



RIGA TECHNICAL  
UNIVERSITY

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**VIRTUAL-PHYSICAL TESTS OF VEHICLES  
WITH COMBINED TRACTION  
ELECTRICAL DRIVE**

Summary of the Doctoral Thesis



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Riga 2021

**RIGA TECHNICAL UNIVERSITY**  
Faculty of Electrical and Environmental Engineering  
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WITH COMBINED TRACTION  
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# **DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE**

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 18 June 2021 at 13.00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 212.

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## **DECLARATION OF ACADEMIC INTEGRITY**

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Ilja Dvornikovs ..... (signature)

Date: .....

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 3 Chapters; Conclusions; 50 figures; 6 tables; 2 appendices; the total number of pages is 111, including appendices. The Bibliography contains 97 titles.

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# **GENERAL CHARACTERIZATION OF THE THESIS**

## **Topicality of the Thesis**

Combined energy equipment (CEE) is one of the vehicles driving efficiency increase technologies that is intensively developing. These are systems combining an internal combustion engine with electrically driven components and mechanical transmission units.

Implementation of CEE potential is a peculiar task with a number of aspects each of which determines the characteristics of the vehicle:

- Selection of CEE optimal structure and scheme and parameters of its components.
- CEE power management.
- Identification of induction motor (IM) parameters.

Solving such a task and choosing components requires an understanding of CEE technology, which is only possible if there are theoretical and experimental tools for research and development. The development of existing tools and the creation of new tools are topical directions with scientific, engineering and production organization activities of which are related to CEE work. This Thesis has been motivated by understanding the importance of this issue and the usefulness of grouping and summarizing the results of the author's research, which allows offering scientifically substantiated improvements and new tools that seem practically useful for calculations at the stage of development of a drive with combined electrical equipment.

## **Hypothesis, Purpose and Tasks of the Thesis**

### **Hypothesis of the Thesis**

The application of the developed CEE parameter verification method shortens the development and laboratory testing time and ensures the fulfilment of industrial orders for new products in short terms.

### **Purpose of the Thesis**

The purpose of this Thesis is creation of improved CEE research tools on the basis of virtual-physical testing technologies. To implement this, it is necessary to solve the following tasks:

- to develop a methodology for creating virtual-physical systems, which allows to perform the identification of energy equipment operating modes and component parameters according to experimental data and expands the functional possibilities of energy equipment testing in laboratory conditions on unit stands;
- to develop mathematical models of CEE components and vehicle which allow to study the CEE power flows;
- to develop and test a method for researching the energy efficiency of the CEE and power flow organization using virtual-physical modelling means;

- to develop and test a virtual-physical test system that expands the functional possibilities of energy equipment research on unit stands.

### **Scientific Novelty of the Doctoral Thesis**

- A methodology has been developed that introduces a generalized approach to the synthesis of virtual-physical energy equipment through the creation of closed automatic control systems that link and synchronize the physical and virtual part of the research object.
- Within the framework of the methodology, a scientific substantiation of the load generation type in virtual-physical tests is provided, an improved method for creating virtual-physical objects for energy equipment tests with several power units is proposed and practically implemented.
- Virtual vehicle models with CEE have been created, which include the influence of external factors, driving conditions and CEE electrical parameters. The models reflect the CEE properties characteristic of the mechanical and electrical environment. The adequacy of the models is confirmed by comparison with experimental data.
- The impact of the physical parameters used in the vehicle dynamics model on the quality of the operating modes (torque on the wheels) of its energy equipment has been studied. The most important parameters have been identified the consideration of which ensures the correctness of the identification.

### **Used Methods and Tools**

The following research methods and means have been used in the Thesis:

- MATLAB/Simulink® 2017 interactive environment for intensive computing, data analysis and visualization.
- Microsoft Excel 2017 software for data analysis and charting.
- Texas Instruments Code Composer Studio v6.2 – a control device for monitoring and control.
- Texas Instruments control SUITE v3.4.5 feature library and subprograms.
- Motor Solve AD for determination of electromagnetic parameters.

### **Practical Significance of the Doctoral Thesis**

The developed mathematical models of the movement vehicle with power unit, CEE and energy equipment components in the MATLAB software can be used for virtual testing which is a part of the process of creating and researching vehicles with CEE and their control systems. Characteristics and performance indicators are the main factors when choosing CEE components and developing its management system.

The obtained results can be used in the design of vehicle control systems and allow to increase the efficiency of their operation and significantly reduce operating costs while

maintaining high quality characteristics of accuracy and speed. The developed algorithms can be used to develop control systems adaptive to the characteristics of the road profile. The proposed algorithms have low requirements to computing resources and allow to reduce the calculation cost of autonomous control systems of transport systems.

## Approbation of Research Results

### Publications

1. Sļiskis O., **Dvornikovs I.**, Marinbahs, M., Mārks, J., Groza, E. Investigation of Electrical Bus Traction Motor Dynamic Using Methods of Physical and Computer Simulation. No: 2019 16th Conference on Electrical Machines, Drives and Power Systems (ELMA), Bulgaria, Varna, 6–8 June 2019. Piscataway: IEEE, 2019, pp. 1–4. ISBN 978-1-7281-1414-9. e-ISBN 978-1-7281-1413-2. Available: doi:10.1109/ELMA.2019.8771668. **SCOPUS**.
2. **Dvornikovs I.**, Marinbahs, M., Zarembo, J., Groza, E., Ketners, K. Investigation of Traction Motor Dynamic Using Computer Simulation and Method of Mutual Loading of Two Pair Motors. In: 2019 16th Conference on Electrical Machines, Drives and Power Systems (ELMA 2019), Bulgaria, Varna, 6–8 June 2019. Piscataway: IEEE, 2019, pp. 1–4. ISBN 978-1-7281-1414-9. e-ISBN 978-1-7281-1413-2. Pieejams: doi:10.1109/ELMA.2019.8771668. **SCOPUS**.
3. **Dvornikovs I.**, Marinbahs, M., Sļiskis, O., Ketners, K. Investigation of Autonomous Traction Motor Dynamic Using Method of Mutual Loading and Computer Simulation. In: 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2018): Conference Proceedings, Latvia, Riga, 12–14 November 2018. Piscataway: IEEE, 2018, pp. 1–4. ISBN 978-1-5386-6904-4. e-ISBN 978-1-5386-6903-7. Available: doi:10.1109/RTUCON.2018.8659827. **SCOPUS**.
4. **Dvornikovs I.**, Sļiskis, O., Ketners, K. Computer Analysis of Lightning Surge Propagation on Overhead Transmission Line Towers. In: 54th International Scientific Conference of Riga Technical University: Digest Book and Electronic Proceedings, Latvia, Riga, 14–16 October 2013. Riga: RTU, 2013, pp. 19.1–19.4. ISBN 9789934104701.
5. **Dvornikovs I.**, Sļiskis, O., Ketners, K. Computer Simulation of Lightning Surge Propagation on Power Transmission System Metal Constructions. In: CIGRE International Colloquium on Lightning and Power Systems, France, Lyon, 12–14 May 2014. Paris: 2014, pp. 1–7.
6. Sļiskis O., **Dvornikovs I.**, Ketners K., Soboļevskis D. Specification of Transmission Tower Structure for Following Surge Protection Simulation. In: 2015 16th International Scientific Conference on Electric Power Engineering (EPE 2015), Czech Republic, Kouty nad Desnou, 20–22 May 2015. Piscataway: IEEE, 2015, pp. 137–140. ISBN 978-1-4673-6789-9. e-ISBN 978-1-4673-6788-2. Available: doi:10.1109/EPE.2015.7161151. **SCOPUS**.



7. Sliškis, O., **Dvornikovs I.**, Ketners, K. Lightning Performance on Transmission Line Towers. No: 7th International Conference on Electrical and Control Technologies (ECT-2012): Proceedings, Lithuania, Kaunas, 3-4 May 2012. Kaunas: Technologija, 2012, pp. 157-160. ISSN 1822-5934. **SCOPUS**.

# 1. ANALYSIS OF THE FUNCTIONALITY OF COMBINED TRACTION ENERGY EQUIPMENT

## 1.1. Development of Research and Testing Tools

The main operating mode of a combined energy equipment (CEE) is the combined mode in which the fuel energy moves the weight of the vehicle accelerating it or maintains the current energy level maintaining a constant speed, compensating for the loss from drag resistance. The choice of the optimal operating mode does not apply to the internal combustion motor (ICE) but to the entire energy equipment and is formulated as ensuring the maximum energy efficiency of CEE with the vehicle (V) equipped with it matching the set operating mode. Ensuring ICE operating mode can be implemented using the means shown in Fig. 1.1, where a scheme with CEE is provided, which are currently implemented in mass vehicles. In Fig. 1.1, the designation *Auxiliary units* designates the electric drive including an electric motor, a power converter (inverter), etc.

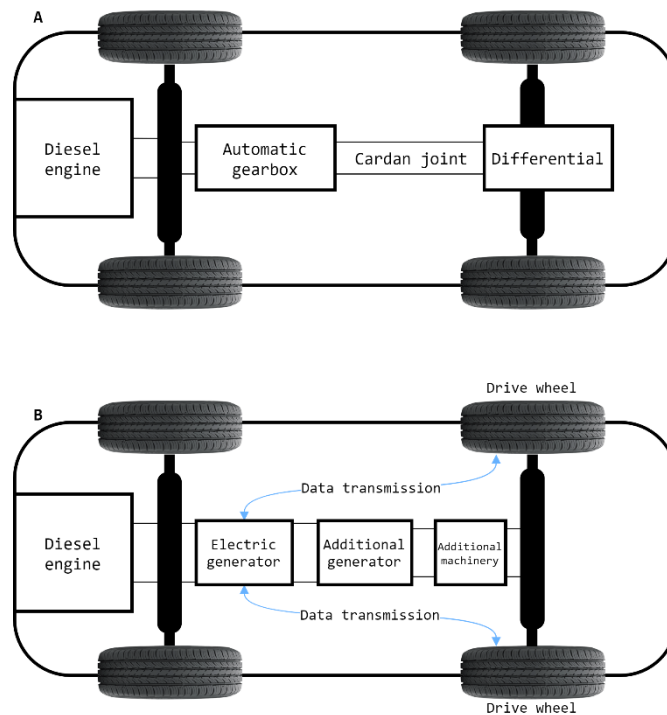


Fig. 1.1. Kinematic diagram of vehicle transmission with electromechanical transmission: A – without CEE; B – with CEE.

Traction drive modes are not set in the time function, since they depend on the operating conditions, e.g., sequence of acceleration, turning, mountain driving, braking modes. Apart from operating conditions, the operational safety of vehicle components is affected by climatic factors. CEE ensures, in one way or another, the independence of the ICE operating mode from the vehicle driving conditions. The main difference between them is in the organization of power flows, i.e., in which ways and how efficiently they transfer and use the

energy generated by ICE. The organization of power flows is one of the key aspects of CEE development and research.

## **1.2. Testing Means**

### **Virtual means**

The most accessible tool for research and development of vehicles with CEE. A model with minimum initial data is virtually always the initial and often the only tool at the first stage of development of new systems. At the following stages, tests of the vehicle on the basis of which the CEE is created and the components of the energy equipment can be performed to adjust the initial data and confirm the adequacy of the developed model.

### **Physical means**

Laboratory tests are the most convenient way to carry out experimental studies of CEE and vehicles equipped with it, especially during driving cycles. Their advantages are repeatability, wide possibilities of measurements of various variables, independence from the season and weather conditions. This is especially urgent in creating new CEE, when experimentally processing engineering solutions and control system elements that cannot be obtained using mathematical modelling or that are not expedient to reflect in the model in order not to complicate it excessively.

### **Road tests**

Most often, road tests are performed to determine the control parameters that characterize specific characteristics of the vehicle (e.g., braking). However, the research also envisages another testing task: obtaining input data for the mathematical model of the research object and checking the modelling adequacy.

## **1.3. Mathematical Model of Power Unit and Powertrain**

Modern electromechanical transmissions are built using traction induction AC electric motors, synchronous AC generators and power semiconductor frequency converters. The generalized scheme of AC electromechanical transmission is shown in Fig. 1.2.

The following designations are used: traction electric motors with kinematic link to driving wheels #1 and #2 via secondary (wheel) reducers; Synchronous traction generator with kinematic link to the diesel motor shaft via primary reductor. Automatic control system unit acts on the traction generator excitation winding via the power converter, on traction and steering motors via the frequency converters #1–#3, and directly on ICE elements.

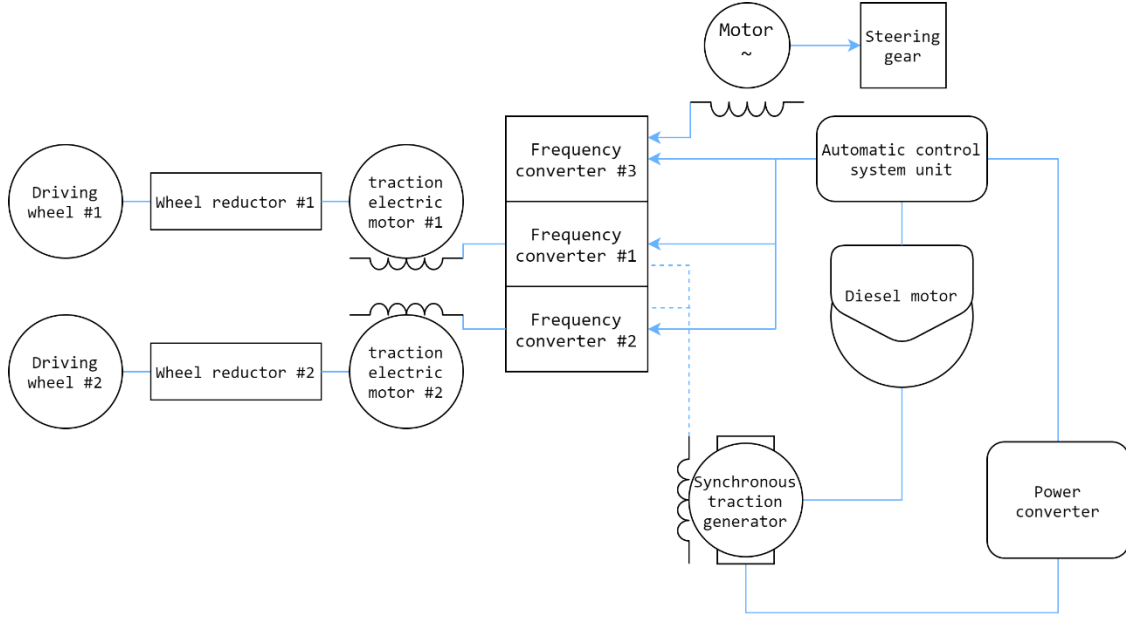


Fig. 1.2. Generalized scheme of AC electromechanical transmission vehicle.

### 1.4. Induction Motor Vector Control Principle

Currently, speed control of IM is performed by a frequency converter made on digital signal processors. High-voltage electric drives use multi-level voltage converters most often formed by a number of H-bridges each of which is powered by its own isolated DC member. Powerful IGBT transistors are used for switching in such converters. The synthesis of the vector drive control system is based on the Park–Gorev equations written for an induction motor with a short-circuited rotor with respect to the stator current and the rotor flow link in a synchronous orthogonal coordinate system  $(d, q)$  oriented along the rotor flow vector. Since all electromagnetic variables in the steady state are constant in the coordinate system of a machine rotating synchronously with the magnetic field, the statics model can be obtained using the following equations [23]:

$$\begin{cases}
 R_s i_{sd} - \omega_\psi L_{\sigma e}^s i_{sq} = u_{sd}; \\
 R_s i_{sq} + \omega_\psi \left( L_{\sigma e}^s i_{sd} + \frac{L_m}{L_r} \psi_r \right) = u_{sq}; \\
 L_m i_{sd} = \psi_r; \\
 L_m i_{sq} = \omega_s T_r \psi_r; \\
 \gamma_\psi = \gamma_{\psi 0} + \int (\omega_e + \omega_s) dt; \\
 M_e = c \frac{L_m}{L_r} \psi_r i_{sq},
 \end{cases} \quad (1.1)$$

where

$\omega_s = \omega_\psi - \omega_e$  are slip frequencies;

$\gamma_\psi$  is stator coupling vector rotation angle.

Analysing the last and the third equations of System (1.1), it can be concluded that the longitudinal component  $i_{sd}$  of the stator current vector determines the car magnetic state characterized with  $r$ , but the transverse current  $i_{sq}$  multiplied by the current value of the flow coupling generates IM electromagnetic torque. In this connection,  $i_{sd}$  is called the magnetizing component (magnetizing current) of the stator current vector and  $i_{sq}$  is called the active or torque generating component (active or torque generating current). Based on this conclusion the so-called Field-Oriented Control (FOC) principle [1] is based, which is interpreted as in [22].

The control laws of IM-based frequency-controlled electric drive can be synthesized on the methodological basis known from the theory of DC electric drive with independent excitation, if the conductive effects on the adjustable current or voltage source are formed in a rotating coordinate system oriented by the rotor flow coupling vector, but they are then converted into a stationary (phase) system. Additionally, IM must be seen as a two-channel control object.

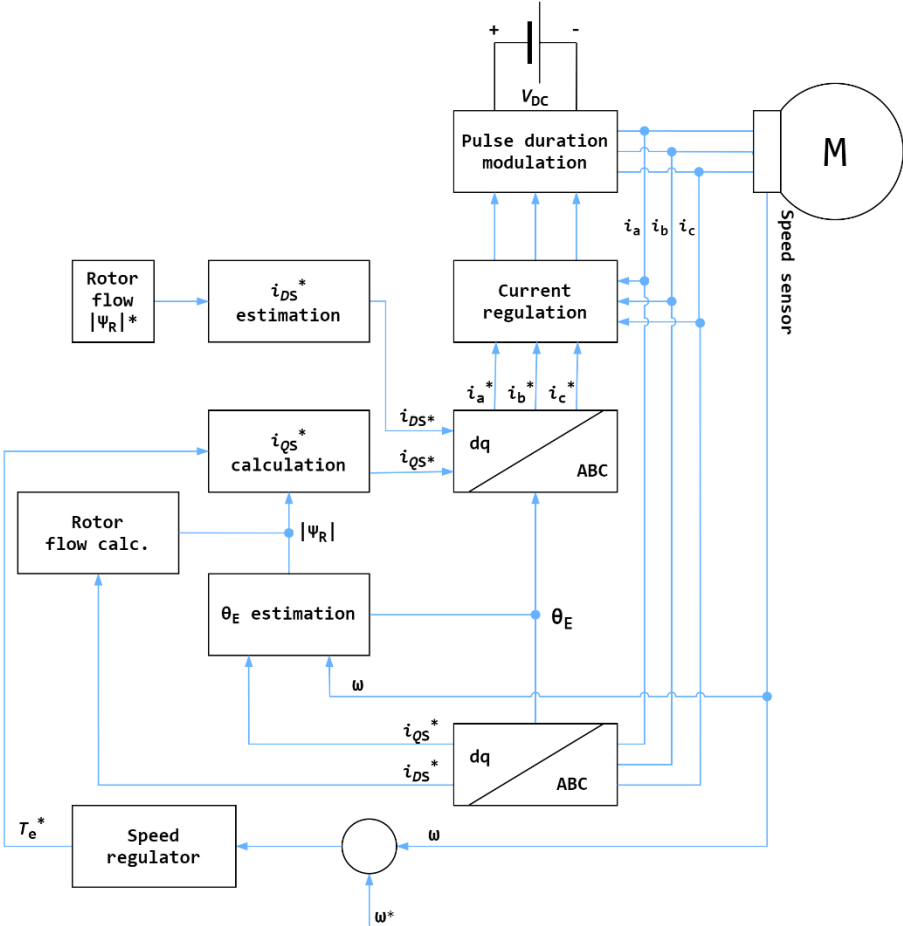


Fig. 1.3. Vector control scheme of induction motor. The following designations are used: M – induction motor; dq/ABC – coordinate converters performing the following transformations: stator current transformations from three-phase system A, B, C to fixed Cartesian coordinate system ( $\alpha, \beta$ ); stator current transformations from axes ( $\alpha, \beta$ ), at axes ( $d, q$ ), using direct field orientation.

The effect on the IM stator current vector transverse component must be used to control the electromagnetic torque in the electric drive mechanical movement coordinate control channel, similar to the DC motor anchor current.

The action on the stator current longitudinal component must be used to control the IM magnetic state (magnetic flow) in order to ensure rational energy electromechanical conversion modes, similar to the DC motor excitation current.

From the first two Equations (1.1) it can be concluded that when supplying the motor from an adjustable voltage source, the stator current vector transverse component must be regulated via the voltage vector projection on the  $q$  axis. The current longitudinal component is regulated by the voltage vector projection on the  $i_d$  axis.

The identifier is intended for computing all values necessary for the implementation of the vector control principle. The calculation of the parameters to be used for discrete modelling of vehicle with short-circuit rotor and the synthesis of the vector control system are given in Part 3 of full text of the Thesis.

### 1.5. Observer Modelling on the Basis of an Adaptive Model (MRAS Algorithms)

To date, the most common IM rotor rotation frequency passive estimation systems [18] in both theoretical and engineering applications are MRAS (*Model Reference Adaptive System*) type algorithms, an adaptive system with an instructive or reference model. The output signals of all these algorithms are estimates of the current frequency of the flow coupling vector and the induction car rotor rotation.

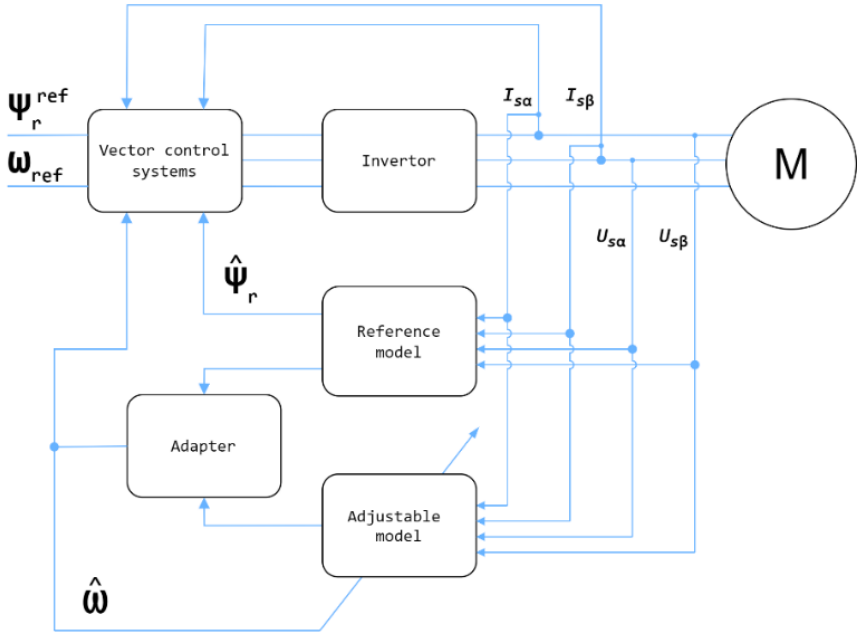


Fig. 1.4. Adaptive algorithm control scheme.

The MRAS type identifiers first proposed by *Colin Schauder* include in their structure two different models computing the estimates of the same state variable (in the general case – vector), e.g., the rotor flow coupling vector. One model not containing an indeterminate parameter is the predecessor, and the variable calculated with it is considered the reference. The second model depending on an indeterminate parameter is adjustable, whereby its adaptation is performed by change of an indefinite variable to be computed. Procedure for the synthesis of the MRAS algorithm leading the multiplication of the rotor flow coupling vectors obtained from the equations of the IM stator circuit model taken as a reference and the IM rotor circuit model which is adjustable to zero. The block scheme of the algorithm is given in Fig. 1.4 [13].

To compile the rotor rotation frequency identifier on the basis of the MRAS method, the IM mathematical model in state coordinates in the fixed Cartesian coordinate system  $\alpha, \beta$  is used, which is strongly related to the stator which has the following appearance:

$$\begin{cases} L_{\sigma e}^s I_s = -R_s I_s - \frac{L_m}{L_r} \dot{\Psi}_r + U_s; \\ \dot{\Psi}_r = \frac{L_m}{T_r} I_s + \omega_r D\Psi_r - \frac{1}{T} \Psi_r. \end{cases} \quad (1.2)$$

Since the stator circuit model only contains one unknown value – the rotor flow coupling vector, it can be used to find it:

$$\dot{\Psi}_r = \frac{L_r}{L_m} \left( -L_{\sigma e}^s I_s + \int (U_s - R_s I_s) dt \right). \quad (1.3)$$

With accurate information on motor parameters, the stator circuit model can be accepted as a reference model. The rotor circuit model contains an adjustable parameter – the car shaft rotation electrical frequency – and is adjustable. Let us consider the IM rotor circuit mathematical model and adjustable model together:

$$\begin{cases} \dot{\Psi}_r = \dot{\hat{\Psi}}_r^{\text{etal}} = \frac{L_m}{T_r} I_s + \omega_e D\Psi_r - \frac{1}{T_r} \Psi_r; \\ \dot{\hat{\Psi}}_r^H = \frac{L_m}{T_r} I_s + \hat{\omega}_e D\Psi_r - \frac{1}{T_r} \hat{\Psi}_r^H. \end{cases} \quad (1.4)$$

Subtracting the equations of the adjustable model from the equations of the observation object – IM rotor circuit model, we get the equations in deviations:

$$\dot{\varepsilon}_\Psi = \omega_e D\varepsilon_\Psi + \delta D\hat{\Psi}_r^H - \frac{1}{T_r} \varepsilon_\Psi, \quad (1.5)$$

where

$\varepsilon_\Psi = \hat{\Psi}_r^H - \Psi_r = \hat{\Psi}_r^H - \Psi_r^{\text{etal}}$  is the rotor flow coupling observation error,

$\delta = \hat{\omega}_e - \omega_e$  is the speed estimate deviation (adjustable parameter).

The stator circuit model is neutrally stable because the two integrators in its structure, which are not covered by the feedback, determine the zero root of the characteristic equation with gradation of two. To make the identifier stable, it is necessary to stabilize the stator circuit model. That will perform stabilization of the stator circuit model by covering the integrator with negative feedback and entering a PI-regulator [18] in it, which will ensure the insensitivity of the identifier to signal zero offsets from current and voltage sensors. Also, according to [12] and [20], adaptive algorithms, including MRAS, are sensitive to deviations of IM parameters from their real values operated by a computer. These deviations can be related both to erroneous information on the parameters obtained at the stage of their previous identification and to changes in the electrical parameters during the operation of the electric drive, in particular to changes in the active resistance of the stator and rotor due to the car heating.

## **Conclusions**

The first chapter provides a description of the concept and methods of testing the CEE and its main components. A mathematical description of the frequency of the induction car as a control object in the adjustable electric drive and the other apparatus required for full testing of the CEE is given. Based on this, mathematical models of IM have been created. On the basis of the common methodological basis, the IM vector control principles have been formulated in coordinates of stator current – rotor flow coupling. The MRAS algorithm has been selected from various control methods, since to date it is the most common in both theoretical and engineering applications with IM rotor rotation frequency estimation.



## 2. VIRTUAL-PHYSICAL TEST SYSTEMS

The chapter discusses several tasks related to the development of tools for researching and developing a vehicle (V) with CEE. The first task is to develop a method for identifying the operation factors of CEE and its components based on the results of testing the energy equipment or a car equipped with it under conditions of limited measurements. The second task is to expand the functional capabilities of the CEE laboratory tests with the help of systems simulating the operation of the energy equipment under different V movement conditions.

In order to obtain experimental data, it is necessary to have access to the development of a mass V or to study the self-developed energy equipment. If it is possible to test V models with CEE, extensive and useful material for analysis can be obtained. However, there is a problem of the closeness of mass vehicle software: since the CEE control algorithm is usually unknown, it is quite problematic to analyse the test results with the help of virtual models.

The solution for both problems can be achieved by combining physical testing methods with computational experiments performed on virtual models. In the first task, the virtual object must reproduce the physical, i.e., it must be “duplicated” being synchronized with it according to the variables to be measured, and represent the variables that are not observed in the physical object. In the second task, the virtual object must represent the part of the tested object that is not physically present in the laboratory. The interaction between the virtual and the physical object must be ensured in such a way that their combination represents a single system – a vehicle with CEE – and the conditions under which they are tested. This requires real-time synchronization of the virtual and physical parts.

### 2.1. Combined Systems

Control systems are developed with the help of various software means, and their integration with the modelling environment, ensuring protection of information, is a labour-intensive task, oblige the car manufacturer to perform it. An acceptable method of use is virtual-physical modelling technology under the international name HiL (*hardware in the loop*). It is used as a testing tool for apparatus controllers in various technical fields and is based on the replacement of the object controlled by the controller and the environment with which the controlled object interacts with a virtual model. The controller exchanges signals through the interface with a model that is real-time synchronized as if it occurred in a physical object.

The CEE apparatus controller is shown in Fig. 2.1. with a VCU (*vehicle control unit*). The speed control of the virtual car is performed by the so-called driver model. For this purpose, it sets the accelerator and brake pedal pressing signals according to the driving cycle operation map and the current speed of the car and sends them to the VCU. Taking into account the diversity of CEE schemes and components as well as the tasks of the developed models for use as mass testing means, they are presented with increased requirements in terms of architectural flexibility, component unification and organization of interface, with the help of which a virtual car with CEE is represented and its parameters are set. Link graphs with the

implementation of software architecture, which is similar to Argonne *Autonomie* or *Simulink* modelling systems, are used as a method of creating a modelling system.

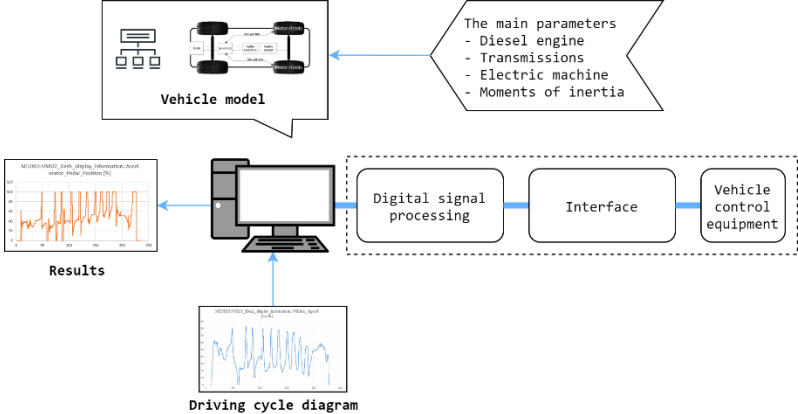


Fig. 2.1. Use of HiL technology in virtual-physical tests of trucks and buses with CEE.

The second variant of procedures envisages stand tests of a complete CEE set with the representation of its work at the movement of the car during the driving cycle. A virtual-physical test system is used for this, the scheme of which is shown in Fig. 2.2.

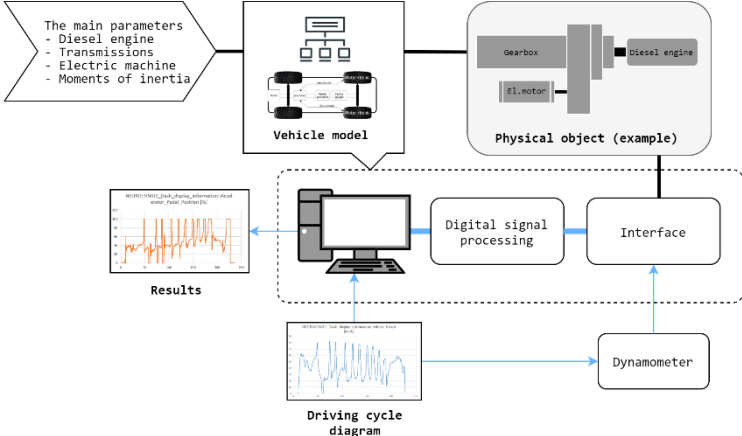


Fig. 2.2. Virtual physical test system for vehicles with CEE.

The load on the tested CEE output shaft is generated by a dynamometer; however, the inertial load, which represents the weight of the car, is not foreseen – it is simulated by the same dynamometer which is controlled by the virtual part of the tested object – the car dynamics model. The car speed is a task signal during which the dynamometer creates a load on the energy equipment shaft. The torque signal measured by the dynamometer is used to start the movement of the car model. The system organized in this way allows to simulate a car of any weight (within the limits of the loading equipment) without using conventional flywheels.

## 2.2. Fully Virtual

There are also virtual systems that duplicate physical objects and in the theory of automatic control of the system use the signals of a physical object to determine its constant parameters, it is called an *observer*. It is a model of a physical object that it “observes”. Descriptive observers are created both on the basis of classical dynamics models of technical systems and using relatively new modelling methods – fuzzy logic and artificial neural networks.

Depending on the functions to be performed, the observers are divided into two types: those identifying the physical or design parameters of an object and those identifying the variables in the state of an object. Figure 2.3 shows the block schemes of both types of systems.

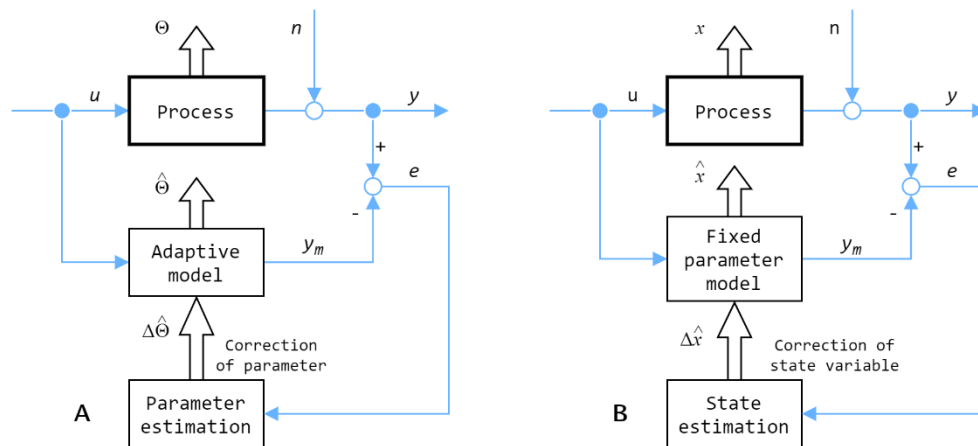


Fig. 2.3. Organization of identification systems for unobservable indicators of a physical object with the help of a duplicating model-observer: A – Identification of physical and/or design parameters; B – Identification of state variables [10].

A physical object is usually controllable. Signal  $u$  is the vector of the controlling effects to be measured. Vector  $y$  of the object’s output variables is also measured. The object is affected by stimulation  $n$ , which is an unobservable random process. The identification of the object parameters  $\Theta$  is performed with the help of an observer, which is the model, respective parameters of which can be adjusted in the work process. The adjustment is performed by the identification block. For this purpose, it uses observation error  $e$ , which is the difference between the measured output signal of the physical object and the output signal of model  $y_m$  obtained with the effect of the same (measured) control  $u$  on it. In order to perform this operation, the model must be synchronized with the observed object, i.e., it must operate in real time. In the identification block, the observation error is used as an argument in the function that calculates the correction values of estimates of parameters  $\Delta\hat{\Theta}$  or states  $\hat{x}$  (symbol “^” means with the estimate result).

In addition to unobservable random disturbances affecting the physical object, the error factor in the identification is the noise pollution of the input and output signal measurements. If the random component in measurements is large, while the parameters of the physical object are known inaccurately, then Kalman filtering can be used to identify its state variable [7], [11]. In this method, a discrete model of the physical object dynamics is used to identify the unobservable state variables, which allows to apply this method in electronic control

systems. In the car sector, it has mainly become prevalent in active safety systems, where it is necessary to know such unobservable or immeasurable variables in mass cars as wheel slip and deflection, adhesion coefficient, normal reactions [5], [11]. The output variant of the Kalman filter only allows the use of linear models of observed objects. If a model has nonlinear sections, they must be linearized with the help of Taylor series. This approach is called Extended Kalman Filtering [11], [16], [17].

Literature provides descriptions of the observer's application for torque identification in the car's power drive [4], [3], [14]. An example of an abbreviated form is the solution of the torque identification problem on individual wheels of a car described in the Thesis [14]. The model was developed for the case of movement on a horizontal smooth road and did not take into account the aerodynamic drag. The car and each wheel were viewed as separate moving masses linked by road contact reactions. The system of equations for the rotating weight of one wheel and the weight of a car moving in a straight line looks as follows:

$$\begin{cases} \dot{\omega}_k I_k = T_k - R_z \varphi_x r; \\ \dot{V}_x M = \sum (R_z \varphi_x), \end{cases} \quad (2.1)$$

where  $\omega_k$  is wheel angular speed;  $I_k$  is wheel moment of inertia;  $T_k$  is wheel torque;  $R_z$  is normal road reaction;  $\varphi_x$  is wheel coefficient of adhesion to the road;  $r$  is wheel radius;  $V_x$  is car straight movement speed; multiplication  $R_z \varphi_x$  is  $R_x$  contact reaction.

Virtually all parameters in the equations can be estimated, i.e., the value can be calculated. Determining them in real V operating conditions itself is a non-trivial task. A description of the methods for identifying the car weight, normal reaction, tyre road adhesion coefficient as well as the road slope angle can be found in [3] and [19]. However, if the observer is intended for research of an actual object through tests, then some part thereof can be measured and the other part can be identified.

### **2.3. Methodology for Creating Virtual-Physical Test Systems for Research and Development of Vehicle with CEE**

In order to solve the CEE research tasks with additional research stands, a virtual system is created which reproduces the part of the tested object that is not physically present in the laboratory. It includes a vehicle (with wheels) as well as energy equipment, power units or chassis assemblies that are not in the physical part of the tests. The virtual and physical system is connected with both informative and power links. Their operation is synchronized in real time, which means, first of all, the use of special real-time computer modelling software. The two systems form a closed circuit, i.e., the bilateral interaction is implemented between them. Their combination represents the whole car with CEE and the conditions under which it is tested.

But for a task type where representation of a sufficiently complete CEE functional picture is intended, its component is represented in the mode point array form under a limited amount of output data taken from the energy equipment component indication measurements which are obtained in the course of laboratory or road tests. The composition of the experimental

data depends on the capabilities of used measurement systems and the observability of specific variables of the energy equipment. In order to solve the task of completing unobservable or immeasurable indicators, a virtual system is created – an observer which duplicates the physical tested object (within the required level of detail) both in terms of structure and properties and behaviour. The structure and properties of the tested object are represented via its mathematical model, and the behaviour is represented by the coupling and synchronization of the virtual and physical object in real or machine time. The dynamic identification task does not envisage the effect of the virtual object on the physical object, i.e., their merging in a closed system. In this regard, only information links, which are signals of physical object indicator measurement systems, are used for coupling and synchronization.

The composition and the level of detail of mathematical models on which the virtual objects are based are determined by the requirements of each individual study, the type of task to be solved (identification or laboratory tests) and the corresponding type of interaction with the physical object.

**2.1.1. Laboratory Test Systems Connecting the Virtual and Physical Object (Combined)**

The virtual-physical object base for laboratory tests is a closed system consisting of a power unit with one output shaft, a virtual model and the informative-power interfaces connecting them (Fig. 2.4). Depending on the used model, this system can reproduce the whole car or a single axle/wheel power drive.

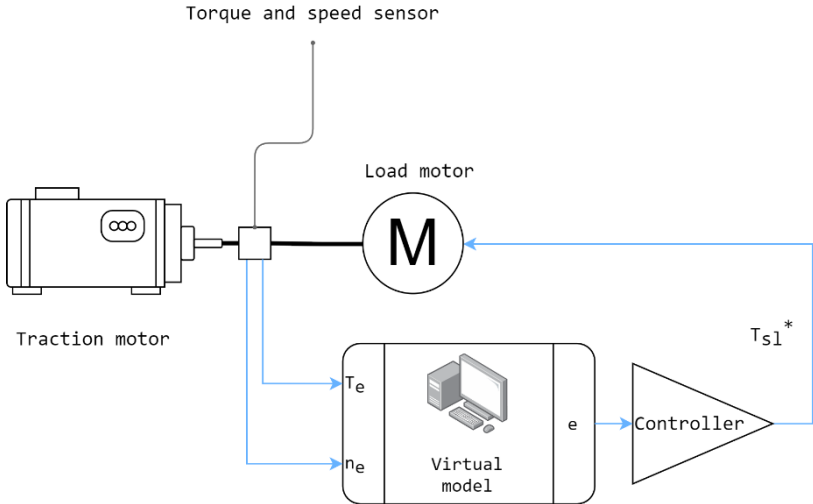


Fig. 2.4. Virtual-physical test base system scheme.

The simulation of the power unit load mode is carried out by a device commonly referred to as a dynamometer which may be, for example, an electric machine. The torque and rotation frequency sensor are installed at the point where the physical part of the tested object ends and the virtual part begins. For the modelling to be correct, the physical part must be completely positioned before the sensor installation location. The dynamometer and all equipment adjusting the load mode must be installed after the sensor.

The initial action that activates the system is the power unit shaft rotation start after a control signal has been received by it (e.g., by depressing the accelerator pedal). In parallel, the virtual part of the system is still stationary and the rotation frequency  $n^*$  of the shaft, which is part of the power unit, is zero. Since the rotation frequency  $n_e$  of the physical shaft measured by the sensor is already different from zero, the kinematic alignment of the physical and virtual parts results in a control difference:  $e = n_e^* - n_e$ . It is transmitted to the dynamometer controller which calculates torque  $T_{sl}^* = f(e)$  that compensates for it. This torque is generated by the load device on the power unit shaft and is measured by the sensor. It is then transmitted in the form of signal  $T_e$  to the virtual model, which starts the movement. In this way, a closed system with information and interaction force channel is created, which synchronizes the virtual and physical part of the tested object.

One of the issues in simulating the power unit load mode is the ratio between the load inertia part and the torque generated by the dynamometer. To determine the role of inertia associated with a dynamometer, let us consider the load structure generated in two types of tests: without the car wheel rundown and with slip. Additionally, the following assumptions will be made:

- The rigidity of the power unit connection to the loading device is not taken into account;
- All loads in the model are considered to be applied to the power unit shaft.

The torque balance equations in the physical and virtual part of the tested object for the case without wheel slip are given in System (2.2), and with slip – in System (2.3).

$$\begin{cases} T_e = T_{sl} + M_{j,din}; \\ T_e = M_{j,auto} + M_{\psi}; \\ M_{j,din} < M_{j,auto}; \end{cases} \quad (2.2)$$

$$\begin{cases} T_e = T_{sl} + M_{j,din}; \\ T_e = M_{j,k} + M_{Rx}; \\ M_{j,din} > M_{j,auto}. \end{cases} \quad (2.3)$$

In the physical part, at the sensor installation place, on one part the power unit torque  $T_e$  acts, and on the other part the sum of torque  $T_{sl}$  equals to it produced by the dynamometer and the reduced moment of inertia  $M_{j,din}$  of the rotating parts of the dynamometer and other devices mechanically connected with it. In a vehicle model that does not take into account wheel slip, the moment of resistance forces  $M_{\psi}$  acts on one mass, which can be reduced to the equivalent flywheel, which creates the inertia moment  $M_{j,auto}$ . The sum of these moments in the virtual model is balanced by torque  $T_e$  measured by the sensor on the shaft. Therefore, the parts of the first and the second equations of System (2.1) are equal. If no additional flywheel is connected to the dynamometer, its inertia will be significantly lower than the V equivalent inertia. The lack of inertia load will be compensated by the dynamometer controller, and it will be included in moment  $T_{sl}$ . When simulating the V accelerated movement, the simulated

weight will increase the required dynamometer braking torque, and with decelerations it will either decrease it or switch the dynamometer into traction mode. In long-term tests with the reproduction of the V accelerated movement, e.g., in driving cycles, the simulation of the V weight with the help of an electric dynamometer will require the dissipation of a significant amount of the generated energy. If it is not technically possible in the laboratory to return it to the power circuit or send it to an accumulator, it must be dispersed in one way or another. To reduce the amount of produced energy, the constant part (charged weight) of the V weight can be simulated with an additional flywheel.

When simulating the operation of a power unit with its driven wheels slipping, the virtual load includes the inertia moment  $M_{j,k}$  of these wheels and the moment  $M_{Rv}$  of contact reaction acting on them (for the purpose of simplifying the example, we ignore the circulation resistance moment). If an additional flywheel is connected to the dynamometer, inertia  $M_{j,din}$  may exceed  $M_{j,k}$ . When reproducing the increased wheel slip accompanied by the acceleration of the power unit shaft, the excess inertia load  $M_{j,din}$  must be compensated by the dynamometer controller via torque  $T_{sl}$ . Given that the angular acceleration of the wheel applied to the power unit shaft through the gear ratio can be quite high, this inertia moment, which will have to be compensated, will also be large. Therefore, in tests of this type, it is not expedient to use a rotating mass attached to the dynamometer, the inertia of which significantly exceeds the inertia of the simulated wheels and the virtual part of their drive.

The following describes a method of controlling the energy equipment test system with a number of power units driving different axles or wheels of V. In the simplest case – V movement modelling without taking into account the wheel slip – load adjustment in the drives of different axles is implemented by means of kinematic proportions between them. If, however, the model takes into account the wheel road adherence properties, the adjustment takes place in the manner illustrated in Fig. 2.5, using the example of straight movement of the all-wheel-drive V. The “interface” block in Fig. 2.5 indicates the set of measuring, information and power equipment synchronizing the operation of the physical and virtual parts of the tested object.

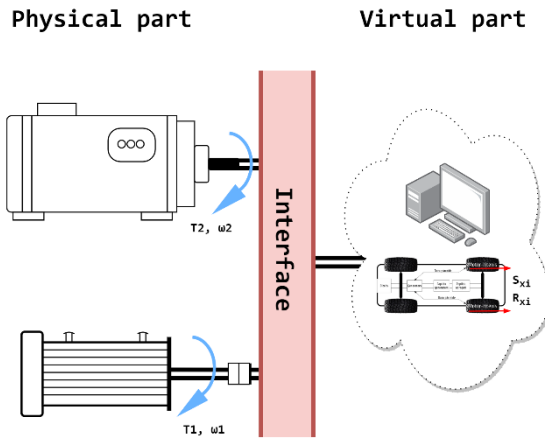


Fig. 2.5. Virtual-physical test base system scheme.

The load control variable is the power unit shaft rotation frequency. It is determined by the angular speed of the vehicle's wheel or axle in the virtual model including slip  $S_{xi}$ . The contact reaction  $R_{xi}$  acting on the wheel is given in the form of its slip function. In implementing the power unit shaft rotation speed calculated by the model, the loading device generates a torque balancing the calculation contact reaction. Since the contact reactions are common force factors for the wheel dynamics model and V, the virtual model of V becomes the connecting link in the coordination circuit of the power unit load mode of the physical part of tested object.

To ensure the correctness of the virtual-physical tests, the adequacy and accuracy of the V model used in its virtual part must be validated. This is implemented using the V road test data in respective movement modes.

### 2.1.2. Laboratory Test Systems Duplicating the Physical Objects (Fully Virtual)

The method of connecting and synchronizing a virtual (duplicating) object with a physical (identifiable) one can be considered as one of the approaches to solving the task of determining the motor operating mode (with the help of a model) of a vehicle moving at a given speed, e.g., in a driving cycle. As it is known, two modelling methods can be used for this: solving the inverse problem of dynamics and solving the direct problem of dynamics [8].

The first method intends the calculation of the power unit load and speed mode according to the set speed and acceleration cycle of V. Figure 2.6 shows a block scheme illustrating this. The "Vehicle model" block contains the equation of its straight movement dynamics allowed in respect of the wheel torque:

$$T_k = f(V_x, \dot{V}_x, a), \quad (2.4)$$

where  $V_x$  is the vehicle straight movement speed set by the driving cycle; and  $a$  is the vector of vehicle parameters required for calculation of movement resistance forces. The torque  $T_k$ , as well as the driving wheel angular speed  $\omega_k$ , are the output variables of the "opposite" model of the vehicle. The "Transmission model" block includes its force and kinematic transmission functions given in such a way that the output signals of the block are motor torque ( $T_e$ ) and its shaft angular speed ( $e$ ).

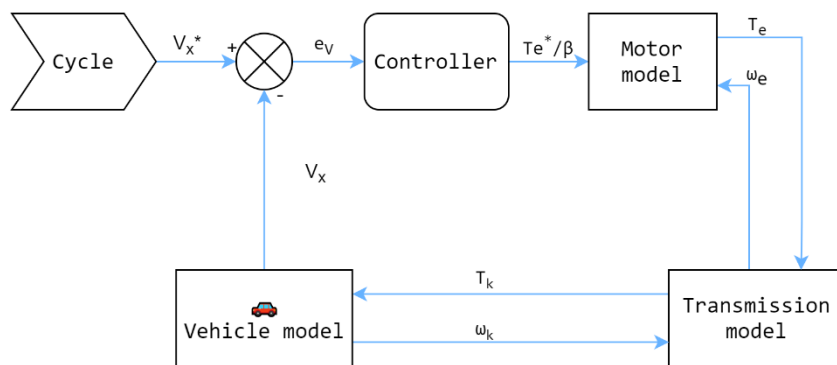


Fig. 2.6. Block schemes of vehicle movement models with a set speed mode and with speed controller.



In Fig. 2.6, driving effect  $T_k$  is the result of conversion of the motor torque  $T_e$  with the direct transmission function. In order for this model to execute the cycle speed mode, it is equipped with a controller that compensates for deviation  $e_v$  of the model  $V_x$  speed from the speed set by cycle  $V_x^*$  for the current moment of time. For this purpose, it generates a giving signal or directly the motor torque  $T_e^*$ , or the accelerator pedal position  $\beta$ . In the model shown in Fig. 2.6, the leading variables, but then also the force variables are transferred from the control system to the V wheels, and the kinematic variables – in the opposite direction. This is a typical concept of “direct” dynamics models, including their formalization with the help of link graph theory [6], [8], [9]. This is related to the numerical integration of the differential equations used in the models. The kinematic variables are the state variables whose derivatives are in the left part of the equations. Their values from the previous iteration are used in the current one for integration and calculation of the force variables, which are their functions. The force variables set by the control signals are calculated and operate at the current step.

In a vehicle movement simulation task with a set speed as such can be used not the operational map of the cycle, but a vehicle speed measurement record obtained during its tests on a stand with travellers or on the road. In this case, the task of identifying the operating mode of the power unit according to the experimental data will be solved. In order to reproduce this test adequately and accurately, it is necessary to determine its load regime. For this purpose, the experimentally obtained resistance forces, the vehicle weight and power drive efficiency must be input to the model. To test the vehicle operating modes, a motor load map (diagram) is created, which will take into account all possible movement modes: the vehicle movement start, uphill, downhill, transport stopping, as well as the main factor is the weight of the transported cargo and the calculated dynamic factor, which depends on the specific resistances of the dump truck movement. Experimental data show that the dump truck movement speed is a complex parameter, which depends on the weight of the transported cargo, the dump truck resulting traction force and dynamic factor determined by the specific road resistances as shown in Fig. 2.7 with the increase of the dynamic factor the dump truck movement speed decreases.

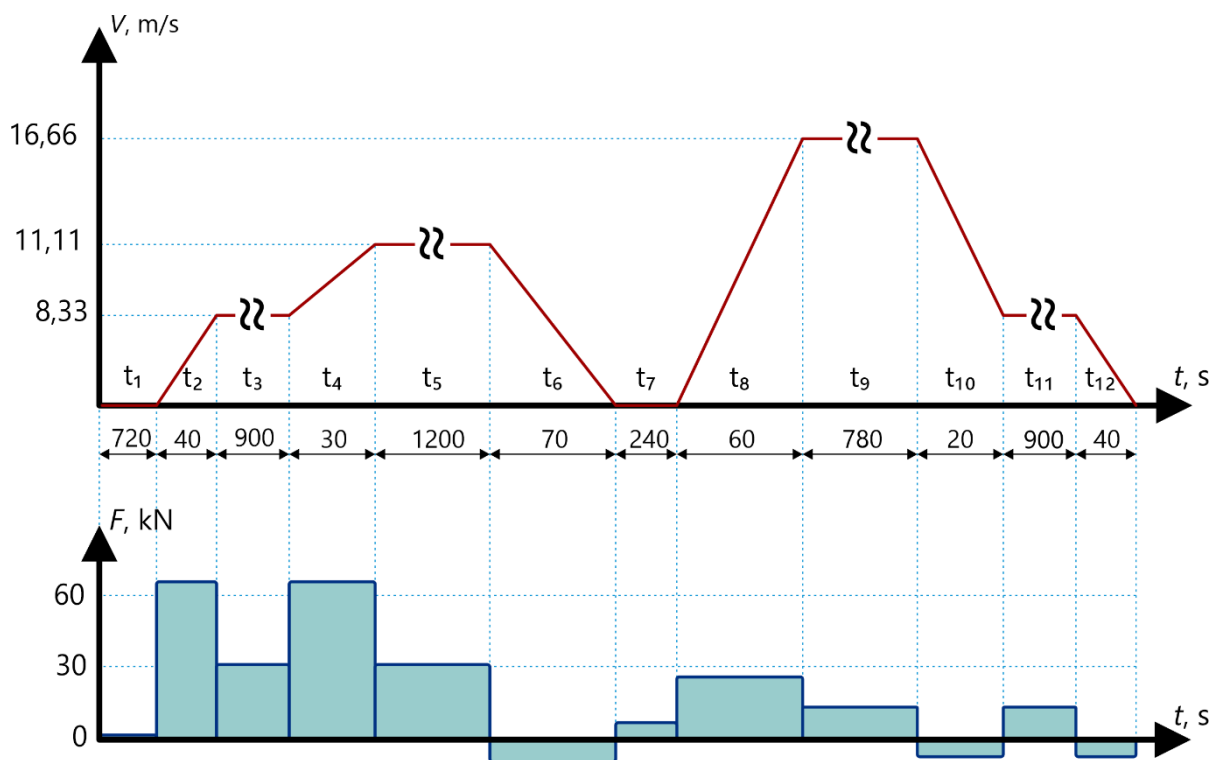


Fig. 2.7. Effect of road slope and vehicle loading on its speed.

Theoretical determination of the relationship between the dump truck movement speed, traction force and dynamic factor is quite difficult. In practice, the analytical method of graphs for determining these characteristics is used, using the nomograms of the manufacturer of the dumper of a specific type and size. An example of such nomograms can be seen in Fig. 2.8.

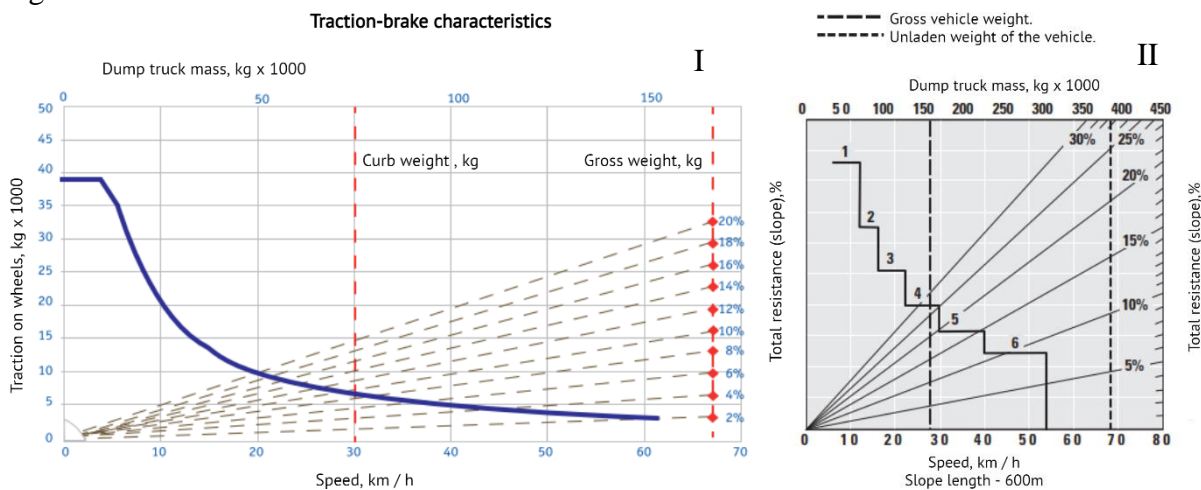


Fig. 2.8. Example of the traction-brake characteristics of the Belaz-75581 (I) and CAT 793D (II) quarry dump truck for determining the amount of lift to be overcome.

For example, in the MATLAB program, motor control is set by two parameters – revolution speed and load on the motor. Similar traction – braking diagrams – graphs for IM load are created, which will simulate different operating modes of the vehicle (Fig. 2.9). The design and identification of traction-braking curves is the most important task for the evaluation of the vehicle IM performance in all operating modes in the virtual environment.

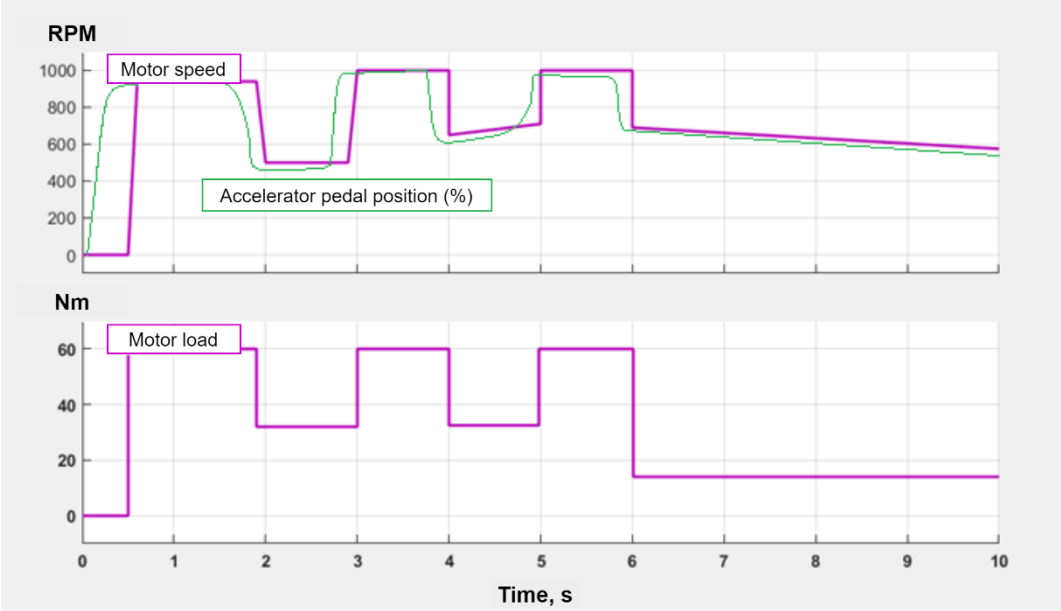


Fig. 2.9. *Signal Builder* block that constructs curves that are the regulatory arguments for IM control.

The identification task can be generalized for a power unit with a number of CEE power units. A direct approach seems to be the most convenient for solving similar tasks. To implement this, it is necessary to connect a controller to each unit model, the operating mode of which needs to be identified, and to assign it a controllable model variable according to the type of feedback, the required value of which is measured in tests of the power unit or the vehicle equipped with it. The correctness of the identification is determined by the accuracy of representation of the resistance forces and the efficiency of the energy equipment components as well as the quality of modelling of the components. Modelling errors will be compensated by controllers, which will make it less adequate to identify the operating modes of the power units to be executed. In order to reduce errors, it is desirable to experimentally determine the characteristics of the components of the energy equipment and to make a separate estimation of the adequacy and accuracy of these components.

A Luenberger observer with a low gain coefficient can be offered as a means of compensating for random disturbances, which will not distort the mathematical model and the results of torque identification.

This creates a virtual model duplicating the tested vehicle and associated with closed control systems using physical object signals and curve graphs and corresponding model signals for identification of the power unit operating modes.

Two methods can be proposed to confirm the correctness of the identification of the power unit operating modes. The first one is a confirmation by torque measurement data in

some other tests of the same or a similar object. The second method is the analysis of a number of indirect confirming signs: compliance of the identified moment with known operating modes of the unit; according to other signs depending on the knowledge of the studied object.

In order to reconstruct the operation of the mechanical braking system, it is necessary to identify the torque of the electric motor and the moments generated by the braking mechanisms on each wheel. The specifics of this case are that in order to solve the task of identifying moments on individual axles or wheels, it is necessary to use a model in which they are not combined with the vehicle mass but have their own degrees of freedom.

The adequacy of the model is confirmed by comparing its result with the control variables which are also measured during the tests: vehicle speed and acceleration. The quality of the identification is determined by the accuracy of representation of the load factors, the main of which are the contact reactions acting on the wheels. They depend on the normal reactions and the tyre adhesion to the support surface coefficient. To determine normal reactions, the vehicle's parameters: weight, weight distribution on the wheels, coordinates of the centre of gravity – must be measured. The adhesion coefficient is calculated by the tyre model. Its parameters are identified by experimental data. The main factors in modelling the tyre adhesion properties are the maximum value of the adhesion coefficient and the respective wheel slip.

When implementing the identification model in a computer environment, its means of synchronization with the physical object – controllers, signals from sensors and feedback – can be organized within one subsystem which performs the function of a controller for the model. If a CEE researcher or developer has to compare the energy equipment operating modes in a mass vehicle with the performance results of his controller, the same CEE model can be used for it by simply replacing the identifiable block with a new control system. The use of a “direct” model of a vehicle with a CEE organized according to link graph theory [6], [9] will also allow for easy replacement of energy equipment components or its scheme to assess the effect of these changes compared to a mass system on the same V under the same test conditions.

## **Conclusions**

Chapter 2 provides detailed descriptions and explanations of the experimental research of IM operation and the equipment with its components for a full CEE as well as of the necessity to apply a laboratory test system with a broader functionality than traditional ones. The use of these systems requires the replacement of a significant proportion of “field” work with laboratory work. Therefore, they have to reproduce the operation of energy equipment in all modes only carried out within the road tests (with wheel slip, on surfaces with different adhesion properties, driving uphill and downhill, etc.). Systems with extended functionality should also be allowed to perform tests of energy equipment with multiple units, including with mechanically non-connected ones.

Creation of CEE performance identification method and expansion of the functional possibilities of CEE laboratory tests can be achieved by combining physical test methods with computational experiments performed on virtual models. In the first task, the virtual object had to reproduce the physical one – it should be “duplicated”, being synchronized with it according to the measurable variables and reconstructing the variables that are not observed in the physical object. In the second task, the virtual object had to represent the part of the tested object that is not physically present in the laboratory. The interaction between the virtual and the physical object must be ensured in such a way that their combination reflects the unified CEE system and the conditions under which it was tested. This requires real-time synchronization of the virtual and physical parts.

### **3. STUDY OF CEE COMPONENTS AND WORK ALGORITHMS**

The studied CEE object and the means of identifying the operating modes of energy equipment are dynamic systems, they can operate in real time synchronized with the tested object via the software interface. But in this study, modelling and testing are done in advance, and the real object is represented by the measurement records performed at the time of its testing.

The scheme of the test system established according to this principle for the CEE under study is shown in Fig. 3.1. in the picture. It shows only those activities and works that are important for testing the operation of the system. Algorithm operations are divided into two branches – virtual (MATLAB environment) and physical (laboratory). Both branches start in a common block, where the initial data of the car are created – mass, speed, operating conditions, basic dimensions, etc. This information is the basis for the design of the vehicle, and the components are designed specifically to ensure the proper functioning of the vehicle. The parallel development of the physical and virtual parts does not intersect until the respective stages of laboratory testing and modeling. Before that, the main traction and energy parameters of the CEE components and important variables are determined and calculated in the virtual part. In the physical part, the issues of the vehicle control system and control algorithm are solved, because it determines the need for components for further development of the whole system. There is no such need in the virtual part, all components can be modeled, so this stage is especially important for the physical part. After the control system is approved, the development phase of the asynchronous motor prototype begins. Both traction and energy and temperature characteristics must be taken into account. In the vehicle CEE bench test laboratory, all relevant components are then assembled into a single load bench system for debugging and testing.

In the virtual part, the calculated virtual model is developed, which will serve as a virtual load stand with electric motors, and CEE electrical equipment. The calculated schemes of the vehicle model are used for the general case of straight-ahead movement, however, depending on the type of tests to be performed, the model may be modified and overgrown with additional blocks, such as a tire block and a body block. The finished virtual model is connected to the testbed, synchronizing the physical and virtual parts of the system, thus obtaining the results of unobservable variables with the help of the stand. In some cases, this helps to debug the control system and algorithm, as the sensors may not be everywhere and it is not possible to receive feedback signals.

The system presented in Fig. 3.2 was implemented in Simulink program, the upper level of the Simulink model.

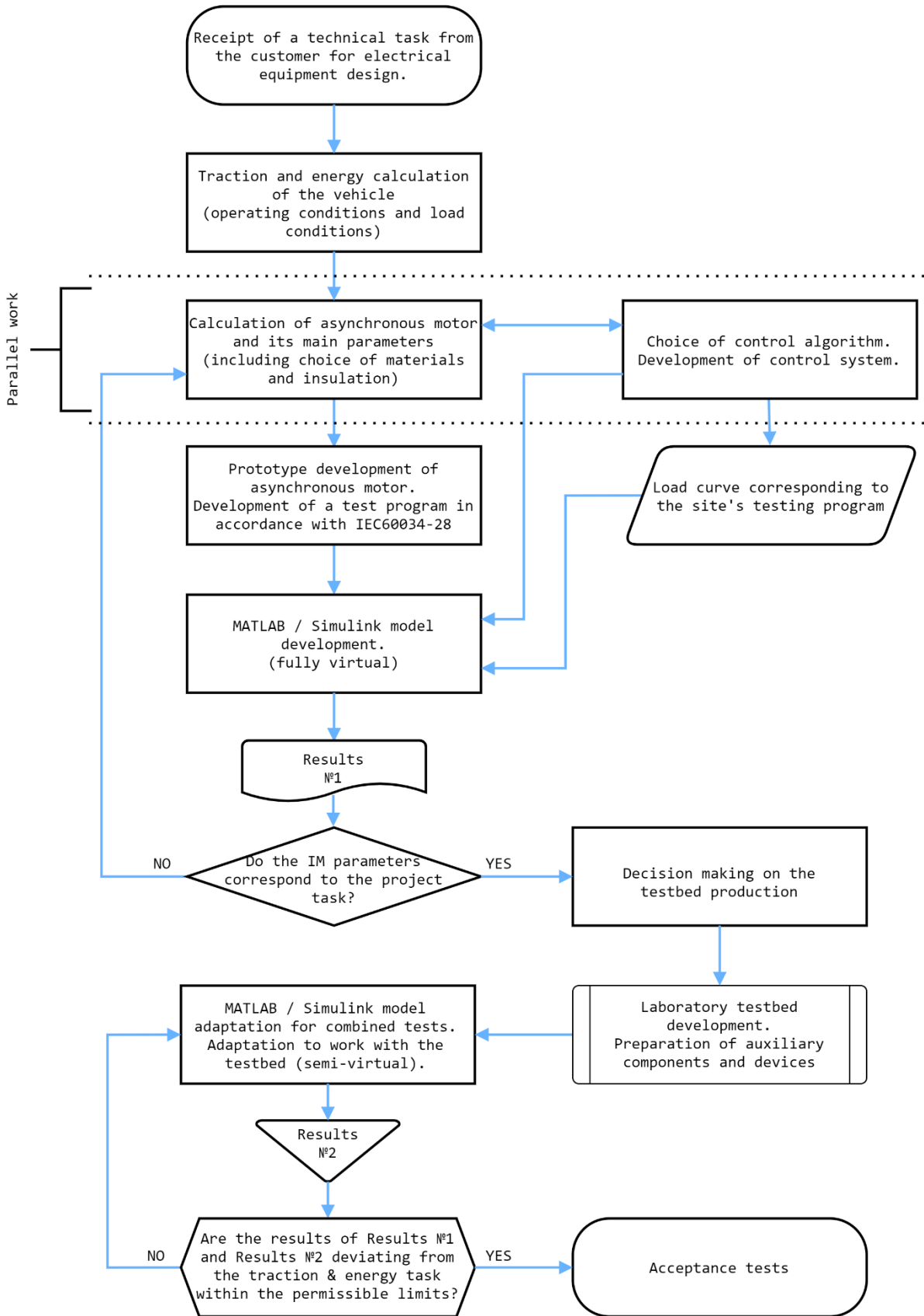


Fig. 3.1. Vehicle testing algorithm.

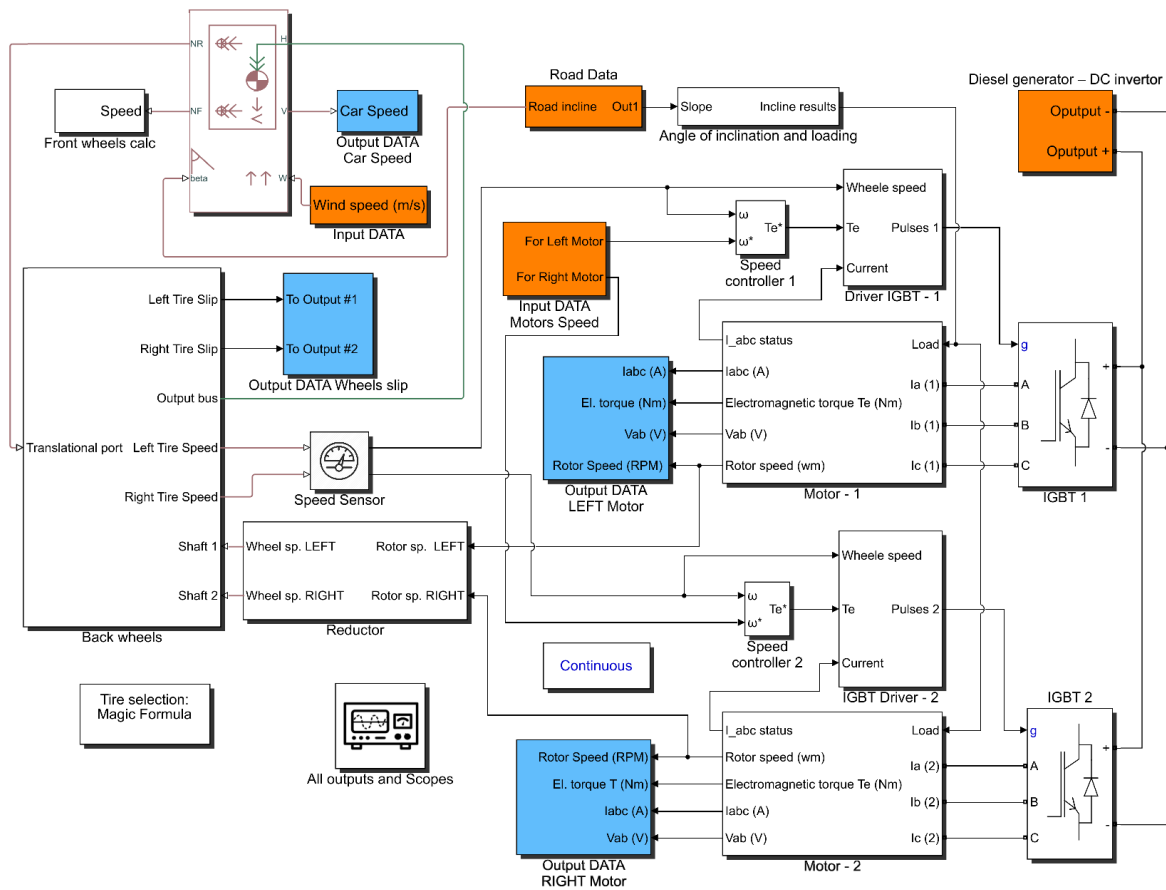


Fig. 3.2. Implementation of the studied vehicle's mathematical model and variable identification system in Simulink.

In order to realize the mathematical models of the vehicle and the energy equipment, their discretization was performed. The subsystems shown in Fig. 3.2 represent the nodes and aggregates of the studied object. Inside the subsystems, there are various model components (differential equations, logic blocks, functions in the form of tables) grouped according to the principle of belonging to one or another vehicle or its energy equipment component. Objects where data needs to be entered are marked in orange, while blocks with output information are marked in light blue. The variable composition of the input and output of a motor model is determined by its links with other components of energy equipment and the vehicle model and the motor characteristics that need to be calculated to solve the research tasks. The model input variables include control signals. For motors these are the required torque or a proportional value. If the implementation of a control system developed within the model is envisaged in the controller of CEE devices, then it is necessary to use the form of signal setting which is recognized by the motor control unit. In modern electrical equipment, signals of various load factors come to the control unit, which are converted to the required moment. The CEE controller must use the accelerator pedal position signal which is set on a scale of 0 to maximum. To model this type of control, it is necessary to know the speed characteristics of the electric motor which link the accelerator pedal signal with the torque in shaft angular speed function.



### 3.1. Implementation of vehicle mathematical model and testing of control methods

In the model, the modelling process of Fig. 3.2 starts in the V from the operation of the diesel generator and the DC converter, which are sources of electrical energy, in the figure marked as subsystem *Diesel gen. & DC Inverter*. The subsystem has been set up to control the power supplied to the motor, where the main components are the insulated-gate bipolar transistor (IGBT) and its controller (*Driver IGBT*).

The input data of the transistor control unit are as follows:

- instantaneous rotor rotation speed;
- rotor rotation base speed at which the motor must currently be aimed;
- stator current values.

The output of the block contains pulses that modulate the signals at the expense of the change in the width of these pulses. The IGBT controller is the connecting link between the motor power supply and the motor itself, the control of this unit consists of two components – feedback to the motor, where instantaneous information about the motor condition and its rotation speed is processed for the further algorithm, and data coming from the speed controller which transfers the kinematic transmission functions, also taking into account the losses. The electric motor performs its function – conversion of electrical energy into mechanical energy by turning the shaft with a reductor and a wheel, which is the next block, which in real transport form a single connection motor-wheel. This block not only calculates the wheel rotation speed but also constantly exchanges data with the vehicle physics calculation unit from which the equation of the vehicle straight movement comes as well as the equation for calculating the normal reaction of the support surface and resistance to movement that directly affect the wheel speed. Once the V speed has been calculated, the data will arrive to the already mentioned controller for further control commands. If there is a variable road profile, correspondingly variable vehicle load data is obtained, which is processed in the load block (*Load data*), where there is already constant data on motor loads that are not related to road profiles. Both values are added and their values arrive to the electric motor unit. It obtains information from the load calculation subsystem which contains both load constants and variables affecting the motor rundown speed. After receiving the power supply and load data, the motor calculates the shaft rotation data which immediately goes to the *Reductor* block where its values will be reduced to the wheel rotation value. This subsystem is a simpler front axle transmission model that sums the forces of the electric drive and braking mechanisms. The main gear model, which represents its power and kinematic transmission functions, is located in the *Back wheels* subsystem.

In this part of the scheme, an algorithm-dependent loop appears – the rear motor-wheel speed block turns into a present vehicle body block where the calculation of the vehicle speed, load from the vehicle weight is calculated, and after transferring data to the speed controller data returns to the rear wheel speed block when transferring data to the speed controller and concluding the vehicle movement data processing cycle. The speed controller compares the speed obtained from the wheels with the speed the vehicle needs to reach and, in the event of

a difference in this data, sends a command to the IGBT transistor controller which, in turn taking into account the new data, generates new impulse commands for the converter feeding the motor.

### 3.2. Solution methods, calculation step size and model detail selection peculiarities

The choice of modelling method is crucial for achieving the modelling result. Solver solving method in MATLAB has a wide selection of problem solutions, but you can stop at some that are well suited to the specifics of the task:

- *ode23t* (mod.stiff/Trapezoidal) – for a solver with variable step ( $T_s$ ), which is suitable for solving electromagnetic field problems and problems related to mechanics physics, based on the trapezoidal method solution with interpolation, it only needs the solution of the previous moment of time. In the case of moderately strict systems of differential equations, high accuracy of the solution can be given.
- *ode45* (Dormand–Prince) – a solver with a variable one-step ( $T_s$ ) 4<sup>th</sup> and 5<sup>th</sup> degree Runge–Kutta method in Dormand and Prince modification. This is one of the popular methods recommended by MATLAB developers for initial solutions of complex problems.
- *Fixed-step Solver* (Discrete) – a discrete solver with a fixed step ( $T_s$ ) size that selects an automatic solver on the basis of model dynamics. The smaller the step size, the more accurate the results and the longer the simulation is executed. Suitable for cases where it is necessary to obtain results in tabular values.

$T_s(s)$  – model calculation step. Decreasing the step increases the accuracy of the whole model calculation but critically reduces the time for calculations in MATLAB environment, by default  $T_s = 1 \cdot 10^{-5}$  s is the most optimal value, at  $T_s = 1 \cdot 10^{-4}$  s the values of some obtained data may be inaccurate and may have a lot of noise (e.g., for IM electromagnetic torque), but at a  $T_s$  value of less than  $1 \cdot 10^{-6}$  s, the model calculation time increases 2.5–5.0 times.

Table 3.1

Model Variables That Are Set at the Initial Stage and Adjusted According to a Specific Experiment

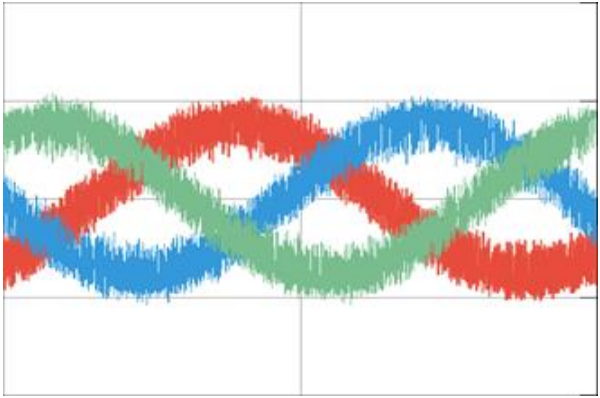
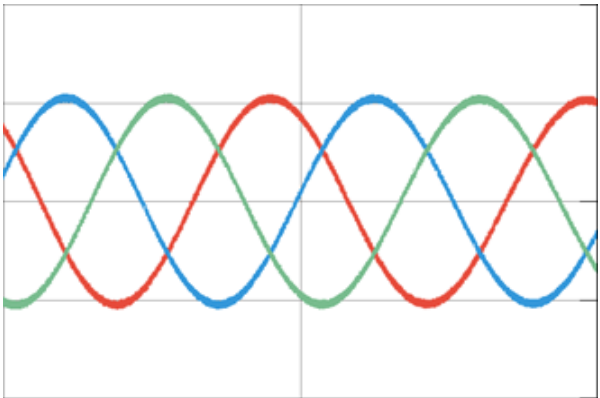
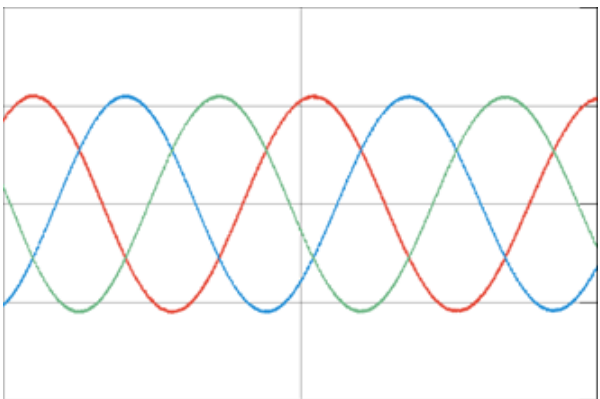
Solver	Took real time, s		Difference in %
	3 second simulation calculation	10 second simulation calculation	
<i>ode45</i>	0:36.2	1:48.7	0 %
<i>ode23t</i>	0:36.0	1:48.4	–0.5 %
<i>Fixed-step</i>	0:31.1	1:31.2	–14 %

All listed solution methods give slightly different results in a simple task, however, each of them will be more correct in a certain type of modelling problems. The step size and the solver type affect not only the accuracy of the calculation, but also the time spent on this calculation. From Table 3.1, calculating the step  $T_s = 1 \cdot 10^{-5}$  s and one model, the calculation time with different solvers is shown. ode23t was chosen due to its variability –  $T_s$  serves as a parameter of the maximum step size, and the step may decrease if the algorithm lacks precision.

Table 3.2 provides solutions with three  $T_s$  times:  $1 \cdot 10^{-4}$  s,  $1 \cdot 10^{-5}$  s and  $1 \cdot 10^{-6}$  s for the Discrete Fixed-step solver. The measured time is done with Simulink built-in tools. Model calculation – 5 seconds of work.

Table 3.2

Effect of Step Selection on the Result of the Model from Fig. 3.2

Chosen step	ED stator voltage drawing
<p style="text-align: center;"><math>T_s = 1 \cdot 10^{-4}</math> s</p> <p>Elapsed time is 13.626 079 s. The fastest calculation.</p>	
<p style="text-align: center;"><math>T_s = 1 \cdot 10^{-5}</math> s</p> <p>Elapsed time is 96.349 403 s. 82.723 324 s slower than the previous one.</p>	
<p style="text-align: center;"><math>T_s = 1 \cdot 10^{-6}</math> s</p> <p>Elapsed time is 724.854 517 s. 628.505 114 s slower than the previous one.</p>	

As can be seen from the two previous tables, the calculation model is affected not only by the step size and the solution method, but also by the complexity of the model. It is affected not only by the number of components in the model, but also by the amount of information types that is transmitted or converted to other values. The model uses an extended library for modelling and simulation of physical systems *Simscape Electrical Specialized Power Systems*. These specialized components and blocks are used to build models with broader and more complex problems in the energy field. But the main components of *Simscape Foundation Library* have only basic components (passive elements and energy sources), as well as they use physical connections – vectors and scalar values with built-in units working only in their environments and automatically outputting differential equations that describe system behaviour. These equations are compatible with the rest of the *Simulink* model and are solved directly. Components from different physical “environments” (e.g., mechanics or hydraulics) are solved together in respect of their variables, thus allowing to avoid algebraic cycling. The disadvantage of using a component library from *Simscape Electrical Specialized Power Systems* is the incompatibility of components and blocks from the *Simscape Foundation Library* (cannot be connected directly), for connection they require additional blocks-converters to convert physical signals to simple numeric *Simulink* signals and vice versa.

Building of the model in Fig. 3.2 is based on the transmission of three types of data between the subsystems which implement mathematical calculations of the vehicle and energy equipment in Fig. 3.3.

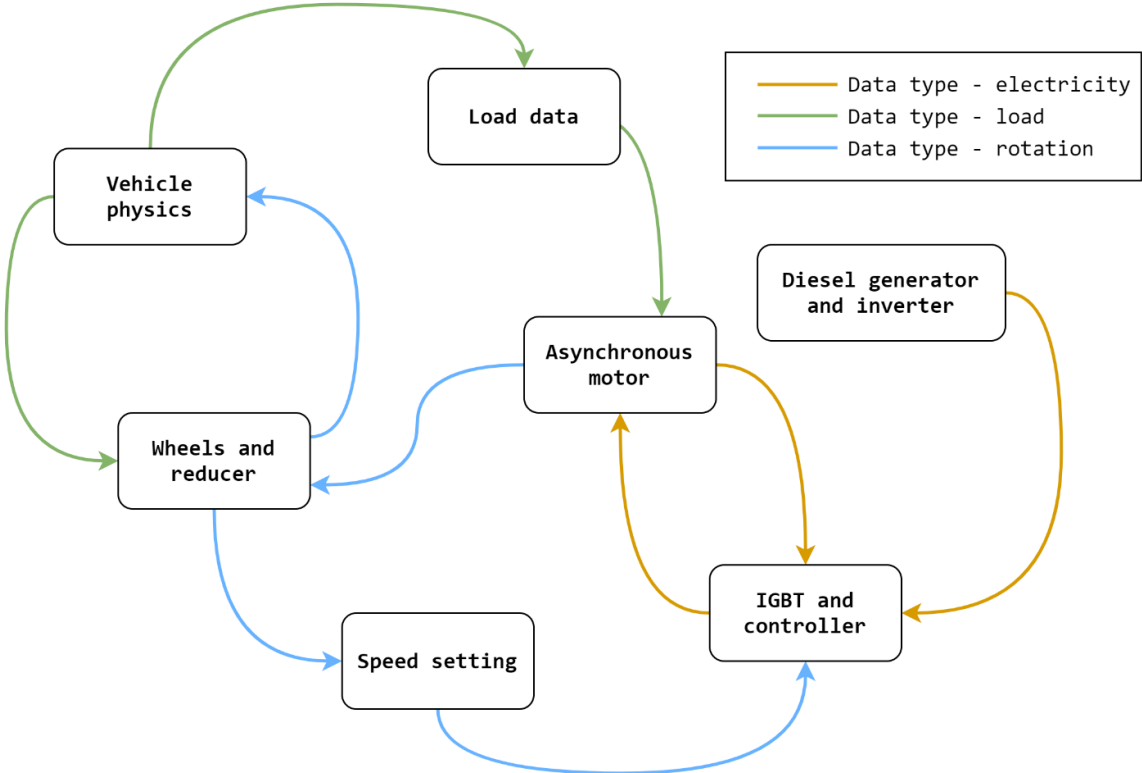


Fig. 3.2. Basic data circulation and conversion in the control system.

### 3.3. Creation of CEE virtual-physical test laboratory system

This chapter is devoted to increasing the functional possibilities of energy equipment tests on unit stands from the point of view of reproducible IM operating modes. The solution of this problem envisages the creation of an object consisting partially of physical components and partially of virtual components. The physical part of the tested object is CEE, which is installed in the laboratory on the unit stand, but the virtual part is the controller program for this energy equipment. Their information-power links and operation synchronization are performed in real time according to the type described in Chapter 1.

The task was to create a laboratory stand test system intended for researching the characteristics and confirming their compliance with the investment of the CEE designer and testing its control system by simulating the operation of energy equipment. The priority movement modes for development were chosen acceleration / braking, uphill / downhill movement with a slope 0 % to 18 %, and the acceleration corresponds to a real vehicle movement up to 90 km/h.

CEE stand tests were created on the base of Riga Electrical Engineering Factory (Rīgas elektromašīnbūves rūpnīca) unit laboratory. Specialists designed and assembled load stands, on one of which was placed energy equipment that realized wheel drive (Fig. 3.4 – I), and on the other – load drive electrical machines as operating in generator mode (Fig. 3.4 – II). Due to the mechanical links between the units, the mutual arrangement of the load stands was composed for operative access. The arrangement in the laboratory is shown in Fig. 3.4. The interaction of the CEE units with the virtual part of the tested object was ensured by the load equipment connected to the rigid coupling via a sleeve.

Between the unit stands was placed CEE electrical equipment, including cabinets with power components for IM power supply.

The author developed and implemented in MATLAB/Simulink program a virtual model of drive and vehicle and on the base of it, using the same tools (formulas and control methods), wrote a code for Texas Instruments controller for control and interaction with the physical part of the tested object: vehicle model with CEE and stand equipment interfaces; subsystems controlling loading equipment; signal acquisition and processing subsystems from stand sensors via CAN links.

During the tests, 10 cycles were performed. Figure 3.5 shows the results of one test. The following variables are shown in graphs top-down:

- motor revolution ( $n$ );
- motor torque;
- stator currents of motor#1 and motor#2.

CEE indicators obtained from CAN bus:

- recalculated according to the rotation frequency sensor readings on automatic transmission output shaft (sensor);
- accelerator pedal signal (acc.) transmitted to CEE controller by the driver model;
- tension on the tyre;
- IM instantaneous power;
- internal combustion engine (ICE) shaft rotation frequencies ( $n$ ).



Fig. 3.4. I – coupling of two IMs; II – control unit; III – converters and power components; IV – laboratory overview.

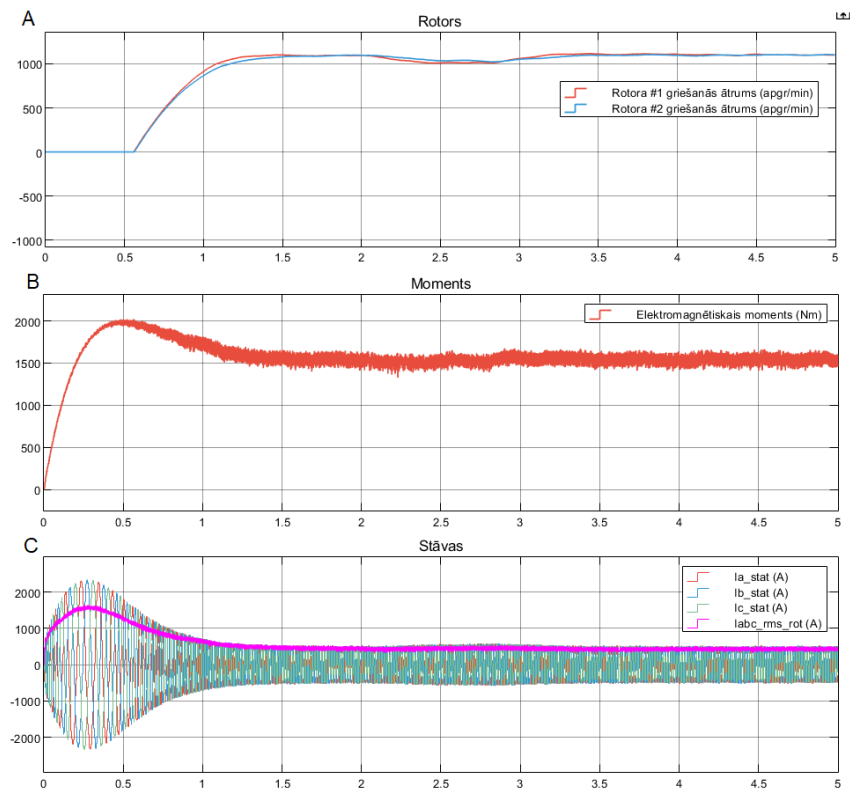


Fig. 3.5. Modelling results of a virtual vehicle with a physical CEE rundown.

Performed tests showed that a closed control system with two controllers connecting the physical and the virtual objects is operational and stable. The loading device controller provided acceptable quality for tracking the model’s set shaft angular velocity. The “driver” model generally provided acceptable quality of cycle performance: the average speed deviation from the required one was approx. 2 %. The increased deviations are mainly related to the electric machine response delays.

### 3.4. Vector control research in Simulink program

Simulation was performed in Simulink environment for the scheme in Fig. 3.2. The estimated speed  $\omega$  for the vector control system was used instead of the feedback signal from the rotor position sensor. The motor parameters used in the model are given in Table 3.3.

Table 3.3

Parameters of the Studied Electric Motor

Nominal power $P$	170 kW	$R_s$	0.030 854 $\Omega$
Nominal phase voltage $U$	530 V	$R_r$	0.0222 $\Omega$
The number of pole pairs (p)	3	$L_s$	0.000 616 H
Current frequency	43 Hz	$L_r$	0.000 527 H

Results of digital modelling of IM sensorless vector control system in Fig. 3.6 are displayed with the PI controller.

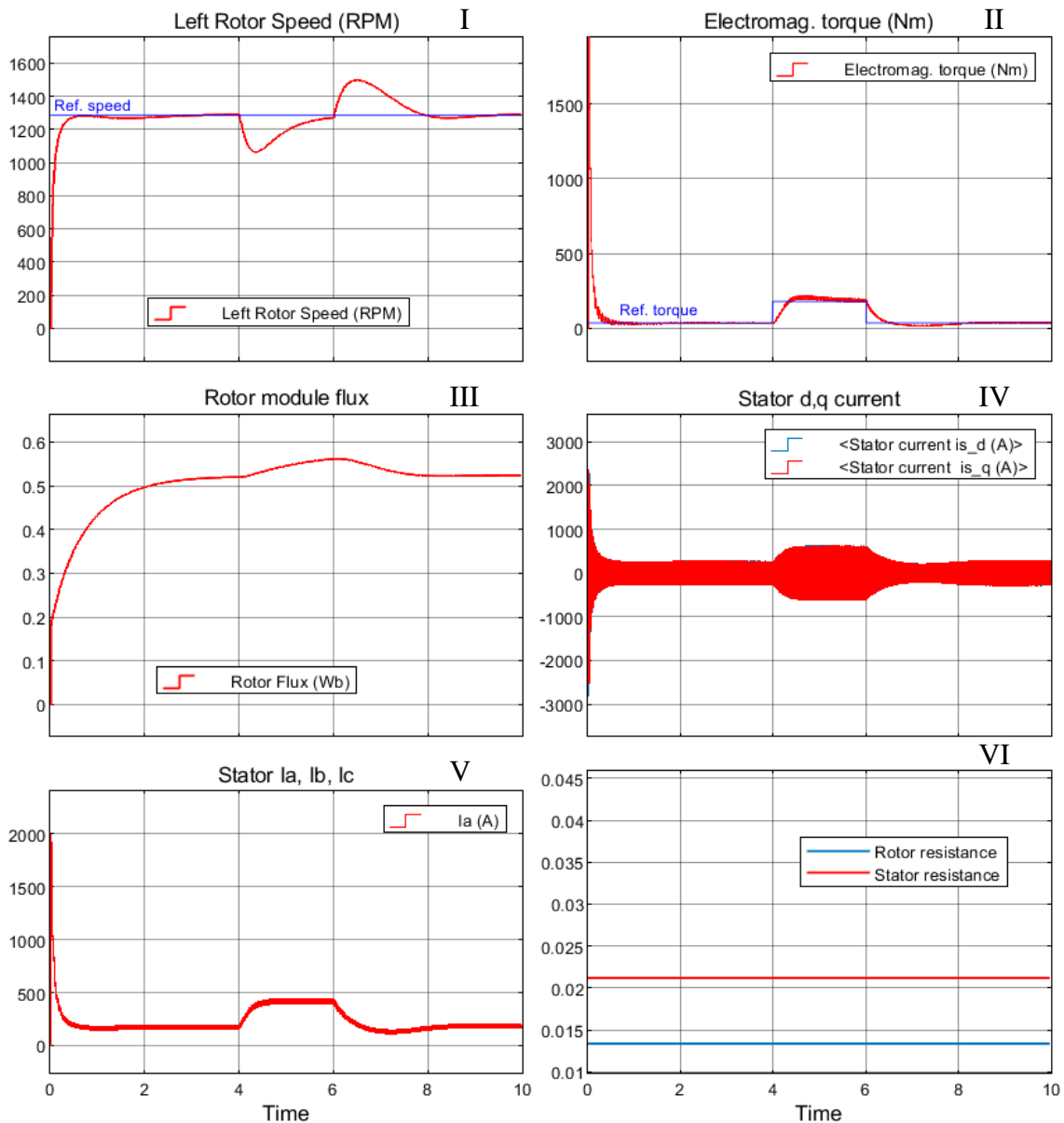


Fig. 3.6. Transition processes in the system with PI controller at start-up to nominal rotation frequency (start-up, load throw, load removal): I – by rotation frequency; II – by electromagnetic torque; III – by rotor flow coupling vector module; IV – by currents in  $d$  and  $q$  axes; V – by stator phase currents; VI – active resistances of rotor and stator.

In a real vector control system, it is never possible to set the exact motor parameters, and some of them change in the process of operation, e.g., the thermal change of the active resistance of the stator and rotor can be more than 50 % of the nominal. Therefore, a system insensitivity estimation simulation test was performed with changes in motor parameters, and the active resistance of the rotor and stator was increased twice. The other tests of the vector control system showed that the changes in resistance up to 50 % are insignificant, that the calculation can be reduced to measurement error, however, changing the resistance by more



than 50 %, the result becomes more obvious, the results are shown with a green graph in Fig. 3.7.

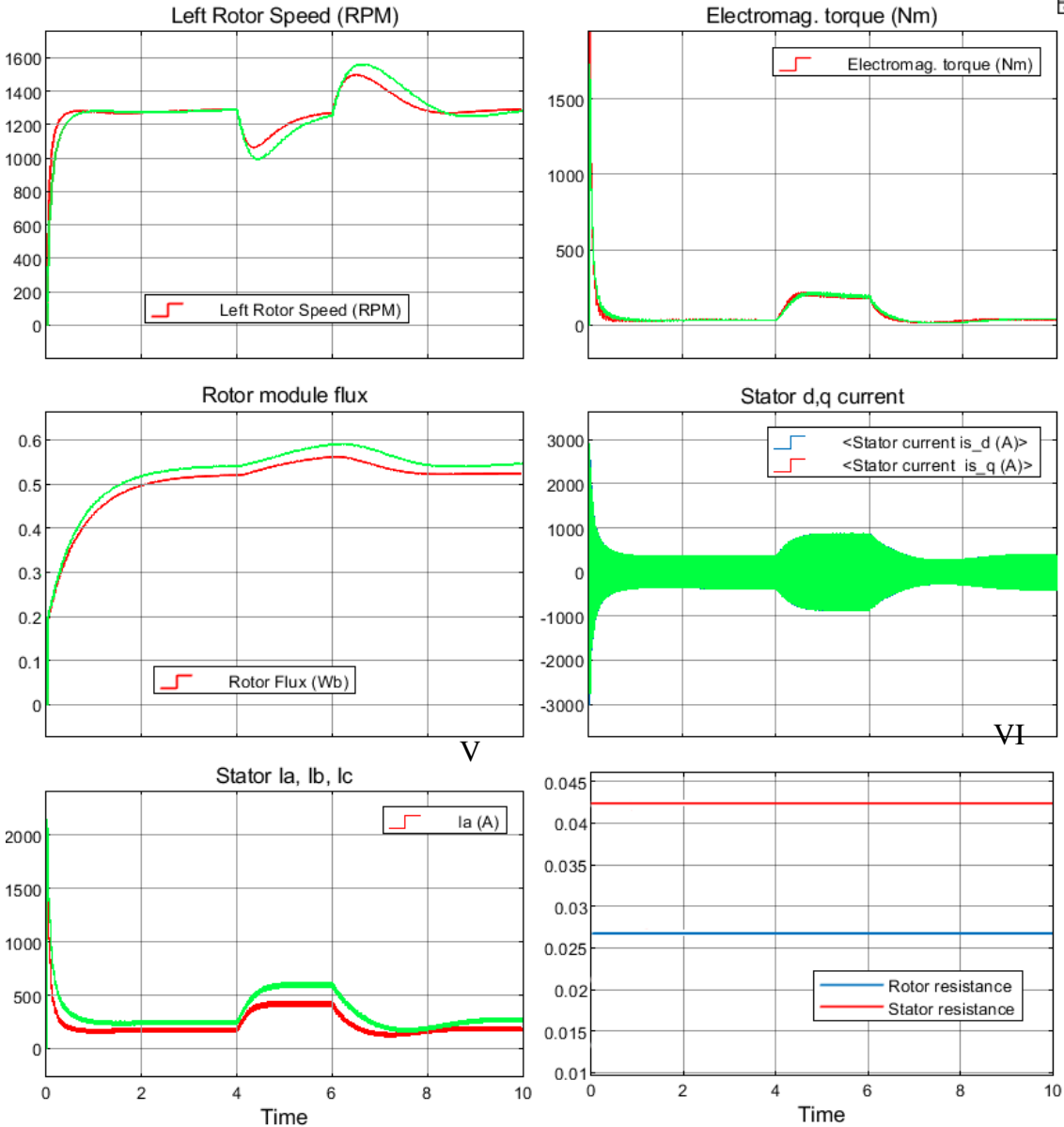


Fig. 3.7. Double change of active resistance of rotor and stator.

As can be seen from oscillograms in Fig. 3.7, a double change in active resistance has virtually no effect on its revolutions. Revolutions are still recovering correctly, the rotor torque corresponds to the set one, only the current consumption has changed, which is clearly seen from the oscillograms, so we can say that the effect of changes of parameters on the vector control system performance generally is insignificant. It should also be taken into account that changes in motor parameters can be tracked and corrected in real time in the vector control system. In Fig. 3.8, the vector control scheme is calculated taking into account the changes in the resistance of the electric motor – in purple, where the results of the oscillograms show the only significant change in the rotor reference flows  $|\psi_r|^*$ .

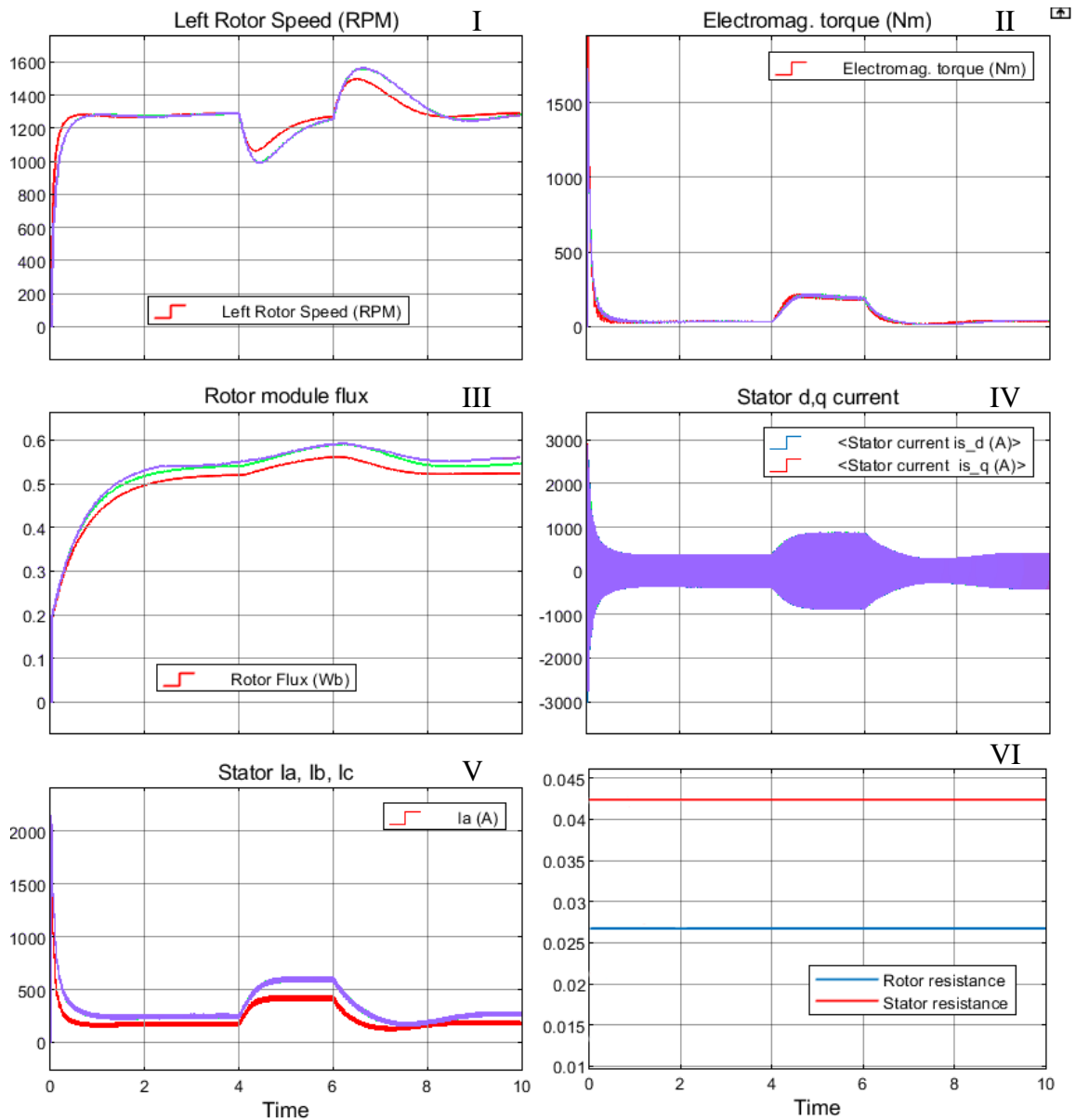


Fig. 3.8. Scheme calculation results with changes in the adaptive rotor and stator resistance vector control model.

Basic methods for the building of IM rotation speed monitoring systems using an observer based on an adaptive model have been studied. As the study showed [2], [15], [21], the traditional methods of building such systems prove to be inoperable in the low and zero speed region due to the nonlinear relationship between the speed observation error and the variable state recovery error. As the modelling showed, this method proved to be sufficiently insensitive to changes in IM parameters, except for the active resistance of the stator. The high sensitivity of the system to  $R_s$  is related to the fact that this parameter is included in the integration operation (the integration operation has the property of accumulating an error) in the equation of this observer reference model. Significant changes of it affect the dependent calculations: the rotor flow coupling module and position  $\Theta_e$  are required to convert the coordinates generated from rotor speed  $\omega_m$  and slip frequency  $\omega_{sl}$ . The advantage of this method for application in vector control systems is its uncomplicated control and simplicity of

understanding. However, for such a system to work, a stator active resistance identification mechanism is required. Therefore, solving the differential equations included in the observer's mathematical description based on the adaptive model, an integration operation is used, which causes certain difficulties in calculations. Frequent integration has a tendency to integrate error from inaccuracy in setting parameters.

Additionally, the virtual model has a built-in virtual part of the vehicle that uses the same motors as in the test, therefore, supplementing the virtual model to a full vehicle. Physically developed moments of CEE power units affect the acceleration of the virtual vehicle, which is accompanied by wheel slip and redistribution of normal reactions. Significant slip is observed on the wheels at the start of the movement, to which most of the torque developed by the virtual units of energy equipment is applied. Figure 3.9 shows the virtual vehicle rundown model.

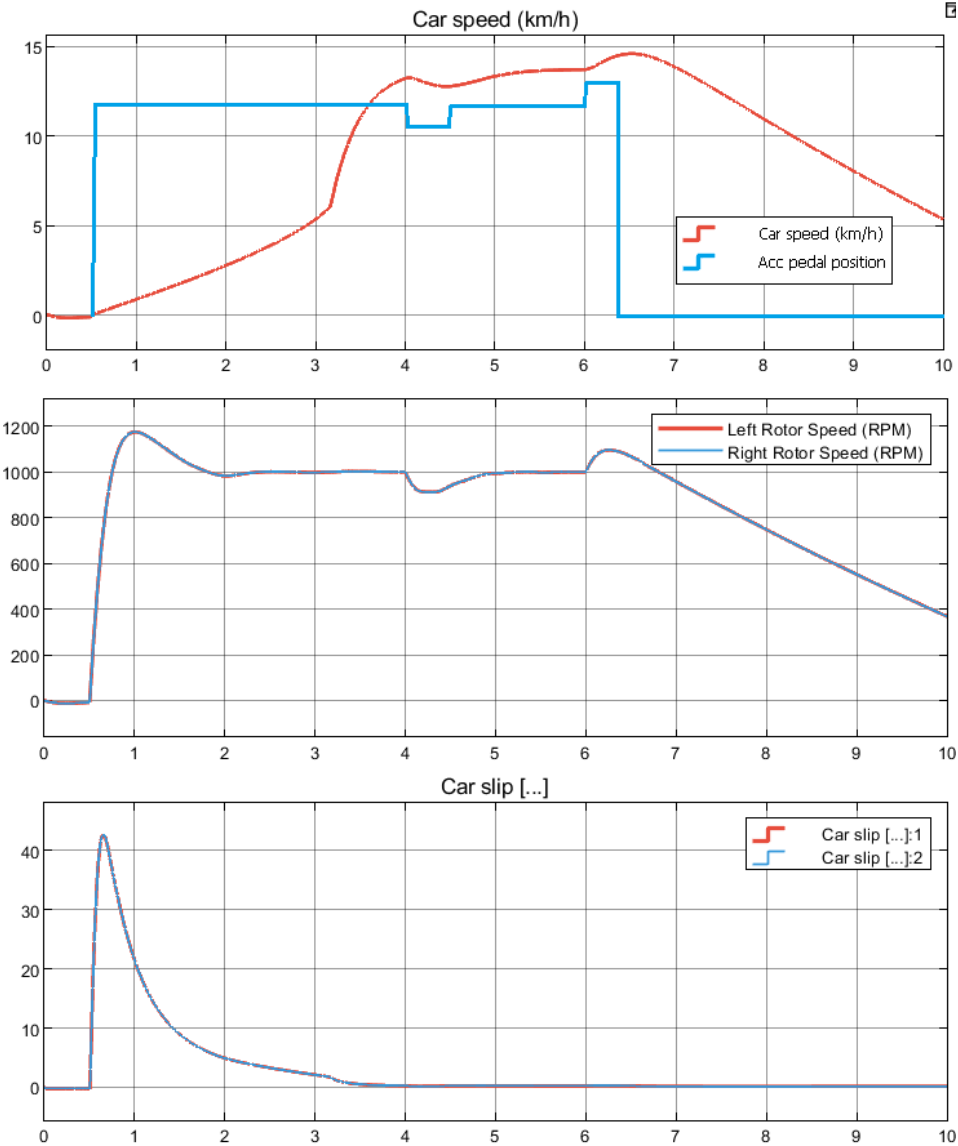


Fig. 3.9. Virtual vehicle rundown simulation. V speed (km/h) with driver, motor revolution, wheel slip.

### 3.5. Comparison of results

The difference between the experimental data and the calculation data obtained as a result of computational experiments can be determined by two types, one of them includes operating errors of torque identification controllers. The accuracy of the controller operation is determined by the values of the coefficients, the regulations of which, in turn, must ensure a balance between the accuracy of the task signal tracking itself and the so-called controller rigidity. A controller with a high gain coefficient can provide high accuracy, however, the compensating reactions to the deviation of the controlled signal from set one may have too high amplitude, causing the compensating effect to fluctuate over too wide an area and making identifying the operating modes of the respective component too rough. To overcome this shortcoming, the gain coefficients were reduced, which to a certain extent reduces the adjustment accuracy. The second type of error includes model errors, i.e., inaccuracies in the response of its output variables to input operations. Since the input signals are generated by the identifying controllers, their errors are added to the modelling errors.

In the shown computational experiments, the mean square control errors consisted of IM rotation frequencies – 0.05...0.94 %, current – 1.5...7.0 %, and voltage modelling errors – 0.44...4.50 %.

## CONCLUSIONS

The Thesis presents the analysis of two CEE testing methods – fully virtual *MATLAB/Simulink* system and combined system – in laboratory conditions, with given a comparison. CEE virtual physical instruments research methodology has been developed. The methodologies can be used in industrial experiments, where virtual and physical parts of closed automatic control systems are mainly used as synchronization tools. This approach provides two types of research tasks:

- Identification of non-measurable variables in ID or CEE experiments via a virtual object;
- Extension of functional possibilities of energy equipment tests on a testbed with the help of virtual objects (for example, movement conditions and load).

Coordinating the work of the physical and virtual part of the system according to the proposed methodology allows to adequately reproduce the CEE operating modes corresponding to the movement of the vehicle, which is characterized by kinematic rotation of the wheels.

The Thesis deals with the issues of creation and testing of the most efficient traction electric drive systems today. The paper presents the analysis of complex tests of traction electric drive from the point of view of efficient production technology.

The developed test methods of traction electrical equipment allow to increase its reliability in a complex way. The developed testing methodologies allow for a more detailed analysis of the compliance of electrical equipment with the initial design requirements.

For a more detailed analysis of the operation of the mutual load scheme in the environment of the program MATLAB (SIMULINK block library) a system asynchronous motor – asynchronous generator model has been created. The model consists of: a three-phase AC source, in the settings window of which the amplitude and frequency parameters are set; a frequency converter with a DC link, consisting of a controlled rectifier and an inverter; for asynchronous machines for which the rotor type is specified in the settings window, the nominal parameters (power, voltage, frequency, number of pole pairs) and equivalent circuit parameters (active and inductive resistances) as well as the characteristics of the mechanical part (moments of inertia and friction). The load of the machines is modeled by the torque setting unit, voltage, current, torque and speed measurements are performed by the variable position measuring unit and measuring instruments. The equivalent circuit parameters of asynchronous traction motors are calculated on the basis of nominal data.

Electromechanical processes in asynchronous machines with a common shaft are interconnected, because the electromagnetic moments of the machines are determined by the common load torque on the common shaft. Modeling of asynchronous machines with a common shaft must be performed by mathematically describing both machines at the same time, taking into account the saturation of the magnetic circuit of both machines, the relationship of machine moments, while taking into account the change of parameters of both machines.

Developed algorithm for testing two-machine system consisting of asynchronous traction motor and asynchronous load motor with common shaft according to the mutual load method with asynchronous motor power supply from adjustable frequency and voltage and asynchronous load motor operation converter to constant voltage phase experimental studies in asynchronous machines with a common shaft. The developed methodology, algorithm and computer program allow to perform experimental research of electromechanical characteristics in automated mode.

A comparison of the calculated and experimental results of electromechanical processes in a two-machine unit test system and energy recovery in a closed circuit shows that the most reliable calculated results with an error of less than 5 % ensures the use of the methodology with the calculation of interconnected electromagnetic fields in the engine and generator with correlation by the electromagnetic moment of the shaft. The use of a sequential model to study electromechanical processes in such electromechanical systems can lead to errors in the detection of electromechanical processes in machines in dynamic operating modes exceeding 30 %.

It has been found that the operation of an induction motor from an adjustable frequency converter with voltage pulse duration modulation in a two-machine unit, when tested by the load method, increases the active power consumption of the motor by 5–7 % and increases the reactive power compared to the sinusoidal voltage supply 6–8 %.

A method for creating a system of virtual objects to be tested has been developed, which is at the same time a tool for research and development of traction electric drives. The synthesis of these objects is possible within the framework of the use of virtual and physical parts of closed systems of automatic control as means of synchronization. This approach provides two types of research tasks:

- Identification of non-measurable variables, such as torques, during traction electric motor tests using a virtual object that duplicates the physical; the identification method is implemented by determining the dynamics of the vehicle, testing the variables with the operator model with regulators that trigger the model of the object under study, automatically determining the unknown torques in the electric power drive;
- Expansion of the functionality of power plant units test in stands using a system with a virtual object (vehicle, traffic conditions) that complements the physical object; the principle of load generation in this type of system is justified.

Verification of the results of the identification procedure, performed by practical implementation of IM vector control systems, using the values of the identified parameters, confirms that the developed algorithm provides the necessary accuracy of parameter determination. At the same time, dynamic and static management quality indicators are provided, which do not differ from the theoretical ones by more than 5 %. The developed algorithms provide much faster performance compared to those used in series products, which allows to specify the IM parameters in the production process.

The proposed methodologies and calculation models can be used to predict electromechanical processes in traction electric drive in order to prevent dangerous operating modes of traction electrical equipment during operation.

### **Basic results of the work**

- A methodology for evaluating the operation of an electric drive has been developed, taking into account the limitations of the traction converter, which allows to determine the required power and control range for traction electric machines, respectively, asynchronous electric motors.
- A laboratory-approved power flow control algorithm for hybrid transmission has been developed, which operates in the transmission DC circuit and ensures autonomous operation of test equipment and a stable energy balance between the power source and the consumer.
- A virtual physical test development algorithm has been developed for the equipment, which can be used for testing and certification of the traction equipment control function.
- A complex of analysis and prototyping of the operation of the program traction electric drive development and control function has been developed, including – examples of basic structures for asynchronous traction electric motors.

The experience gained in the development of the work allows to perform the design of traction electrical equipment sets and control algorithms in a short time, ensuring diagnostics of the transmission and its elements, safe testing in laboratories and during commissioning.

## BIBLIOGRAPHY

- [1] Blaschke F. *Das Prinzip der Feldorientierung die Grundlage für die Transvektor – Regelung von Drehfeldmaschinen*. Siemens Zeitschrift, 1971. Bd., pp. 757–760.
- [2] Chao K. H., Liaw C. M., *Speed sensorless control performance improvement of induction motor drive using uncertainty cancellation*. IEEE Proc. Electr. Power Appl. 147 (4) (2000).
- [3] Chen H., Gao B. *Nonlinear Estimation and Control of Automotive Drivetrains*. – Science Press Beijing, Springer-Verlag Berlin Heidelberg, 2014, pp. 125–145.
- [4] Dolcini P. J., de Wit C. C., Béchart H. *Dry Clutch Control for Automotive Applications*. – Springer-Verlag London Limited, 2010, pp. 83–100.
- [5] Doumiati M., Charara A., Victorino A., Lechner D. *Vehicle Dynamics Estimation using Kalman Filtering: Experimental Validation*. ISTE Ltd and John Wiley & Sons, Inc., pp. 2013–239.
- [6] Fredriksson J., Silberholz G., Six C. *Final report of the Research Program (VTP1) on an Emissions and CO2 Test Procedure for Heavy Duty Hybrids (HDH). Final Report*. TNO report, TU Graz, Chalmers Univ. of Technology, IFA, 2013. 136 p.
- [7] Grewal M. S., Andrews A. P. *Kalman filtering: theory and practice using MATLAB*. 4th Edition. John Wiley & Sons, Inc. 2015. 617 p.
- [8] Guzzella L., Sciarretta A. *Vehicle Propulsion Systems. Introduction to Modelling and Optimization*. Third Edition. Springer-Verlag Berlin Heidelberg, 2013. 409 p.
- [9] Halbach S., Sharer P., Pagerit S., Folkerts C., Rousseau A. *Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems*. SAE Technical Paper. – 2010. – no. 2010-01-0241. 11 p.
- [10] Isermann R. *Mechatronic Systems Fundamentals*. Springer-Verlag London Limited, 2005. 19–21, pp. 293–331.
- [11] Isermann R., Münchhof M. *Identification of Dynamic Systems. An Introduction with Applications*. Springer-Verlag Berlin Heidelberg, 2011, pp. 539–550.
- [12] Mohamed S. Z. *A stable adaptive flux observer for a very low speed-sensorless induction motor drives insensitive to stator resistance variations*. Faculty of Engineering, Minoufiya University, Egypt 2011, pp. 5–7.
- [13] Ohyama K., Asher G., Sumner M. *Comparative Analysis of Experimental Performance and Stability of Sensorless Induction Motor Drives*. IEEE Trans. Indus. Electr. – February 2006. – vol. 53, no. 1., pp. 178–186.
- [14] Ouahi M., Stéphant J., Meizel D. *Evaluation of Torque Observer in Automotive Context*. Proceedings of the 18th IFAC World Congress. 2011. 6 p.



- [15] Park C.-W., Kwon W.-H. *Simple and robust speed sensorless vector control of induction motor using stator current based MRAS*. Electric Power Systems Research 71 (2004).
- [16] Plett G. L. *Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs Part 1. Background*. Journal of Power Sources. 2004, pp. 252–261.
- [17] Plett G. L. *Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs Part 3. State and parameter estimation*. Journal of Power Sources. 2004, no. 134, pp. 277–292.
- [18] Schröder Dierk. *Elektrische. Antriebe – Regelung von Antriebssystemen*. München, 2009.
- [19] Vahidi A., Stefanopoulou A., Peng H. *Experiments for Online Estimation of Heavy Vehicle's Mass and Time-Varying Road Grade*. ASME 2003 International Mechanical Engineering Congress and Exposition Dynamic Systems and Control. 2003. Volumes 1 and 2, pp. 451–458.
- [20] Диаб А. А. Заки. *Векторное управление асинхронными электроприводами на основе прогнозирующих моделей*. Диссертация на соискание ученой степени кандидата технических наук, Новосибирск 2014, с. 49–50.
- [21] Котин Д. А., Диаб А. А. З., Аносов В. Н. *Векторное управление асинхронными электроприводами на основе прогнозирующих моделей*. Новосибирский государственный технический университет, с. 82–90.
- [22] Панкратов В. В. *Векторное управление асинхронными электроприводами*. Учеб. пособие. – Новосибирск: Изд-во НГТУ, 1999, 66 с.
- [23] Панкратов В. В., Котин Д. А. *Принципы векторного управления и алгоритмы ориентирования по полю в синхронизированном синхронном электроприводе*. Мехатроника. Автоматизация. Управление. 2010, 4, с. 46–51.