties and parameters needed for the result - for control system design. In practice, many environmental and object properties are not taken into account because of the practical aim and availability of initial data or are included fictitiously if the real object is not yet available or destroyed. The composition of the following simulation model is based on the following simplifications and assumptions.

1. Protection systems are not modelled in stable operation modes. It is assumed that system operates in a stable mode and its structure does not change. Modelling of protection systems together with control algorithms is necessary if the same model is used for real-time control of a traction drive.
2. Initial values of state variables and changes of operation modes are referenced. A simple and stable operation mode, such as freewheeling or standstill, can be chosen for the initial point, thus wheel surface speed can be set equal to the vehicle speed. Stability of the simulation model at the initial point is assured via the choice of initial values of state variables.

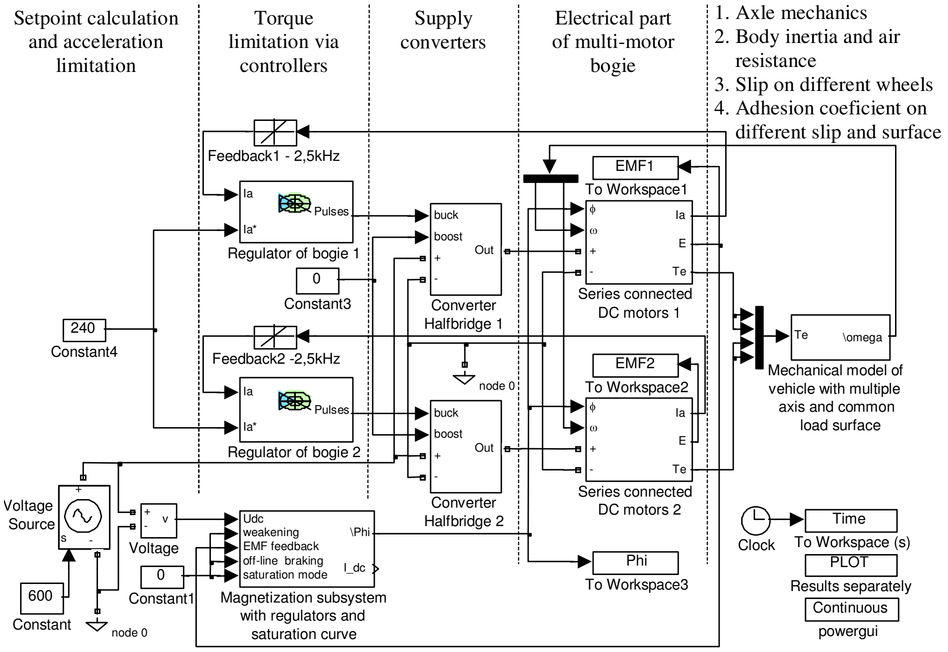


Fig. 2.2 Structure of the simulation model of multi-motor traction drive

The structure of the simulation model suitable for tuning and scrutiny of the control system is given in Fig. 2.2. This structure contains control reference blocks with controller blocks and other components needed for electric drive control. Reference signals and road conditions can be simplified or fictitious according to the aims. In addition to control blocks, this structure also contains component models of the control object, such as models of supply converters, models of electromagnetic part of traction motors, models of electromechanical part of vehicle bogie and the model of vehicle body dynamics. Changes of environmental conditions are included fictitiously, because it does not describe certain driving conditions but allows imitating very different conditions. Simplified function block of the motor and control system that has reference power as input [W] and real speed and real input power [W] as outputs takes into account torque limit, power limit and inertia, but does not include electrical parameters. One of such programs is the modelling program for autonomous hybrid electric vehicles ADVISOR [WIP99] that includes tire slip and adhesion model of road surface. The influence of surface slip of wheels on the operation of multiple traction motors has to be taken into account for multi-motor rail vehicles.

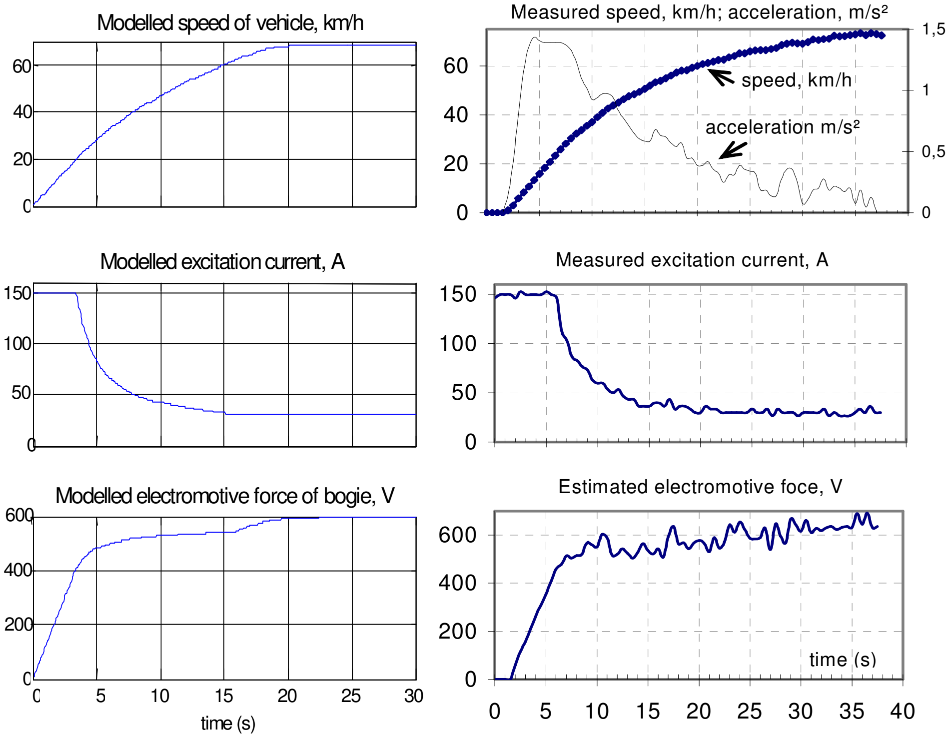


Fig. 2.3 Comparison of acceleration process calculated using the simulation model of multi-motor traction drive with measurement result on prototype tram

Comparison of simulated results calculated using the simplified model and experimental results measured on track are given in Fig. 2.3. In the experiments, the speed was measured from bogie axle, but the speed calculated via the model is the vehicle speed. Actual speed that is independent of the wheel slip can be measured using special contact-less measurement equipment [FAI02]. Torque oscillations are caused by the poor quality of armature current control. The inductance of armature branch is low, thus changes in armature current are instant. This leads to the use of fast current control and feedback circuits. Oscillating speed sensor causes oscillations of estimated electromotive force. Both analogue measurement amplifiers and digital pulse sensors were replaced for improving control properties in all the following prototype vehicles.

2.3. Dynamic Model of Mechanical Part

Control methods applicable for vehicle control are tightly bound with the construction of a vehicle and its cars, bogies and traction motor configuration. The dynamic model of the electromechanical part suitable for design, verification and tuning of the control system takes into account moments of inertia of bogie axles and inertia of the car body. Moments of inertia of all rotating component of bogie, such as wheels, brake drums or discs, gear wheels, rotors of motors etc., can be withdrawn to bogie axle.

Speed and torques on all the axles can be studied separately by dividing the **mechanical part** into separate parts and modelling separate axles of bogies. This property is important on creep, antilock and re-adhesion system modelling. The model of the mechanical part consists of four components that describe the following: inertia and gear, summing of traction and braking forces on all wheels, vehicle body that describes body inertia with resistance forces, and the environment model. Multi-axle and gear model includes wheel contacts for all wheels and inertia for all axles. The environment model describes track conditions, including inclination, resistance forces and adhesion function from the wheel slip. The amount of summed traction forces depends on the construction of the vehicle and bogies. This summing block can be replaced with the multiplication coefficient in simplified models where all wheels are driven with equal torque and have the same gear construction. This multiplication coefficient is taking into account the amount of wheels or axles. Integration of wheel contact and axle inertia to one dynamic block allows flexible specification of axial weights, initial speeds and other parameters. This also enables modelling of different adhesion coefficients on different axles.

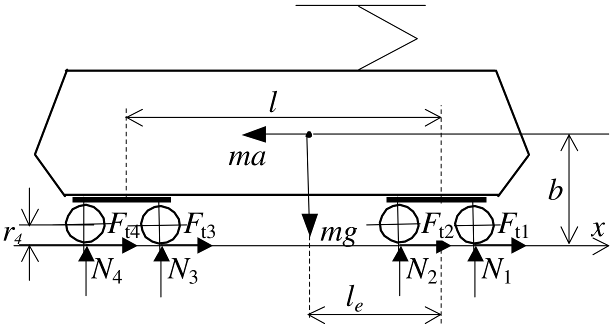


Fig. 2.4 Force directions in the dynamic model of a rail vehicle

Simplified dynamic equations of a vehicle can be used for the investigation of traction force distribution.

$$0 = F_{t1} + F_{t2} + F_{t3} + F_{t4} - ma - F_r \tag{2.1}$$

$$0 = N_1 + N_2 + N_3 + N_4 - mg \tag{2.2}$$

In the case of a simple rail vehicle with two bogies and four axles, the following equation of normal and traction forces can be used:

$$0 = b(F_{t1} + F_{t2} + F_{t3} + F_{t4}) + l_e(N_1 + N_2 + N_3 + N_4) - l(N_3 + N_4)\,, \tag{2.3}$$

where: $F_{t1}, F_{t2}, F_{t3}, F_{t4}$ – traction forces of bogie axles, l_e – mass centre distance from the first bogie, l – distance between bogies, b – mass centre height from rail surface, N_1, N_2, N_3, N_4 – normal forces of bogie axles, r_1, r_2, r_3, r_4 – average radius of axle wheels, a – acceleration in the direction of x-axis, g – acceleration of gravity, F_r – resistance force.

The drives of rail vehicles are more evenly loaded as compared to short vehicles (motor-cars) with high acceleration such as passenger cars because of lower acceleration, low mass centre and greater length. Traction forces on bogie axles are also not equal, because when bogie moves forward on acceleration, then the rear wheel pair has a larger total normal force than the front wheel pair. The simulation model of the mechanical part allows detailed investigation of torque distribution compared to the simplified equation, including on the wheel slip described previously. To achieve detailed results and to evaluate vehicle mass centre, the measurement of axial weight in dynamic modes is expedient. The reference ramp of speed or torque can be configured according to adhesion characteristics in the simulation model. This allows achieving stable traction forces on acceleration. The torque control block included in the simulation model of the mechanical part takes into account the effect of acceleration ramp and motor field weakening according to the back-electromotive force and supply voltage. Separate outputs of torque reference block are transferred using double precision floating point numbers and state variables of wheels as arrays of floating point numbers (indicated using bold lines in Fig. 2.5).

The following aspects are considered in the torque reference block of the simplified model: smooth acceleration of the vehicle, thus the acceleration and shove (S-shaped acceleration and braking ramp), limitation of the drive and control system, including nonlinearity of motor magnetization saturation characteristics and nonlinear characteristics of the boost converter in the braking mode. This leads to modelling of excitation control algorithms of traction motors. The reserve of a voltage is needed for stable control of torque on unequal distribution of speeds caused by unequal wheel diameters, axle weights and adhesion. A non-linear wheel surface adhesion characteristics is used in the load model.

The adhesion coefficient is positive in both acceleration and braking, but the change of wheel slip direction changes the sign of axle traction force F_d. Traction force sign is set according to the slip direction. Determination of initial conditions is complicated on simulation, thus starting from standstill is always an instable condition. The problem is increased because of the reduction of computation accuracy at smaller values, this leads to the same problems on braking simulation at the stopping point. To avoid such situations, the value of the traction force in the simulation model (Fig. 2.5) can be limited in several ways. The lower limit of the adhesion coefficient determines the minimal traction force; the upper limit determines the maximal traction force; and a ramp function (derivative limit) is used for limiting of traction force change.

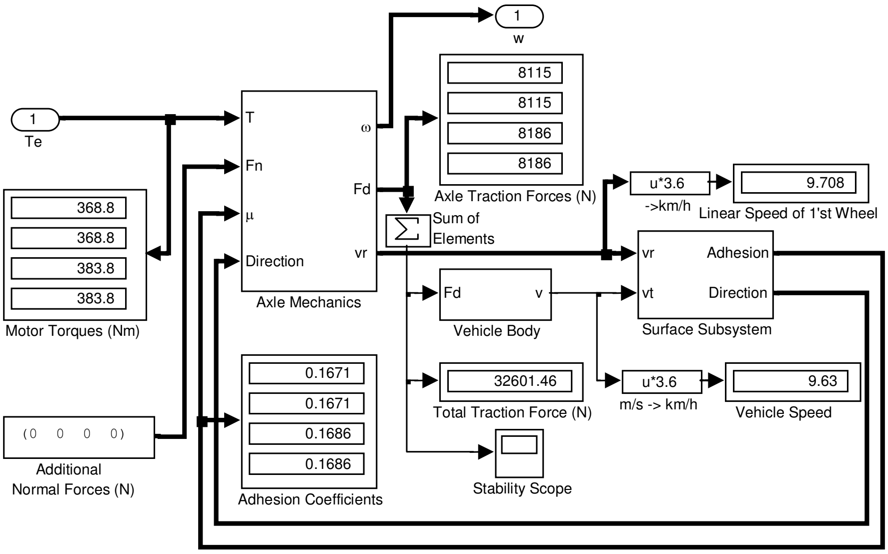


Fig. 2.5 Simulation model of multi-motor traction drive describing axial weights, friction (adhesion) coefficients and wheel diameters

Proper evaluation of initial conditions, such as values of excitation and armature currents of motors is important. The initial values for the adhesion coefficient and the traction force are complicated to determine, because the used adhesion function is not suitable for static adhesion modelling at standstill and the accuracy of the model is limited. This leads to additional workaround conditions that limit traction force change on the starting point and keep state variables of the model stable on standstill. Changes in the summed traction force and stability can be observed and checked graphically in real-time. Changes in the sum of traction forces do not allow one to analyze oscillations between different bogie axles, thus changes of separate traction forces have to be monitored.

Limitations of the model are following.

1. Adhesion-slip curve (friction curve) is the same for all wheels, but the adhesion of different bogie axles can be different.
2. Track inclination and rolling resistance values are equal for all bogie axles.
3. Air resistance is included as a function of speed, but disturbances, such as changes in wind, are not currently included.
4. Cardan shaft play effects and other plays in the drive and are not taken into account.

The previously described mechanical model can also be used in a simplified form (Fig. 2.6). Equations of the mechanical part of motors and voltage-electromotive force equations are placed in different blocks [SER02] according to the structure of energetic macro models.

This model, as different from other models, has an input value of current and feedback of electromotive force that enables simplified modelling of the current controller without modelling electrical processes in motor windings. The modelling of switching elements and motor armature voltages is needed to model electrical processes [FLI93]. These models of electrical circuits have voltages on motor windings as input values.

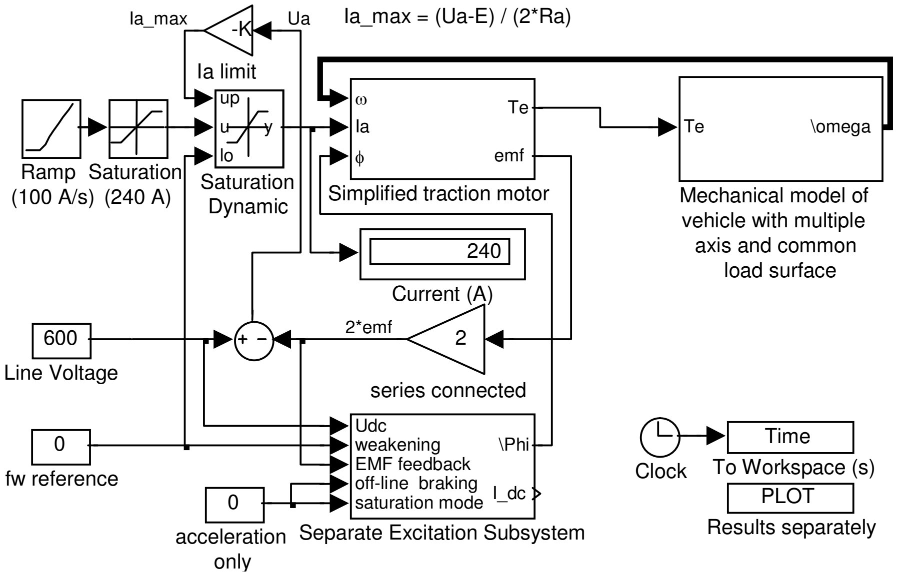


Fig. 2.6 Simplified simulation model using equal electrical reference torques

The simplified electromechanical model of an ideal motor shown in Fig. 2.6 does not describe electrical parameters of windings and supply network, controllers and converters are modelled as ideal. Thus, the exact shape of the current curve of traction motors should be set manually. The acceleration process calculated using the simplified simulation model is given in Fig. 2.7.

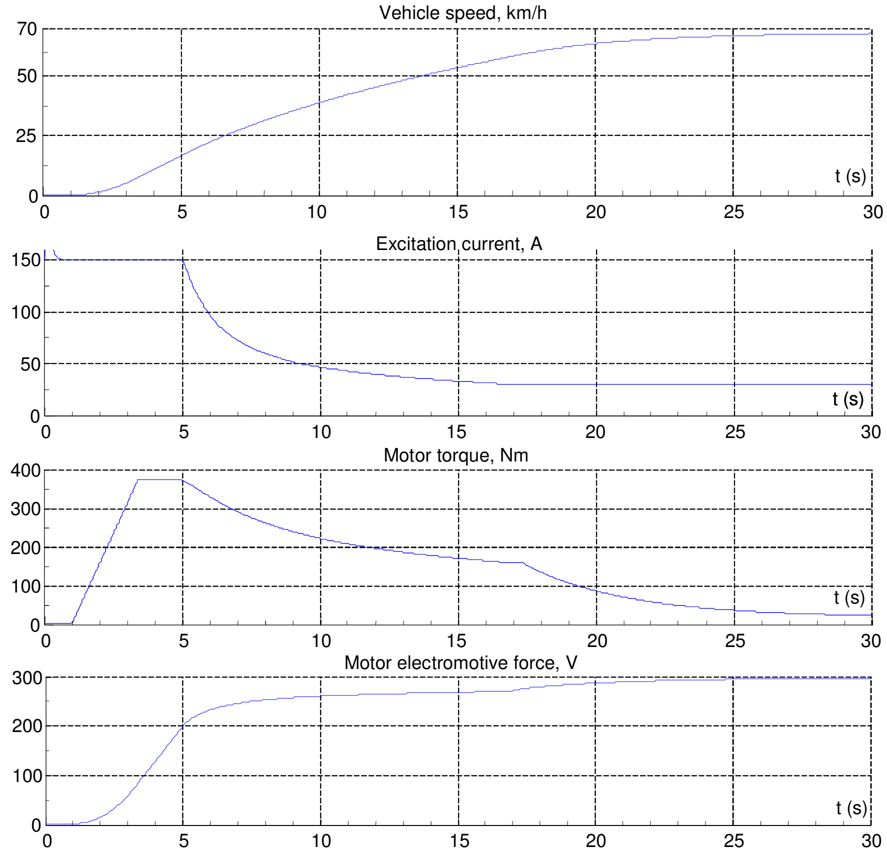


Fig. 2.7 Acceleration process calculated using the simplified simulation model

The simplified simulation model can be used if high-frequency electrical processes, wheel slip on different axles and torque control are not considered in detail. This simplified model includes the control of the field-weakening process and limits for electrical parameters, such as supply DC voltage and motor current.

2.3.1. Dynamic Model of Vehicle Body

Dynamic models where track adhesion and air resistance are integrated into one block [CHA01]. The author of the thesis proposes a structure where the calculation of adhesion coefficients is in a separate block. This allows calculating different adhesion coefficients for multiple wheels using the same block with a different wheel slip or on a different axial weight. The body of a rail vehicle moves with bogies, but speeds of bogie axles and wheel surfaces can be different from the vehicle speed because of the wheel slip on braking and acceleration.

The movement of the car body and bogies can be described via the movement of the mass centre using the differential equation:

$$M\frac{dv}{dt} = F_d - F_a - Mg \cdot \sin\theta, \tag{2.4}$$

where: F_a – air resistance force that depends on the measurements and the shape of the car body, F_d – total traction effort of all wheels, $Mg \cdot \sin\theta$ – gravitation effects that are zero on zero inclination (θ - inclination), M – mass of the vehicle body and bogies (without rotating masses).

Vehicle mass per bogie axle (axial weight) and inertia of axle are included in the dynamic model of the bogie axle and are not included into this model. The model can be improved by taking into account vehicle mass centre shift if needed. The dynamic model of the vehicle body does not include the static resistance force, because this has been included in the models of bogie axles and is not significant for the vehicle body model. The vehicle body model does not include track inclination θ as it models vehicle movement on zero inclination. Inclination can be added externally, because inclination has also impact on vehicle mass-centre shift that has to be included also in bogie axle models. The dynamic model of the vehicle bogie is shown in Fig. 2.8.

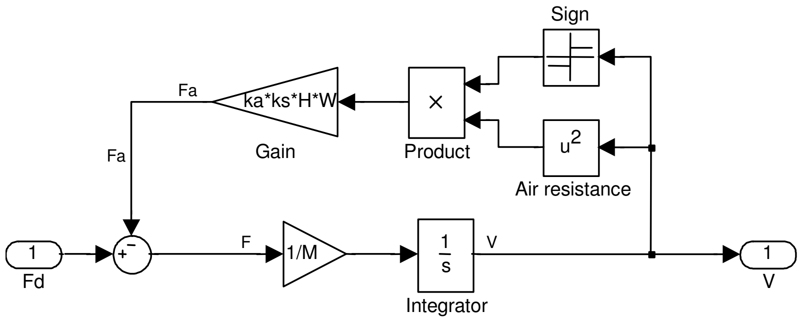


Fig. 2.8 Simulink block for including vehicle body inertia of and air resistance

Dynamic resistance force (air resistance) is modelled using the equation:

$$F_a = k_a \cdot S \cdot v^2, \tag{2.5}$$

where: v – speed of a vehicle m/s, k_a – coefficient of air resistance, S – air resistance surface, m^2.

$$S = k_s \cdot H \cdot W, \tag{2.6}$$

where: k_s – coefficient of air resistance surface for including resistance of equipment located on the vehicle and under the vehicle, such as current collector, converter, bogies etc., H – vehicle height, m, W – vehicle width, m.

Parameters of the vehicle body model are mass of the vehicle body (for inertia), measurements of the vehicle body, and shape coefficients for air resistance calculation.

2.3.2. Modelling of Wheel-Rail Adhesion

Road and track surface adhesion modelling is one of the most complicated problems on the modelling of vehicle dynamics. Adhesion is a measure of the resistance of friction to slippage between two parallel planes. Such physically different friction coefficients as static, kinetic, deformation, molecular and rolling friction can be distinguished. Adhesion that can be maintained depends on acceleration of the rail-wheel with respect to the steel rail. Adhesion coefficient and its factors are described in literature [SEN93] [LOG80]. The current problem is the application of the theoretical principles for the modelling of light-rail transport.

The non-linear function of the adhesion coefficient depends on several factors and is different in different conditions. Relative motion between the wheel and the rail can be described using the slip or adhesion coefficient. The slip varies on stable operation between 0 and 2%. The effect of track inequality depends on the absolute value of the vehicle speed. Track inequalities are reducing the normal force, thus adhesion coefficient μ decreases with the increase of the vehicle speed.

Contaminants and dirt have a significant influence on the adhesion coefficient. Very high tension and forces at the contact point of the wheel and rail allow high values of friction coefficients, but even the molecular amount of the contaminants reduces it significantly. Rails and wheels have a different effect, like surface roughness and contaminants like water, oil, sand etc. These effects are very random and cannot be accurately modelled in practice, but each system should be capable of working in difficult environmental conditions.

Wheel-rail adhesion of the rail vehicle has been modelled with the software package MatLAB Simulink [SEN93]. Three regions and their transitions can be distinguished. These regions are rolling surface contact (on wheels of trailer cars) that does not transfer a longitudinal force, creep region that allows changing of longitudinal force without significant changes in the slip and region of wheel spin or slip. The increase of the longitudinal force in the wheel-spin or slip region causes a dashed increase of the wheel slip due to the decrease of the friction coefficient.

Rail-wheel adhesion functions of wheel-slip on different surfaces

Empirical curves of adhesion coefficient shown in Fig. 2.9 describe very limited conditions, like temperature surface properties and contaminants [HAR02] found in literature [LOG80]. Because of these limitations, a more flexible adhesion model [HIL97] containing the fuzzy-logic model has been provided in literature. The start region up to the maximal available adhesion coefficient is named *pseudo-creep region*. The slip does not change significantly when increasing the traction force in this region.

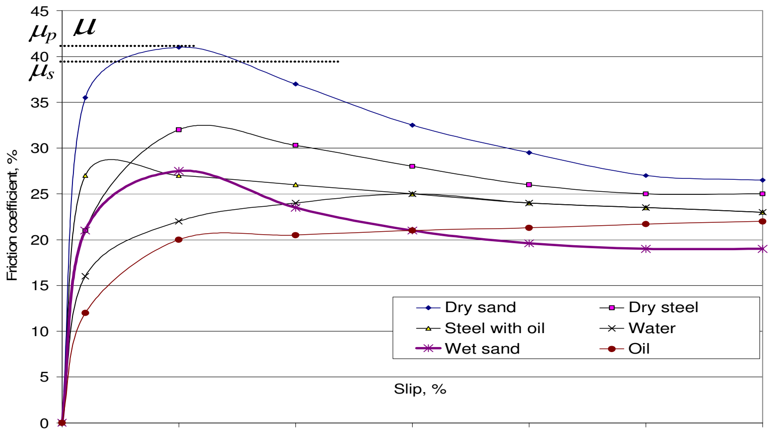


Fig. 2.9 Wheel slip-adhesion curves used in Simulink models

The maximal available traction and braking force depends on the peak friction coefficient μ_p. The force, slip and adhesion coefficient can be increased up to this peak value of adhesion coefficient μ_p in the elastic-slip or micro-slip region. The range of the slip over the peak-friction coefficient point μ_p is called a combined-slip or a macro-slip region. The slip increases fast with wheel lock and the reduction of traction or braking force. There is a transition region between the peak friction and the slide friction coefficient μ_s that is called the region of dynamic instability. This is the main operation range of antilock systems [DAY02].

Dependence of adhesion from vehicle shape and speed

The decrease of adhesion on the vehicle speed increase is a random process, but a statistic trend can be determined in certain conditions [SEN93]. According to literature [HIL96], the correction function can be added for the correction of adhesion model depending on the vehicle speed. The speed and effects of speed are relatively low for trams, thus it can be neglected for simplified modelling. Empirical equations are used to describe the adhesion that can be applied only certain track conditions and is not applicable for all driving conditions.

Slip and adhesion simulation

The simulation model of the adhesion consists of the wheel-slip calculation block, non-linear function block of the friction coefficient and logic blocks of initial conditions. Absolute slip is a normalized difference of speeds on the wheel surface and the contact point:

$$\lambda = \left| \frac{v_r - v_t}{\max\{v_r, v_t\}} \right|, \tag{2.7}$$

where: v_r – liner speed of wheel traction surface, v_t – speed of the wheel and rail contact point (speed of vehicle). The slip and adhesion calculation block applicable in the simulation model is shown in Fig. 2.10.

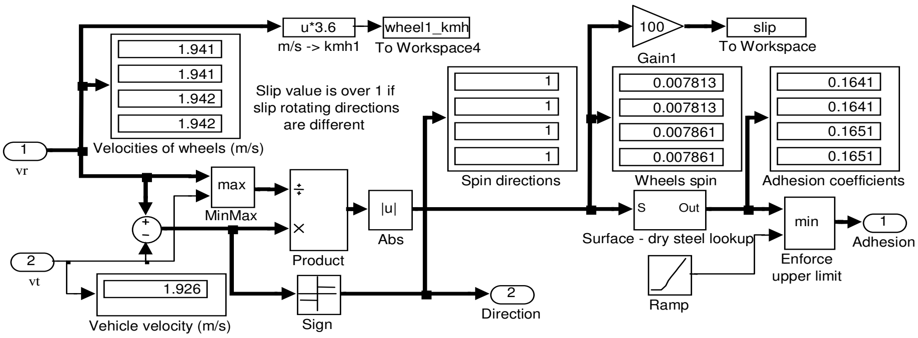


Fig. 2.10 Slip calculation and adhesion reference block

The ramp function in Fig. 2.10 is used for changing the friction coefficient from zero to the actual value at model start-up. All linear speeds of wheel surfaces and the vehicle speed, wheel slips and adhesion coefficients can be monitored during simulation.

Describing rail-wheel adhesion functions of wheel-slip

Adhesion coefficient μ as a function of absolute slip λ can be described using different equations, including equations similar to the torque characteristics of the induction machine (Kloss formula), where power *k* has been included by the author of the thesis to achieve a better description of the curve shape:

$$\mu = \frac{2 \cdot \mu_p}{\left(\frac{\lambda_v}{\lambda}\right)^k + \left(\frac{\lambda}{\lambda_v}\right)^k} \tag{2.8}$$

Another formula is known from literature [SEN93] that does not model adhesion on micro-slip region, thus is only applicable on high slip values.

$$\mu = \mu_p \cdot \left(\frac{1 - 1.8 \cdot \lambda}{1 + 2.26 \cdot \lambda}\right), \tag{2.9}$$

where: μ_p - peak adhesion coefficient λ_v - slip at peak adhesion and *k* - power for better describing of curve shape. This equation can be used to check the operation of the control system, but is not suitable for study or optimization of the real slip. Different calculation blocks for track adhesion modelling are shown in Fig. 2.11.

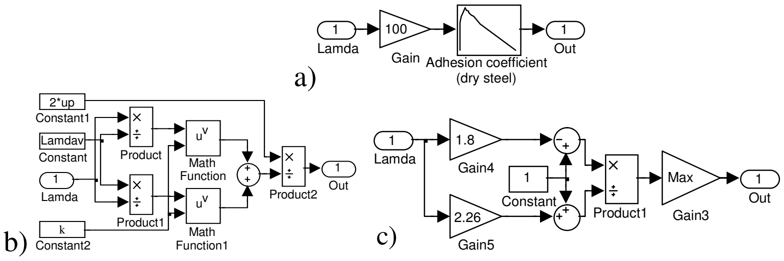


Fig. 2.11 Simulation models for describing the wheel-rail contact function

Adhesion functions of slip (from Fig. 2.9) described using the tables are shown in Fig. 2.11.a, a function 2.8 shown in Fig. 2.11.b, and a function 2.9 shown in Fig. 2.11.c.

Limitations for adhesion changes in the simulation model

Model instability is a problem on system tuning at low values of speed and the friction coefficient. The essence of the problem is related to calculation tolerance of the simulation model. The author of the thesis recommends the use of ideal low-pass filter blocks (derivative limits), such as *rate limiter* for the friction coefficient at low speeds. This limit is meant to avoid huge instantaneous changes in the friction coefficient. On realistic changes in the adhesion, this filter has no effect. For example, rate limit 10 Hz corresponds to the limit $10\,\mathrm{Hz} \cdot 4950\,\mathrm{kg} \cdot 9.81\,\mathrm{m/s^2} = 485595\,\mathrm{N/s} = 486\,\mathrm{kN/s}$ of the traction force, which has no effect in normal conditions. The upper and lower limit of integration time-step should be also properly evaluated to avoid of convergence problems.

2.3.3. Dynamic models of axles, wheels and gears

A mechanical gear with wheels is an energy accumulative element. Vehicle axles are modelled as rotating mass and its dynamic model consists of load torque T_d, moment of inertia J and losses described via reaction force F_r. Rotation is described using the differential equation:

$$J\frac{d\omega}{dt} = T_m - T_d - T_{loss}\,, \tag{2.10}$$

where: J – moment of inertia, T_m – motor torque, T_d – reaction torque and T_{loss} – additional torque loss. Losses can be included in different ways. Separate dynamic losses (related to rotation) can be added as a function of angular velocity:

$$T_{loss} = f(\omega). \tag{2.11}$$

If losses of the mechanical model are related to the linear movement, such as friction of wheels caused by track bends, then it can be added to the linear resistance force.

$$T_d = (F_d + F_r)\cdot k_{bogie}\,, \tag{2.12}$$

where T_d includes torque caused by both traction force F_d and linear resistance forces F_r. Both linear resistance force F_r on the wheel surface and resistance torque T_d on the motor shaft can consist of static and dynamic components. The axles and the motor shaft with brakes are rotating at different speeds and wheels have different diameters, thus the transfer coefficient should be used between the wheel surface and motor shaft.

The transfer ratio of a bogie according to Fig 2.12 is:

$$k_{bogie} = \frac{r}{n}, \tag{2.13}$$

where n is a gear ratio and r is a wheel radius. Transfer from motor shaft to wheels is

$$\begin{cases} v_r = k_{bogie} \cdot \omega \\ T_d = k_{bogie} \cdot F_{contact} \end{cases}, \tag{2.14}$$

where: v_r - linear velocity of wheel traction surface. Wheel-rail contact force is calculated by

$$F_{contact} = F_d + F_r = \mu \cdot N + F_r \,. \tag{2.15}$$

The parameters that can be set to the axle and gear models are: N - axial weight (kg), J moment of inertia (kgm²), r - wheel radius (m), and n - gear ratio.

The equation

$$\omega = \int \frac{T_m - T_{loss} - k_{bogie} \cdot (\mu \cdot N + F_r)}{J} dt \tag{2.16}$$

shows that the reduction of load (on adhesion/friction decrease) will cause the increase of speed. The structure of the mechanical model of wheels and gears is shown in Fig. 2.12.

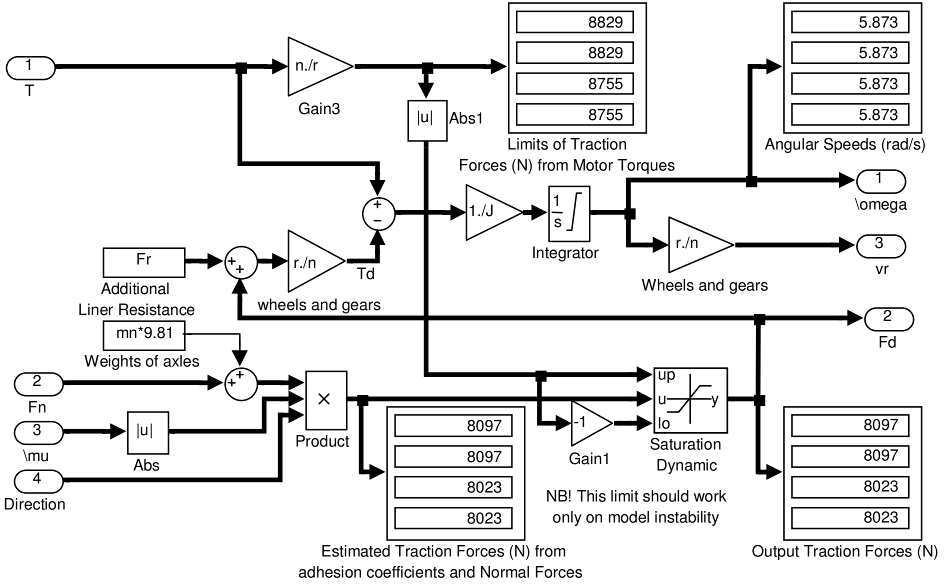


Fig. 2.12 Dynamic models of axles, wheels, gears, brakes and motor mechanics

The inputs of this block are values of electrical torques T (Nm), adhesion coefficients μ (input 3, "*mu*"). Resistance force F_r (N) allows taking into account track-bend resistance, inclination and other disturbance forces that have its effect directly on the bogie axle.

Outputs of this block are values of traction force F_d and speeds. The linear velocity of traction surface v_r is for slip calculations and the angular speed of motor shaft ω is for feeding back the load reaction to the electromechanical model block. The limiting of the output of the axial traction force according to the motor torque does not avoid the self-braking effect, but keeps the model stable in the case of incorrect parameters or initial conditions.

The traction force is proportional to the variable normal force in dynamic conditions with the variable slip and axle weight.

$$F_d = \mu \cdot N , \tag{2.17}$$

where: μ – adhesion coefficient, N– wheel-rail contact force.

The normal force on the bogie axle changes on acceleration and braking together with the movement of vehicle mass-centre [JOL01E]. Complex models can be applied for the research of dynamic load distribution [ZHA97] on the availability of sufficient computation performance and exact data about shock absorbers (dampers), springs and mass distribution. The developed model in Fig. 2.12 requires setting values of initial linear speeds (m/s) of wheel surfaces on all axles.

2.4. Dynamic Model of Electromechanical Part

The model of the electromechanical part consists of the models of one or more traction motors and their electrical connections. The model consists of models of motor windings and is connected with the electromagnetical model of motors, the mechanical model and the supply source model. The supply source model should contain model of converter.

Series connection, parallel connection or their combination series-parallel connection is used for the connection of multiple DC motors. Equal electrical torques in a simplified model of the mechanical part correspond to series connection of DC motors, e.g. to a situation where both armature windings and excitation windings are connected in series.

2.4.1. Configurations of motor windings and load distribution

Multi-motor traction drives, where separate traction motors are driving separate axles or separate wheels or separate bogies, are widely used on trams and electric multiple units (trains). Load torques and powers of different machines are equable on balanced condition. Electromechanical conversion with an unbalanced distribution of a load leads to different values of torques T_m and motor angular speeds ω .

Series or parallel connection is often used in drives with DC motors. On railway vehicles like trains where operation is altered rarely, the reconfiguration from series to parallel and vice versa is used for speed control. More flexible and smooth control of torque is required for LRVs for city traffic. The series connection of motors is a widely used method in traction drives with multiple DC motors for better load distribution if motors are located on the same bogie. Excitation and armature windings are both connected separately in pair wise series that allows magnetization control. The equation for two DC motors with armature and excitation windings connected separately in series is:

$$\left(L_{a1}+L_{a2}\right)\frac{di_a}{dt}=u_{chop}-e_{\Sigma}+\left(R_{a1}+R_{a2}\right)\cdot i_a\,, \tag{2.18}$$

where i_a – armature current that is equal for both motors, u_{chop} – instantaneous value of converter output voltage, L_{a1} and L_{a2} – inductances of armature windings and interpoles, R_{a1} and R_{a2} – resistances of armature windings and interpoles, and e_{Σ} – sum of back-electromotive forces. Armature currents are equal and back electromotive forces are summed according to a series connection

$$\begin{cases} i_a=i_{a1}=i_{a2}=T_e/k\Phi \\ e_{\Sigma}=e_{a1}+e_{a2}=k\Phi\cdot\left(\omega_{t1}+\omega_{t2}\right) \end{cases}, \tag{2.19}$$

where T_e – electrical torque without mechanical losses, ω_{t1} and ω_{t2} – angular speeds of motor shafts, k – machine constant, and Φ - excitation flux. Excitation and machine constants can be considered as equal if excitation windings are connected in series, characteristics of motors are equal and armature reaction is not included because of equal currents.

Thus, on modelling of separately magnetized traction motors their armature windings and main excitation poles can be described with separate blocks. These motor circuits are bound via magnetic circuit and electrical circuits of windings. Thus, connections are described via variables of magnetic flux, armature current and the sum of electromotive forces.

Two different model variants of electromechanical part are shown in Fig. 2.13. The first allows detailed investigation of electrical processes with a switch-mode converters and another is a behavioural model for checking of motor control properties. The simulation model shown in Fig. 2.13, a. allows calculating of series connections of two or more motors. The transfer functions should not be used for modelling of windings because setting of current initial values is complicated. This simulation model enables a detailed investigation of the processes caused by a series connection of DC motor windings.

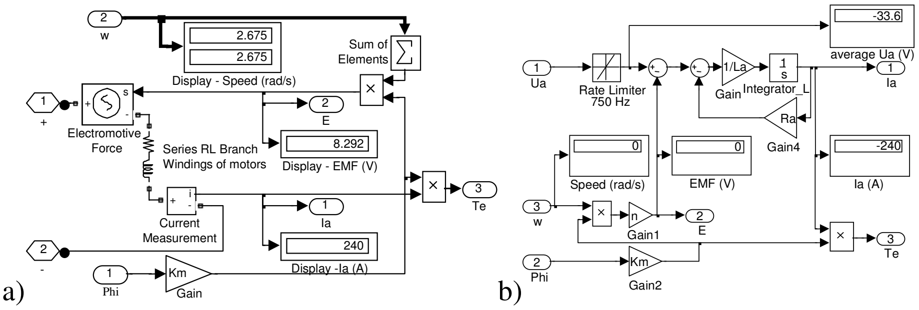


Fig. 2.13 Simulators of armature circuits of electrically series connected DC traction motors

The output variable T_e (electrical torque) of both simulation models does not include mechanical torque losses, which should be included in the mechanical model block. The limit of the derivative (*rate limiter*) shown in Fig. 2.13, b. is needed for filtering of high frequency pulses and corresponds to the effect of motor winding capacitance.

Electrical parameters of traction motors and electrical output torques T_e depend on the mechanical parameters, such as load torque T_m and speed ω. The speeds of bogie axles can be different because of different adhesion of wheels.

The inductances and resistances can be summed for simplified modelling of series connection with multiple motors. The following parameters are used in both models in Fig. 2.13: L_a – total summed inductance of series connected windings, R_a – total summed resistance of series connected windings, K_m – machine constant. If multiple values are set to parameters K_m, inputs U_a or feedbacks ω as array, then block output is also an array with multiple electrical output torques T_e.

2.4.2. Advantages of separate control of traction motors

Separate control of traction motors has separate control of motor voltages and current via control system. This enables flexible control or equalizing of both output torques and speeds. The currents and voltages of different bogies using only torque limit are shown in Fig. 2.14. Torque control without speed equalization leads to the wheel spin or slip.

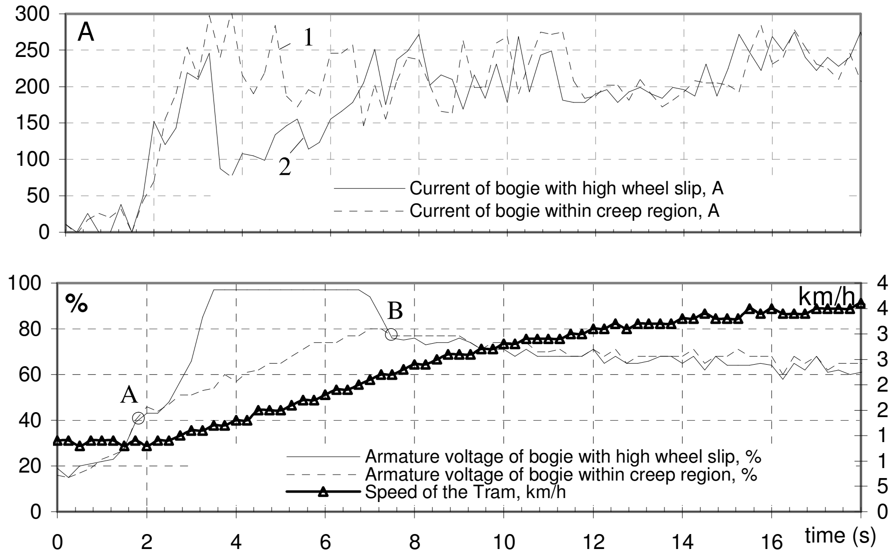


Fig. 2.14 Electrical effects of wheel slip in drive without traction control

Output voltages and current (see 1 and 2 in Fig. 2.14) of converters are shown between points *A* and *B*. Current controller is trying to keep constant current (constant torque) during the wheel slip. Thus, output voltage is increased up to the maximal value. Oscillations between bogies can be seen after re-adhesion.

A control system should also limit speeds in addition to torque control to avoid situations shown in the figure. Speed on different bogies is limited using the voltage control of separately controllable converters. A separately magnetized drive allows using of voltage limit for speed limiting. The tram traction drive developed by the author of the thesis uses speed control via voltage limiting together with current limit via the current controller. Current is not limited when its instantaneous value is lower than reference value, which is estimated maximum according to other bogies. Voltage reference integrator is integrating up only limited conditions when some of the currents are not limited via the current controller.

The advantage of separate converters is lower power and output current of converters compared to the supply of all motors from a single converter. The system developed by the author uses separate control of bogies that is also a more flexible configuration for antilock and creep control.

2.5. Dynamic Model of Electromagnetic Part

Calculation of back-electromotive force requires information about motor magnetization curves. Excitation windings of two DC traction motors are usually connected in series, but also more motors or windings can be connected in series. Only properties of main poles are included in simplified models. Complex models include also properties of interpoles and the effect of armature reaction. The latter can be neglected in steady-state conditions and if magnetization windings are supplied from a separate converter with a PI controller. Thus, there are no static errors in the excitation current as the PI controller compensates all disturbances.

2.5.1. Modelling of magnetic saturation of DC motor poles

Models of magnetization and excitation are needed for real-time control of the drive system and for the simulation of a separately magnetized drive. The model uses a total sum of resistances R_f and inductances L_f because of a series connection of excitation field windings. The structure of a simplified saturation model for magnetization poles is shown in Fig. 2.15.

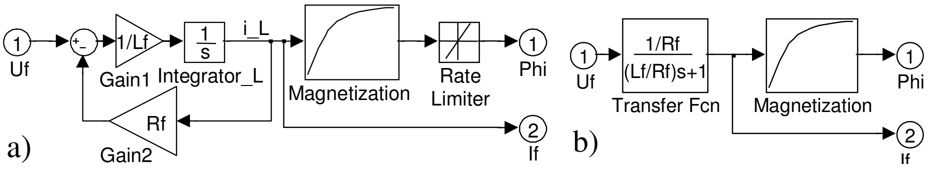


Fig. 2.15 Simplified Simulink models of excitation field windings

Simulation models in the figure take into account saturation of excitation poles according to the magnetization curves measures in real motor conditions. Functions are entered in the tabular form and linear approximation is used for output calculations. The structure shown in Fig. 2.15.a enables setting of initial conditions when 2.15.b can only be used if initial values are zero.

The control system uses the polynomial curve function (2.20) instead of linear approximation from the table.

$$\Phi' = A_3\left|i_f\right|^3 + A_2 i_f^{\ 2} + A_1\left|i_f\right|, \tag{2.20}$$

where: Φ' – relative magnetic flux, A_1, A_2, A_3 – polynomial coefficients that describe the shape of the magnetization curve, and I_f – excitation current.

This simplified model of excitation poles does not take into account the effect of interpoles or armature reaction. More complicated two-dimensional saturation models are recommended in literature [ZHA98] for more accurate describing of

DC traction motors. The simplified model is usable if auxiliary poles are compensating effects of armature reaction.

Use of the simplified model on drive control is reasonable because of faster response of control when the accuracy is also sufficient for control. This is also applicable for modelling of multiple series-connected motor windings in a simplified consideration that a magnetic flux depends only on the excitation current.

2.5.2. Modelling of Motor Pole Interaction

A traditional DC traction motor has windings of main poles and interpoles in stator slots and armature winding in rotor slots. Both pole windings and also the armature winding have effect on the magnetic field of the poles. Two-dimensional saturation models described in literature [ZHA96] [ZHA98] enable modelling of both pole windings together with the armature reaction.

The application of these models requires detailed data about the effects of both windings on the magnetic field. Thus, composing of such two-dimensional function (surface) requires very bulky experimental measurements. The function of the Simulink model given in literature [ZHA98] has two tables that contains magnetization curve of main-poles and interpoles. The simulation software enables the use of linear approximation form functions, represented using the tables. In addition to saturation modelling, these models also include armature reaction effects. Leakage inductances and changes in armature inductance on the saturation of the main poles or interpoles are taken into account in detailed models of magnetization. The model described in literature [ZHA98] is shown in Fig. 2.16 include the main pole and interpole saturation effects on the output torque and electromotive force.

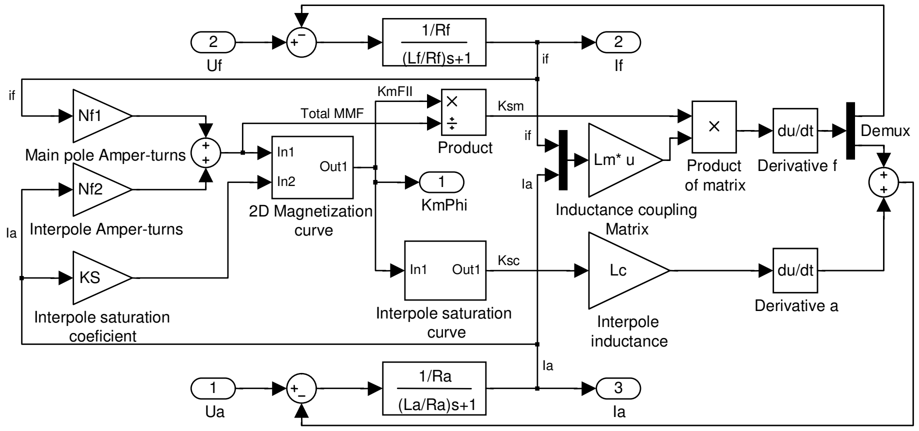


Fig. 2.16 Detail magnetization model with main pole and interpole saturation

Electrical torque is calculated using two output variables $K_m\Phi$ and armature current i_a. In the calculation of those two variables, mutual inductance of the main pole and interpole windings has been taken into account.

$$T_e = K_m\Phi \cdot i_a . \tag{2.21}$$

The model in Fig. 2.16 uses the following symbols: K_{sm} – main pole saturation coefficient, K_{sc} – interpole saturation coefficient, N_{f1}, N_{f2} – amper turns on the main poles and interpoles, L_m – inductive coupling matrix, L_c – inductance coefficient of interpoles.

The following simplifications have been made in modelling. The effect of the interpole field to the main pole saturation is not taken into account. Neither are armature reaction effects on the field separately taken into account but should be considered in the two-dimensional function. This model of traction motor magnetization is applicable in computer simulation, but it is too complex and thus too slow for real-time control.

There are also several practical problems related to the application of this model. Inductances, including leakage coefficients of the interpoles and the two-dimensional saturation curve should be measured. The advantage of this model is detailed behavioural modelling of electromotive forces caused by armature reaction and interpoles. Detailed description of armature reaction modelling for simulations is provided in literature [LOB99].

Sufficient accuracy on constant excitation current I_f (separately magnetized drives) is achieved using only the simplified single-dimensional model. This single dimensional model can be achieved by setting K_{SC} to zero.

2.6. Models of Supply System and Converters

2.6.1. Simulation Models of Power Semiconductor Switches

Traction converters can be divided into separate blocks for flexible modelling. Models of semiconductor switches are included into one block and filters of DC link, the braking resistor and overvoltage protection devices into another block. The Simulink model of power semiconductor inverter half-bridge switches with freewheeling diodes is described in literature [HIL96]. The electrical equivalent circuit of this push-pull AC switch is similar to the switch of the buck-boost DC converter, but its behaviour is different. Models of half-bridge semiconductor switches are shown in Fig. 2.17.

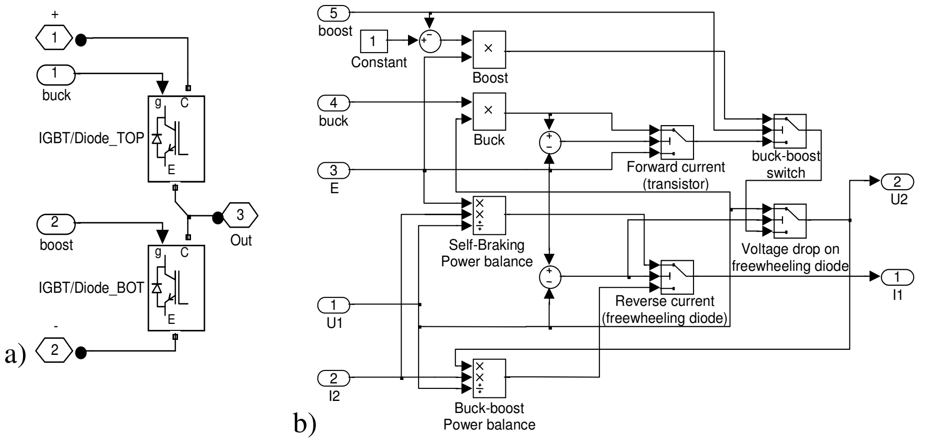


Fig. 2.17 Simulation models of half-bridge switches of buck-boost converter circuit in SimPowerSystems and Simulink

The SimPowerSystems equivalent circuit of transistor half-bridge is shown in Fig. 2.17,a and the behavioural model of an ideal buck-boost switch for bi-directional direct-current conversion using power balance is shown in Fig. 2.17,b.

Simple switch-mode converters can be modelled as continuous without taking high-frequency processes into account. Modelling of high-frequency processes is important to the extent that it has an effect on current control and dynamic properties of drive, including values of speed and torque. One important object in traction drive that requires high frequency modelling is a boost-converter with a binary controller because of its non-linear characteristics. The output voltage of a boost converter in simplified models can be calculated using the equation [MOH95]

$$\frac{U_{dc}}{e_{\Sigma}} = \frac{1}{\frac{R_a}{R(1-D)} + 1 - D}, \tag{2.22}$$

where: D – duty cycle, U_{dc} – output DC-link voltage, e_{Σ} – input voltage or back electromotive force of the bogie, R_a – resistance of armature windings, interpoles and wires of traction motors, R – output load (resistance of braking resistor with the supply of excitation on electrodynamic braking).

Voltage gain of this converter decreases on the increase of motor circuit resistance R_a or switching period. A characteristic of the boost converter with a DC motor bogie is shown in Fig. 2.18.

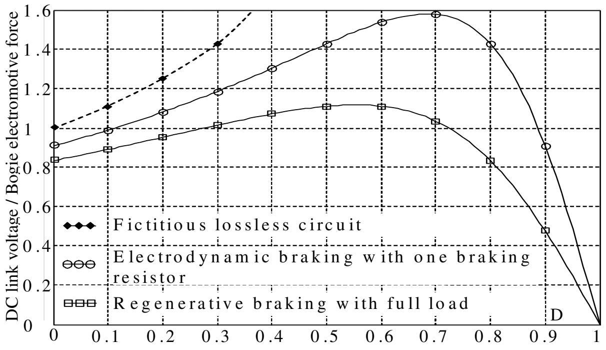


Fig. 2.18 Output voltage characteristics of a boost converter and a DC motor

Boost converters are used to increase the DC-link voltage level to the contact-line voltage level to allow regeneration of braking energy. These converters are also used in autonomous hybrid vehicles [MCK05]. The series connection of large amount of low voltage sources, like batteries [MUN05], fuel cells [MAR05] or ultracapacitors is not usable because of lack of room. Thus, boost converters have to be used for higher voltages. One such application of the boost converter is a hybrid electric vehicle Toyota Prius [MUN05], where the boost converter raises voltage to a level of 500 V DC from the battery with 168 elements with total voltage only 202 V. In addition, discontinuous current operation has its effect on voltage. The output DC link current has to be controlled for keeping the traction converter in stable operation and avoiding discontinuous operation. Thus, the DC link voltage should be reduced according to the electromotive force decrease on traction motors. The braking process of the traction drive in different operation modes, including freewheeling, regenerative braking, end of regeneration, switching input contractor, electrodynamic braking with a braking resistor, and stopping is shown in Fig. 2.19.

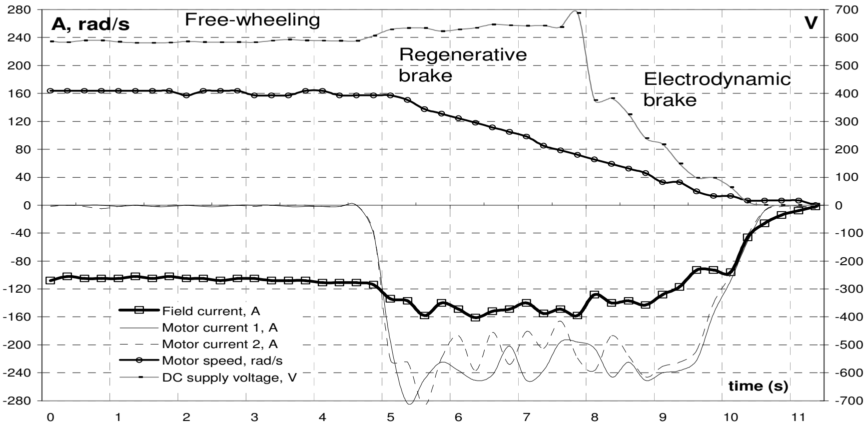


Fig. 2.19 Experimentally measured braking process of multi-motor drive

Currents of traction motors, voltage of DC-link and vehicle speed is shown in Fig. 2.19. Oscillations in motor currents are caused by the variable DC-link voltage and slow control. The increase of DC voltage on regenerative braking and voltage decrease on electrodynamic braking together with deceleration are also shown in the figure. Boost converters are increasing DC-link voltage and thus contact-line voltage on regenerative braking. The electromotive force reduces on deceleration and thus gain of the boost converter should be increased. The converter will be switched to the off-line electrodynamic braking mode when regeneration to line voltage level is not possible.

2.6.2. Simulation models of DC-link and supply circuits

Connecting of traction drive to DC contact network requires several components, such as an input switch (line contactor), input filter (including input choke), radio-frequency interference filter and charging circuits for capacitor banks. These components form an input circuit that is controlling and filtering current and voltage. DC-link that consists of the converter capacitor bank is required for modern voltage-source traction converters. This consists of a capacitor bank, discharging resistors, voltage limiting devices, a voltage sensor and braking circuit with braking chopper transistor. Mainly metal-oxide varistors are used for limiting of overvoltages. The developed model of DC-link is independent of the electric drive type and is applicable for the simulation of different traction drives including inverter controlled AC drives and series-magnetized DC drives. Braking resistor is used for limiting of the DC link voltage. In addition, reversing-contactor can be used for the altering of voltage polarity on excitation windings of DC motors.

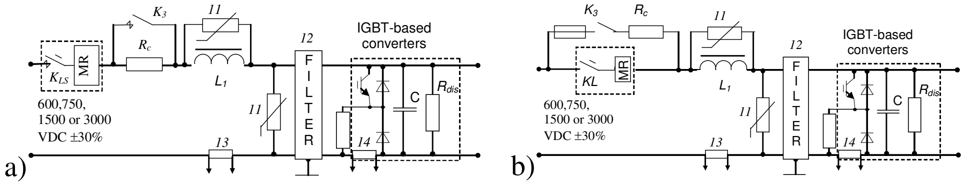


Fig. 2.20 Different input circuit configurations on tram traction drives

The input circuits shown in Fig. 2.20 (a - Tallinn, Riga, b - Tallinn, Cottbus) consist of converter capacitor bank *C* with voltage balancing and discharging resistors with total resistance R_{dis} and input choke L_1. DC-link is connected to the supply line via input switches K_{LS}, K_3, charging resistor R_c and the current collector of the vehicle. SimPowerSystems model is shown in Fig. 2.21 and Simulink model in Fig. 2.22.

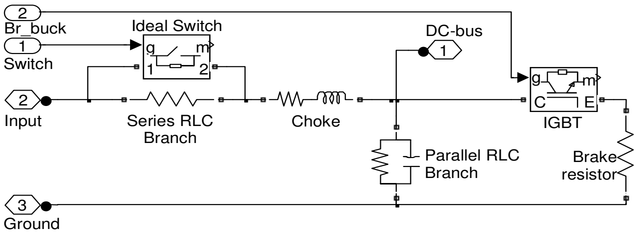


Fig. 2.21. SimPowerSystems model of converter DC-link with input switch, braking chopper and resistor circuits

The model shown in Fig. 2.22 is applicable for simulation of both power circuits described in Fig. 2.20. Model structure corresponds to the electrical circuit diagram shown in Fig. 2.20, but a braking resistor and a braking chopper transistor have been added.

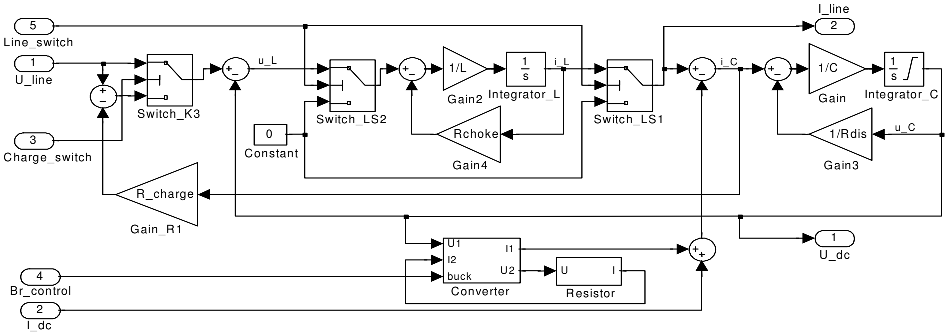


Fig. 2.22 Behavioural Simulink model of converter DC-link with input switch, braking chopper and resistor circuits

The model shown in Fig. 2.22 uses the following parameters: resistance of input circuit R_{choke}, inductance of input choke L, capacitance of converter DC-link C, total discharge resistance of converter DC link R_{dis} that includes all discharge resistors, charging resistor R_{charge}, and braking resistor R_{brake}. Input voltage is connected to the input U_{line}, load pulses of the converter are connected via input I_{dc}, pulses of control of the braking chopper is connected to input $Br_{control}$ and the control signal of the input switch is connected to input *Line_switch.* Initial voltage of converter DC link and initial current in the input choke can be set as an initial condition for simulation.

Discontinuities that can cause calculation problems on simulation can occur because of included logic conditions (switches). For smoothing this problem, several techniques can found in literature, one such method is the *dynamic node technique* [FLI93] that takes into account parasitic resistances and wire capacitances of the real circuit. In addition, methods for avoidance of convergence problems on DC traction drive simulation can be found in literature [CHA02]. Models of virtual capacitor and parallel inductances are used in these cases. This method is developed for simulation of large systems. The author of this thesis also recommends using of temporary low-pass filters or derivative limits during model parameter tuning [LEH06].

Some limits exist to the application of this model, because the effect of the varistor and other nonlinear components to the line and DC voltage are not included. Switching process is modelled as instant (ideal switch), current in the input choke disappears instantly, and the electric arc in not modelled. Energy dissipation from the disconnected choke is linear according to internal resistance. Measurement and protection circuits are not modelled. Modelling of the electrical braking mode requires a model of the supply network. The most important component in the supply network model is a model of the substation. A substation supplies network via a diode rectifier only in one direction from the general AC electrical network to the contact network. Processes in the AC network are not considered, thus a simplified diode rectifier model can be used together with a substation output filter model. The simplified SimPowerSystems model of the diode substation and its output circuit, including the contact line, is shown in Fig. 2.23.

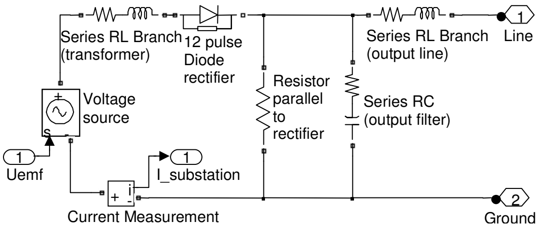


Fig. 2.23 Simplified simulation model of substation and supply line

The transformer in the simplified substation model (Fig. 2.23) is described as a voltage source. The following parameters are set for simulation: output electromotive force of supply transformer U_{emf}, parameters of substation output filter (capacitance $C_{d,}$ resistance R_d) and the resistance of the contact line. The composed model of vehicle input circuit and substation for simulation of a braking chopper operation is shown in Fig. 2.24.

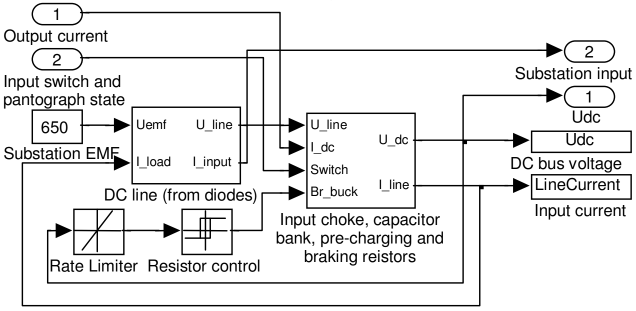


Fig. 2.24 Simulation model of supply circuit with a braking resistor and chopper

Simplified control of a braking resistor using a binary voltage controller is shown in Fig. 2.24. Simulation results are shown in Fig. 2.25,b.

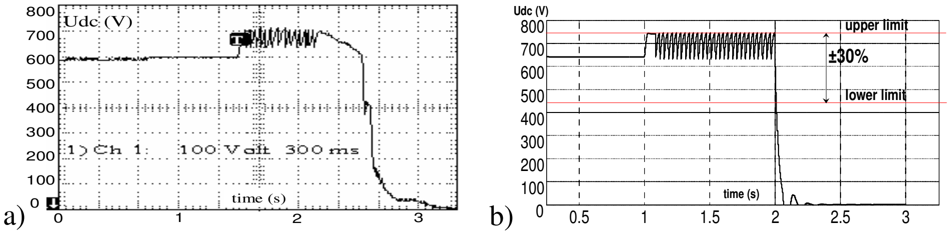


Fig. 2.25 Control and limitation of DC-link voltage via brake resistor

The measured voltage of the converter DC link during the brake-chopper operation is shown in Fig. 2.25, a. Simulation results with different loads in the contact network are shown in Fig. 2.25, b. The converter capacitor bank is pre-charged at start-up, because the capacitor bank with high capacitance cannot be charged directly from the contact network. The voltage control levels of charging are set in the control algorithm according to voltage levels in the contact network, thus to enable traction drive to operate in the required limits of input voltage and input current. High input current pulses cause transients in the contact line voltage that also could cause overvoltages in the converter DC-link.

The acceleration of a vehicle is possible after completion of the charge process when the input contactor is switched on. The input contactor K_3 is controlled by the voltage level and time. The simulated charging process with motor excitation as an additional load is shown in Fig. 2.26.

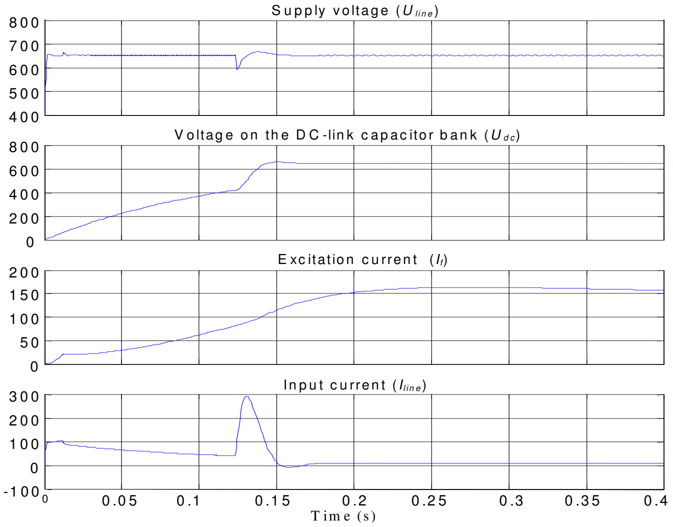


Fig. 2.26 Charging of capacitor bank of the converter loaded with excitation circuit

The charging process through an input choke, a charging resistor, an input switch and a transient on the switching capacitor to the contact network with voltage 650V DC is shown in Fig. 2.26. Charging current spike is up to 280 A and control of the excitation controller up to current 150 A are shown in the figure. Charging of capacitor bank is started on vehicle start-up when the driver starts traction drive and releases the brake pedal. Driving mode is blocked when the capacitor voltage does not obtain the required level because of a failure or abnormally low voltage in the contact network. Charging is allowed only if converter error signals are inactive in the control system. Power semiconductor based charging circuits are also possible, but the total cost of the additional converter is generally higher than the total cost of contactors and power resistor. Charging process has different length in freewheeling and start-up, because of different output loads of the excitation converter. Charging process from off-line freewheeling or braking mode is slower because of the excitation of traction motors is switched on to enable electrical braking. Charging is activated also when voltage in the converter DC-link drops below the minimal required limit. This can occur in the case of voltage interruptions in the electrical network.

3. CONTROL SYSTEM DEVELOPMENT

3.1. Special-Purpose Programmable Controller

The construction of traction drive and its power circuit are developed according to the required functions and modes of operation. The control function can be implemented in several ways: using electromechanical switches, semiconductor-based solid-state switches or software controlled converters. Use of modern and fast power semiconductor switches with software-based control methods allows a significant reduction of power circuit components. The following conditions should be considered on the design of the control system. Bogies of rail vehicles have multiple motors that require joint control. The system should have a modular structure and consist of separate cards and modules for flexible maintenance. Replacing these blocks enables fast restoration of operation and flexible repair. In addition, technical-economical properties, like overall cost are important in the choice of the structure and modular design. Power-stacks that are located next to each other can be feasibly controlled from one control unit.

The multi-processor structure can be used in vehicle with multiple cars. One control unit in multi-processor system operates as a master and the others as slaves. Slave modules are controlling drive torques and speeds according to reference values from the master module and perform local checking of lockage and protections. The master unit is equalizing drive torques, converter voltages and wheel speeds using feedbacks from all the units via computer network.

Computer network is feasible due to reduced amount of wiring, cost and disturbances. Network can be applied to control the train with multiple light-rail vehicles. Modularity and redundancy of control circuits allows partial operation in failure conditions. Technical properties like vibration, temperature range, electromagnetic compatibility, humidity etc. are described in various standards [IEC 60571] [EN 50207]. The main components of electric traction drive, including input and output circuits, are shown in Fig. 3.1. Control and feedback signals are shown using arrows. All the blocks described in the figure can consist of multiple separate parts or modules.

Different drive types require control systems with different performance. Mainly model-based control is used in modern drive control systems that require high calculation performance and fast feedback circuits.

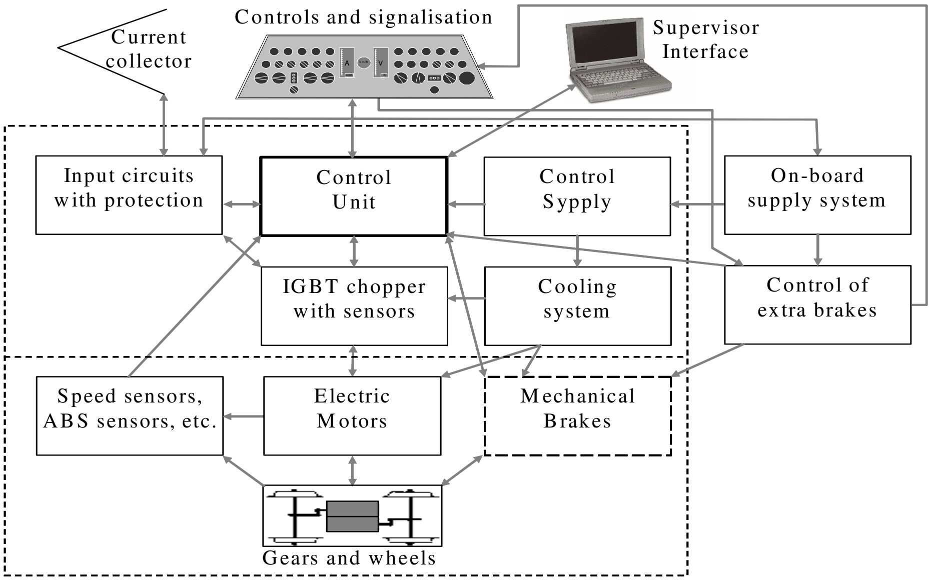


Fig. 3.1 Functional blocks of electric traction drive

Power circuit [EE332U] proposed by the author is meant for further redesign of the drive system, thus the performance of CPU and its interfaces allow further development or expansion. The current trend is to apply inverter supplied AC drives, including vector controlled AC drives.

New microcontrollers (MC) and signal processors (DSP) with integrated multichannel modulators and analog-digital converters have become available for such drives. The application of programmable logic devices (CPLD) and microcontrollers (MC) allows reduction of circuit components, because there are many functions implemented in one chip. Thus, system reliability is increased. The structure of the applied microcontroller [SIE96] is shown in Fig. 3.2.

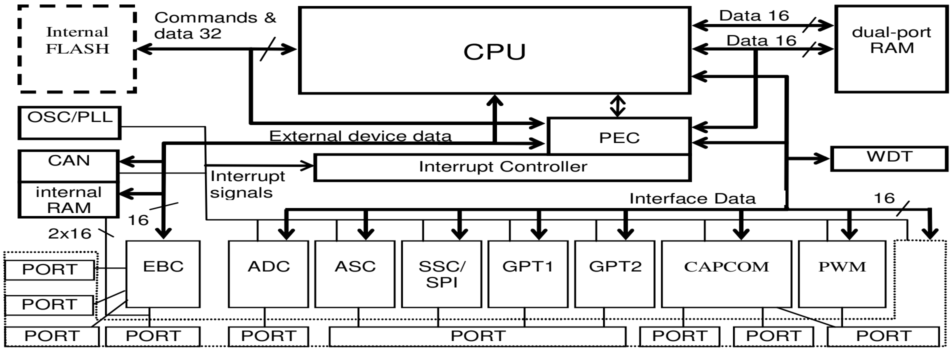


Fig. 3.2 Functional block diagram of microcontroller chip

The functional block diagram of the microcontroller shown in Fig. 3.2 has the following symbols: central processing unit CPU, pulse capture and timer compare unit CAPCOM that is used with the pulse sensor, pulse width modulator unit PWM, controller area network interface CAN, general-purpose timer units GPT, multi-channel analog-digital converter unit ADC, hardware-based watchdog timer for software cycle checking WDT, asynchronous serial interface ASC, synchronous serial interface SSC, programmable oscillator OSC and external bus controller EBC needed for connecting and addressing of external memory chips FLASH, SRAM, NVRAM, etc. On-chip RAM has two ports that allow simultaneous exchange of information between CPU and RAM and the programmable event controller (PEC) and RAM. The programmable event controller copies data from peripherals, independent of CPU. This is similar to the operation of direct memory access controllers (DMA) used in personal computers. Input and output ports are multi-functional and applicable as inputs, output or special ports.

In addition to technical properties, economical properties, cost, compatibility, popularity in other similar systems, availability of support and complexity of programming are important for the selection of the microprocessor or the microcontroller for traction drives produced in small-series. Availability of programmers ensures support from third-parity companies in the future. In terms of software, availability of development software and its price quality relationship, re-use possibilities of program source code and availability of freeware tools for further development are important. The control of high frequency transistor-converters and model-based or vector-controlled drives require a high-performance controller with fast analog inputs. In addition, technical properties, like performance, energy consumption and measurements are important. A 16-bit industrial microcontroller module was chosen for the control of traction converter according to the analysis of the given technical-economical properties. A special-purpose solution with an additional memory was assembled, based on 80C167 series microcontroller [PHY96] form companies Infineon, Siemens or ST microelectronics. An overview of the control unit is shown in Fig. 3.3.

Control unit and its printed circuit boards (PCB) were designed by the author of this thesis. Several prototypes were tested. All PCBs were changed to expand the alternative selection options of components. This also enabled improvements in electromagnetic compatibility and technical properties of interfaces. Other prototypes were implemented with new circuit diagrams and increased amount of inputs and outputs for the application of systems on vehicles with low-floor sections. The cards designed are flexible and are applied in several other research projects of Tallinn University of Technology, such as laboratory equipment and research of energy storage devices. Printed circuit boards were produced in company Brandner PCB located in Tallinn using computer-aided manufacturing (CAM) data prepared by the author of this thesis.

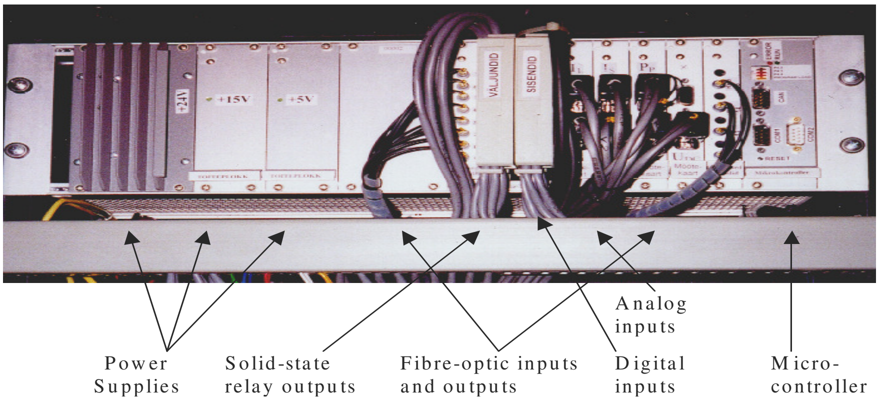


Fig. 3.3 Control unit of a special purpose drive developed by the author of the thesis

Technical data of the control unit developed by the author and shown in Fig. 3.3 are provided in Table 3.1.

Table 3.1 Technical specifications of the developed control unit

Component	Technical specifications, explanatory notes
CPU, frequency, instruction set	Infineon C167, 40 MHz, RISC
Supply voltages	+3V; +5V; +15V or 10..30 VDC
Digital inputs including optically separated electrical and fibre-optic	4 fast 50 ns electrical interrupt inputs and inputs with 400 ns to 26 ms checking 8 pcs. Fast digital inputs are applicable in several binary controllers.
Fibre-optic digital inputs	4 fast 50ns fibre-optic interrupt inputs
Analog inputs	0...±10V (3); 0...±75mV (2); 0..+5V (2) 0..+10V (1)
Digital solid-state relay outputs	8 separately controlled and 2 bound with fibre optic outputs
Fibre-optic digital outputs	8 pulse width modulated
CAN automation network	Priority-based communication, Full CAN 2.0
Random access memory (RAM)	SRAM: 256KB up to 1MB
RAM for electricity- and odometer	SRAM: 256KB up to 1MB, battery supplied
Read only memory (ROM) of program firmware	1 MB FLASH, protected, on-board programmable using programmer software, but not during system operation.
Memory for configuration setting and error log	Separate 1 MB sector wise erasable and on board programmable FLASH.
Clock and calendar chip	EPSON RTC-8564 with internal quartz-oscillator, Year 2000 compatible
Serial interface	2 x RS232
Status indication	Light emitting diodes (LED)
Temperature range of all components	-25..+70 °C

Connections of the control unit described in Fig. 3.3 to the drive and vehicle control circuits are shown in Fig. 3.4.

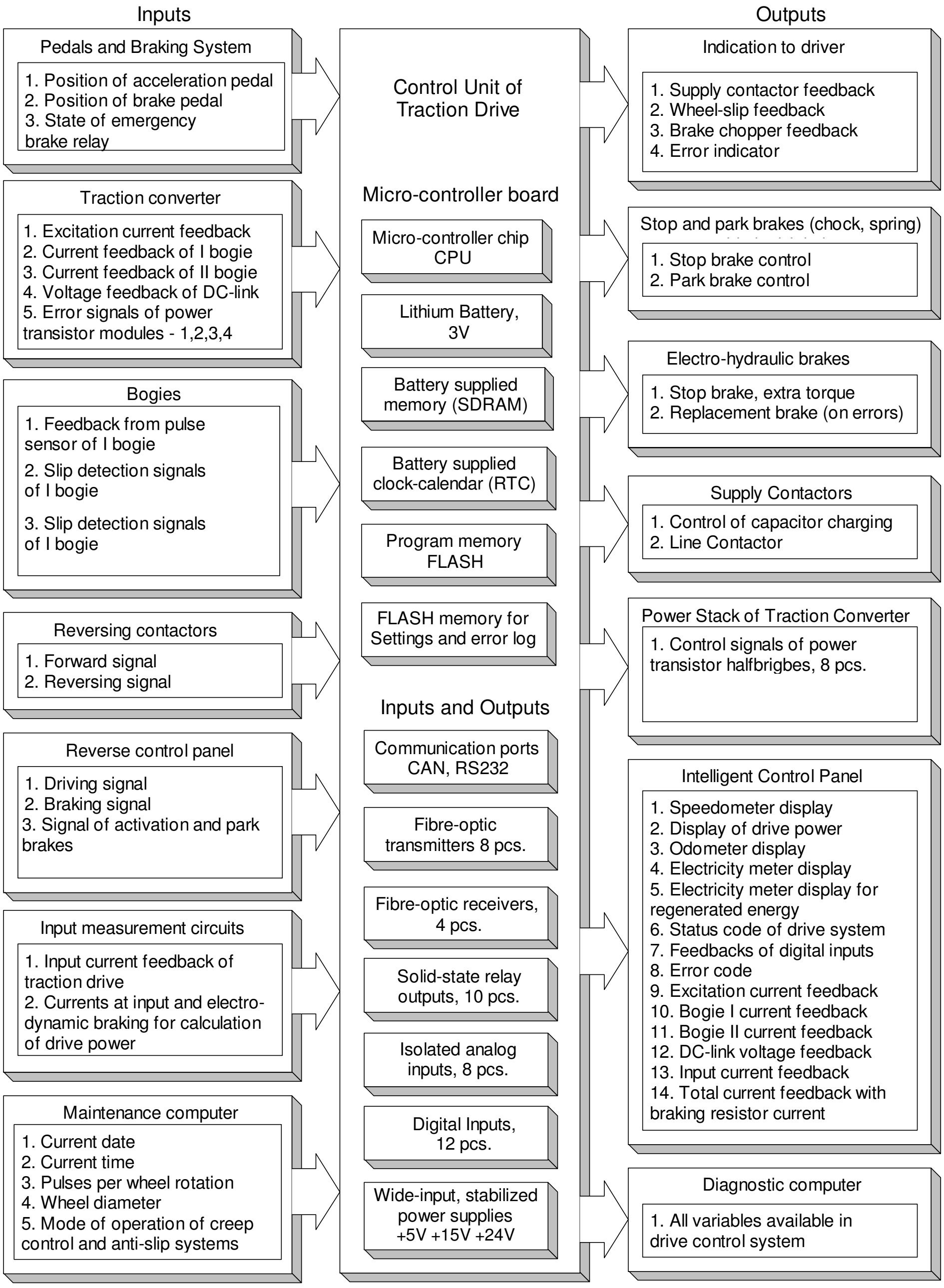


Fig. 3.4 Systems and equipment connected to the control unit

3.2. Modernization of Power Circuit

3.2.1. Reasons for Tram Reconstruction

The control of all bogies with one acceleration rheostat is used on old ČKD Tatra tramcars (also in Tallinn). Such a system does not allow separate control of bogies or anti-slip control. The bridge circuit shown in Fig. 3.5 is used to stabilize magnetization on electrical braking. Series connection of different motors is the only possibility for torque and current equalization there.

Excitation of motors on freewheeling and brake force equalization

The armature current of one bogie is series connected with the excitation of another bogie using such a bridge circuit. This circuit is also keeping magnetization current on freewheeling and thus has a weak self-braking effect. Real systems in addition to circuits described in the simplified circuit diagram, require eight contactors for drive reversing, six contactors for field weakening control and contactors for switching between the driving and braking mode.

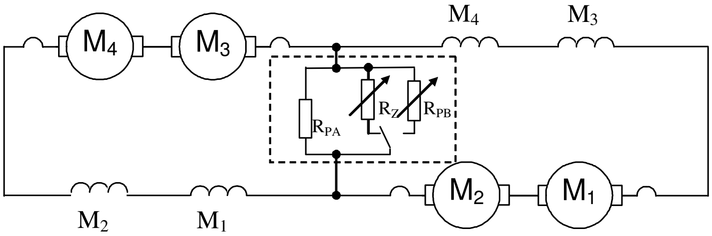


Fig. 3.5 Simplified main circuit on braking of an old rheostat-controlled tram

Several resistors are used for control and limiting of current - R_{PA} that is continuously in circuit and required for magnetization and R_Z or acceleration rheostat used for the control of traction and braking force. The given circuit does not allow complete freewheeling because of magnetization supply that causes weak self-braking. In addition to rheostat R_Z, the current is controlled using resistor R_{PB} that is on the roof of ČKD Tatra KT4 tramcar. Given braking circuit is also widely used in many switch-mode converter based traction drives - in Riga [GAN02] and Cottbus [KIE01]. The boost converter is connected instead of rheostat R_Z and resistors R_{PA}, R_{PB} that allow regeneration of braking energy to the contact network. The main disadvantage of this circuit is the complexity of operation and a large amount of contactors.

Speed control on driving mode

The system with one rheostat described in Fig. 3.6 lacks torque equalization possibilities because both bogies are connected in parallel and currents cannot be separately controlled.

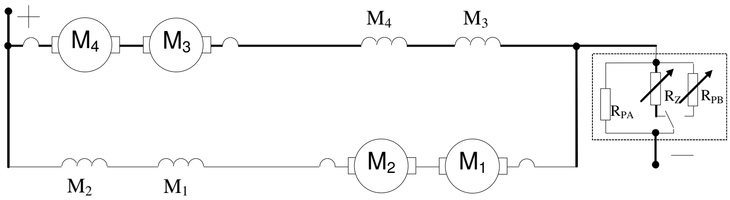


Fig. 3.6 Simplified main circuit on driving of an old rheostat-controlled tram

The main drawback of such a circuit is lack of constant speed operation mode. Constant speed cannot be kept without freewheeling or braking which leads to high losses in the acceleration rheostat and inefficient operation of traction motors.

3.2.2. Development of Universal Power Circuit

Specific gauge of Tallinn tramway track 1067 mm that is not spread in European cities leads to small-series production of vehicles. Measurements of electronic equipment depend on the available width of vehicles. The choice of DC motors is economically reasonable because of the reliability of existing traction motors and remaining long lifetime. Thus, the need for special solution led to the development of a new traction drive. The power unit [EE332U] hardware developed by the author of the thesis is designed for use with both DC traction motors and AC traction motors (asynchronous motors). The new drive system enables effective regeneration of the braking energy to the contact network and combined regenerative braking mode with the use of the braking resistor. The common magnetization circuit and its control allow the simplification of the power circuit with reduced component amount and cost. Separate power circuit wiring is needed for separate control of bogies, but the system is more flexible, redundant and allows the use of smaller and cheaper power modules than the single converter system. Traction and braking force are controlled automatically using separate modules of the traction converter. Limiting of armature current of DC motors using switch-mode converters is needed for limiting of the output torque and power on acceleration and braking. Replacement of series-excitation with separate magnetization leads to more stiff characteristics of traction motors. This problem can be smoothed via appropriate control of traction motor currents. The voltage of magnetization is low that leads to very small duty-ratio of the excitation converter. Switch-mode is suitable because of high time-constant that avoids discontinuous current operation. The main circuit diagram of the new drive system is given in Fig. 3.7.

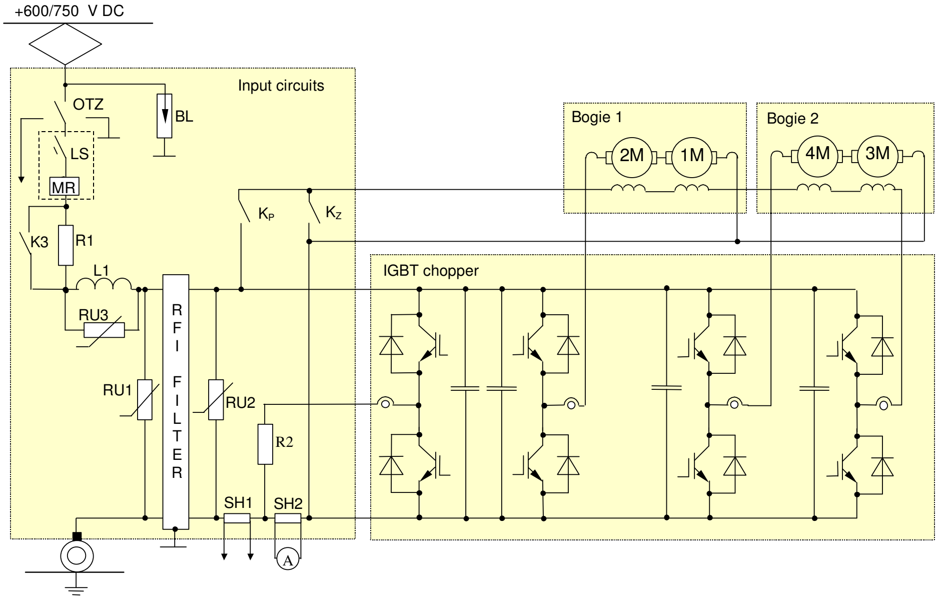


Fig. 3.7 The new main circuit for modernization of Tatra trams in Tallinn

The magnetization of all traction motors in tramcar (according to Fig. 3.7) is supplied through one converter, thus magnetization cannot be separately controlled. The electromotive force of all bogies is checked to allow field weakening of all bogies. This is done via output voltage monitoring of all current controllers. A speed sensor is used in system to estimate electromotive force for ensuring stable magnetization control on freewheeling and instability conditions.

Excitation circuit as a control object

The excitation voltage should be continuously controlled to keep excitation current stable because the input voltage of the vehicle varies in a wide range and resistance R_f of the series connected excitation winding depends on the temperature. Numerical PI controller can be used for the compensation of these disturbances. Stable regulation of magnetization is important because transients and dynamic errors of magnetization current lead to transients in electromotive forces of all traction motors. The control of excitation current in the new drive is shown in Fig. 3.8, and in Fig. 3.9.

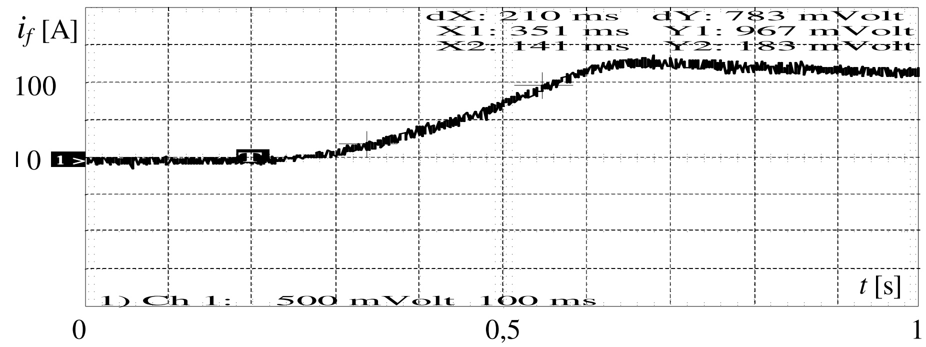


Fig. 3.8 Experiment of excitation current increase 5...150 A

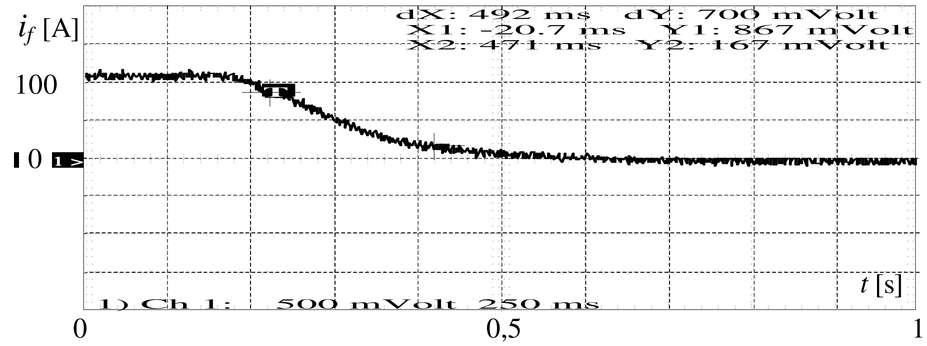


Fig. 3.9 Experiment of excitation current decrease 150...5 A

Magnetization circuit is a slow control object because of high inductance. Current control on the steep step-change of the reference value is shown in Fig. 3.9. The windings of four traction motors were connected in series during the experiment. The following conclusions can be drawn from the experiments:

1. Control is slow because of high inductance, but this is not a disadvantage as it reduces the effects of disturbances.
2. All reversing contactors in the magnetization circuit should be switched off with delay to avoid electric arc on contacts. Anti-parallel freewheeling diodes on contactor windings can be used for delaying of contactors in the switching process.
3. Field weakening of all motors can be controlled using a single converter in the multi-motor traction drive.

Magnetization is controlled differently in different modes of operation and conditions.

1. The controller is disabled (switched off) when the DC-link voltage is below the minimal voltage needed for magnetization supply. This allows stable excitation of motors at low supply voltages. Low voltages of DC-link and thus low voltages of magnetization occur on unstable braking when the system is disconnected from the network (off-line mode).

2. Upper limits of the magnetization current and voltage are needed to avoid saturation of magnetization poles that could lead to inefficient operation of motors. Increasing of the magnetization current for higher acceleration or braking torque is not reasonable because the increase of magnetic flux and torque is not significantly high on the increase of the magnetization current. The limit of the magnetization voltage is needed to limit the magnetization current in the case of failure in magnetization current feedback.
3. Lower limit of the magnetization current is needed to limit the maximal driving speed. Higher speed cannot be allowed because the required braking power cannot be achieved, as the electromotive force cannot be increased over the maximal allowed voltage of DC-link capacitor bank. The maximal speed of traction motors is also limited for mechanical reasons.
4. The temporary limit of the magnetization current is needed when the magnetization circuit cannot be supplied from the network with the required power. This leads to the temporary limitation of the electromotive force of motors. This is needed during the charging process of the DC-link capacitor bank.
5. Temporary limit of electromotive force is used in the unstable uncontrollable self-braking mode. Outer-loop of control cascade is switched off and excitation is controlled only for reducing of the electromotive force. The operation of the outer loop is restored when self-braking ends. This allows bringing of self-braking bogie to a stable operation mode without trips in the overcurrent or overvoltage protection systems.

3.2.3. Comparison of Motor Control Circuits

Control methods of traction drive systems can be divided according to the available modes of operation. Main operation modes of tram drives are the driving mode (on acceleration, deceleration or constant speed), the freewheeling mode without output electrical torque, and braking mode (including regenerative and dynamic brake).

Different control and switching apparatus is needed for reversing, braking and field weakening of traction motors. The main disadvantage of series-magnetization is its complicated power circuit and large amount of contactors needed for the control of magnetization. A multi-motor drive that has only one controllable rheostat or chopper requires contactors for field weakening and reversing of all series-magnetized traction motor groups. A comparison of different power circuits used on ČKD Tatra tramcars is given in Table 3.2. All the given configurations have the same amount and type of traction motors, but different control properties. New modernized drives have the control of traction and braking implemented via control systems with faster response. The amount of switches, such as contactors and power transistors, counted according to the circuit diagrams of vehicles is given in Table 3.2. The maximal speed of trams used in Riga [GAN02] and Cottbus [KIE01] is lower because of the smaller amount of contactors used for field weakening. Acceleration and maximal speed are also different because of different gear ratio and vehicle weight.

Table 3.2 Switching elements in different drives with four DC traction motors

Function of switches	Symbols on original Tatra KT4	ČKD Rheostat KT4SU, KT4D	T3 Ganz-Transelektro (Riga)	KT6NF Kiepe (Cottbus)	KT4, KT6T (Tallinn)
Reversing contacts	P, Z	8	8	8	2
Field weakening contacts	F	6	4	2	0
Brake-mode contacts	B, M	5	4	2	0
Current control contacts	R	2 and acceleration rheostat	0	1	0
Supply line contactor contacts	LS	1	2	2	2
Separately controlled semiconductor switches	-	0	3	3	7

The use of separate magnetization in all modes of operation reduces the amount of contactors and allows the improvement of drive control properties. Slip problems occur because of stiff characteristics at low speeds [JOL02]. Thus, current or torque limits should be used in the constant field range and in the fieldweakening range. In addition, more complicated software is needed than on series-magnetized drive systems. An original power circuit requires special controllers and control algorithms.

3.3. Control Software and Operation Modes

Different control methods are used in different modes of operation, thus also different data objects and sub-programs are used. Different control cascades with different controller parameters are used in different modes. Overview of control algorithms, sub-programs and tasks of the traction drive is given in Fig. 3.10.

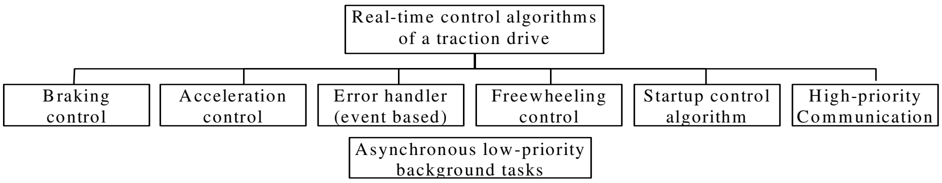


Fig. 3.10 Classification of algorithms in the control systems of traction drives

Information about states and operation modes is stored in flags (bit-variables) in the memory of the microcontroller. Operation algorithms are selected according to the conditions of these flags and other conditions, such as positions of controls set by the driver and other input signals. Flags are formed to status-word for diagnostic purposes and for transfer of status information over computer networks.

Reference values of controllers are transferred via computer network to the slave controllers of traction drives, such as traction drives of hitched trailer cars. Tasks performed in the control system are divided into three priority levels shown in Fig. 3.11.

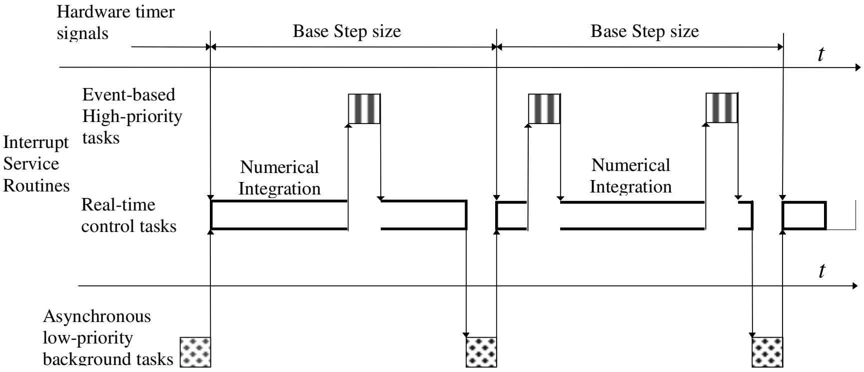


Fig. 3.11 Time diagram for processing of tasks with different priorities

High priority tasks are servicing of hardware such as an analog-digital converter, processing of signals and protection algorithms of the converter. Processing of signals, models, controllers and numerical integration algorithms of meters are working with a given interval. Other random processor performance is used for low-priority background tasks, including for data acquisition and communication with displays and diagnostic interfaces.

3.3.1. Development of Acceleration Control Structure

Development of the control structure for the driving mode is related to the development of the acceleration structure with anti-slip systems and freewheeling structure in different modes of operation. The driving mode of operation can be divided as the nominal-field operation and fieldweakening operation according to control properties. These ranges depend on the properties of traction motors, gears and supply voltage.

The speed-load characteristics of separately magnetized DC traction motors at constant nominal magnetization are almost linear. This mode of operation can be divided according to control as the torque-limit operation or the speed-limit operation. Magnetization depends on the speed and supply voltage on the field weakening operation, thus load-speed characteristic is nonlinear. Transition from the nominal-field operation to the fieldweakening operation occurs when the increase of the power or speed is not possible via other methods. The increased speed in the field weakening operation is achieved at the expense of traction force decrease because the motor torque is reduced on the weakening of magnetic flux. Field weakening with maximal reference leads to constant power operation in the case of constant line voltage up to the end of the fieldweakening region. All traction motors in the multi-motor drive are controlled accordingly via one reference block. This reference block sets the reference speed, reference torque and reference intensity of field weakening to all separately controllable motor groups. The position of the control lever or pedal is filtered and converted to the reference value according to the reference function.

Speed reference function

Speed reference according to the driver pedal position is used in the separately magnetized traction drive system developed by the author. The intensity of acceleration is lower at the beginning of the ramp to avoid shocks. S-shaped acceleration curve is widely used in industrial electric drives, only the first half of this is needed in traction drives. Speed reference according to the pedal position is calculated using the square function. This function reduces the effect of the pedal position at low speeds, thus allowing more accurate speed control at low speeds. The end of acceleration is not easily controllable in separately magnetized drives because the armature current and acceleration stop immediately when voltage is reduced below back electromotive force value. Voltage level between freewheeling and driving depends on line voltage and back electromotive forces of bogies, thus it can be different at different line voltages and for different bogies. Thus, steep change in the reference between the freewheeling and driving mode could cause oscillations in the DC-link voltage that could lead to instability and self-braking. Torque controllers that control armature currents on separate bogies are added to avoid such situations.

Ramp functions of speed and torque

Three reference values - torque, speed and field weakening are controlled via two ramp functions that are controlled using logic rules according to the mode of operation.

1. Acceleration ramp is used to limit acceleration using the limitation of armature voltage on bogies with DC motors. The acceleration ramp starts together with the torque ramp in the driving mode. The acceleration of separate bogies is controlled separately using separate power circuits of converters. Voltage limit is started only with current on at least one bogie to avoid response delay. Voltage rise and fall times are not limited if the current in all motors is zero. This allows fast response while the voltage ramp starts on values higher than the back electromotive force of motors.

2. Continuous integrator of torque reference is needed for smoothing of traction forces on different bogies and wheels, thus for equalizing of loads of on traction motors. Controllers of armature currents of DC motors are used separately for all bogies to limit motor output torque and power. These current controllers should have fast response because small time-constant of armature windings and external disturbances, such as fluctuations of contact line voltage and load. Fast control via magnetization is not possible because of its high time-constant.

Control possibilities in the fieldweakening range are limited because the difference of back electromotive force and line voltage should be sufficient for acceleration and field should be kept as high as possible to allow sufficient motor torque. Thus, field weakening intensity is also controlled using the acceleration ramp (see Fig. 3.12).

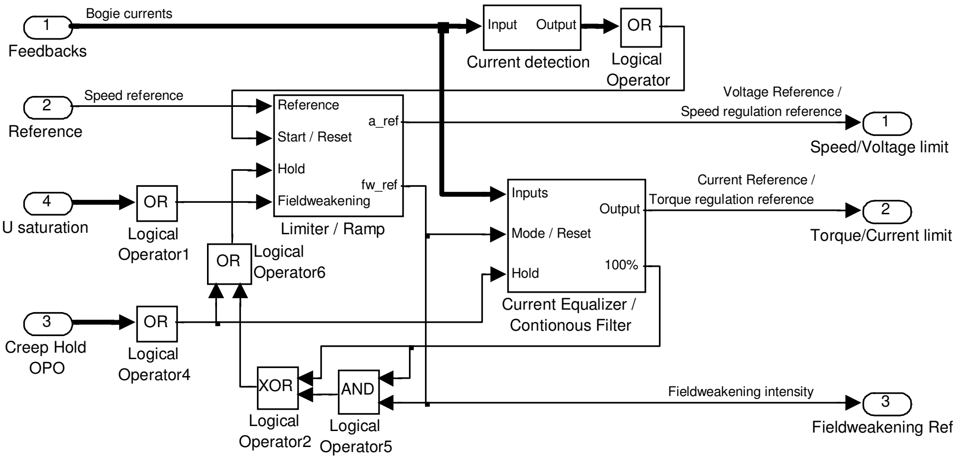


Fig. 3.12 Speed and torque control of the multi-motor drive in the driving mode

The aim of the control structure shown in Fig. 3.12 is smooth control of speeds and torques in all wheels and bogies, including in slip conditions. Bold lines show data arrays that contain multiple variables. The application of such a structure assumes separate control of bogies of axles. Common reference signal (input 2 in Fig. 3.12) and current feedbacks from all bogies (input 1 in Fig. 3.12) are used for control of the torque reference value. Field weakening control uses the voltage limit (saturation) signal (input 4 in Fig. 3.12) from current controllers. This is formed using logical summing of voltage limit signals of all armature current controllers in the multi-motor drive. Thus, the fieldweakening signal is active when at least one output voltage of the current controller is at its upper limit. Creep control uses a signal (input 3 in Fig. 3.12) from slip-detection units. This signal is also the logically summed value of slip signals of all bogies. Thus, torque reference and speed reference are not increased when at least one bogie has an active slip signal.

Torque differences between different bogies are equalized using controllers of armature currents. Separately controllable voltage converters allow smooth start-up and acceleration on the deviation of wheel diameters and motor parameters. Reference values of currents in the driving mode are controlled using the filtered average value of all bogies. The structure used for filtering of the measured current values of different bogies is shown in Fig. 3.13.

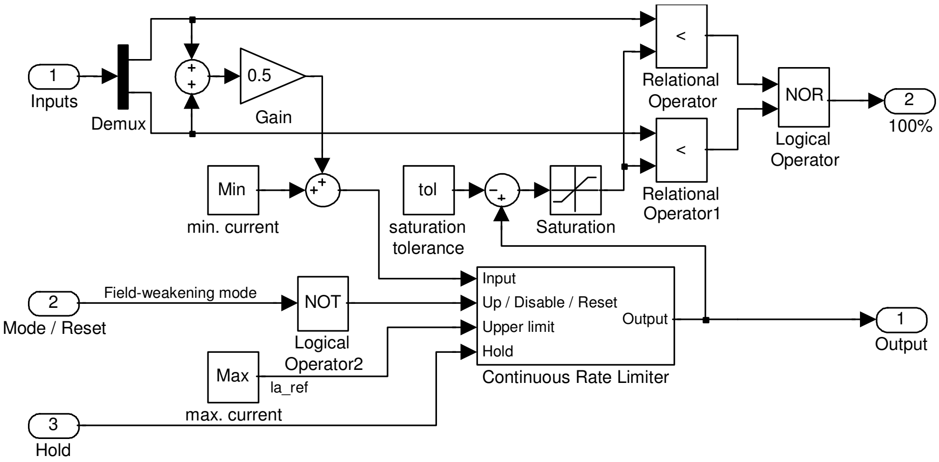


Fig. 3.13 Structure of the torque equalization system

The reference value for all bogie-controllers is calculated according to Eq. 3.1 and the structure shown in Fig. 3.13. Average measured values of all bogie currents are used as inputs for average current calculation.

$$I_{av\_ref} = \frac{\sum_{i=1}^{n} I_i}{n} + I_{Min}, \qquad (3.1)$$

where: n - number of separately controllable traction motor groups, I_i - armature currents of separately controllable motor groups, and I_{MIN} - minimal current value required for acceleration from start-up. Signal 100% (output 2 in Fig. 3.13) is a torque limit output signal that is needed to stop the speed reference integrator.

Reference values of speed and torque limit are common to all bogies of the vehicle. The driving mode uses the speed control in the conditions where the torque is below its limit. Signal *Hold* (input 3 in Fig. 3.13) is used to stop the torque ramp integrator and thus used for the torque limiting in the wheel-spin conditions. Signal *Mode/Reset* (input 2 in Fig. 3.13) enables stopping of the torque integrator in the case of traction motor failures. Armature current limit is set to constant value in this case.

Binary controller of traction and braking torque

Binary controller (hysteretic control, bang-bang control, ripple regulator) is controlling the output current of the traction converter directly via switching of transistors using the error value calculated from the reference and feedback signals. The feedback time-constant limits its maximal switching frequency. The maximal duty-ratio (pulse width) of step-down buck-converter is limited according to the inductance of traction motor windings and DC-link voltage.

Binary controllers are operating independent with separate traction converter control to limit torques of bogies independently using common reference value. The binary controller for a traction motor armature current control is shown in Fig. 3.14.

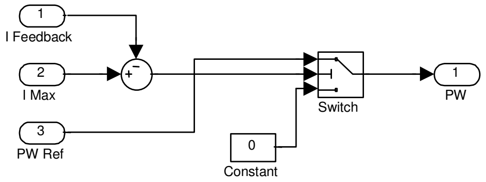


Fig. 3.14 Simulink diagram of simple binary controller

Binary controllers are used for the control of boost converters on braking. An output voltage and duty-ratio characteristic of the boost converter is nonlinear. A binary controller is suitable for the control of nonlinear objects and it does not have many parameters. These parameters are cycle length and difference of switching levels. Minimal length of the cycle depends on the cut-off frequency of feedback amplifier and processing cycle of the algorithm of a binary controller.

3.3.2. Development of Brake Control Structure

Control of brakes includes the control of traction motors and mechanical brakes. Control of braking is complicated for the following reasons: because of independent and redundant control of different braking systems, corresponding control of traction drive with several mechanical braking systems, nonlinear characteristics of boost-converter, magnetization stabilization on variable current and voltage conditions, and because of the off-line operation.

Control of braking force

Traction force is controlled according to the reference value of the traction motor torque in combined regenerative-electrodynamic braking. Braking torque is referenced via the armature currents of DC traction motors. These reference values of currents are controlled via the anti-slip system of the vehicle.

Braking, as different from the acceleration mode, where current control has nearly linear characteristics, uses boost converters with nonlinear characteristics.

Braking currents are passing freewheeling diodes of the same transistor modules that were used in acceleration. Energy stored (buffered) in armature winding inductances L_a is used for boosting voltage up the from bogie level to the DC-link level. The output of the binary controller and switching frequency of transistors is limited via the constant modulation frequency. Outputs of binary controllers in the off-line mode are limited according to boost-converter characteristics for keeping drive magnetization stable and converters in efficient operation. The block diagram of braking control is shown in Fig. 3.15.

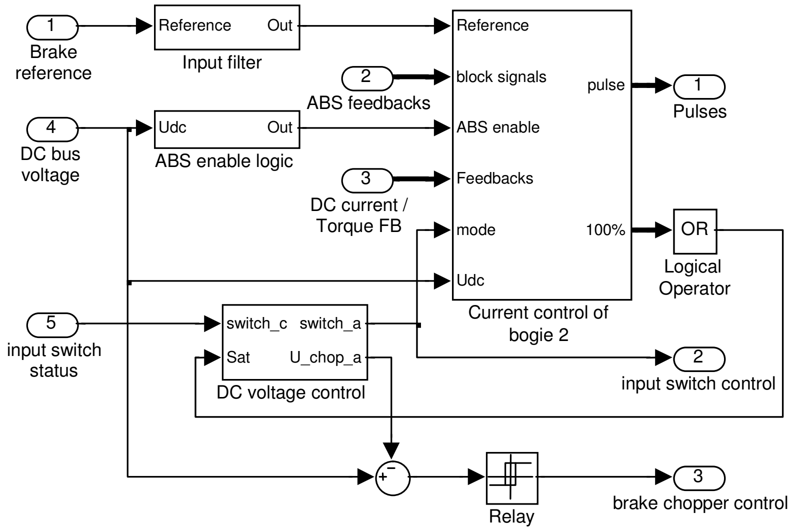


Fig. 3.15 Electrical and regenerative brake control for multi-motor drive with common DC-link

Current feedback signals from all traction motors (input 3 in Fig. 3.15), and slip-detection signals (input 2 in Fig. 3.15), from slip detection units, are used for centralized control of braking torques on all bogies. Binary controllers are used for the control of currents in separate bogies.

DC-link voltage of the traction converter in regenerative braking is also limited using a binary controller. This voltage is limited according to the standard [EN 50163] (*Supply voltages of traction systems*) in regenerative braking. Voltage is increased when the contact network is not able to receive this energy and the remaining power is redirected to the brake-resistor. Supply contactors are switched off the in off-line mode, thus regenerative braking is not possible and only the braking resistor is used for electrodynamic braking. The DC-link voltage is limited according to the operation mode and maximal allowed voltage on the electrolytic capacitor bank. Voltage of the DC-link is reduced according to the decrease of the back electromotive forces of motors. Magnetization during the decrease of the DC-link voltage is kept stable using an excitation controller. This allows stable supply of magnetization and power flow from the motors to the DC link through the boost converter and freewheeling diodes of the traction converter. The block diagram of binary controllers and the antilock controller is shown in Fig. 3.16.

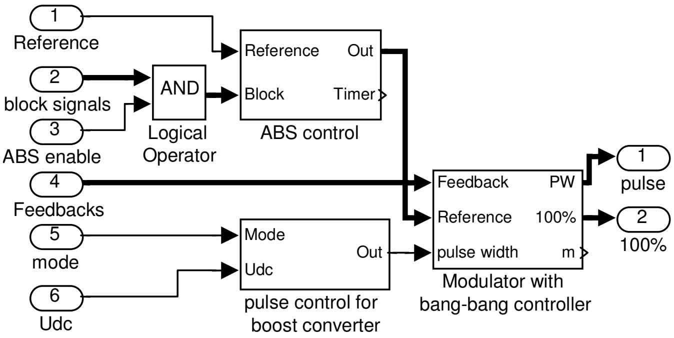


Fig. 3.16 Cascade control structure for brake torque, boost converter and antilock control of the bogie current

Structure of the DC-motor current control is shown in Fig. 3.16, bold lines indicate multiple signals from and to separate bogies.

Depending on the status of input contactors and the required braking power, different braking modes are used in the traction drive, such as the electrodynamic brake with the braking resistor, regenerative brake and regenerative brake combined together with the electrodynamic brake. Only DC-link voltage control is used for braking at low speeds and DC-link voltages (Fig. 3.15). Then boost converters and braking resistor are not used and all the power from traction motor armature windings is redirected to their excitation windings. The braking ends in the off-line mode with the decrease of the magnetization current of motors to zero.

Control of electrodynamic antilock brakes

Control block of antilock braking (ABS) consists of a binary controller with cycle time limits used for the reference torque control of traction motors. The control algorithm of antilock-braking block is shown in Fig. 3.17.

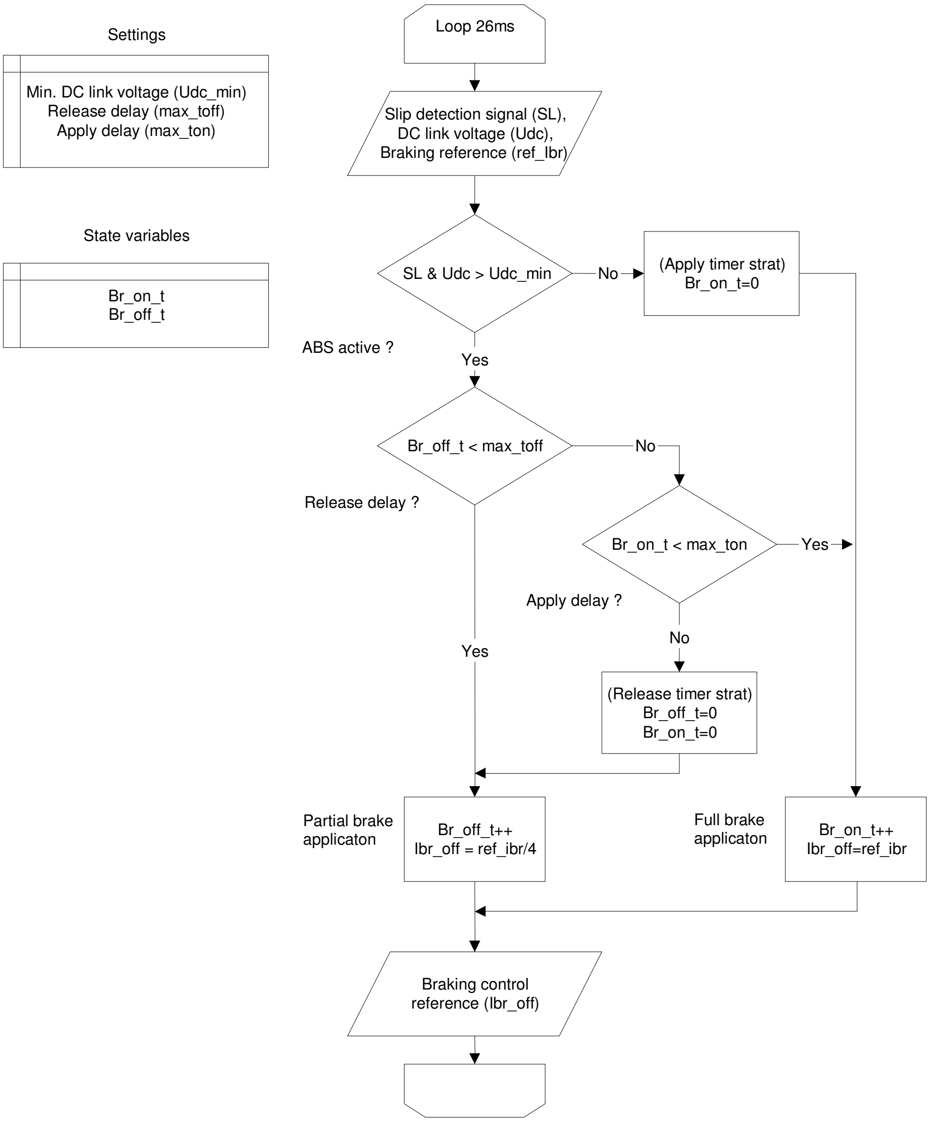


Fig. 3.17 Control algorithm of binary antilock controller

Two software-based timers are used for each bogie. Variable *Br_on_t* in Fig. 3.17 is used for time measurement of braking with the referenced torque and variable *Br_off_t* is used to measure the time of braking with the reduced torque. Braking torque decrease is controlled via the anti-slip system signal *SL* (input 2 in Fig. 3.16). The antilock system is switched off during low DC-link voltages and low speeds to keep motor electromotive forces stable.

3.3.3. Control of Mechanical Brakes

The required braking torque is complicated to achieve with traction motors at low speeds, thus mechanical brakes are used for complete stopping. The application of these stopping brakes, including park brakes, is controlled from the control system of the traction drive. Stopping brakes are needed for the smooth application of park brakes when braking with traction motors is not applicable because of too low braking current. Solenoid block-spring (shoe) brakes together with electro-hydraulic pad-brakes are applied on stopping.

Park brake is used to keep the vehicle on standstill without supply voltage or pressure in brake systems. Thus, brake-pumps and solenoids are switched off and the vehicle is only kept using blocks (or shoes) of spring brakes.

Traction motors alone are not capable of achieving required deceleration in dangerous situations. Minimal required deceleration and maximal braking distance are defined in regulations [BOStrab] [RTL641] for different speeds. Required deceleration can be achieved using the braking force of all brakes, including all service brakes, track-braking magnets and sand-systems without the wheel slip. Additional electromechanical or mechanical brakes can also be used to achieve the required deceleration such as pad-based electro-hydraulic service brakes.

Redundancy

Braking torque of electric motors is replaced with the torque of other brakes during failures in the traction drive (*Replacement braking, Ersatzbremse*). Failed traction converters or motors are replaced according to required minimal decelerations and maximal allowed braking distance.

Emergency braking systems (*notbremse*) and forced braking (*zwangs-bremsung*) operation are controlled using separate hardware (safety relay). This control loop allows activation of these systems, independently of control system software. Passengers can also apply emergency brake by using buttons located next to vehicle doors. The purpose of forced braking is automatic stopping of a vehicle including dead-man control.

3.4. Model-Based Control of Motors

3.4.1. Structure for Electromotive Force Control

The purpose of electromotive force control cascade is keeping the electromotive force of traction motors at its maximum to enable effective operation at high torque. The sum of electromotive forces of series connected motors must also be kept lower than the line voltage to avoid uncontrollable regenerative self-braking through the freewheeling diodes of transistor modules.

The drive is consuming power on freewheeling for the supply of excitation windings. The control of the magnetic field is needed to ensure stability of electrodynamic and regenerative braking. The outer loop of control cascade in Fig. 3.18 is used for control the electromotive forces of bogies according to the contact line voltage with the limitation of excitation current using the inner control loop. This control structure is used for vehicle acceleration in the field-weakening mode. This is done via the control of electromotive forces of the traction motors. This structure is also needed to keep stable excitation on nominal-field operation, freewheeling and electrical braking.

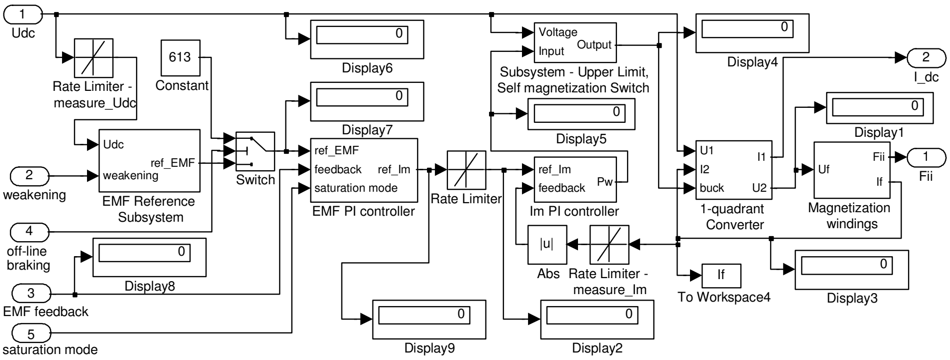


Fig. 3.18 Model of separate excitation control system

The cascade control structure is shown in Fig. 3.18 where the inner loop is used for the excitation current control and the outer loop for the electromotive force control. The control of the excitation current is done via the control of the duty-cycle of pulse-width modulation.

The excitation supply system has different modes of operation. The following signals are used for the control of the operation mode: *offline* (input 4 in Fig. 3.18) is used for control of magnetization in the off-line mode, *saturation* (input 5 in Fig. 3.18) is needed to reduce magnetization during the charging of the DC-link capacitor bank, and A_{ref} is the field weakening intensity reference (input 2 in Fig. 3.18) that is needed for acceleration in the fieldweakening mode.

Feedback signal (input 3 in Fig. 3.18) is a value estimated using the magnetization curve of the average traction motor. Direct measurement of the electromotive force is complicated because motors are supplied from switch-mode converters. As different from model used for real-time control, the simulation model includes also the frequency characteristics of measurement feedbacks, including cut-off frequencies of measurement amplifiers.

PI controllers used in control cascade

The PI-controller suits well for systems where the static error of the output value is not permitted. The control error of the electromotive force $\Delta E = (E_j - E_{arv})$ is calculated as the disparity of referenced electromotive force E_j and estimated feedback value E_{arv}. The electromotive force controller can be described in a simplified form using Eq. 3.2.

$$I_{e\_j}(n) = k_P \cdot \Delta E(n) + \frac{k_I}{\tau_n}\sum_{j=0}^{n} \Delta E(j), \tag{3.2}$$

where: k_p – proportional gain, k_I – integrative gain and τ_n – integration time coefficient that describes the intensity of integration and allows using the same parameters with different integration algorithms at different time-steps.

Numerically implemented PI-controllers that are shown as SIMULINK models in Fig. 3.19 include properties of the integration algorithm, such as time-step and conversion of feedback signals via an analog-digital converter.

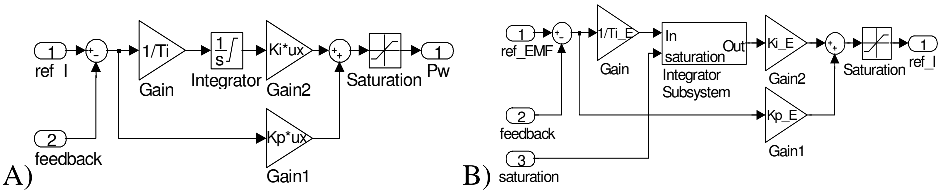


Fig. 3.19 PI controllers

Two PI controllers are shown in Fig. 3.19, where A is the controller with the integrator limitation (saturation) and B has the controllable integrator limit. In addition, output values of both controllers are limited. The output limit of the outer control loop *If_max* and *If_min* in the control cascade is the reference limit for the inner control loop. The upper limit for the excitation current is needed to avoid motor pole saturation. Gain *ux* in the controller model means that the calculation of the control error can be done in the units measured via an analog-digital converter. This allows the use of the same controller parameters (K_p, K_i) with different sensors and measurement channel gains.

3.4.2. Feedback via Motor Magnetization Model

The application of model for electromotive force estimation is shown in block diagram in Fig. 3.20.

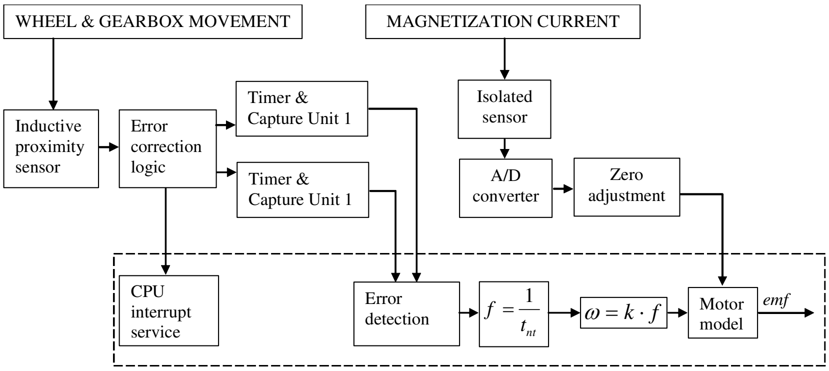


Fig. 3.20 Structure of electromotive force feedback via traction motor model

The estimation system of the electromotive force is based on the traction motor magnetization model that uses instantaneous values of the measured speed and excitation current. Speed feedback uses pulse sensors installed into drive gears. The timers measure time between the pulses. The Pulse period is converted to the frequency value that is proportional to the vehicle speed by using the dividing instruction of the microprocessor. Electrically isolated current sensors that are integrated into the intelligent power module are used for motor current feedback together with the analogue-digital converter that is integrated into the microcontroller. The estimated electromotive force is calculated using the following formula:

$$E_{EMJarv} = p \cdot k\Phi\left(I_f\right) \cdot \omega \qquad (3.3)$$

Where $k\Phi$ is the function from excitation current I_f and p is the amount of electrically series-connected motors. The electromotive force cannot be negative because of the existence of anti-parallel freewheeling diodes in the traction converter. Excitation current can be negative on the reverse direction driving because of reversing circuits. The following polynomial function (Eq. 3.4) is used for the calculation of the estimated electromotive force of bogie with multiple series connected DC motors.

$$E_{EMF} = p \cdot \left(P_1 \cdot I_f^{\,2} + P_2 \cdot \left|I_f\right| + P_3\right) \cdot n\,, \qquad (3.4)$$

where ω - angular speed of motor shaft [rad/s], *P1, P2, P*3 coefficients of polynomial that describe the shape of magnetization curve of the DC motor, n is the speed of the motor shaft in rotations per minute (rpm).

Described model-based control system does not include detailed parameters of motors, processes of armature reaction are not modelled and it has slow response. However, it is sufficient for real-time control of electromotive force because excitation circuit response is accordingly slow. This model is not accurate on low speeds below 10 km/h. This model is not used for control on low speeds because the controller of electromotive force is switched off for constant field operation.

Speed Measurement System

Detection of speed difference on different axles of multi motor traction drive is important for anti-slip and anti-blocking control. Many traction drive systems [FRE99] [HEI95] have no speed-sensor and control systems are estimating speed using models and signals from voltage and current sensors. Separately magnetized traction drive requires accurate electromotive force feedback signal to avoid self-braking via freewheeling diodes of traction converter during freewheeling and braking. The direct measurement of electromotive force is complicated because of direct connection to boost converter. Speed sensor was developed by the author and is used for magnetization control of traction motors, for anti-slip control of multi-motor system and for control of mechanical brakes.

The electromotive force comparison via voltage relays can be used for speed difference detection, because it costs less than speed sensors on all axles. The use of speed sensors in all axles could allow more accurate anti-slip control compared to binary controllers with slow feedbacks and response.

There are two main possibilities for speed measurement for gear-integrated pulse sensor – counting of pulses in time interval or measuring time interval between pulses. The measurement of time interval between pulses allows smaller delay that is important for control. Angular speed of motor shaft using measurement system with 16-bit timer can be calculated accordingly:

$$\omega = \frac{2\pi}{60} \cdot \frac{\left(2^{16} - 1\right)}{n_t} \cdot k_{RPM} \,, \tag{3.5}$$

where n_t is discrete time interval measured using timer and k_{RPM} transfer gain for conversion of measured result to unit of rotates per minute (rpm). Transfer gain between motor shaft speed and discrete time interval of 16-bit timer is calculated using formula:

$$k_{RPM} = \frac{60 \cdot n}{z \cdot \left(2^{16} - 1\right) \cdot t_{CLK} \cdot 2^{Tx}} \,, \tag{3.6}$$

where t_{CLK} - period of timer clock signal (that is $t_{CLK} = 50\text{ns}$ on clock frequency 20 MHz), z – amount of pulses per turn on wheel axle (amount of gear wheel teeth), Tx – divisor of clock frequency and n – transfer ratio of gear.

The delay of the result depends on the speed when using the pulse sensor. The time between the pulses is longer at low speeds, thus the delay is longer. The measurement range of the timer is chosen according to the minimum permitted delay, the lowest measured speed value and clock frequency is chosen according to the required accuracy of speed measurement.

3.4.3. Reference of Field Weakening Intensity

Torque reference for DC traction motors in the fieldweakening range is set using the cascade control structure of excitation and the electromotive force shown in Fig. 3.18. Changes of the reference value of the electromotive force and its limits are defined differently in different operation ranges.

Additional fast and precise torque control uses the separate armature current controllers because of slow response (high inductance) of the excitation circuit. The reference value of the electromotive force in on-line operation modes is calculated according to the measured contact line voltage U_{dc} and field weakening intensity A_{ref}.

$$E_j = U_{dc} \cdot \left(0.9 - 0.1 \cdot A_{ref}\right), \tag{3.7}$$

where U_{dc} – voltage of DC-line (between 400...730 V on 600V line) and A_{ref} – reference intensity of field weakening. Voltage reserve is needed for separate control of bogie armature currents because of differences of motor electromotive forces and fluctuations in the contact line voltage. This is also included in reference value of electromotive force as the electromotive force of bogie is kept on 90% level from the contact line voltage. Differences in electromotive forces occur because of different motor parameters, wheel diameters, axle loads, and adhesion conditions. This is also necessary to avoid of self-braking and ensure drive stability on fluctuations in the contact line voltage, including the steep decrease of DC voltage or overshoot of motor electromotive force. Self-braking is dangerous to power semiconductor devices and can lead to unstable operation. Back electromotive force and thus voltage on the traction converter DC link can be higher than the line voltage only on the off-line operation mode. The reference value of the electromotive force

$$E_j = U_{DC\_NOM} \tag{3.8}$$

may be constant in that case and set to the nominal value of the contact line voltage $U_{DC\_NOM} = 600$ V.

3.5. Voltage Control on DC-link and Contact Line

The input choke and the capacitor bank of the power semiconductor stack form the LC-filter that is used for input current smoothing. Both pulses caused by switch-mode converter and disturbances caused by the contact line, such as arc on the pantograph, are smoothed. Components of DC-link are chosen to allow the operation of the traction drive in the required limits of the input voltage standard, existing voltages in real conditions, and could allow a sufficient power transfer to the contact-line or the brake-resistor. According to standard IEEE 11-2000 [IEEE11], the regenerative braking could increase the contact-line voltage locally.

The designed output voltage of substations and the input voltage of vehicles should be equalized, to enable the transfer of regenerated power to other vehicles and loads. Braking choppers and braking resistors are used to limit the DC link voltage according to the values in the line voltage standards and to protect against overvoltages. Braking choppers and braking resistors can also damp overvoltages caused by other vehicles on the on-line operation, such as driving, regenerative braking, and freewheeling, thus can improve voltage quality. In addition to active damping of overvoltages, the metal-oxide varistor based voltage limiting devices are used.

Boost converters cannot operate efficiently when the difference between the DC-link voltage and back electromotive force of motors increases over limit that does not allow regeneration to the line voltage level. Thus, off-line operation is needed to decrease the DC-link voltage and re-enable the electrodynamic braking mode. The opening of input contactors allows the reducing of the DC-link voltage. Lower voltage in the DC-link in off-line mode allows better control of the braking torque at low speeds and thus more stable supply of the excitation circuit of motors. Higher voltage in the DC-link allows the dissipation of higher power on the brake resistor. DC-link voltage in different modes of operation of the traction converter is shown in Fig. 3.21.

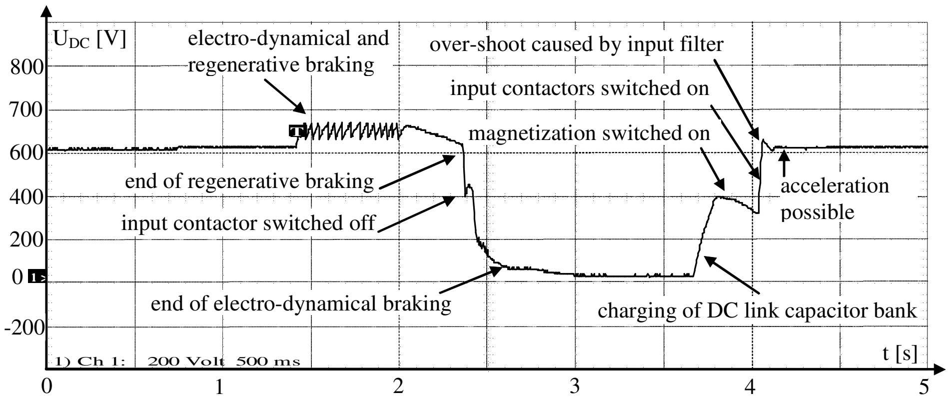


Fig. 3.21 **Voltage of converter DC-link on different modes of operation**

Voltage on the traction converter DC-link on freewheeling, regenerative braking, at the end of regeneration, on switching of input contactors, charging of the capacitor bank, and switching of the magnetization supply can be analyzed using recordings and oscilloscope picture shown in Fig. 3.21.

The decrease of the contact line voltage forces a decrease of the back electromotive forces of traction motors via excitation control to avoid self-braking. This leads to a decrease of the maximal value of motor voltage, maximal available traction force, maximal speed, and maximal acceleration in the fieldweakening mode. The driving mode is blocked and charging of the capacitor bank via the current limiting resistor is started when voltage in the DC-link drops below the lower limit (<400 V on 600 V line). This is needed to avoid input overcurrent caused by unintended charging of the DC-link capacitor bank. Driving over line-disconnector with voltage differences in different line-sections can cause transients in the DC-link voltage. Driving to the line-section with a higher voltage causes a high current charging pulse to the DC-link capacitor bank. Similar problems occur when driving on the contact-line covered with ice. Short oscillations occur on switching when the contact is retrieved. Input choke is used for smoothing of these pulses.

3.6. Protection System Design

3.6.1. Fault Symptoms

Different models are used for the detection of fault symptoms in the control system of the traction drive. Simple signal models are based only on filtering of signals, e.g. low pass filters and voltage level comparison. More complicated process models include multiple parameters of component signals and state, including component temperature. Safe operating areas of components are checked according to these models. These models depend on component parameters and can be linear or nonlinear. The system includes also integrated protection algorithms of intelligent components, such as intelligent power modules in addition to different signal and process models. The task of the control and protection system is to check and process these signals read from intelligent power modules [HER98]. The classification of protection algorithms according to a traction drive subsystem groups is shown in Fig. 3.22.

Traction motors	Brake system	Converters	Supply circuits	Control system
Overcurrent protection of motors	Monitoring of emergency brake signal	overvoltage protection of DC-link	Line input overcurrent protection	Monitoring of processing timestep
Monitoring of electromotive force and excitation	Monitoring of mechanical brake signals	Over-temperature protection of power modules	Over-temperature protection of charging resistor	Test and monitoring of reference controls
Monitoring of load distribution on multiple motors	Brake resistor protection via temperature model	Fast short-circuit protection via current and U_{ce}	Voltage monitoring of control system supply	Monitoring and testing of feedback signals
monitoring of motor cooling system	Traction motor current monitoring on braking	Output overcurrent protection		Memory test and drive status code monitoring

Fig. 3.22 Classification of protection signals via drive subsystem groups

Faults that can be detected via control system software are shown in Fig. 3.22 according to subsystem groups, such as traction motors, mechanical brakes, traction converters, supply circuits and control systems. Protection trip-levels can be set using appropriate diagnostic interface menus in the control system. Faults and malfunctioning can be caused by different vehicle failures but also different processes caused by faulty vehicles driven on the same contact line.

3.6.2. Fault Detection and Processing

A protection system has no effect on a system in stable operation, but it is needed in fault conditions. Error processing algorithm is started automatically when an error is detected. Errors have different risk levels, thus these are divided into different groups such as:

1. Errors and faults with high risk that are mostly related to dangerous failures of electrical or control circuits and could cause further damages (high risk, possible failure or breakdown).
2. Faults with low risk include faults that could be caused by external disturbance or temporary malfunctioning. This includes faults of control devices and sensors that do not block the stable operation of the traction drive.

All fault codes according to the symptoms are recorded in the error log with time and can be later analyzed using diagnostic software.

Power semiconductor stack has the following protections against damage and abnormal malfunctioning operation. The following protections exist in the hardware:

1. Intelligent power modules have internal short circuit protection and overcurrent protection. Short-circuit protection that is based on transistor collector-emitter voltage monitoring [ISH05] and current monitoring in parallel branches [TUR01] [HOF99]. These integrated protection algorithms block control signals and output the error signal. The control system has a second overcurrent protection system in addition to protection integrated in power modules. This is implemented using output current monitoring in the control system software. According to software filtering, both average and instantaneous values of currents can be used for fault detection. Protection in the supply input is ensured via a circuit braker, but control system software also includes additional overcurrent protection algorithms.
2. Overvoltage protection system has different levels. Voltage on the traction converter DC link is monitored via voltage sensors located in the intelligent power modules. Voltage is limited using the brake resistor and the chopper control. The system is switched off from the supply line when voltage rises over the allowed limit of electrolytic capacitor bank (>790 V on 600 V nominal line voltage). Short overvoltage pulses can be damped using metal-oxide varistors connected parallel to the supply input and DC-link.

Condition monitoring of functional blocks in the traction drive system is needed to avoid further damage and provide easier fault location. Following monitoring functions are applied in the system hardware.

1. Power semiconductor stack has an integrated temperature measurement of the cooling contact surface of transistor modules and over-temperature protection. When temperature rises over the allowed limit (115°C), the operation is blocked and an error signal is sent to the control system. Reasons of over-temperature can be different, such as failure of the cooling fan or the air filter jamming.
2. Monitoring of low voltage self-supply is integrated in intelligent power modules. Error output signal is set when voltage drops under the minimal level. In addition, control system software has several self-supply checking algorithms. The control system is checking input signal ranges, including positions of controls and buttons, program cycle limits etc. When these parameters exceed the allowed limits, then the fault is recorded in the error log and system operation is blocked.

3.7. Communication System Design

The use of automation networks, such as CAN, allows reducing the amount of wiring and distributed placing of equipment. Prototype tram no. 99 has panel-computer with touch screen on the driver panel instead of electromechanical displays. The panel-computer can access data from various on-board systems. The author developed communication interface for traction drive based on the Controller Area Network (CAN). The advantage of the intelligent displays that are based on panel-computer displays or microcontrollers is flexibility and communication capabilities over computer networks. Control systems of traction converters and the on-board controller are connected via the CAN network. Driver panel-computer is connected to the controller of the auxiliary on-board systems via the Ethernet network. The controller of on-board auxiliary systems is a gateway between the Ethernet and CAN networks. Thus, the CAN network (Fig. 3.23) operates separately from other systems and can be used as a drive-by-wire network for the traction drive and its primary controls.

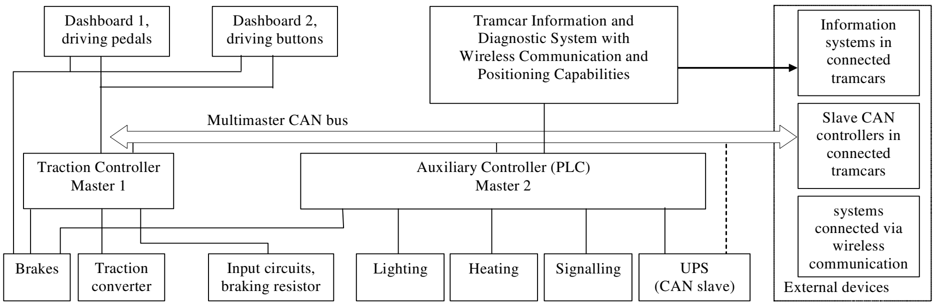
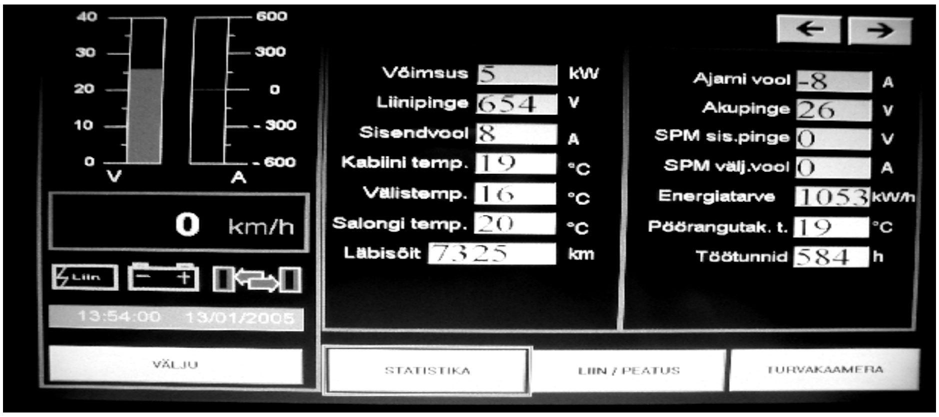


Fig. 3.23 Structure of CAN network of a prototype tram

Different networks are used for different purposes. Ethernet can be used for multimedia networks, RS-485 can be used for control of simple passenger displays, and CAN for drive-by-wire and powertrain management networks. In addition, programmable controllers, such as a programmable controller of traction drive and a controller of on-board systems have their programming interfaces that can be used for diagnostic purposes. The system described in Fig. 3.23 allow use of computer for driver panel displays. Panel computer can access operational information from the traction drive but also enables transmitting of operational information over the wireless network to the server database. The recorded information enables one to analyze vehicle condition, traffic conditions, and transmitted power. A picture from the driver panel computer [ROS04] with traction drive information is shown in Fig. 3.24.



0 km/h

13:54:00 13/01/2005

Võimsus 5 kW
Liinipinge 654 V
Sisendvool 8 A
Kabiini temp. 19 °C
Välistemp. 16 °C
Salongi temp. 20 °C
Läbisõit 7325 km

Ajami vool -8 A
Akupinge 26 V
SPM sis.pinge 0 V
SPM välj.vool 0 A
Energiatarve 1053 kW/h
Pöörangutak. t. 19 °C
Töötunnid 584 h

Fig. 3.24 Traction drive information on the display of the panel-computer

Traction drive displays in Fig. 3.24, such as power meter, speedometer and warning displays that are supplement to the information from warning indicators. Left side displays include values read from the traction drive, such as speed and power, right side includes traction drive statistics that can be viewed on the computer, such as distance, energy consumption, and time of operation. In addition to the computer, several other indicators are used.

The indicator of supply circuits shows that the driving mode is on and regenerative braking is possible. Brake resistor indicator shows the intensity of braking resistor use on combined electrodynamic and regenerative braking. Wheel slip indicator is used to detect of wheel slip in bad adhesion conditions and it allows the driver to reduce the traction force when needed and thus makes driving more convenient. These indicators are intended for helping the driver to select the driving style for reducing energy consumption, for effective use of regenerative braking and for avoiding of malfunctioning.

The operation modes, including braking capabilities of the traction drive are limited in the failure conditions, thus there is an indicator on the panel and a buzzer to inform the driver. To avoid damages to a vehicle and equipment, there are several locks in use. In addition, the operation of the traction drive is partially blocked when malfunctioning symptoms are detected. The driving mode is ensured only if several conditions are fulfilled, such as inactive brakes, closed ramp of a door, turn-passing mode is inactive, and failure signals are inactive. In some cases, only the warning signal is activated in the driver cab, such as driving with open door.

3.8. Configuration and Diagnostics Software

3.8.1. Memory for Configuration Settings

Control systems and software should be flexible and usable on vehicles with different configurations, such as vehicles with low-floor sections, vehicles with information systems, trailer vehicles etc. Different vehicles have different weight, power, maximal speed and configuration of control circuits that require changes in the control software.

The amount of electronic components and units is small in small-series vehicle production, reconstruction and modernization. Thus, keeping large component stock is not feasible. The design of the control system should consider possible changes and alternatives from component suppliers. Software should be able to detect different chip types. Different types of microcontroller modules are used that have a different amount of random access memory, flash memory and different clock chips. The hardware of the microcontroller and the connection of external memories and their supply are important for system configuration and memory of settings. Read only memory (ROM) is divided into two chip-groups on the microcontroller board. Control program firmware is protected against writing when the other part as user memory is byte wise writable and sector wise erasable. Writable part is used to record of fault log and to keep traction drive settings. In addition, random access memory (RAM) is divided into two groups where one is the battery supplied and usable for storing of actual values of the electricity meter and odometer. Adjustments of other parameters, such as the amount of pulses per wheel turn and wheel diameters are needed when different sensor types and configurations are used.

3.8.2. Development of Diagnostic Interface

The developed diagnostic interface allows monitoring of traction drive to help the maintenance staff on fault location, analysis and parameter tuning. Software works in the on-board control system and is accessible via client terminal program. The system is based on simple text menus that enable sending of diagnostic information, such as error messages and codes, to mobile and non-graphical terminal interfaces or personal computers.

Automatic self-testing of the control system

Initial system test (*Power-On Self Test*) is executed on powering of the system. This test consists of the memory test and the test of external devices. After the initial test, initial settings are read and checksum of the settings is calculated. An error message to the fault log is generated and settings are set to the initial values when the checksum does not match with the recorded one. The initial test screen, including the test of settings is shown in Fig. 3.25.

```
Start:
 Default           - FLASH bank 1
 ADDRSEL1 = 1006H - RAM bank 1
 ADDRSEL2 = 0000H - RAM bank 2
 ADDRSEL3 = 2006H - FLASH bank 2
 ADDRSEL4 = 4000H - Serial port 2
Loading settings:
 Flash-Devices:     AMD 29F010
 Flash-Area:        200000H-23FFFFH
 CurrentDevice    = 0424E6H
 FstWriteAddr     = 20AAAAH,        SndWriteAddr  = 205554H
 Settings from 238000H  Incorrect checksum: CRC=0C28, readCRC=FFFF
Converting default settings:
 Processing settings... Clock not set.
 F_m_mod
 F_a_mod
 F_br_mod
 U_brt
 Idp_m, Idppk_m
 Idp_a, Idppk_a
 Idp_br, Idppk_br
 Udp_max, Udp_min, Udp_on
 Idc_switch
 Ia_brake
 Va_acc
 BR_off_I
 BR_on_speed
 BR0U_on_speed
 BR_chopper_off
 BR_chopper_on
 Brake_chopper_off
 Brake_chopper_on
 Ir_aa_max
 Ir_aa_min
 Ir_ab_max
 V_max
 Ir_m_max
 Ir_m_min
 V_fldwk_start
 ABS_br_tmax, ABS_tblank, ABS_Umin
 NO FLASH SETTINGS
```

Fig. 3.25 Names of checked system variables that are printed on diagnostic computer during system start-up

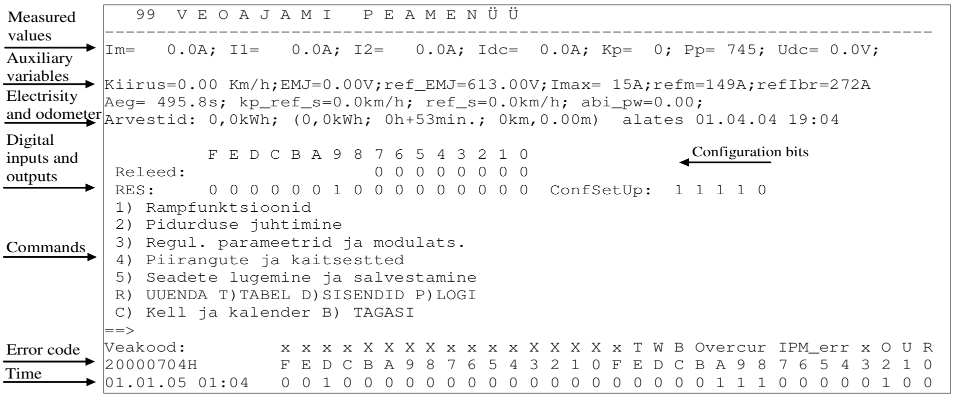
The main menu for maintenance shown in Fig. 3.26 is displayed after checking and application of settings shown in Fig. 3.25.

3.8.3. Menu-system for Configuration and Diagnostics

Software consists of menus for both installation and maintenance. Tuning functions are divided into separate sub-menus. Several menus were developed because of different vehicle configuration used, such as drive parameter menu for controller parameters, protection-setting menu for protection trip-levels, driving acceleration settings menu for ramp function tuning and brake settings. These allow adjusting of parameters according to the vehicle and brakes. Frequently used maintenance menus and settings are located in separate settings menu that also includes clock settings, clearing of error memory and clearing of meters with initial date recording.

Diagnostic menu for maintenance

Diagnostic menu is intended for maintenance and allows monitoring of different parameters during drive operation including parameter recording to hard disk of the maintenance computer during tests in traffic conditions. Different parameters can be monitored, such as state parameters, reference signals (pedal positions), measurement results of voltage and current sensors (feedback signals), state variables of pulse counters (speed and position), controller states (values of numerical integrators), work parameters of power and measurement circuits, and operation mode codes including error codes.



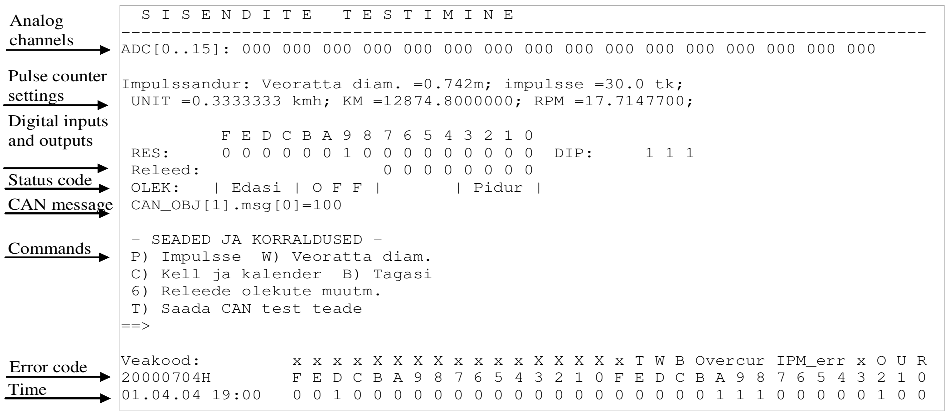
```
   99  V E O A J A M I   P E A M E N Ü Ü
--------------------------------------------------------------------------------
Im=   0.0A; I1=   0.0A; I2=   0.0A; Idc=  0.0A; Kp=  0; Pp= 745; Udc= 0.0V;

Kiirus=0.00 Km/h;EMJ=0.00V;ref_EMJ=613.00V;Imax= 15A;refm=149A;refIbr=272A
Aeg= 495.8s; kp_ref_s=0.0km/h; ref_s=0.0km/h; abi_pw=0.00;
Arvestid: 0,0kWh; (0,0kWh; 0h+53min.; 0km,0.00m)  alates 01.04.04 19:04

          F E D C B A 9 8 7 6 5 4 3 2 1 0
 Releed:                  0 0 0 0 0 0 0 0
 RES:     0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0  ConfSetUp:  1 1 1 1 0
 1) Rampfunktsioonid
 2) Pidurduse juhtimine
 3) Regul. parameetrid ja modulats.
 4) Piirangute ja kaitsestted
 5) Seadete lugemine ja salvestamine
 R) UUENDA T)TABEL D)SISENDID P)LOGI
 C) Kell ja kalender B) TAGASI
==>
Veakood:         x x x x X X X X x x x x X X X X x T W B Overcur IPM_err x O U R
20000704H        F E D C B A 9 8 7 6 5 4 3 2 1 0 F E D C B A 9 8 7 6 5 4 3 2 1 0
01.01.05 01:04   0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 1 0 0
```

Fig. 3.26 Drive parameter monitoring in diagnostic interface

The menu used for parameter monitoring is shown in Fig. 3.26. Both measured parameters and parameters calculated from the models are also accessible via this menu. States of input signals and error code flags are also included into this menu. Sub-menus branching from the diagnostic menu are excerpt menus for making excerpts of the error log and meters, testing menu for monitoring of inputs and outputs and the data-recording menu for data logging during test in traffic conditions.

3.8.4. Tuning and Testing of Analog Input Channels

Additional menus are needed for system developers and testers. These menus allow changing of parameters for testing. Thus, these menus can be used for development, assembly of testing of a new drive system. An input-testing menu allows testing of power and measurement circuits. Power circuit testing and communication system testing functions are also provided. The menu for monitoring of input signals is shown in Fig. 3.27. Unprocessed raw values read from the analog-digital converter channels are displayed without the conversion to SI system. This allows testing and tuning of analog channels. Special simulators can be used for automated testing of control systems used in traction drives [BIA00].



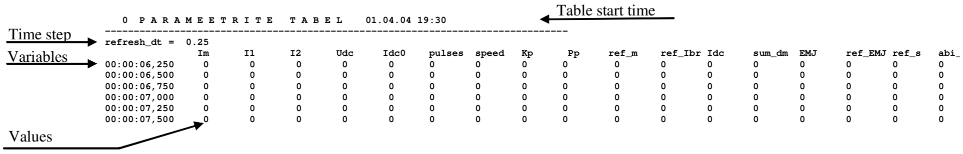
```
  S I S E N D I T E   T E S T I M I N E
--------------------------------------------------------------------------------
ADC[0..15]: 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000 000

Impulssandur: Veoratta diam. =0.742m; impulsse =30.0 tk;
 UNIT =0.3333333 kmh; KM =12874.8000000; RPM =17.7147700;

          F E D C B A 9 8 7 6 5 4 3 2 1 0
 RES:     0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0  DIP:     1 1 1
 Releed:                  0 0 0 0 0 0 0 0
 OLEK:   | Edasi | O F F |       | Pidur |
 CAN_OBJ[1].msg[0]=100

 - SEADED JA KORRALDUSED -
 P) Impulsse  W) Veoratta diam.
 C) Kell ja kalender  B) Tagasi
 6) Releede olekute muutm.
 T) Saada CAN test teade
==>

Veakood:          x x x x X X X X x x x x X X X X x T W B Overcur IPM_err x O U R
20000704H         F E D C B A 9 8 7 6 5 4 3 2 1 0 F E D C B A 9 8 7 6 5 4 3 2 1 0
01.04.04 19:00    0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 1 0 0
```

Fig. 3.27 Menu interface for testing of microcontroller inputs and outputs

The developed software of the control unit allows testing of inputs using the external controllable signal generator. For safety reasons, inputs and outputs of the control unit are checked before testing of power circuits. Power circuits of the drive are tested together with the control unit and sensors. Power circuit tests are started with low voltages <5V that allows safe testing of measurement channels and outputs of power modules.

3.9. Experiments with Driving Cycle Recorder

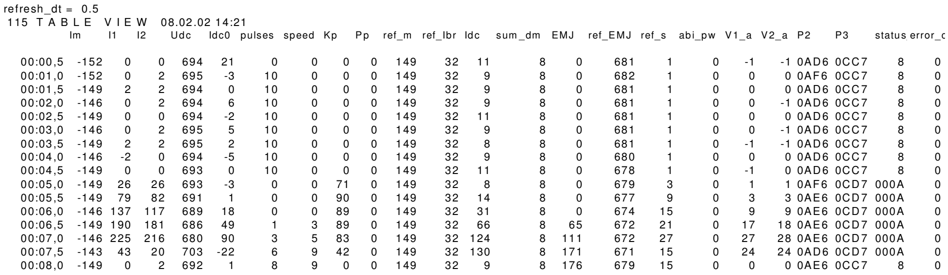
Recording of electrical and mechanical parameters during test-driving allows analyzing of faults and malfunctioning modes of operation. Data is recorded to the hard disk of notebook computer in the table form. Suitable output interval can be set for data output. Time interval has been set to half a second, an example shown in Fig. 3.28. All the variables that are viewable in the diagnostic menu can also be recorded to the hard disk.



```
   0 P A R A M E E T R I T E   T A B E L    01.04.04 19:30
-----------------------------------------------------------------------------
refresh_dt =  0.25
                 Im       I1       I2       Udc      Idc0     pulses  speed   Kp      Pp       ref_m    ref_Ibr Idc      sum_dm  EMJ      ref_EMJ ref_s    abi_
00:00:06,250     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
00:00:06,500     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
00:00:06,750     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
00:00:07,000     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
00:00:07,250     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
00:00:07,500     0        0        0        0        0        0       0       0       0        0        0       0        0       0        0       0        0
```

Fig. 3.28 Printout of recorded variables in the table form

The recorded values can be viewed and processed in spreadsheet programs, such as Microsoft Excel, Calc, etc. Spreadsheet software allows converting of values to a suitable form and printing out as tables or charts. These systems include all the necessary tools for converting charts to the printable form. Spreadsheet with column headings is shown in Fig. 3.29.



refresh_dt = 0.5
115 TABLE VIEW 08.02.02 14:21

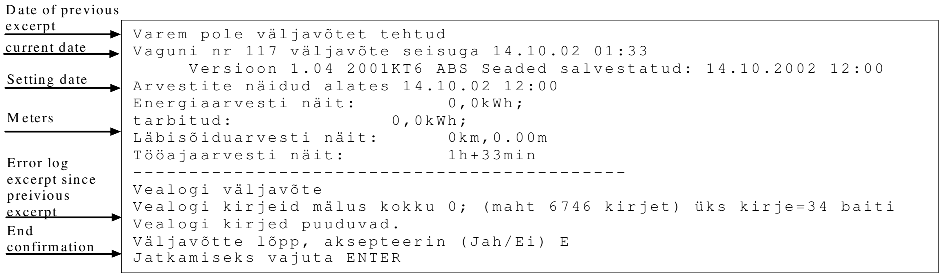
	Im	I1	I2	Udc	Idc0	pulses	speed	Kp	Pp	ref_m	ref_Ibr	Idc	sum_dm	EMJ	ref_EMJ	ref_s	abi_pw	V1_a	V2_a	P2	P3	status	error_c
00:00,5	-152	0	0	694	21	0	0	0	0	149	32	11	8	0	681	1	0	-1	-1	0AD6	0CC7	8	0
00:01,0	-152	0	2	695	-3	10	0	0	0	149	32	9	8	0	682	1	0	0	0	0AF6	0CC7	8	0
00:01,5	-149	2	2	694	0	10	0	0	0	149	32	9	8	0	681	1	0	0	0	0AD6	0CC7	8	0
00:02,0	-146	0	2	694	6	10	0	0	0	149	32	9	8	0	681	1	0	0	-1	0AD6	0CC7	8	0
00:02,5	-149	0	0	694	-2	10	0	0	0	149	32	11	8	0	681	1	0	0	0	0AD6	0CC7	8	0
00:03,0	-146	0	2	695	5	10	0	0	0	149	32	9	8	0	681	1	0	0	-1	0AD6	0CC7	8	0
00:03,5	-149	2	2	695	2	10	0	0	0	149	32	8	8	0	681	1	0	-1	-1	0AD6	0CC7	8	0
00:04,0	-146	-2	0	694	-5	10	0	0	0	149	32	9	8	0	680	1	0	0	0	0AD6	0CC7	8	0
00:04,5	-149	0	0	693	0	10	0	0	0	149	32	11	8	0	678	1	0	-1	0	0AD6	0CC7	8	0
00:05,0	-149	26	26	693	-3	0	0	71	0	149	32	8	8	0	679	3	0	1	1	0AF6	0CD7	000A	0
00:05,5	-149	79	82	691	1	0	0	90	0	149	32	14	8	0	677	9	0	3	3	0AE6	0CD7	000A	0
00:06,0	-146	137	117	689	18	0	0	89	0	149	32	31	8	0	674	15	0	9	9	0AE6	0CD7	000A	0
00:06,5	-149	190	181	686	49	1	3	89	0	149	32	66	8	65	672	21	0	17	18	0AE6	0CD7	000A	0
00:07,0	-146	225	216	680	90	3	5	83	0	149	32	124	8	111	672	27	0	27	28	0AE6	0CD7	000A	0
00:07,5	-143	43	20	703	-22	6	9	42	0	149	32	130	8	171	671	15	0	24	24	0AD6	0CD7	000A	0
00:08,0	-149	0	2	692	1	8	9	0	0	149	32	9	8	176	679	15	0	0	0	0AE6	0CC7	8	0

Fig. 3.29 Processing of measured parameters using spreadsheet program

Recorded parameters in the table columns are shown in Fig. 3.29. The first column is time and the table includes both directly measured and calculated parameters. Hours, minutes and seconds are separated using colons and fraction part can be separated with a comma or a point depending on the language. Data is exported according to Estonian standard [EVS8] according to the needs of the user. Spreadsheet programs and tables of recorded data allow graphical view of the recordings.

3.10. Electricity meter and Odometer

Traction converters are equipped with software-based electricity meter and odometer. Software-based metering functions enable continuous monitoring of the consumed energy and driven distance. Consumed energy and driven distance can be read and monitored via diagnostic or maintenance computer connected to the on-board control system. Printed variables include the consumed energy in kWh, consuming time in seconds, driven distance and the last date of clearing these values. To take into account the consumed energy at a certain time, initial values are needed. Thus, it is reasonable to have a notebook for writing the last values. The excerpt program (Fig. 3.30) records the meter values automatically for the next excerpt.



```
Varem pole väljavõtet tehtud
Vaguni nr 117 väljavõte seisuga 14.10.02 01:33
     Versioon 1.04 2001KT6 ABS Seaded salvestatud: 14.10.2002 12:00
Arvestite näidud alates 14.10.02 12:00
Energiaarvesti näit:        0,0kWh;
tarbitud:              0,0kWh;
Läbisõiduarvesti näit:      0km,0.00m
Tööajaarvesti näit:         1h+33min
--------------------------------------------
Vealogi väljavõte
Vealogi kirjeid mälus kokku 0; (maht 6746 kirjet) üks kirje=34 baiti
Vealogi kirjed puuduvad.
Väljavõtte lõpp, aksepteerin (Jah/Ei) E
Jatkamiseks vajuta ENTER
```

Fig. 3.30 Excerpt from electricity meter and odometer

The excerpt function shown in Fig. 3.30 allow detailed information about the consumed and regenerated energy in a certain period since the last excerpt.

4. FUTURE RESEARCH AND DEVELOPMENT

4.1. Future Research Topics

Several additional topics to be studied have appeared during the investigation of the topics described in the thesis.

Use of energy storage devices for reduction of line voltage-drop
Usage of more powerful vehicles in the network with a sparse-placed substation causes voltage-drop problems in the far line section. Energy-storage substations are available nowadays to compensate voltage-drops. Usage of ultra-capacitor modules in storage substations is efficient and feasible in networks with lower voltage (trams, trolleybuses and metros) due to series connection of ultra-capacitors. Energy storage substations also allow storing energy of regenerative braking in networks with non-reversible and sparse-located distributed supply substations. The use of energy-storage substations could become feasible with higher traffic intensity. If the usage of energy-storage devices in vehicles is expensive, and not feasible then these can be applied in substations for the improvement of voltage quality.

Management and communication of drives and converters
Use of communication networks allows better allocation of controllable intelligent devices in a vehicle, thus the amount of wiring can be reduced. Also, control possibilities of energy exchange appear with other in-vehicle systems. Traffic control systems for the minimization of energy consumption could allow improved use of regenerative braking energy. In conjunction with the use of new energy storage devices, the in-vehicle energy management, including the optimization of energy management in autonomous vehicles, becomes more important.

Models of vehicles, traction drives, and supply converters
The developed methods, equipment and models are already used in several research and development projects of Tallinn University of Technology, including for the development of a control converter for an energy storage unit and on-board supply converters. Further development of models could allow including detailed models of inertia that could enable detailed operation analysis of low-floor sections. Detailed modelling of mechanical brakes could allow simulation of braking modes of tram-train with mechanical brakes. Detailed modelling of freewheeling axles and axles with only mechanical brakes could allow detailed research of braking processes in many vehicle types, including in vehicles with low-floor sections.

Medium-voltage drives

The research of control of converters in medium-voltage and multi-system drives is required for application of such drives and converters in vehicles. Research of protection and switching, and other algorithms is necessary for safety and reliability of vehicles with a multi-system supply. In these systems limiting of the over-voltages on the motor windings using hardware and software-based methods and different modulation types is important. The application of new power semiconductor devices could require more detailed investigation and modelling of parasitic parameters, losses and energy exchange.

Electronically commutated traction motors

The development of new low-floor vehicles could require application of new compact brushless motors in new low-floor bogies. Thus control methods for AC and especially for induction motors and traction converters with AC output should be investigated and developed. Brushless DC traction motors that are widely applied on low power and off-road vehicles could soon become applicable in light-rail vehicles. Permanent magnet and switched reluctance traction motors and improvement of their control methods need to be studied. Optimal control of new traction motors in a wide speed range and their protection against failures and malfunctioning in multi-motor systems require detailed investigation.

Control of low-floor vehicle bogies

The study of parallel supply and torque equalization between wheels and axles is needed for the improvement of the operation of new traction motors. Also, parallel operation of induction motors has to be investigated. The control of bend passing and bogie-turn problems is very important on the control of low-floor vehicles without through axles.

Voltage quality of traction and auxiliary converters

Problems to be studied in the field of construction and control of converters for electric vehicles are: flexible converters with high efficiency applicable for different types of motor, control of multi-level converters and problems involved in electromagnetic compatibility (EMC). These problems are tightly bound with the control methods of converters - like modulation, switching frequency and patterns. Areas of application of converters with soft switching and hard switching should be defined in electric traction. Soft switching converters allow high switching frequencies, but their disadvantage is complexity and a large amount of components that means additional losses.

New power semiconductor devices

Application possibilities of new power semiconductor devices, like high-blocking 6.5kV IGBTs and ultra-fast silicon carbide reverse diodes, require additional research.

4.2. Future Development

Further research and development work is required to extend the areas of application of practical results introduced in this thesis for different traction systems.

Hardware of control units
Additional modules are to be developed to increase flexibility. Developed modules have been used also in auxiliary power converters and in the research of energy storage devices in addition to the traction controller. Further development is also related to the usage of the developed system in AC drives and converters. Improvements of testing and tuning possibilities of measurement modules and development of intelligent (with microcontroller) power supplies with a wide input voltage range are important in the further development. It is related to technology and production, in particular to improvements in the mechanical construction and electromagnetic compatibility. To achieve compactness, new automated assembly of surface-mount components can be applied.

Further development of in-vehicle communication networks
Standardized communication protocols should be used in vehicles, such as CAN and Ethernet because these allow flexible application of components from different producers and allow integrating different systems. The development of supplements for drive control software and communication interfaces is needed for synchronizing traction drives in tram-trains. Usage of different mechanical interfaces and connectors with different communication networks should be analyzed. The development of standardized application protocols based on protocols like *CANopen* and *TCP/IP* could allow improvements in flexibility and compatibility with different components and products.

Further development of control panels, controls and user interfaces
Hand controls are used in many rail vehicles. Thus, support for different hand controller types should be added to the control system. This is also related to the application of standardized communication protocols and intelligent controls. For further development of driver control panels the *Linux* operating system can be applied instead of *Microsoft Windows* that allows reduction of the overall price of the system. Standardized programming languages can be used for the development instead of expensive process visualization software. Functional buttons can be used instead of touch-screen in cheaper panel-products. Improvements of diagnostics software include further modelling of malfunctioning and errors for better location of faults and development of a maintenance expert system. Completely or partially automated rail vehicles with artificial intelligence can be applied in the near future. Thus, user interfaces of such systems require detailed research.

4.3. Recommendations for Vehicle Operators

For effective application of results introduced in this thesis several recommendations are given for vehicle operator companies.

1. Training of vehicle drivers should be continuously improved to ensure compliance with the recent level of technology and comfortable, economical and safe driving.

2. Technical equipment of vehicles should be developed to improve comfort and attraction of public transportation.

3. The use of obsolete vehicles with rheostat-control should be reduced for efficient use of energy including regenerative braking energy.

4. Vehicles should be continuously renovated to reduce consumption of electrical energy and improve comfort of passengers.

5. Diagnostic and energy consumption information should be collected, to avoid failures, traffic-jams. Maintenance staff should take continuous training.

6. Renovate and repair road and rails to increase lifetime of vehicles

7. Renovate in-vehicle supply wiring to increase lifetime of equipment and for reduction of failures.

8. Renovate traction substation to enable voltage control, to improve voltage quality, and to enable shutting down of non-loaded transformers.

9. Thermal insulation of vehicles can be improved to reduce losses in Estonian climate conditions.

10. New vehicles are needed to replace vehicles after wear-out it the renovation is not feasible.

CONCLUSION

The main theoretical results are methods for the development of model-based control systems for electric vehicle traction drives and converters.

The following novel methods and theoretical aspects are introduced in the thesis:

1. Technical properties of traction drive systems have been analyzed [LAU02] according to the possibilities of new technologies. Based on the comparison of analyzed traction drives, a universal design solution was developed which was also registered as a utility model [EE332U] in Estonian Patent Office. The developed hardware is also applicable in powerful industrial drive applications.
2. A generalized modular structure for modelling of multi-motor traction drives has been developed, including its SIMULINK representation. Models are used to implement control functions and new software based solutions. For the development of these models, an experimental study was carried out in the laboratory, tram depot and during vehicle operation in traffic. The modular structure enables separate development of component models and assembly of complete model of the vehicle. The complete vehicle model can be used to investigate multi-motor drive operation in different dynamic operation modes. Experimental testing of all operation and malfunctioning modes is not possible in traffic [LEH03] because of the amount of labour required, high risks and high costs of experiments.
3. A new model-based control method for multi-motor traction drives with DC motors has been introduced in the thesis. Methods for the control of multi-motor traction drive with common magnetization circuit have been developed, including hardware for the control of traction drive and model-based or software-based solutions for all the required functions [LEH05]. Model-based control of a separately magnetized DC traction motor has been investigated in detail.
4. The control algorithm of an electro-dynamic antilock braking system has been developed.
5. An analysis of operation modes [LEH04] in separately magnetized DC traction drive is provided in chapters describing modelling and design. This is needed for the development of control functions and protection algorithms, including the analysis of faults in different operation modes (for the application of diagnostic methods).
6. Design method of modern traction converter hardware and software and other technical challenges are introduced in the chapter describing design. One important part of this is the modelling of the control object and components. Existence of exact models about system components allows a significant reduction of experiments and efforts made for tuning and testing of these systems.

The **practical result** is in the intellectual property applicable in further control system designs. Technical information such as circuit drawings, instructions and program listings are not included, but their general principles have been introduced in utility models and patents. According to practical results the following products can be formed:

1. Control unit hardware developed by the author of the thesis is applicable to the control of different drives and supply converters. The use of fibre-optic connections allows locating the control unit away from the power unit that improves its operation in the case of possible failures or disturbances from the power circuit.

2. Testing principles, instructions, equipment and software have been developed for series production. The software developed by the author allows functional testing and tuning of control system cards.

3. Control software for microprocessor controlled traction drive has been developed and applied on 28 trams in Tallinn Tram Fleet. The developed software can be adapted for the control of different vehicles and traction drives.

4. Traction converter power unit registered [EE332U] as a utility model was designed for the control system and software developed by the author of the thesis.

5. Data for computer-aided manufacturing (CAM) of printed circuit boards (PCBs) were prepared by the author. These have been used for small-series production of 28 control systems. Assembly instructions have been developed to allow assembly of control units with different configurations. The developed hardware is also applicable for control of other power-semiconductor converters and drives.

6. Test methods for series production and troubleshooting algorithms for maintenance and repair have been developed.

7. Diagnostic interfaces based on the CAN-bus have been developed. Linking the traction drive with the CAN-bus that is widely spread in vehicles enables connection of the traction drive with other in-vehicle systems. This allows monitoring of traction drive operation modes and enables possibilities for further application on rail vehicles of different types. Further integration of traction drive and its control system to the vehicle energy management and

general traffic control and management system should be possible. This also assumes the existence of models and standardized communication protocols. The author of this thesis has developed the communication systems for traction drive and auxiliary power supply.

8. The thesis provides an overview of the developed models that are applicable to research and development of different electrical drives. A special *model library* has been developed for developers of traction drive systems. The modular structure allows its further development in a flexible modular way, thus changing of components allow replacing software partially without changing the entire structure. Adding parameters on these blocks enables assembly of different pre-configured blocks for different rail-vehicles, including trams.

9. Electrical part is original and applicable to specific configurations, but the control method block diagrams are applicable also to other types of electric vehicles that are supplied via the contact line.

The author has published 15 pre-reviewed international publications on subjects related to the thesis, five of these are also included in the international database Inspec and accessible via the Internet, one is also accessible via the IEEE database.

1. The author has reported his results at conferences EPE-PEMC 2004, BEC 2004, CPE 2003, IEE Power Electronics and Variable Speed Drives 2000, etc. during writing of the thesis.
2. Systems produced in small-series have been applied on 28 trams in Tallinn Tram Fleet.
3. The traction converter and an auxiliary power supply have been registered as Estonian utility models.
4. The products developed have been introduced at exhibitions in Estonia (Tallinn) and abroad (Riga, Dresden, etc.).
5. Besides practical development, the author has published 15 international publications on research subjects related to the thesis.

References

[8NGTW] *Elektrische Ausrüstungen für Niederflur-Strassenbahn 8NGTW Der Kasseler Verkehrsgesellschaft AG* /Vossloh Kiepe GmbH, http://www.kiepe-elektrik.com/schienenfahrzeuge/kassel/, 20.07.2006

[AÇI04] Açıkbaş, S., Söylemez, M.T. *Energy loss comparison between 750 VDC and 1500 VDC power supply systems using rail power simulation.* Computers in Railways IX; Dresden, Germany, 2004. pp. 951-960.

[BEA98] Beaton, R. J., Andre, T., Bangor, A., Barker, J., Ho Chung, K., DiDomenico, A., Grenville, D., McCreary, F., Olsen, E. *Legibility of In-Vehicle Displays.*, Virginia, 1998 http://filebox.vt.edu/users/eolsen/files/papers/andre_bangor_barker_chung_didomenico_grenville_mccreary_olsen_1998.pdf, 21.07.2006

[BER00] Bernet, S. *Developments of High Power Converters for Industry and Traction Applications.* IEEE Transactions on Power Electronics, Vol. 15 (6), 2000, pp. 1102-1117.

[BIS98] Bishop, Arthur Ernest; *Self-steering railway bogie*. US5730064, Patent, 24.03.1998

[BOD01] Bodson, J. M., Colasse, A., Masselus, J. E., Zorzynski, D. *3kV refurbishment chopper designed with 6,5kV IGBT modules.* EPE'2001: European Conference on Power Electronics and Applications, Graz, Austria, 2001, 10 p. on CD-ROM

[BOD99] Bodson, J. M., Bou Saada, J., Colasse, A., Colignon, P., Delporte, L., Masselus, J. E., Mathys, P., Osée, M. *Study of direct series connection of IGBT for a 3 kV chopper.* EPE'99: European Conference on Power Electronics and Applications, Lausanne, Switzerland, 1999, 9 p. on CD-ROM

[BOI04] Boiko, V., Laugis, J. *Behavior of the Dual-Motor Traction Drives in the Different Operation Modes.* 11-th International Power Electronics and Motion Control Conference, ISBN 9984-320707, September 2-4, Latvia: Riga Tech. University, 2004

[BOStrab] *Straßenbahn-Bau- und Betriebsordnung.*BGBl. I S. 2648, 1987 http://www.rechtliches.de/info_BOStrab.html, 21.07.2006

[BOU03] Bouscayrol, A., Delarue, Ph. *Weighted control of drives with series connected DC machines.* IEMDC'03: IEEE International Electric Machines and Drives Conference, 2003, pp. 159-165.

[BRI03] Briginshaw, D. *First tram-train line in Paris opens in 2005 Rapid Transit: Light Rail Innovations.* International Railway Journal 7/1/2003

[CHA01] Chang, C.S., Khambadkone, A., Zhao Xu *Modelling and Simulation of DC Transit System with VSI-fed Induction Motor Driven Train Using PSB/MATLAB*. 4-th IEEE International Conference on Power Electronics and Drive Systems, Vol. 2, 2001, pp. 881-885.

[CHA02] Chang, C.S., Khambadkone, A., Kumar, S. *Fast, accurate and stable simulation of power electronic systems using virtual resistors and capacitors.* IEE Proceedings - Electric Power Applications, Vol. 149, (5), 2002, pp. 385-394.

[CHA03] Chapman, P.L., Krein, P.T. *Motor Re-Rating for Traction Applications – Field Weakening Revisited.* IEMDC'03: IEEE International Electric Machines and Drives Conference, Vol. 3**,** 2003, pp. 1388-1391.

[CHA97] Chan, C.,C., Chau, K. T. *An Overview of Power Electronics in Electric Vehicles.* IEEE Transactions on Industrial Electronics, VOL. 44 (1), 1997, pp. 3-13.

[CHE02] Cheli, F., Corradi, R., Mapelli, F., Mauri, M. *Motion Control of a Bogie with Independently Motorized Wheels.* EPE-PEMC 2002: 10-th International Power Electronics and Motion Control Conference, ISBN 953-184-046-6, Cavatat & Dubrovnik, 2002

[CHU01] Chu, C.L., Tsai, M.C., Chen, H.Y. *Torque control of brushless DC motors applied to electric vehicles.* IEMDC 2001: IEEE International Electric Machines and Drives Conference, 2001, pp. 82-87.

[DAY02] Day, T.D., Roberts, S.G. *A Simulation Model for Vehicle Braking Systems Fitted with ABS*. SAE Technical Paper Series, 0559, Reprinted From: Accident Reconstruction 2002, SP-1666, Society of Automotive Engineers, 2002, 19 p.

[EE332U] Joller, J., Lehtla, M., Laugis, J., Heinvere, U. *Elektrisõiduki veomuundur*. EE00332U1, The Estonian Patent Office 15.10.2002; Applicant: Tallinn University of Technology.

[EN50163] *Railway applications - Supply voltages of traction systems*. Standard EN 50163, European Committee for Electrotechnical Standardization, 2004

[EN50207] *Electronic power converters for rolling stock*, European Committee for Electrotechnical Standardization, 2000

[EVS8] *Requirements on Information Technology in Estonian Language and Cultural Environment*. Standard EVS 8:2000, Estonian Centre for Standardisation, 2000

[FLI93] Flinders, F., Senini, S., Oghanna, W. *Mixed Electrical and Mechanical Simulations using Dynamic Systems Analysis Packages.* IEEE/ASME Joint Railroad Conference, 1993, pp. 87-93.

[FLI97] Flinders, F., Oghanna, W. *Simulation of a Complex Traction PWM Rectifier using SIMULINK and the Dynamic Node Technique.* IECON 97: 23rd International Conference on Industrial Electronics, Control and Instrumentation, Vol. 2, 1997, pp. 738-743.

[FRE99] Frenzke, T., Hoffmann, F., Langer, H.G. *Speed Sensorless Control of Traction Drives – Experiences on Vehicles.* EPE'99: European Conference on Power Electronics and Applications, Lausanne, 1999, 7 p. on CD-ROM

[FRY03] Frylmark, D., Johnsson, S. *Automatic Slip Control for Railway Vehicles* Master's thesis performed in Vehicular Systems, LiTH-ISY-EX-3366-2003, 6-th February, 2003

[FUC99] Fuchs, A., Friedrich, T., Marquardt, R. *Advanced multi-system locomotives using 6.5 kV-power semiconductors.* EPE'99: European Conference on Power Electronics and Applications, Lausanne, Switzerland, 1999, 6 p. on CD-ROM

[GAD97] Gadjár, T. Rudas, I., Suda, Y. *Neural network based estimation of friction coefficient of wheel and rail.* IEEE International Conference on Intelligent Engineering Systems, 1997, pp. 315-318.

[GAN02] *Ganz Transelektro Traction Electrics Co. Ltd.: Reconstructed Four-Axle Tramcar for the Riga Tram and Trolleybus Company (Latvia) 1999-2002,* http://www.traction-ganztrans.hu /en/products/vehicles/8.php, 20.07.2006

[GAY02] Gay, S., Ehsani, M. *On-board Electrically Peaking Drive Train for Electric Railway Vehicles.* IEEE 56-th Vehicular Technology Conference, Vol.2, IEEE, 2002, pp. 998-1001.

[GEL95] Gelder, R., Overbeeke, F. *A Universal traction drive system with minimal levels of interference currents for use on AC and DC supply systems.* International Conference on Electric Railways in a United Europe; IEE Publications No. 405, 1995, pp. 101-105.

[GLI03] Glinka, M., Marquardt, R. *A New Single Phase AC/AC-Multilevel Converter For Traction Vehicles Operating On AC Line Voltage.* EPE'2003: European Conference on Power Electronics and Applications, ISBN 90-75815-07-7, Toulouse, 2003, 10 p. on CD-ROM

[GUI04] *Guideline for In-vehicle Display Systems*, Japan Automobile Manufacturers Association, 2004, http://www.jama.or.jp/safe/guideline/pdf/jama_guideline_v30_en.pdf, 21.07.2006

[GUS95] Gustafsson, F. *Slip-based estimation of tire - road friction.* Technical Report LiTH-ISY-R-1755, Sweden: Linköping, Department of Electrical Engineering, Linköpings Universitet, 1995,ftp.control.isy.liu.se/pub/Reports/1995/1730.ps.Z, 21.07.06

[GUS98] Gustafson, F. *Monitoring tire-road friction using the wheel slip.* IEEE Control Systems Magazine, Vol. 18 (4), 1998, pp. 42-49.

[HAD00] Hadeler, R., Mathony, H.J. *Design of Intelligent Body Networks.* SAE Technical paper series, 0152, Reprinted from: In-Vehicle Networks SP-1509, Society of Automotive Engineers, 2000, 8 p.

[HEI95] Heino, T. *NAC - Kokeiluraitiovaunu HKL 11.* Verkkolehti Raitio 3/1995, Finnish Tramway Society, http://www.nettilinja.fi/~ahellman/historia/nac.htm, 21.07.06

[HER98] Herzer, R., Schimanek, E., Bokeloh, C., Lehmann, J. *A universal smart control IC for high-power IGBT applications.* IEEE International Conference on Electronics, Circuits and Systems, ISBN 0780350081, Vol. 3, Lisboa, Portugal, 1998, pp. 467-470.

[HIL94] Hill, R.J. *Electric Railway Traction. I. Electric traction and DC traction motor drives.* IEE Power Engineering Journal, 1994, pp. 47-56.

[HIL96] Hill, R.J., Lamacq, J. *Railway traction vehicle electro-mechanical simulation using SIMULINK.* Proc. of 5-th International Conference on Computer Aided Design, Manufacturing and Operation in the Railway, 1996, pp. 81-90.

[HIL97] Hill, R.J., de la Vassière, J.-F. *A fuzzy wheel-rail adhesion model for rail traction.* EPE'97: European Conference on Power Electronics and Applications, Vol. 3. Norway: Trondheim, 1997, pp. 3416-3421.

[HOF99] Hofer-Noser, P., Karrer, N. *Monitoring of paralleled IGBT/diode modules.* IEEE Transactions on Power Electronics, ISSN: 0885-8993, Vol. 14/3, 1999, pp. 438-444.

[HOR98] Hori,Y., Toyoda, Y., Tsuruoka, Y. *Traction Control of Electric Vehicle.*, IEEE Transactions on Industry Applications, Vol. 34 (5), 1998, pp. 1131-1138.

[HOR99] Horie, A., Mizobuchi, T., Nakamura, K. *Efficient Train Traction System That Reduces Maintenance Work.* Hitachi Review, Vol. 48 (3), 1999, pp. 138-143.

[HUS99] Husain, I., Mohammad, S. I. Design, *Modeling and Simulation of an Electric Vehicle System.* Advances in Electric Vehicle Technology, SP-1417, International Congress and Exposition Detroit, Technical Paper Series, Society of Automotive Engineers, 1999, 9 p.

[IEC60571] *Electronic equipment used on rail vehicles*, Standard IEC 60571-12; International Electrotechnical Commission, 2006

[IEEE1475] *IEEE Standard for the Functioning of and Interfaces Among Propulsion, Friction Brake, and Train-borne Master Control on Rail Rapid Transit Vehicles*. Institute of Electrical and Electronics Engineers, Inc., 1999

[IEEE11] *IEEE Standard for Rotating Electric Machinery for Rail and Road Vehicles*. ISBN 0-7381-1922-9, Institute of Electrical and Electronics Engineers Inc., 2000

[ISH05] Ishikawa, K., Suda, K., Sasaki, M., Miyazaki, H. *A 600V driver IC with new short protection in hybrid electric vehicle IGBT inverter system.* ISPSD: The 17-th International Symposium on Power Semiconductor Devices and ICs, ISBN 0780388909, 2005, pp. 59-62.

[JAH01] Jahns, T. M., Blasko, V. *Recent advances in power electronics technology for industrial and traction machine drives.* Proceedings of the IEEE, Vol. 89 (6), 2001, pp. 963-975.

[JOC04] Jockel, A. *Traction drive*. US0222761 A1, Patent, 2004, Applicant: Siemens AG

[JOL01] Joller, J. *Research and Development of Energy Saving Traction Drives for Trams.* Thesis of Tallinn Technical University, ISBN 9985592050, Tallinn Technical University Press, 2001, 27 p.

[JOL01E] Joller, J. *Trammide energiasäästlike veoajamite uurimine ja väljatöötamine.* Thesis of Tallinn University of Technology, Tallinna Tehnikaülikool, 2001, 79 p.

[JOL02] Joller, J., Lehtla, M., Lehtla, T., Laugis, J. *Tram traction drives and comparison of their control methods*. BEC'2000: 7-th Biennial Conference on Electronics and Microsystem Technology, ISBN 9985-59-179-8, October 8-11, Estonia: Tallinn University of Technology, 2000, pp. 203-204.

[JOL0422] Joller, J., Laugis, J., Pettai, E. *Elektrisõiduki veoajam.* Patent application 0422/02PV, 30.07.2002; Applicant: Tallinn University of Technology, 2002

[KAI05] Kaida, F. *Redesign of tram driver's position.* Research report of Wiener Linien GesmbH &Co KG, European Agency for Safety and Health at Work, 2005, http://agency.osha.eu.int/publications/reports/101/en/index_13.htm

[KAR95] Kara, G. *Electric Traction Drives and Public Transport Development at Ganz Ansaldo.* IEE Electrical Machines and Drives Conference, IEE Publication No. 412, 1995, pp. 325-331.

[KEM89] Kemp R.J. *Developments in electric traction.* Power Engineering Journal, ISSN 0950-3366, Vol. 3(2), 1989, pp. 71-82.

[KET97] Ketteler, K. H. *Verfahren und schaltung zur umformung elektrischer energie*. International patent WO97/33766, Process and circuit for conversion of electrical energy, Applicant: ABB Daimler-Benz Transportation AG, 1997

[KIE01] *IGBT-Gleichstromsteller- Antriebsausrüstung für Strassenbahn-Gelenktriebwagen KT-NF6 Der Cottbusverkehr Gmbh* /Vossloh Kiepe GmbH, http://www.vossloh-kiepe.com /modernisierung/cottbus/index.htm, 20.07.2006

[KOW01] Kowalczewski, M., Mysiński, W., Zając, W. *A New Concept of The Converter for Dual System Trams.* EPE 2001: European Conference on Power Electronics and Applications, Graz, Austria, 2001

[LAU02] Laugis, J., Lehtla, T., Joller, J., Boiko, V., Vinnikov, D., Lehtla, M. *Modernization of electrical transport systems in Estonia.* EPE-PEMC 2002: 10-th International Power Electronics and Motion Control Conference, ISBN 953-184-046-6, Cavatat & Dubrovnik, Abstract on p. 449, full text 8 p. on CD-ROM, 2002

[LEE02] Leen, G., Heffernan, D. *Expanding Automotive Electronic Systems*. Computer 1/2002 (Vol. 35, No. 1), The flagship magazine of IEEE Computer Society, 2002, pp. 88-93.

[LEH03] Lehtla, M.; Joller, J.; Laugis, J. *Operation and diagnostics of the tram traction drive.* CPE'2003: Compatibility of Power Electronics, ISBN 83-88317-03-2, Gdansk, Poland 2003, Abstract on pp. 61-63, full text 5 p. on CD-ROM

[LEH04] Lehtla, M., Laugis, J. *Control System for Electric Traction Drive.* BEC'2004: 9-th Biennial Baltic Electronics Conference, ISBN 9985-59-406-2, October 3-6, Estonia: Tallinn University of Technology, 2004, pp. 331-332.

[LEH05] Lehtla, M. *Magnetization Model for Separately Magnetized Traction Motor Control*. Topical Problems of Education in the Field of Electrical and Power Engineering, ISBN 9985-69-0338, Tallinn University of Technology, 2005, pp. 82-83.

[LEH06] Lehtla, M. *Control and Protection of a Traction Supply System.* Topical Problems of Education in The field of Electrical and Power Engineering, ISBN 9985-69-036-2, January 16-21, Kuressaare: Tallinn University of Technology, 2006, pp. 93-98.

[LOB99] Lobosco, O.S. *Modeling and simulation of DC motors in dynamic conditions allowing for the armature reaction.* IEEE Transactions on Energy Conversion, Vol. 14 (4), 1999, pp. 1288-1293.

[LOG80] Logston C.F., Itami G.S. *Locomotive friction creep studies.* ASME Journal of Engineering and Industry, Vol. 102, 1980, pp. 275-281.

[LOH04] Lohner, A., Evers, W. *Intelligent Power Management of a Supercapacitor based Hybrid Power Train for Light-rail Vehicles and City Busses.* PESC 2004: 35-th Annual IEEE Power Electronics Specialists Conference, Aachen, Germany, 2004, pp. 672-676.

[LÕH04] Lõhmus, L. *Elektriraudtee alustas kolme mootorvaguniga.* Horisont 6/2004, MTÜ Loodusajakiri, 2004.

[MAR05] Marshall, J., Kazerani, M. *Design of an efficient fuel cell vehicle drivetrain, featuring a novel boost converter.* IECON 2005: 32nd Annual Conference of IEEE Industrial Electronics Society, 2005, pp. 1229-1234.

[MAT95] Mathew, R., Flinders, F., Oghanna, W. *Locomotive "total systems" simulation using SIMULINK.* IEEE International Conference on Electric Railways in a United Europe, 1995, pp. 202-206.

[MCK05] McKeever, J. W., Nelson, S. C., Su, G. J. *Boost Converters For Gas Electric And Fuel Cell Hybrid Electric Vehicles.* U.S. Department of Energy FreedomCAR and Vehicle Technologies, EE-2G /Prepared by: Ridge,O., Olszewski, M., 2005
www.ornl.gov/~webworks/cppr/y2001/rpt/122923.pdf, 20.07.2006

[MES01] Mesic, S., Jörg, M., Enzensberger, G. *IGBT Auxiliary Converter Integrated into a traction Converter.* EPE'2001: European Conference on Power Electronics and Applications, Graz, Austria, 2001, 7 p. on CD-ROM

[MEY00] Meyer, J. M., Rufer, A. *A DC Hybrid Circuit Breaker with Ultra Fast Contact Opening and Integrated Gate-Commutated Thyristor (IGCT).* PCIM Conference, Nürnberg, 2000, 6 p. on CD-ROM

[MEY03] Meyer, W. *The European tram "Saar-Lor-Lux" project.* Pubic Transport International 3/2003, pp. 24-27, http://www.uitp-pti.com/img/cover3_2003/saar-lor-lux.PDF, 1.7.2006

[MOH95] Mohan, N., Undeland, T., Robbins, W. *Power Electronics: Converters, Applications, and Design.* New York: John Wiley & Sons, 1995, 824 p.

[MUN05] Munehiro Kamiya; *Development of Traction Drive Motors for the Toyota Hybrid System.* IPEC-2005: International Power Electronics Conference, Japan: Niigata, IEEJ Transactions on Industry Applications, Vol. 126-D/4, 2006, pp.473-479

[NIL00] Nilsson, R. *A Combined Brake-Accelerator Pedal and its Evaluation.* 13-th ICTCT workshop, Intelligent Transport Systems, Corfu, 2000, pp. 247-255.

[NOL03] Nolte, R. *EVENT: Evaluation of Energy Efficiency Technologies for Rolling Stock and Train Operation of Railways.* Final Report International Union of Railways, Berlin: IZT Institute for Futures Studies and Technology Assessment, March 2003, 120 p., www.izt.de/pdfs/IZT_EVENT_Final_Report.pdf, 21.07.2006

[OHI00] Ohishi, K., Ogawa, Y., Miyashita, I., Yasukawa, S. *Adhesion control of electric motor coach based on force control using disturbance observer.* IEEE Proceedings. 6-th International Workshop on Advanced Motion Control, Nagoya, 2000, pp. 323-328.

[OHI98] Ohishi, K., Miyashita, I., Nakano, K., Yasukawa, S. *Anti-slip control of electric motor coach based on disturbance observer.* IEEE Proceedings. 5-th International Workshop on Advanced Motion Control, Coimbra, 1998, pp. 580-585.

[OKA98] Okamoto, I. *How Bogies Work.* Railway Technology Today 5, Japan Railway & Transport Review No. 18, EJRCF: East Japan Railway Culture Foundation, 1998, pp. 52–61

[ÖST92] Östlund, S. *A Primary Switched Converter System for Traction Applications.*, Thesis of Royal Institute of Technology, Stockholm, Sweden, ISSN 1100-1631, 1992, 152 p.

[PAL94] Palm, R., Storjohann, K. *Torque optimization for a locomotive using fuzzy logic.* ACM symposium on Applied Computing, 1994, pp. 105-109.

[PAR01] Park, D-Y., Kim, M-S., Hwang, D-H., Kim, Y-J., Lee, J-H. *Hybrid re-adhesion control method for traction system of high-speed railway.* ICEMS 2001: Fifth International Conference on Electrical Machines and Systems, Vol. 2, 2001, pp. 739-742.

[PAR03] Parry, J. *A tram incorporating flywheel energy storage and a prime mover*. GB2377680, Patent Office of the United Kingdom, 22.01.2003

[PET0424] Pettai, E., Laugis, J., Lehtla, T., Joller, J., Rosin, A. *Toiteliiniga seotud sõidukite energiavahetuse juhtimisssüsteem.* Patent application 0424, 31.07.2002; Applicant: Tallinn University of Technology.

[PHA00] Pham, K., Eacker, R., Burnett, M., Bardslkey, M. *A Step Forward or Backward? Sound Transit Opts for 1500 Vdc Traction Electrification.* 2000 ASME/IEEE Joint Railroad Conference, Newark, NJ, USA, 2000, pp. 67-72.

[PHY96] *MiniMODUL-167 High-end SBC featuring CAN in Credit-card Dimensions* /PHYTEC Messtechnik GmbH, 2002
http://www.phytec.com/products/sbc/C166-xc166-st10-xa/miniMODUL-167.html, 21.07.2006

[RAH98] Rahman, K.M., Fahimi, B., Suresh, G., Rajarathnam, A.V., Ehsani, M. *Advantages of switched reluctance motor applications to EV and HEV: design and control issues.* IEEE Industry Applications Conference, 1998. Thirty-Third IAS Annual Meeting. Vol. 1, 1998, pp. 327-334.

[ROS04] Rosin, A., Lehtla, M., Möller, T. *Intelligent Control and Diagnostics System for Tallinn Trams*. EPE-PEMC 2004: 11-th International Power Electronics and Motion Control Conference, Vol. 6, ISBN 9984320707, 2004, pp. 185-188.

[RTL641] *Trammi ja selle haagise tehnoseisundile ja varustusele esitatavad nõuded ning nende tehnoseisundi kontrollimise ja registreerimise eeskirjad.* Teede- ja sideministri 28. märtsi 2001. a määrus nr. 30, ISSN 1406-5630, vol. 45/641.

[RUF03] Rufer, A., Barrade, P., Hotellier, D., Hauser, S. *Sequential Supply for Electrical Transportation Vehicles: Properties of the fast energy transfer between supercapacitive tanks.* Industry Applications Conference, 2003. 38-th IAS Annual Meeting, Vol. 3, 2003, pp. 1530-1537.

[SAEJ1138] *Design Criteria Driver Hand Controls Location for Passenger Cars, Multipurpose Passenger Vehicles, and Trucks*, J1138, Society of Automotive Engineers, 1999

[SCH00] Schraut, M., Naab, K., Bachmann, T. *BMW's Driver Assistance Concept for Integrated Longitudinal Support.* 7-th World Congress on Intelligent Transport Systems, Turin, Italy, 2000, 12 p., www.naser.ofogh.net/tara/trafic6/torino/PDF/2121.pdf

[SCH97] Schwartz, H. J., Kresse, R. *Implementatio of An Advanced Wheel Creep Control With Searching Stategy on a Light Rail Vehicle.* EPE'97: European Conference on Power Electronics and Applications, Vol. 3, Norway: Trondheim, 1997, pp. 3434-3438.

[SEK05] Yasuhiro Sekine; *Modern Traction System.* Mitsubishi seminar material: Seminario Material Rodante, Mitsubishi Electric Corporation,2005; http://www.railforum.net/PresentacionesPonencias/2005/18 - Material Rodante - Marzo 2005 /10.35 - 10.55 Yasuhiro Sekine - Mitsubishi.pdf, 21.07.2006

[SEN93] Senini, S., Flinders, F., Oghanna, W. *Dynamic simulation of wheel-rail interaction for locomotive traction studies.* IEEE/ASME Joint Railroad Conference, 1993, pp. 27-34.

[SER02] Ioan Serban, P., Popescu, M. O., Popescu, C. *Energetic Macroscopic Representation applied to an Electrical Urban Transport System.* The Annals of "Dunarea de Jos" University Of Galati Fascicle III, ISSN 1221-454X, 2002, pp. 34-39.

[SIE05] *Siemens Transportation Systems - Shaping Tomorrow's Railways*. Japan Railway and Transport Review 42, December 2005, pp. 26-31.

[SIE96] *C167 User's Manual* /Siemens AG 1996, Infineon Technologies AG, München, 2000

[SOR01] Sorin, J., Dalmau, I., Mondelo, P. *A R&D Project currently carried out in transport ergonomics.* CAES´2001:International Conference on Computer-Aided Ergonomics and Safety, ISBN 84-931134-7-6, Hawaii, 2001.

[STE04] Steiner, M., Scholten, J. *Energy Storage on board of DC fed railway vehicles.* PESC 2004: 35-th Annual IEEE Power Electronics Specialists Conference; Aachen, Germany, 2004, pp. 666-671.

[STE99] Steiner, M., Deplazes, R., Stemmler, H. *A New Transformerless Topology for AC-Fed Traction Vehicles using Multi-Star Induction Motors.* EPE'99: European Conference on Power Electronics and Applications, Lausanne, Switzerland, 1999, 10 p. on CD-ROM

[TAK03] Takahara, E., Yamada, J. *A Study for Electric Double Layer Capacitor Application to Railway Traction Circuits for Energy Saving.* EPE 2003: European Conference on Power Electronics and Applications, Toulouse, 2003, 8 p. on CD-ROM

[TCR95] *Applicability of Low-Floor Light Rail Vehicles in North America.* Transit Cooperative Research Program Report 2, ISBN 0-309-05373-0, National Academy Press, Washington D.C., Booz-Allen & Hamilton Inc. McLean 1995, 46 p.

[TSE98] Yii Shen Tzeng, Ruay-Nan Wu, Nanming Chen *Electric network solutions of DC transit systems with inverting substations.* IEEE Transactions on Vehicular Technology, Vol. 47 (4), 1998, pp. 1405-1412.

[TUR01] Tursky, W. *Devices and their Packaging Technology.* FEPPCON 2001: IEEE IV Workshop Future of Electronic Power Processing and Conversion, Italy: Salina, 2001, 6 p.

[VUL01] Vulturescu, B., Pierquin, J., Bouscayrol, A., Hautier, J.P. *Behaviour Model Control Structures for an Electric Vehicle.* EPE 2001: European Conference on Power Electronics and Applications, Graz, Austria, 2001

[WAT02] Watanabe, T., Yamashita, M. *Basic study of anti-slip control without speed sensor for multiple motor drive of electric railway vehicles.* IEEE, Proceedings of the Power Conversion Conference, Vol. 3, 2002, pp. 1026-1032.

[WIP99] Wipke, K. B., Cuddy, M. R., Burch, S. D. *ADVISOR 2.1: a user-friendly advanced powertrain simulation using acombined backward/forward approach.* IEEE Transactions on Vehicular Technology 48/6, 1999, pp. 1751-1761.

[YAS97] Yasuoka, I., Henmi, T., Nakazawa, Y., Aoyama, I. *Improvement of re-adhesion for commuter trains with vector control traction inverter.* IEEE, Proceedings of the Power Conversion Conference, Vol. 1, Nagaoka, 1997, pp. 51-56.

[ZHA96] Zhang, J., Mathew, R., Oghanna, W. *Analysis of two-dimension saturation for simulation in dc traction motors*. International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Vol. 1, 1996, pp. 300-306.

[ZHA97] Zhai, W., Cai, Z. *Dynamic interaction between a lumped mass vehicle and a discretely supported continuous rail track.* Computers and Structures, Vol. 63 (5), Elsevier Science, 1997, pp. 987-997.

[ZHA98] Zhang, J., Mathew, R., Flinders, F., Oghanna, W. *Simulator of DC traction motors including both main pole and interpole saturation.* IEE Proceedings - Electrical Power Applications, Vol. 145 (4), 1998, pp. 377-382.

Abstract

The thesis covers research, development and application of control systems for traction drives. The control methods applicable in traction drive with a new original power circuit, circuit connections with different electric vehicles and user interfaces were analyzed. Both experiments and computer modelling were used to study different vehicles and control methods. Modelling describes a general integrated model of an electric vehicle and its components developed by the author of the thesis.

Simulation models were used in control system design, including the selection of circuit components. Models are usable for the analysis of vehicles with regenerative braking capability. Simulation model is intended to be used for modelling of emergency modes that cannot be carried out experimentally because of safety reasons and cost. The wheel slip problems in multiple-motor traction drive were analyzed. The developed traction converter and its control system are flexible, usable for different electric traction motors and adaptable for rail vehicles and other electric vehicles.

The most important result of the thesis is software and hardware development for traction drive with an original power circuit for Tallinn Tram and Trolleybus Company. The components of the control system have been used to develop a traction controller and an auxiliary power supply. The Estonian utility models were applied for a traction converter and an auxiliary power supply.

A future vision about electric traction drives, recommendations for further research and practical recommendation for product development and reduction of energy losses in contact network are given.

Lühikokkuvõte (Annotatsioon)

Doktoritöö käsitleb veoajamite juhtimissüsteemide uurimist, väljatöötamist ja juurutamist. Analüüsitakse originaalse jõuahelaga veoajamis kasutatavaid juhtimismeetodeid, juhtimissüsteemi sidumist elektersõidukite ja kasutajaliidestega. Juhtimismeetodite ja erinevate sõidukite uurimiseks on kasutatud nii eksperimente kui arvutimudeleid. Modelleerimise osas käsitletakse sõiduki ja töö autori poolt väljatöötatud veoajami tervikmudeli ülesehitust ja komponente.

Mudeleid kasutati juhtimissüsteemi väljatöötamisel, sh. ahelate komponentide valikul. Mudel on eriti sobiv rekuperatiivpidurdusega sõidukite analüüsimiseks. Arvutimudel on mõeldud kasutamiseks avarii jt. olukordade simuleerimisel, kui eksperimente pole võimalik läbi viia nende ohtlikkuse või kõrge maksumuse tõttu. Analüüsitud on ka veorataste libisemise probleeme mitmemootorilises veoajamis. Väljatöötatud veomuundur ja selle juhtimissüsteem on paindlik, kasutatav erinevate elektrimootorite toiteks ja kohandatav nii rööbastega kui ka rööbasteta elektersõidukitele.

Doktoritöö tähtsaimaks tulemuseks on originaalse skeemilahendusega veoajami juhtimissüsteemi riistvara ja tarkvara väljatöötamine Tallinna Trammi- ja Trollibussikoondisele. Juhtimissüsteemi komponente on kasutatud nii veoajami juhtimissüsteemi kui ka trammide abitoitemuundurite väljatöötamisel. Trammi veomuunduri ja abitoiteallika kohta on Eesti kasuliku mudeli tunnistused.

Kokkuvõttes on esitatud veoajamite arengu tulevikunägemus, soovitused edasiseks uurimistööks, praktiliseks tootearenduseks ja energiakadude vähendamiseks kontaktvõrgus.

Publications

1. Lehtla, M. *Control System Development Environment with MatLAB SIMULINK Real Time Workshop*. Baltic Electrical Engineering Review 1(7), ISSN 1392-0774, Vilnius Electrical Engineering Centre Inc., 1998, pp. 21-24.
2. Lehtla, M. *Hardware and Software of IGBT power converter*. Actual Problems of Electrical Drives and Industry Automation, ISBN 9985-69-015-X, Estonia: Tallinn, 1999, pp. 67-70.
3. Joller, J., Lehtla, M. *Development System for Special Purpose Electrical Drives and Converters*. Electromotion´99: Proceedings of 3-rd International Symposium on Advanced Electromechanical Motion Systems, Greece: University of Patras,1999, pp. 637-640.
4. Lehtla, T., Joller, J., Lehtla, M., Laugis, J. *Parameter Identification and Comparison of an Induction Motor Models*. Proceeding of 8th International Conference of Power Electronics and Variable Speed Drives, IEE Conference Publication No. 475, ISBN 0-85296-729-2/ ISSN 0537-9989, London, 2000, pp. 201-205.
5. Joller, J., Lehtla, M., Lehtla, T., Laugis, J. *Tram traction drives and comparison of their control methods*. BEC'2000: 7th Biennial Conference on Electronics and Microsystem Technology, ISBN 9985-59-179-8, October 8-11, Tallinn Tech. University, 2000, pp. 203-204.
6. Lehtla, M., Vinnikov, D. *Supply for the Auxiliary Systems of the Rail Vehicle*. Actual Problems of Electrical Drives and Industry Automation, ISBN 9985-69-020-6, Tallinn Tech. University, 2001, pp. 68-70.
7. Vinnikov, D., Lehtla, M. *Auxiliary Power Converter for Tram*. Summer Seminar on Nordic Network For Multi Disciplinary Optimised Electric Drives, Taipalsaari, Finland. 2002, pp. 56-57.
8. Joller, J., Lehtla, M. *Power Analyse and New Loss Minimisation Possibilities of a Tram System*. EPE-PEMC 2002: 10-th International Power Electronics and Motion Control Conference, Cavatat & Dubrovnik, ISBN 953-184-046-6, Abstract on p. 488, full text 6 p. on CD-ROM, T11-038, 2002
9. Laugis, J., Lehtla, T., Joller, J., Boiko, V., Vinnikov, D., Lehtla, M. *Modernization of electrical transport systems in Estonia*. EPE-PEMC 2002: 10-th International Power Electronics and Motion Control Conference, Cavatat & Dubrovnik, ISBN 953-184-046-6, Abstract on p. 449, full text 8 p. on CD-ROM, T9-068, 2002
10. Vinnikov, D., Lehtla, M. *Development of auxiliary power supply for tram*. BEC'2002: 8th biennial Baltic Electronic Conference, ISBN 9985-59-292-1, Tallinn Tech. University, 2002, pp. 389-390.
11. Joller, J., Lehtla, M. *Power analyse of a tram system with energy storage devices*, BEC 2002: 8th biennial Baltic Electronic Conference, ISBN 9985-59-292-1, Tallinn Tech. University, 2002, pp. 395-396.

12. Lehtla, M., Joller, J. *Control of Operation modes in a traction drive*. Actual Problems of Electrical Drives and Automation, ISBN 9985-69-027-3, May 17-21, Tallinn Tech. University, 2003, pp. 77-82.
13. Lehtla, M., Joller, J., Laugis, J. *Operation and diagnostics of the tram traction drive*. Compatibility of Power Electronics CPE2003, ISBN 83-88317-03-2, Abstract on pp. 61-63, full text 5 p. on CD-ROM, Gdansk, Poland, 2003
14. Lehtla, M., Laugis, J. *Control System for Electric Traction Drive*. BEC'2004: 9th Biennial Baltic Electronics Conference, ISBN 9985-59-406-2, Tallinn Tech. University, 2004, pp. 331-332.
15. Rosin, A., Lehtla, M., Möller, T. *Intelligent Control and Diagnostics System for Tallinn Trams*. EPE-PEMC 2004: 11th International Power Electronics and Motion Control Conference, Vol. 6, ISBN 9984-32-070-7, Latvia: Riga Tech. University, 2004, pp. 185-188.
16. Lehtla, M. *Microprocessor based Traction Control System and Diagnostic Algorithms for the Traction Drive TVM1*. Topical Problems of Education in the field of Electrical and Power Engineering, ISBN 9985-69-030-3, Kuressaare: Tallinn University of Technology, 2004, pp. 58-61.
17. Винников, Д., Бойко, В., Лехтла, М., Росин, А., Лаугис, Ю. *Об опыте института электропривода и силовой электроники ТТУ в области модернизации электроподвижного состава Таллиннского трамвайного парка*. Технічна електродинаміка ISSN 0204-3599, Kiiev 2004, pp. 52-55.
18. Laugis, J., Lehtla, T., Pettai, E., Joller, J., Rosin, A., Lehtla, M., Vinnikov, D. *Modernization of Trams in Estonia*. UEES'04: Unconventional Electromechanical and Electrical Systems, Vol. 2, ISBN 83-88764-19-5, Alushta, Crimea, Ukraine, pp. 561-564.
19. Lehtla, M. *Magnetization Model for Separately Magnetized Traction Motor Control*. Topical Problems of Education in the Field of Electrical and Power Engineering, ISBN 9985-69-033-8, January 17-22, Kuressaare, Tallinn University of Technology, 2005, pp.82-83.
20. Lehtla, M. *Elektroonikaseadmete raalprojekteerimine*. Tallinn: Infotrükk, 2002, ISBN 9985-69-025-7, 140 p.

Intellectual property

1. "Traction converter for electric vehicle" (*Elektrisõiduki veomuundur*). Utility model EE00332U1 approved on 15.10.2002 by Estonian Patent Office under. Authors: Jüri Joller, Madis Lehtla, Juhan Laugis, and Uno Heinvere, Applicant: Tallinn University of Technology.
2. "High-frequency auxiliary power supply for electric vehicle" (*Elektrisõiduki kõrgsageduslik abitoiteallikas*). Utility model EE00331U1 approved on 15.10.2002 by Estonian Patent Office. Authors: Dmitri Vinnikov, Jüri Joller, Madis Lehtla, Oleksandr Kiritsenko, and Juhan Laugis, Applicant: Tallinn University of Technology.

LISA / ANNEX 1

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi: Madis LEHTLA
Sünniaeg ja -koht: 17.09.1974, Tallinn
Kodakondsus: Eesti
Perekonnaseis: vallaline
Lapsed: —

2. Kontaktandmed

Aadress: Asunduse 9-53, 11413 Tallinn, Eesti Vabariik
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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	1999	tehnikateaduste magistrikraad (elektriajamid ja jõuelektroonika)
Tallinna Tehnikaülikool	1998	inseneri diplom (energiatehnika)
Tallinna 43. Keskkool	1993	keskharidus
Tallinna 60. Keskkool	1990	põhiharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Inglise	Kõrgtase
Vene, Soome	Kesktase
Saksa	Algtase (kursus läbitud Tallinna Tehnikaülikoolis)
Rootsi	Algtase (algtaseme kursus Lundi Rahvaülikoolis)

5. Täiendõpe

Õppimise aeg	Õppeasutuse või muu organisatsiooni nimetus
07.08.1996 – 08.08.1996	”Sähkovoimatekniikan Tutkijakoulu”, Imatra, Soome
28.02.2003 – 25.03.2003	Turundus ja kliendisuhted, Tallinna Tehnikaülikool
05.03.2003 – 02.04.2003	Projektijuhtimine, Tallinna Tehnikaülikool
14.02.2003 – 17.03.2003	Intellektuaalomandi ja patendinduse alused
04.02.1998 – 20.04.1998	Lundi Ülikooli ja Lundi Rahvaülikooli korraldatud rootsi keele algkursus välismaalastele
28.02.1997	Uusi nõudeid elektripaigaldiste projekteerimises ja käidus, Võsu, Tallinna Tehnikaülikool
12.05.2005	Elektripaigaldiste ja tööstuse elektriseadmete projekteerimine paketiga CADS, KymData OY

6. Teenistuskäik

Töötamise aeg	Ülikooli, teadusasutuse või muu organisatsiooni nimetus	Ametikoht
06.1996 – 08.1996	Helsingi Tehnikaülikool	teadus-assistent (tutkimusapulainen)
1998	Tallinna Tehnikaülikool	insener
09.1998 – 08.2003	Tallinna Tehnikaülikool	teadur
09.2003 – 2005	Tallinna Tehnikaülikool	teadur

7. Teadustegevus

01.01.2001 - 31.12.2003	Sihtasutuse Eesti Teadusfondi (ETF) uurimistoetusega teema G4852 ”Elektriajamite ja jõupooljuhtmuundurite parameetrite diagnostika talitluse tõhustamiseks ja töökindluse suurendamiseks” täitja
15.05.2002 - 08.03.2004	Eesti Tehnoloogiaagentuuri (ESTAG) arendustoetusega teema 245F ”Elektertranspordi veoajamid, automaatika ja infosüsteemid” täitja
01.01.1997 - 31.12.2001	Haridusministeeriumi sihtfinantseeritava teema T222 (ERIS SF0140222s98) ”Energiasäästlike elektriajamite väljatöötamine ja rakendamine Eesti energeetikas, tööstuses ja transpordis” täitja
01.09.2004 - 31.12.2004	T002 Elektritranspordi ajami- ja automaatikasüsteemid
alates 01.01.2003	Haridusministeeriumi sihtfinantseeritava teema T513 (ERIS SF0142513s03) ”Energiamuundus- ja -vahetusprotsesside uurimine elektriajamite ja pooljuhtmuundurite jõuvõrkudes” täitja
täitja alates 01.01.2005	Sihtasutuse Eesti Teadusfond (ETF) uurimistoetusega teema ETF6175 ”Ülikondensaatorsalvestiga elektriajami energiavahetuse uurimine”
1998-2006	Haridusministeeriumi sihtfinantseeritav doktorandi teadustöö (ERIS SF0141721s00) ”Jõupooljuhtmuundurite, ajamite ja ajamitel põhineva tehnoloogia energiavoo optimaalne juhtimine”

8. Kaitstud lõputööd

magistritöö “Jõupooljuhtmuunduri arendus- ja talitlustarkvara“, TTÜ, 1999
diplomitöö “Sagedusmuunduri tarkvara “, TTÜ, 1998

9. Teadustöö põhisuunad

Jõupooljuhtmuundurite, ajamite ja ajamitel põhineva tehnoloogia energiavoo juhtimine, energiamuundusprotsessid, ajamid ja nende juhtimistarkvara, elektersõidukite veoajamid ja muundurid

10. Teised uurimisprojektid

1999-2000	Siseriikliku lepingu L908 ”Tallinna Trammipargi trammi nr. 107 peaelektriajami moderniseerimine” täitja, finantseeris Tallinna Trammi- ja Trollibussikoondise AS
19.08.2003 - 31.12.2004	Siseriikliku lepingu 358L ”Elektriajamite jõupooljuhtmuundurite katsepartii madalapõhjalise keskosaga ja rekonstrueeritud infosüsteemidega trammidele” täitja, finantseeris Tallinna Trammi- ja Trollibussikoondise AS
18.01.2001 - 30.06.2002	Siseriikliku lepingu 105L ”Trammide veoajamite rekonstrueerimine” täitja, finantseeris Tallinna Trammi- ja Trollibussikoondise AS
01.01.2002 - 31.12.2002	Siseriikliku lepingu 202L ”Trammide elektriajamite ja jõumuundurite moderniseerimine” täitja, finantseeris Tallinna Trammi- ja Trollibussikoondise AS
03.05.2001 - 31.12.2001	Siseriikliku lepingu 126L ”Trammi staatilise pingemuunduri väljatöötamine” täitja, finantseeris Tallinna Trammi- ja Trollibussikoondise AS
1997-1998	Mikroprotsessorjuhtimisega IGBT transistor-komplektelektriajami väljatöötamine”, finantseeris Eesti Innovatsioonifond Ravori Investeeringute AS (Elektrimasinaehituse AS tehas Volta) osalusel.
30.09.2001 - 30.12.2001	Siseriikliku lepingu 130L ”Elektriraudtee kontaktvõrgu ja veoalajaamade tehnilise seisundi uuring” täitja, finantseeris Elektriraudtee AS
01.07.1996- 15.02.1997	Siseriikliku lepingu L612 ”Keskpingelise türistorsagedusmuunduri maketi mikroprotsessor-juhtsüsteemi ja programmvarustuse väljatöötamine”, Innovatsioonifond, RAS ESTEL, täitja

Allkiri

Kuupäev: 20.07.2006

CURRICULUM VITAE

1. Personal information

Name:	Madis LEHTLA
Place and date of birth:	17.09.1974, Tallinn
Citizenship:	Estonian
Marital status:	single
Children:	—

2. Contact information

Address: Asunduse 9-53, 11413 Tallinn, Estonia
Telephone: (+372) 56460049
E-mail address: mlehtla@cc.ttu.ee

3. Education

Institution	Graduation date	Education
Tallinn University of Technology	1999	Master of Science in Technology (Electrical Drives and Power Electronics)
Tallinn Uniersity of Technology	1998	Diploma engineer (Energy Technology)
Tallinn Secondary School No. 43	1993	Secondary Education
Tallinn Secondary School No. 60	1990	Basic Education

4. Languages

Language	Level
English	High
Russian	Middle (secondary school course)
Finnish	Middle (practice in Finland)
German	Basic (course in Tallinn University of Technology)
Swedish	Basic (Basic Course of Swedish for Foreigners)

5. Special Courses

Date	Organization
7-8.08.1996	Researcher School of Electrical Energy Technology ”Sähkovoimatekniikan Tutkijakoulu”, Imatra, Finland
28.02.2003 – 25.03.2003	Marketing and Client Relations, Organized by Tallinn University of Technology, Estonia
05.03.2003 – 02.04.2003	Project Management, Organized by Tallinn University of Technology, Estonia
14.02.2003 – 17.03.2003	Basics of Intellectual Property and Patents, Organized by Tallinn University of Technology, Estonia

04.02.1998 – 20.04.1998	Basic Course of Swedish for Foreigners, Organized by Folkuniversitet Lund, Sweden
28.02.1997	New Requirements for Electrical Installations, Organized by Tallinn University of Technology, Võsu, Estonia
12.05.2005	Electrical Installation Design using CADS, Organized by KymData OY, Finland

6. Professional Employment

Date	Organization	Position
06.1996 – 08.1996	Helsinki University of Technology	research assistant (tutkimusapulainen)
1998	Tallinn University of Technology	engineer
09.1998 – 08.2003	Tallinn University of Technology	researcher
09.2003 – 2005	Tallinn University of Technology	researcher

7. Scientific Work

01.01.2001 - 31.12.2003	G4852 ”Diagnostics of electrical drives and power electronic converters for improvement of operation and reliability”, Estonian Scinece Foundation research grant
15.05.2002 - 08.03.2004	245F ”Traction drives, automation and information systems”, Enterprise Estonia (ESTAG) development support contract
01.01.1997 - 31.12.2001	T222 (ERIS SF0140222s98) ”Development and application of energy efficient electrical drives in Estonian energy systems, industry and transportation”, target financed main topic funded by the Ministry of Education and Research
since 01.01.2003	T513 (ERIS SF0142513s03) ”Energy conversion and exchange processes in power networks of electrical drives and power electronic converters”, target financed main topic funded by the Ministry of Education and Research
since 01.01.2005	ETF6175 ”Research of energy exchange of an electric drive with ultracapacitor energy storage”, Estonian Scinece Foundation supported research grant
01.09.2004 - 31.12.2004	T002 ”Drive and automation for electricity-driven vehicles”, target financed topic funded by the Ministry of Education and Research
1998-2006	Doctoral research grant ERIS SF0141721s00 ”Control of energy flows in power semiconductor based converters, drives and in drive-based technology, funded by the Ministry of Education and Research

8. Theses

Software for a frequency converter, (1998, Dipl. Eng)
Software of an Power Semiconductor based Converter, (1999, M.Sc.)

9. Main Areas of Scientific Work

Control of energy flows in drives and in drive-based technology, energy exchange processes, software based control of drives, traction drives and converters of electric vehicles

10. Other Research Projects

1999-2000	L908 ”Modernization of traction drive in Tallinn tram fleet tram no. 107”, financed by Tallinn Tram and Trolleybus Company Ltd.
19.08.2003 - 31.12.2004	358L ”Pilot series of power converters of electrical drives for trams with low-floor middle part and modernized communication systems”, financed by Tallinn Tram and Trolleybus Company Ltd.
18.01.2001 - 30.06.2002	105L ”Reconstruction of trams’ traction drives”, financed by Tallinn Tram and Trolleybus Company Ltd.
01.01.2002 - 31.12.2002	202L ”Modernization of tram electrical drives and power converters”, financed by Tallinn Tram and Trolleybus Company Ltd.
03.05.2001 - 31.12.2001	126L ”Design of static voltage converter for trams”, financed by Tallinn Tram and Trolleybus Company Ltd.
1997-1998	Development of a microprocessor controlled elektric drive with IGBT’s, development support contract of Innovation foundation (Enterprise Estonia) in cooperation with Ravori Investeeringute AS (Volta Ltd.)
01.07.1996-15.02.1997	L612 ”Software developemnt for medium-voltage thyristor frequency converter prototype”, Innovation foundation (Enterprise Estonia), RAS Estel
30.09.2001 - 30.12.2001	130L ”Research of technical status of traction substations and contact networks of Estonian electric railway”, financed by the Estonian Electric railway Ltd.

Signature Date: 20.07.2006