Proceedings

Battery Electric Drive of Excavator Designed with Support of Computer Modeling and Simulation †

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† Presented at the First World Energies Forum, 14 September–05 October 2020; Available online: https://wef.sciforum.net/.

Published: 12 September 2020

Abstract: The motivation for this article was to describe the creation of a battery electric drive of a smaller excavator of a well-known manufacturer. The aim of the excavator electrification research was to replace its internal combustion engine with an electric motor. The innovated excavator does not burden its surroundings with gas exhalations and excessive sound emissions, so that it can work in confined spaces or protected areas. Simulation models of electric and hydraulic parts of the drive were created to select the most suitable solutions verified or predicted by simulations in Matlab/Simulink environment. Tests have shown that the excavator is capable of operating for at least 7 h without recharging the battery. The further main achieved results of the project are a functional model of zero-emissions of mini-excavator exhalation gases with significantly reduced noise, a proven control algorithm in the form of software and its utility model according to the patent application 2018-35127 adopted by the Industrial Property Office of the Czech Republic. Innovation of the solution of the excavator was awarded the Gold Medal at the Brno International Engineering Fair in 2018.

Keywords: battery; electric; drive; excavator; hydraulic; innovation; modeling

1. Introduction

The worldwide trend in construction of building, earthmoving, forest and similar machines is not only to reduce their fuel consumption, but also to reduce the load of gaseous and acoustic emissions that burden their surroundings. There are a number of solutions of researchers and designers. One of the major pathways is the electrification of the drive using electric battery (electric accumulator). Mathematical modeling and computer simulation play an important role in this research, enabling the search for optimal solutions in virtual space. The aim of our research was to create an electric battery drive of a small excavator up to 2 ton by replacing the diesel engine with an electric motor together with the creation of a new system of internal control of the excavator subsystems. The new design was made in our own way after completing a patent search to avoid a patent conflict.

Within the framework of a grant project, Bosch Rexroth [1], in cooperation with Brno University of Technology, developed the drive and control of a gas emission-free excavator after previous cooperation involving the kinetic energy recovery of heavy vehicles with frequent starting and braking.

As the excavators are often used in the building industry, considerable attention has been paid to their construction and improvement in respect of electrification worldwide. The advantage of the described excavator is the drive without gas exhalations.

Recently, new electrified excavators of various innovative designs and properties can be found on the world market. Caterpillar [2], along with Pon Equipment, produced an all-electric 26-ton excavator with a 300-kWh battery pack in an effort to electrify the construction equipment. They built a prototype in Gjelleråsen, Norway, for the construction company Veidekke.

Komatsu Ltd. [3] developed an electric battery-driven excavator. When fully charged, this battery enables from two to six hours of operation. The machine allows for real-time monitoring of power consumption and charging conditions on the built-in monitor panel. It also allows for the remote monitoring of that information together with the machine location and operating conditions via the system KOMTRAX.

The Liebherr [4] electric excavator R 9200 E with a rated output of 850 kW is the biggest excavator on Eurovia mine's 350 sites—up to 25 % less maintenance cost compared to a diesel excavator.

Takeuchi [5] developed e240 4 t class battery-powered excavator in 2017. The e240 is a battery version of the company's TB240 diesel model. The machine operates for nine h at 65% of full load. It charges from a standard 220 V power outlet and take around 10 h to go to full charge from zero.

Wacker Neuson [6] debuted its first fully electric, battery-powered EZ17e compact excavator in 2018. All hydraulic functions are as powerful as those of the conventional model. The battery is integrated in the existing engine compartment. The EZ17e weighs almost exactly the same as the diesel version and can be transported on a trailer.

Bobcat [7] rolled out the E10e, its first electric mini excavator. The machine—fully-electric, 1-ton mini excavator—was built alongside its diesel-powered siblings, the E08 and E10z. mini excavators.

A lot of different solutions is proposed in the literature to improve the machinery fuel efficiency, and many of these are based on hybrid solutions. The aim of Casoli [9] was to present a hybridization methodology which allows to compare different system layouts, to dimension the energy storage devices, and finally to determine the more effective hybrid system layout.

Electrification of excavator was described in Vauhkonen [10]. For this study, a JCB Micro excavator was chosen as a building platform. The 14-kW diesel powered engine with its required equipment was replaced with a 10-kW electric motor. Four lithium titanate batteries, with a total voltage level of 96 V and a capacity of 60 Ah, power the electric motor.

With the electric drive, while maintaining the same performance, the operating time was substantially reduced compared to the diesel-powered drive.

Xu [11] studied modeling of mechanical and hydraulic subsystems for the simulation, design, and control development of excavator systems. As a result, various approaches in the hydraulic system modeling were presented. A recent trend in the development of off-highway construction equipment, such as excavators, is to use a system model for model-based system design in a virtual environment.

Modeling of hydraulic systems dynamic by means of differential and algebraic equations can be found e.g., in Nevrly [12], Nepraz [13]. Casoli [14] presented the results of a numerical and experimental analysis conducted on a hydraulic hybrid medium size excavator. Its standard version was modified using the energy recovery system; its layout was designed to recover the potential energy of the boom, using a hydraulic accumulator as a storage device. The recovered energy was utilized through the pilot pump of the machinery which operates as a motor, thus reducing the torque required from the internal combustion engine. An experimental fuel saving of about 4% was noted over a JCMAS working cycle.

The objective of the thesis of Alvin [15] was to develop a fast simulation model to replicate the functioning of the excavator system. The paper by Nevrly et al. [16] introduced a simulation of drive for electric-hydraulic excavator, basic model schemes of the drive system, simulation models of the electric motor system, of the pump driven by the electric motor. Examples of simulation results—time courses of model quantities—were received either by means of Matlab/Simulink or a set of differential equations.

An energy recovery system integrating flywheel and flow regeneration for a hydraulic excavator boom system is described in Li [17]. Implementing the energy recovery system is a solution to improve energy efficiency for hydraulic excavators. A flywheel energy recovery system is proposed based on this concept. A hydraulic pump motor is employed as the energy conversion component and a flywheel is used as the energy storage component. The implementation of flow regeneration has two benefits; downsizing the displacement of "hydraulic pump motor" and extra improvement of energy efficiency. A potential energy recovery and regeneration system for hybrid hydraulic excavators based on a multi-cylinder structure working device as a new invention is presented in Zhang [18].

Energy balancing for zero emission excavator was described in Jurik [19]. The author shows that efficient balancing of energy flows cannot be solved only by optimizing one subsystem but only the consistency of these subsystems enables for efficient balancing of energy flows for the efficient use of limited power sources—battery packs.

Improving energy efficiency of an electric mini excavator using a special start & stop logic system is described in Hassi [20]. The benefits of this system were measured using a test cycle with the old and new configurations. According to the authors, improvement in the operating time proved to be at least 50 % longer than that of the old configuration. The efficiency study of an electric-hydraulic excavator was presented in Salomaa [21]. A Matlab/Simulation model was utilized to study the total energy consumption and power distribution of the micro-excavator. The model consists of the hydraulic and mechanical systems related to the actuation of front hoe, i. e. boom.

In Liu [22], achievement of fuel savings in a wheel loader by applying hydrodynamic mechanical power split transmissions was described. In this paper, the torque converter was replaced with a hydrodynamic mechanical power split transmission for improving the fuel economy of wheel loader. Based on the probability similarity theory, the typical operating mode for the vehicles was constructed and used to evaluate the energy consumption performance of the selected solutions.

As part of the development of the electric excavator, we prepared a patent study to avoid a patent collision with previously patented solutions. These included, in particular, patents from Kubota, Takeuchi, Hitachi and Terex (Demag).

2. Overall Characteristic of Solution

Based on the patent search, the possibilities of solving the electric drive of the excavator were analyzed, then the structure of the functions was determined, and the elements of the excavator system were selected. A risk analysis was performed and the E19 excavator manufactured by Bobcat was chosen as a suitable starting machine for this task (Figure 1).

To solve the electrification of the excavator, it was expedient to divide the whole excavator into partial parts, e. g. according to Figure 2. The diagram shows the functions that will subsequently be manifested in mathematical modeling. To monitor and analyze the internal and external context of the physical quantities involved, a design of a virtual solution, the concept of the structure of subsystems, including the control system, was performed. Mathematical models of subsystems in the Matlab/Simulink environment of MathWorks were compiled using the industry-oriented toolboxes Simscape, SimHydaulics and SimMechanics. Subsequently, variant solutions were developed and verified by simulations and measurement. Testing of machine functions was performed by a system of targeted measurements of excavator parameters with subsequent data processing and verification of mathematical models.

Figure 1. Diesel driven excavator E19, producer Bobcat.

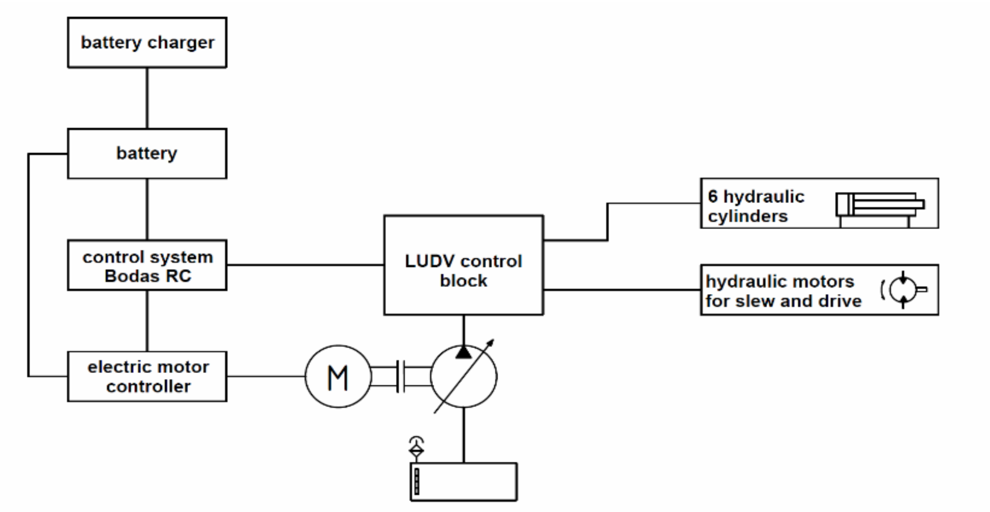

Figure 2. Basic block diagram of the electric drive of the excavator E19.

The drive of the excavator was designed, including the battery power supply system and the combination of the motor and the frequency converter. The connection of the electric motor, controller, and elecric battery is evident from the model of the drive subsystem in Figure 3.

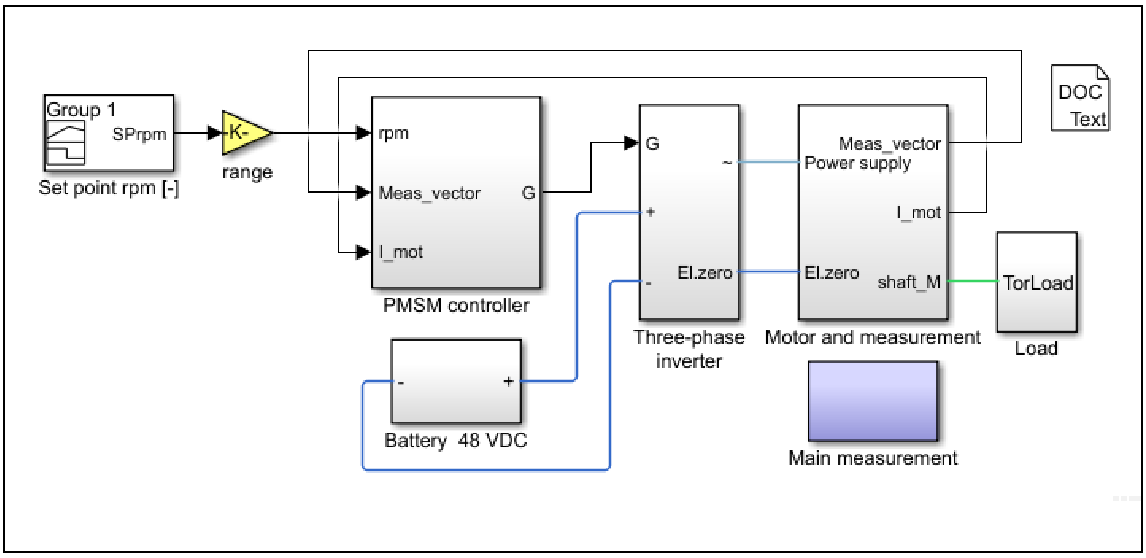

Figure 3. Model of the electric motor pump drive subsystem.

3. Electrical Part of the Solution

3.1. The Electric Motor

The electric motor is a synchronous three-phase motor with permanent magnets powered by electric accumulator. It drives the pump via a belt drive. It was developed for application in an emission-free excavator.

Engine type: PMSM-prototype	Maximum speed: 6000 rpm
supply voltage: 48 V	current: approx. 200 A (continuous), max. Approx. 400 A
number of poles: 6	torque: 40 Nm (permanent), 80 Nm (short-term)
weight: 17 kg	maximum power: 20 kW

3.2. Electric Battery 48 V, Li-Fe Cells

The battery consists of pack of connected electric cells (Figure 4 and Figure 5). This battery is the only source of energy for driving the excavator's electric motor. The battery includes a BMS module (Battery Management System), which monitors the status of the cells. The battery was developed based on specifications from Bosch Rexroth.

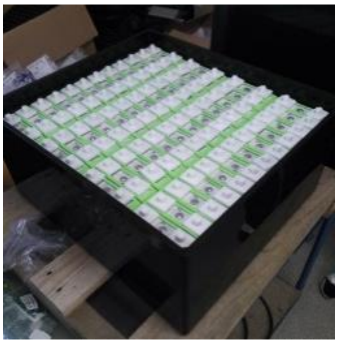

Figure 4. Electric battery.

battery pack capacity: 15 kWh	
battery pack voltage: 48 V	cell voltage 3.65 V
weight: up to 90 kg	dimensions: 550 × 490 × 360 (height) mm

Model name	ZG-LFP060AH
Nominal voltage (V)	3.20 V
Nominal capacity (Ah)	60 Ah (@0.3C)
Rated charge voltage (V)	3.65 V
Maximal voltage (V)	3.80V
Discharge voltage (V)	2.80V
Minimal voltage (V)	2.50 V
Rated discharge current 0.3C (Amp)	< 20 A
Maximal continuous discharge current 3C (Amp)	180 A
Rated charge current 0.3C (Amp)	< 20 A
Maximal charge current 1.5C (Amp)	90 A
Internal resistance (mOhm)	< 2 mOhm
Cycle life (80% DOD at 20°C)	> 2000 cycles at 25A
Self discharge rate (% per month)	< 3%
Operating temperature (charging)	0 to 50 °C (at 0.3C or less)
Operating temperature (discharging)	-20 to 50 °C (at 0.3C or less)
Dimensions width x length x height (mm)	130 x 186 x 36 mm
Weight (tolerance +/- 50g)	1.685 kg

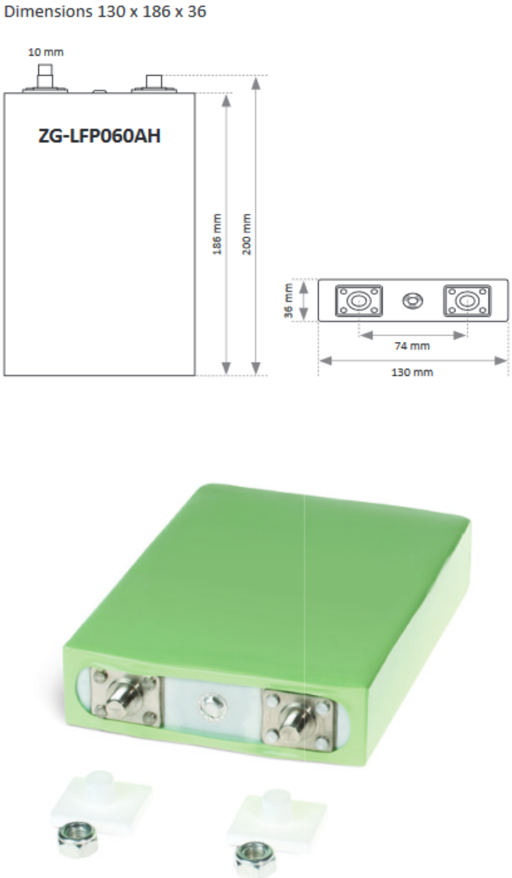

Figure 5. Parameters of the Li-Fe battery cell.

An important factor is the charging time to reach full capacity of while complying with all safety rules, such as the temperature of individual cells. This is approximately 5 h; the power supply has an output of 1.5 kW at a voltage of 240 V. One of the ways to improve charging is to use three-phase charging of the battery (Figure 6).

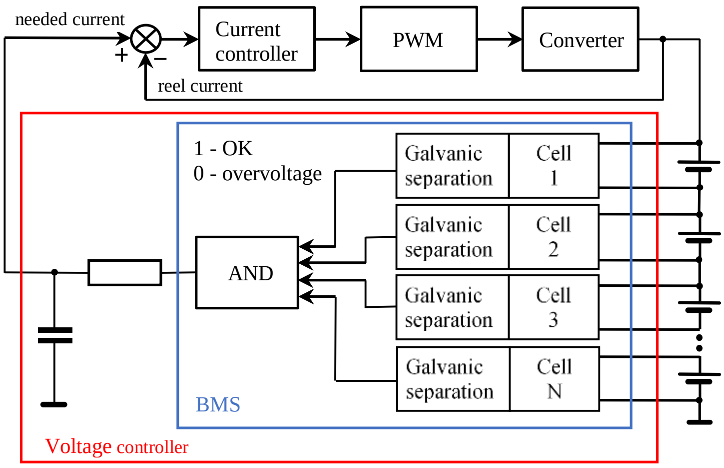

Figure 6. LiFePO4 battery charging control strategy.

Electrical parts were laboratory measured, inspected and, if necessary, modeled and computer simulated (Figure 7). Special care was given to the electric battery and a specially made electric motor.

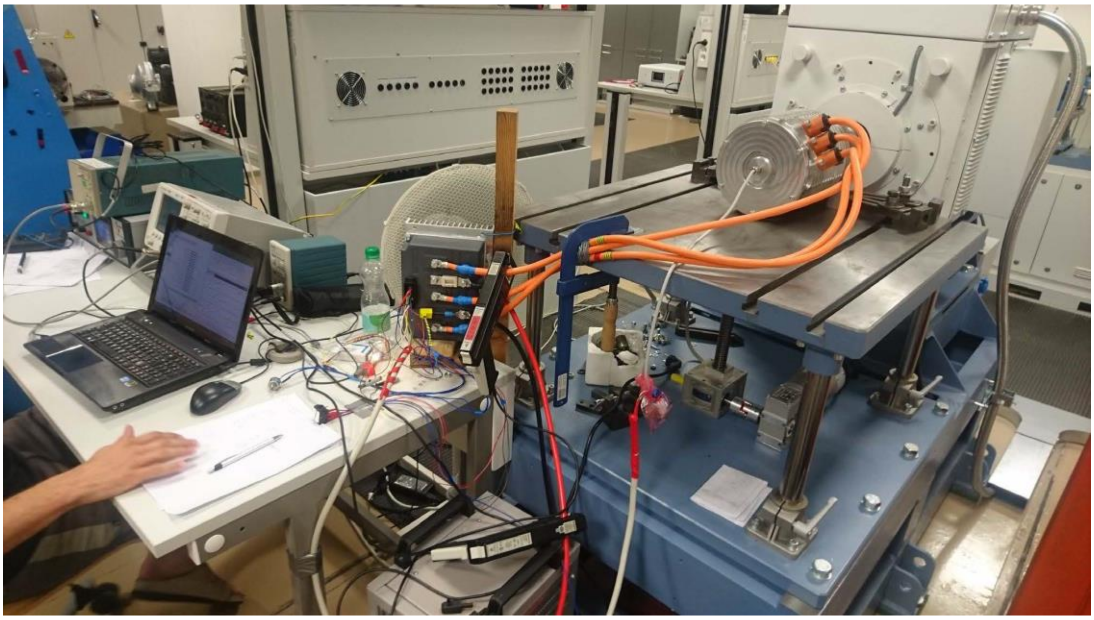

Figure 7. Electrical workplace measurement.

4. Excavator Hydraulics

In terms of force, the hydraulic system is of fundamental importance for the operation of the excavator. The simplified diagram of a standard hydraulic excavator can be seen in Figure 8 that shows the functional links between the basic elements of the system—the pump of drive, main valve, hydraulic rotary motors, and hydraulic cylinders.

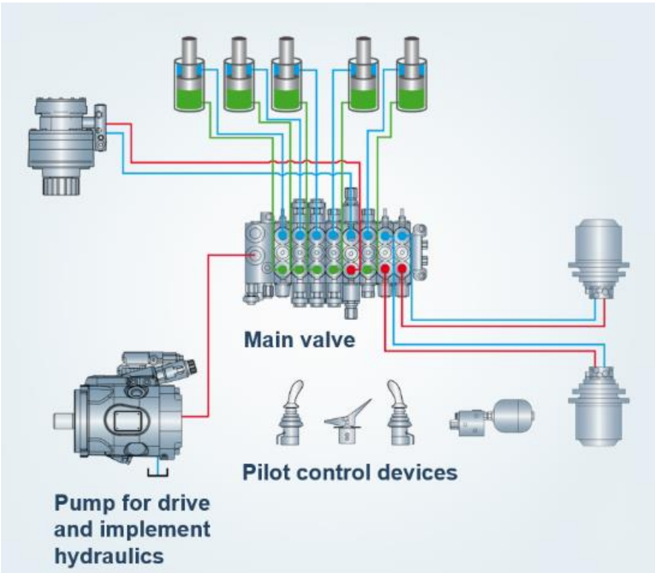

Figure 8. Standard hydraulic system of excavator.

A more detailed hydraulic diagram of a substantial part of the hydraulic system of the excavator E19 is shown in Figure 9, where the details of the connection of hydraulic cylinders, directional valves, auxiliary valves, etc. can be seen.

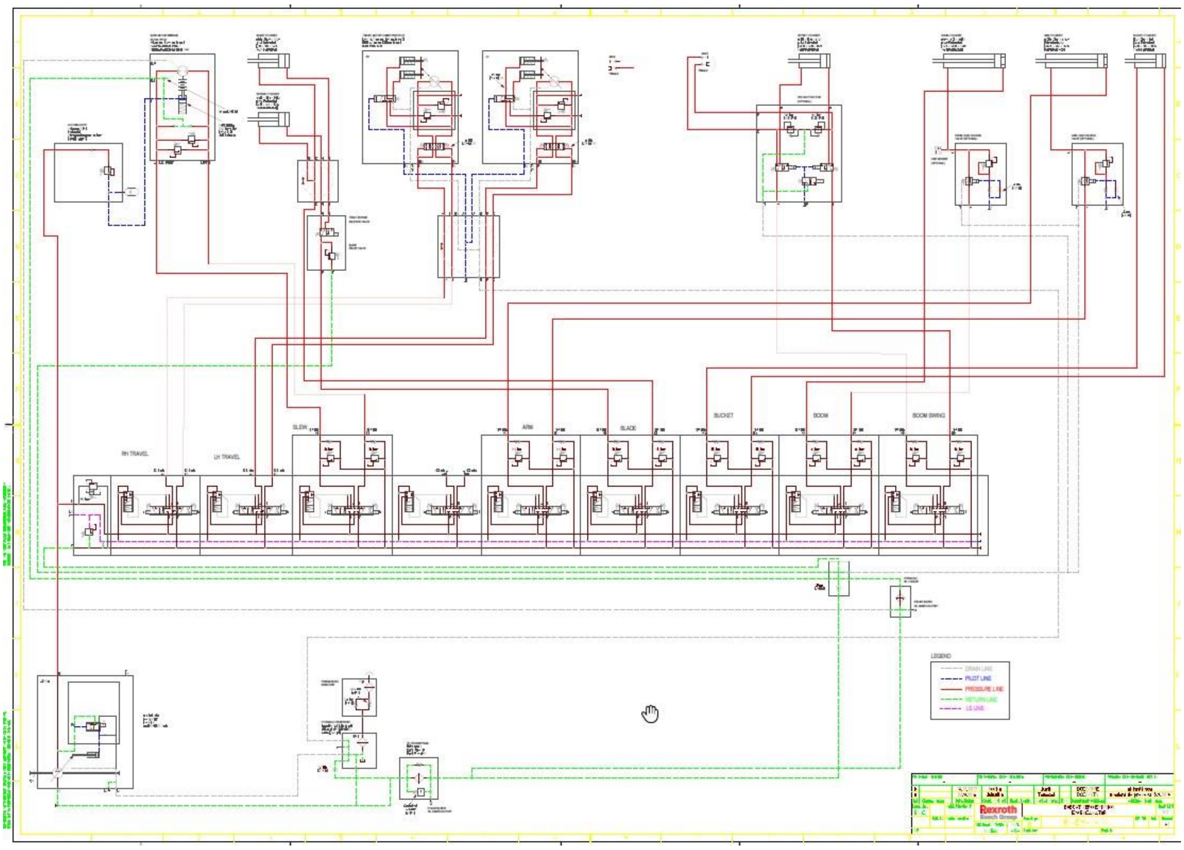

Figure 9. Scheme of the hydraulic system of the excavator E19.

5. Mathematical Models, Simulation

5.1. Modeling of Processes in the Excavator

The aim was to create models of excavator systems and their subsequent use for the purposes of simulation prediction, function verification and optimization. For reasons of clarity, greater versatility of use, and easier work with models, a modular and multi-level model concept was chosen. The models developed in the Matlab/Simulink environment are sufficiently universal and enable simulations of various excavator processes. Separately applicable bucket, arm, boom and boom turn subsystems are available to facilitate simulations of the excavator's main movements. As an example of a hydraulic subsystem, Figure 10 shows the model of the pump and its connection to the hydraulic system. The control signals are optionally generated by the Signal Builder block and control the speed and the ideal source of torque. This source controls the variable displacement and pressure compensated pump, while all significant mechanical and hydraulic quantities are automatically registered, as shown in the diagram.

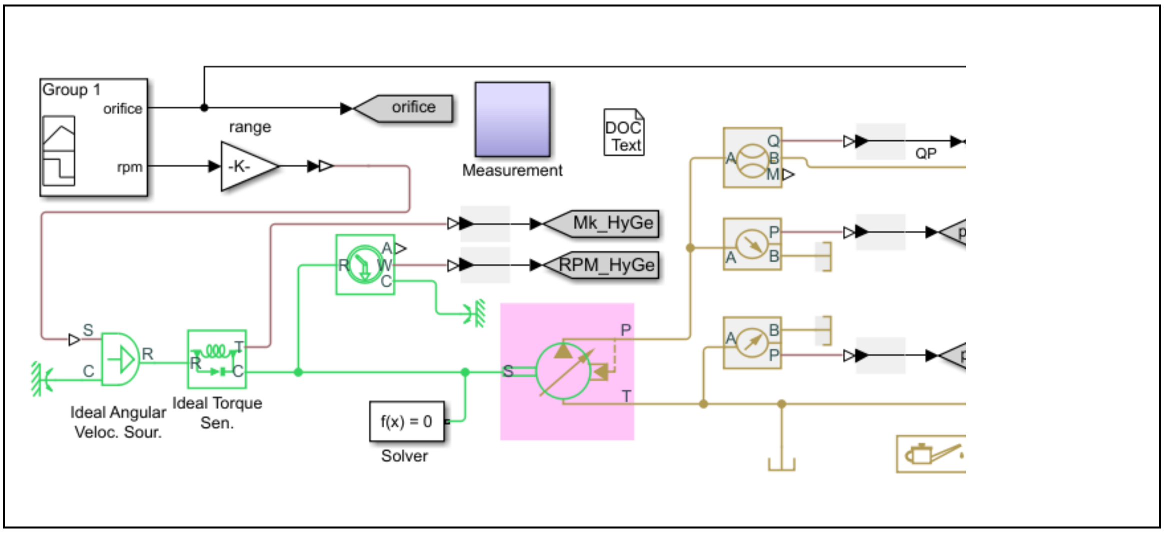

Figure 10. Model of the pump connected to the hydraulic systém.

Another example is the model of the 4-way directional flow valve (Figure 11). Such a valve distributes the oil flow according to the control electric signal.

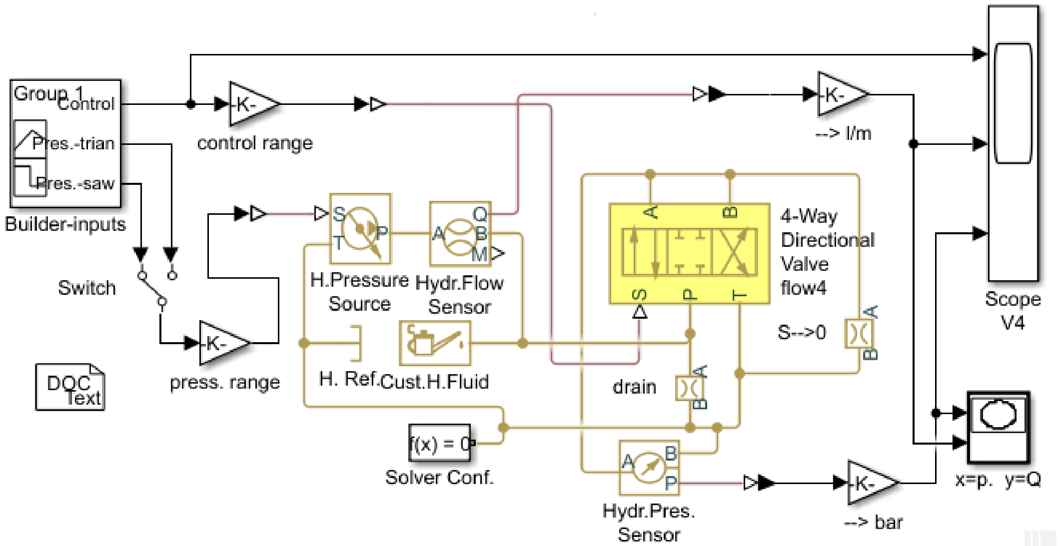

Figure 11. Example of the model of the directional valve connection.

When modeling hydraulic directional valves, the goal was to find the parameters of the models so that the behavior of the models corresponded as closely as possible to the characteristics of the directional valves listed in their catalog sheets. The models and their parameters were made more accurate during the work after tests on a functional sample of the excavator. The proposed directional valve models include physically existing nonlinearities (insensitivity, saturation transition).

5.2. 3D Modeling of Aggregate Placement

3D models of the drive elements were created and variant designs of their installation into the excavator structure were made, after which a variant of the installation solution according to Figure 12 was selected.

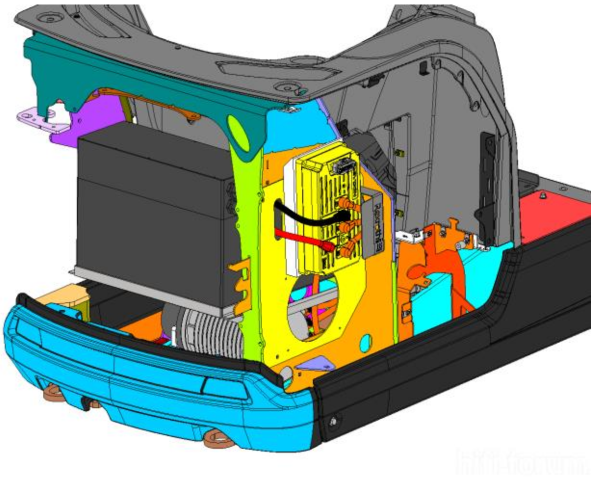

Figure 12. Location of elements in the excavator frame.

6. Control of Subsystems and Excavator System

Following the results of the patent search, a specific control algorithm was created; this is the basic distinguishing element of the solution in comparison with other currently known solutions for controlling the excavator drive. The algorithm was created on the modular basis of the Bodas system. The hierarchy of the main parts of the control system is shown in Figure 13. The superior control system controls the battery module (with the connected charging block), electric motor control, hydraulic functions control and diagnostics.

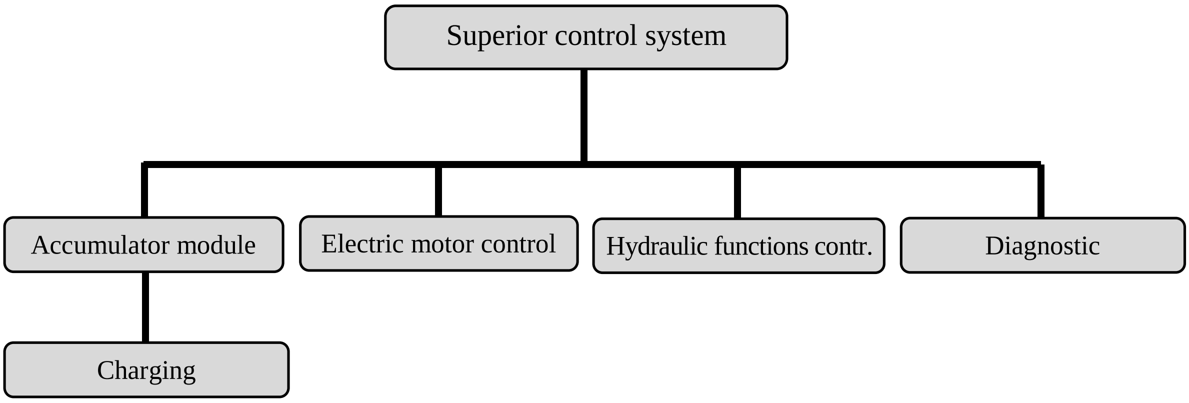

Figure 13. Main parts of the control system.

A more detailed scheme of excavator control is shown in Figure 14. The initiating electrical signals come from the manual control block of the excavator operation to the hydraulic directional valve block and to the drive block (frequency converter, electric motor). Th electric current from the electric accumulator leads to this block and then goes on to the pump block and further to the hydraulic directional valves. The pressure oil flows from the hydraulic distributors to the hydraulic motors which move the working mechanisms of the excavator.

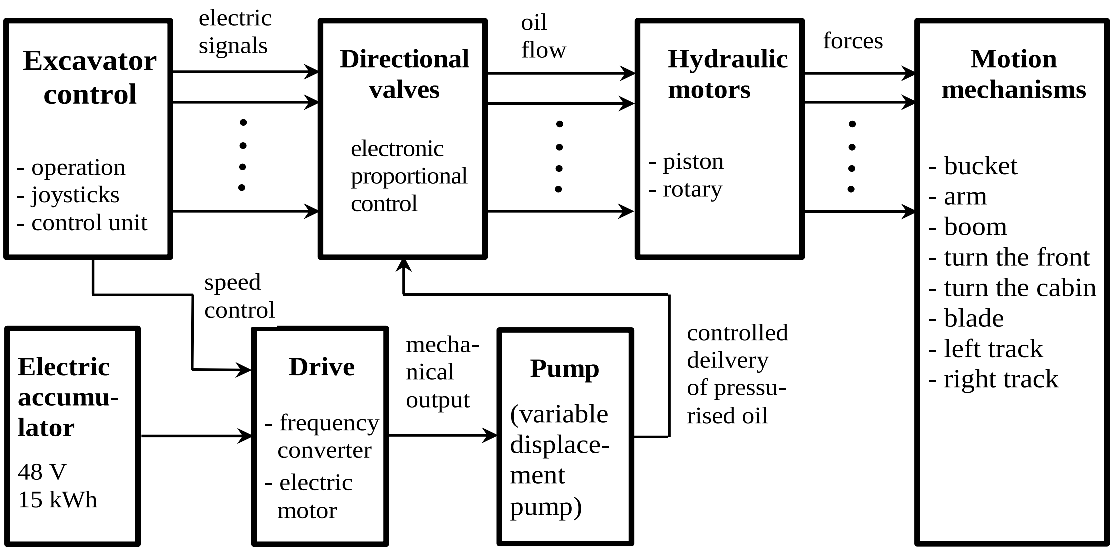

Figure 14. Block diagram of electric excavator control.

From the point of view of control, the decisive block is "Operation control", which implements the interaction between the operator and the excavator. It contains a microcomputer control unit that generates control electric currents for controlling of oil flows in directional valves. Control is of a type "off line", i. e. without a feedback from the actual controlled movements.

The data flow structure of the basic software modules for controlling the switchboards, the electric motor controller and the pump can be seen in Figure 15. The inputs are signals from the manual control, from the battery management, and from the pressure sensor. These signals enter a set of sub-blocks, such as e. g. low limiter, current protection of the accumulator, ramp block, etc. The output signals go to the coils of the electromagnets of the hydraulic routers, the motor controller, and pump coils.

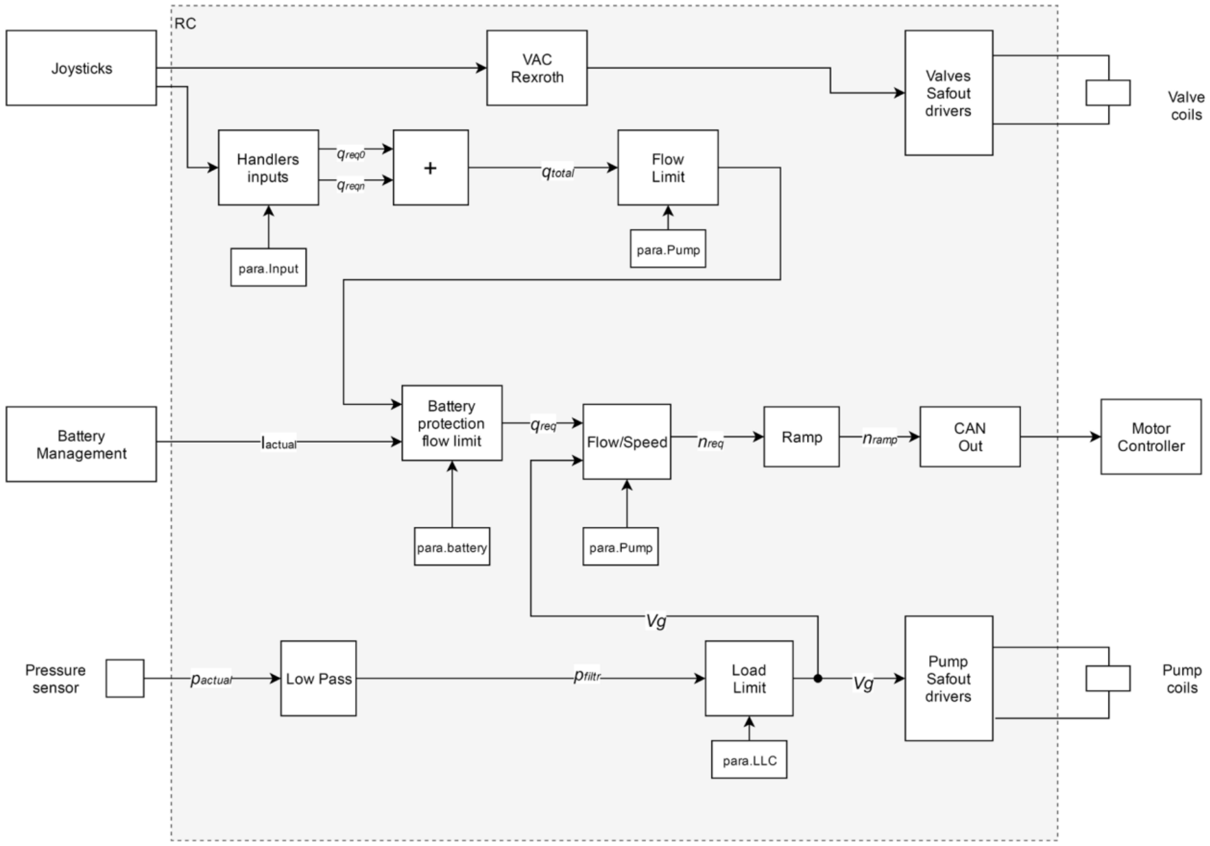

Figure 15. Diagram of data flows of basic software modules.

7. Experiments

The research used a methodology of theoretical and experimental verification of drive parameters, including measurement of electrical, mechanical, hydraulic and functional safety parameters of the excavator. The functional test methodology consisted of methodologies for excavation, travel and load transfer.

Figure 16 shows an example of the result of measurement of the speed (actual versus target), torque, battery current, etc. when starting and stopping the electric motor.

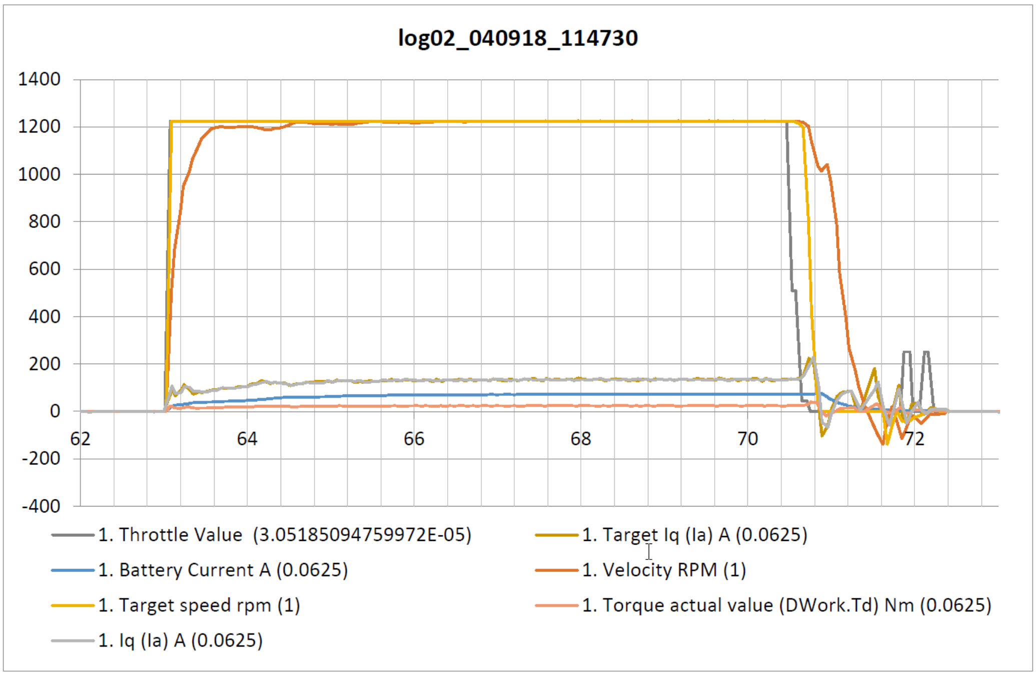

Figure 16. Results of measurement of excavator system parameters during start and stop.

The following values of energy consumption within one hour were reached using the electrical parameter tests:

excavation: consumption from 1.61 to 3.85 kWh
relocation: consumption from 0.76 to 1.39 kWh
travel: consumption from 0.64 to 5.46 kWh

A specific feature in the assessment of the actual use appears to be the ability to work and the endurance of the machine operator when working in full concentration and maintaining safety for the specified period. During tests in ideal spatial conditions, operators were changed after 1 hour of work; this allowed us to achieve a relatively high performance at work.

Example of Simulated Event

The characteristics of the electric rotary motor for the pump drive were first simulated (Figure 17) and subsequently measured. Motor acceleration from 0 to 2000 rpm without load. In 0.4 s, a torque impuls of 0–30 Nm was applied to the motor.

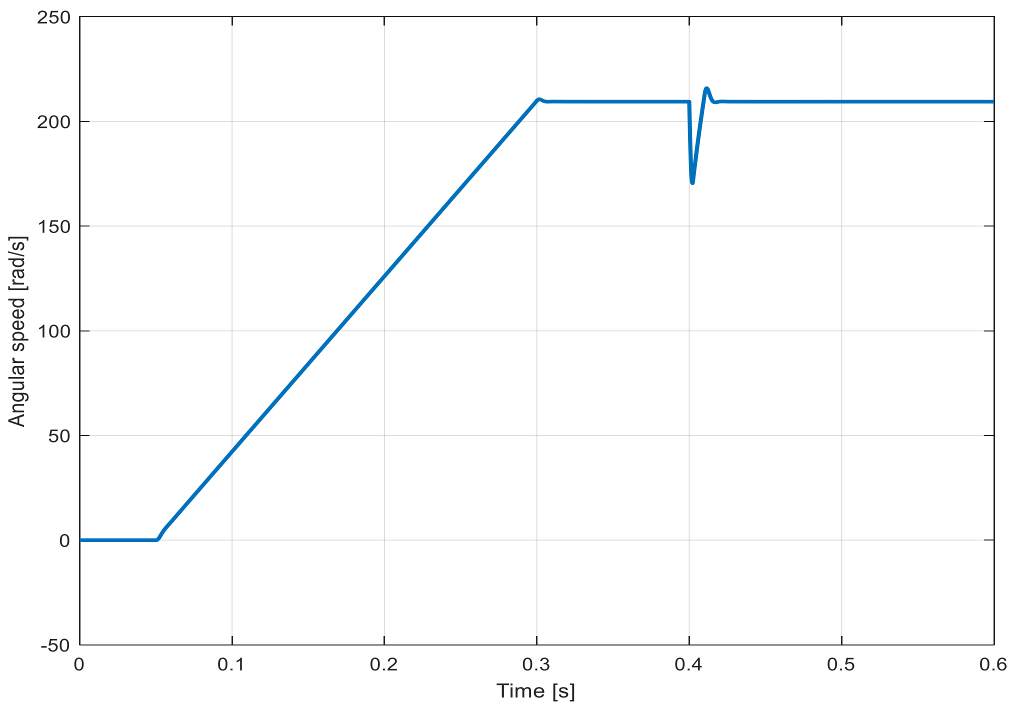

Figure 17. Simulated course of the angular velocity of the electric motor at a load of 25 Nm.

Figure 18 shows the results of simulation of hydraulic, mechanical and electrical quantities during several rapid movements of the excavator bucket, while the load changes stepwise almost to the maximum (Force piston, max = 27,000 N for both directions of movement). The drive is already slightly overloaded (actual speed is lower than required).

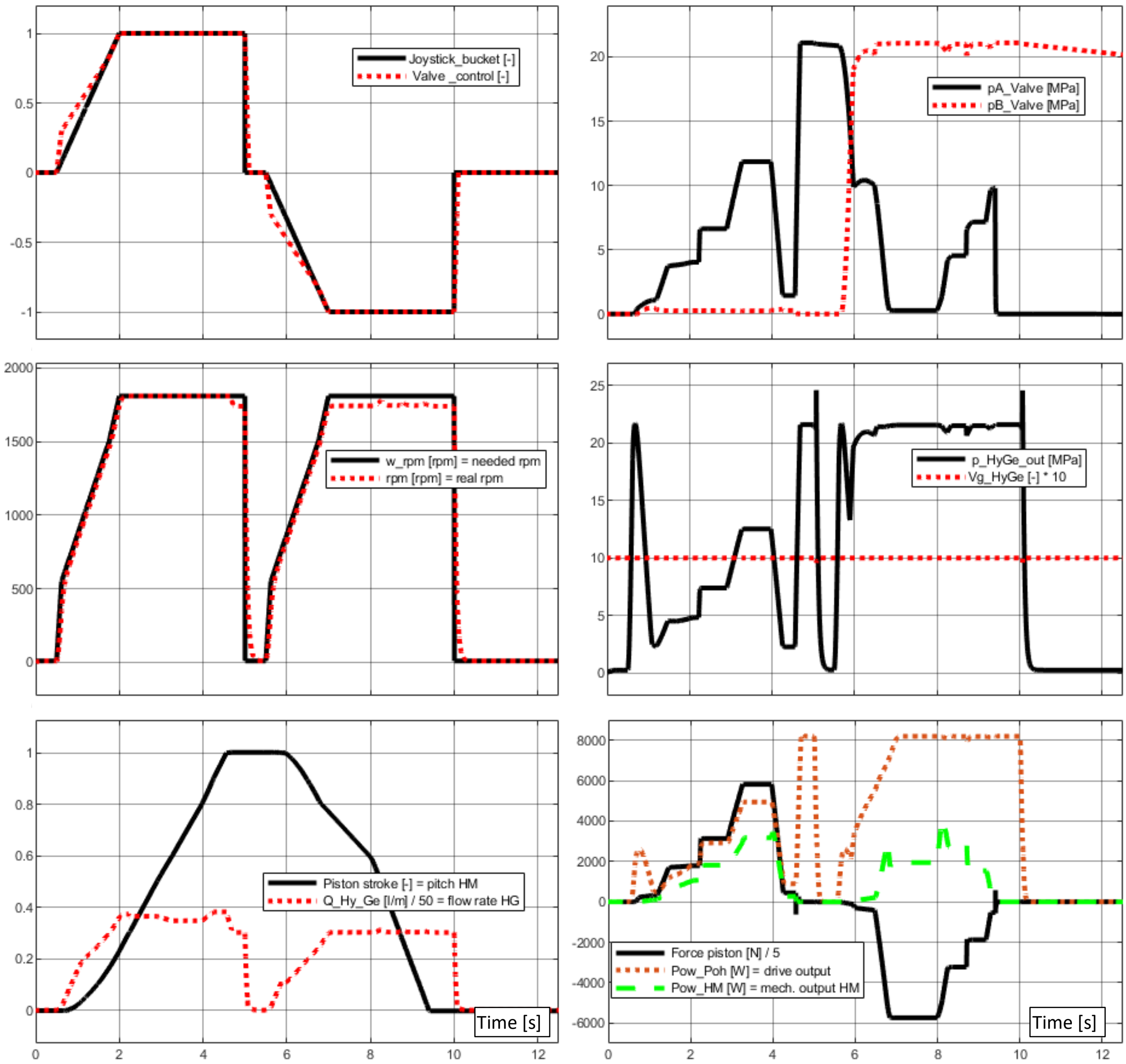

Figure 18. Simulation of rapid bucket movements by variable load.

8. Results

An electric drive of the excavator (Figure 19) was created with a patented control system of its subsystems, the operation of which is free of gaseous and, to a large extent, also noise emissions, unlike the original drive using an internal combustion diesel engine. Functional tests have shown that the machine is able to operate in standard operating mode. The measured values indicate a good energy utilization of the machine. With a used battery, it is possible to achieve real working performance of 7 h. It can be stated that the knowledge gained within the framework of the project is reflected in the design and development of prototype part of the excavator as well as, specifically, in the “flow sharing” block of the RSxx series and the axial pump type A10VO, both from the company Bosch Rexroth.

The developed mathematical models can be used even after the end of the project for the work on other types of similar machines (see Appendix A).

Figure 19. The electric excavator E19 when digging.

9. Discussion

The new type of drive predetermines the use of the excavator especially for such places where the operation without gas exhalations and with lowered noise otherwise emitted by internal combustion engine is required, i.e. in enclosed spaces, protected areas, such as hospitals, rehabilitation facilities, protected landscape areas, etc.

The limiting factor for achieving a higher perfection of the models (accuracy, reliability) is the limited availability of parameters of the modeled parts of the device. Some parameters must then be determined by expert judgment. Also, the possibilities of model verification are complicated by the fact that, currently, the measurements on a real excavator could contain only a limited number of measured quantities and some of them (mainly torque) showed a certain unreliability. The verification had to be performed by a detailed analysis of only some of the mutually corresponding parts of the measurement and simulation records.

The standard drive system of excavators powered by hydraulic motors seems to be somewhat i nefficient due to the repeated conversion of energy: electric (in the case of a battery excavator)—mechanical—hydraulic—mechanical. This causes some energy losses. A direct electric drive with one conversion, electric—mechanical, could theoretically lead to an increase in drive efficiency. A change of this kind was not among the objectives of the described project, but it seems to be a potential topic for the next phase of electrification of excavators and similar machines.

A battery electric drive brings new possibilities to the field of mobile working machines as for the efficient use of installed energy. The simulations and functional tests show the advantages and disadvantages of this solution.

Due to the designation of the machine for operations requiring zero gas exhalations, it is now difficult to compare its economic parameters, such as machine price, all operating costs and return on investment, to the parameters of a standard machine with an internal combustion engine, while achieving the same or longer machine life. The results of the development as mathematical models were usable not only during the solution of the project, but they can also be used after the end of the project for similar development work. The knowledge from modeling is transferable to similar applications of control of hydrostatic drives, hydraulic motors in building, earthmoving machines and the like.

10. Patents

Proven control algorithm in the form of software and its utility model according to patent application 2018-35127. The application was submitted to the Office for the Protection of Industrial Property.

Author Contributions: Conceptualization, M.F. and M.J.; methodology, M.F.; software, modeling Z.N. and P.P.; validation, P.V. and J.N.; experiments, M.J. and P.P.; writing—original paper preparation, J.N.; writing—review and editing and supervision, M.F., Z.N. and P.V.; project administration and funding acquisition, M.F. and D.K. All authors have read and agreed to the published version of the manuscript.

Funding: The project TRIO of the Ministry of Industry and Commerce of the Czech Republic in 2016–2018, project registration number: FV10411.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A. Example of Application of Methods and Models Created during the Development of the E019 Machines

The electrification of the Dapper 5000-wheel loader [23], the manufacturer of VOP CZ, which is currently being worked on, can serve as an example of the application of methods and models created within the development of the E19 excavator electric version to other machines. It is again a replacement of a diesel engine drive with an electric drive, energy supply from an electric accumulator. Even in this case, it is a working machine in which the drive of the end working parts is ensured by hydraulic motors.

Figure A1. The Dapper 5000—wheel loader**.**

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