Test bench for experimental research of hybrid powertrain algorithms based on rapid control prototyping unit

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Abstract. The transition from simulation to a real object in case of developing control algorithms for complex systems can be difficult for several reasons. In particular, this process can take a long time due to the lack of hardware of control systems. One of the possible solutions is rapid control prototyping technology. This article discusses the experience of developing a test bench for research of series hybrid powertrain for a bus, in particular, the development of a test bench control system. The use of rapid control prototyping technology is described to the tasks of control system checking and debugging on real objects without hardware developing.

1. Introduction

Today, the traditional initial step of R&D is the stage of mathematical simulation to determine the optimal parameters of the object under research. At this stage, high level control algorithms are being developed, the details of which depend on the assumptions made in the simulation model. Most often, at this stage, issues of integrating the elements of the object under research into the general structure are not considered, the problems of information exchange between system elements are not addressed. Therefore, the next step is to make a prototype of the object or system under research that allows checking the control algorithms developed at the stage of simulation, refine and supplement them taking into account the real behavior of the control object. However, making a prototype requires development of controllers and writing application software. This process takes a lot of time.

It is possible to reduce the time of algorithms debugging on the prototype of the object or system under research by applying the technology of rapid prototyping of embedded control systems. The main idea of the technology is a quick transition from the model of the control system in a simulation environment to controlling a real object or its prototype, while the control system from the development environment is transferred to a rapid control prototyping unit without manual programming. Rapid Control Prototyping Unit (RCPU) is a computer that is designed to perform a wide range of tasks in real-time. The ability to solve various problems is achieved using the input/output modules of analog and digital signals using various data transfer protocols (SPI, I2C, CAN et al.). The real-time problem solution is achieved by a computer running a real-time operating system.

This technology allows solving a complex problem: determine the parameters of the hardware of the control system, check and debug control algorithms. This approach is widely used to solve problems in various fields of science and technology. For example, Lam, Q.L., Bratcu, A.I., Riu, D.,
Boudinet, C., Labonne, A., Thomas, M. used RCPU RT-LAB for development of hybrid power generation system control and analysis of its sustainability [1], Hong, R.L.J., Mahyuddin, M.N., Arshad, M.R., Koo, Y.C. applied RCPU NI MyRIO-1900 for controlling the robot arm for educational purposes [2], Song Hu, Stefano d’Ambrosio, Roberto Finesso, Andrea Manelli made a comparison of models for model-based combustion control in diesel engine using ETAS ES910 [3], Razman Ayop and Chee Wei Tan checked a controller that produces a stable and fast converging operating point for the photovoltaic emulator using RCPU dSPACE ds1104 [4], Davide Tavernini, Mathias Metzler, Patrick Gruber and Aldo Sorniotti tested the developed traction control algorithm for electric vehicle via RCPU dSPACE MicroAutoBox [5]. Rapid Control Prototyping technology has also been used in studies [6 - 10].

2. The goal of the research
Currently, BMSTU (with financial support from the Russian Ministry of Education and Science under Agreement No. 14.574.21.0178, unique work identifier: RFMEFI57417X0178) is implementing research and development project for a hybrid bus powertrain. The project aims to create a suburban bus with the possibility of movement in Zero Emission mode within the city. To ensure competitiveness, this bus have to meet the following requirement:

- possibility of operation without the use of charging stations,
- the ability to move only by battery energy,
- the lowest cost of components.

One of the solutions to achieve the fulfillment of the above requirements is the use of a series type of hybrid powertrain. This type of hybrid powertrain differs in driving wheels only with the help of a traction electric motor (TEM). Thus, there is no mechanical connection between the drive wheels of the bus and the internal combustion engine (ICE), which is used only to drive a generator that charges batteries and provides the necessary power for TEM in heavy traffic conditions. The lack of a mechanical connection between the ICE and the drive wheels also makes it possible to operate the bus in Zero Emission mode.

The key factors in developing of the bus with a serial hybrid transmission that determine its future performance are the right selection of transmission unit parameters and the quality of the control system. In this regard, verifying and adjusting the technical solutions adopted at the early stages of the project is an important task before a full-size prototype of the bus will be made. To solve this problem, it was necessary to make a test bench for researching a prototype of the hybrid powertrain.

3. Methodology
The parameters of the powertrain units, as well as the basic control algorithm, were determined using a simulation mathematical model. A description of the model and an approach to determining the parameters of its subsystems are given in [11-13].

Rapid prototyping technology was used to solve the problem of creating a control system for hybrid powertrain of the bus.

Figure 1 illustrates the transition from a simulation model of the bus with a hybrid powertrain to a test bench. The test bench consists of real powertrain units (TEM, generator, ICE, batteries), the mathematical models of which are highlighted in red in the block diagram. The control system model of hybrid powertrain was transferred to the RCPU.
To control the experimental model of the powertrain at the test bench, the control system developed at the stage of the simulation was refined, due to the fact that the bus model did not take into account the methods of data transfer between the unit controllers [12], as well as low-level algorithms for their start-up and initialization. Control system software consists of:

- control algorithms of hybrid powertrain developed using a simulation mathematical model (figure 2),
- algorithms responsible for the initialization and start-up of control systems for the units of the test bench (inverters of the TEM and generator, battery management system, ICE ECU), ICE start and stop algorithm (figure 3),
- algorithm for switching stand operation modes,
- blocks of reception and transmission of analog and digital signals, including CAN signals.

As shown above, in the transition from control algorithms developed based on the simulation model to the control system of the test bench, the amount of software increased several times. Rapid prototyping technology has reduced the time required to develop software for test bench controlling due to the lack of the need to switch to another development environment — test bench control system, as well as hybrid powertrain control algorithms, were developed in MATLAB/Simulink. This allowed avoiding errors that could occur when transferring basic algorithms to another development package.

The drive wheels create resistance on the TED during the movement of the bus. At the test bench, this resistance is simulated using a load device, which is also controlled by the RCPU. To reproduce the movement of the bus along the driving cycle at the test bench the load device creates a moment of resistance, obtained in the form of a time dependence by simulation.
With the help of the developed test bench, studies of the operation of the hybrid powertrain prototype in various modes were carried out, for example, movement with a low battery state of charge (SOC), movement in Zero Emission mode, the battery charge during the operation of ICE in various modes, transient processes, such as ICE start-up via generator, were analyzed. Below, there are the graphs of changes in the parameters of the test bench units, obtained in the course of research.

Figure 2. StateFlow Diagram of Hybrid Powertrain Control System.

Figure 3. StateFlow Diagram of ICE Start-up via Generator.

Figure 4 shows a graph of the ICE and generator speeds changing in the ICE start mode (155 - 157 s), followed by maintaining the speed when operating under load created by the generator (157 - 211 s) and stopping (212 s).
Figure 5 shows the electric power developed during the start of the ICE, obtained according to the voltage and current sensors installed on generator and battery. Figure 6 shows the change in currents on the TEM, generator and battery:

1) 0 – 1250s Zero Emission Mode,
2) 1250 – 1350s Power Follower Mode,
3) 1350 – 1500s Battery Charging via ICE.

Figure 4. Rotational Speed of ICE and Generator.  
Figure 5. Charge and Discharge Power at ICE Startup and Operation.

Figure 6. Current of Units in Different Modes of Operation.

4. Conclusion
1. The use of rapid control prototyping technology made it possible in a short time to create an experimental test bench for researching a prototype of hybrid powertrain.
2. Hybrid powertrain control algorithms developed using simulation mathematical modeling were tested on real objects, their performance was proved.
3. The control system of the hybrid powertrain prototype at the test bench developed based on algorithms synthesized at the stage of simulation can be integrated without changes into the general bus control system.
4. Integration of hybrid powertrain units into the general system of the traction drive of the bus using the test bench which was controlled by RCPU made it possible to draw up objective technical requirements for the control system hardware.

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