

used. Functional features of the integrated amplifier are incorporated into the simulation model. The results of computer simulation of the interferences measuring are confirmed by experimental data.

Key words: class D amplifiers, electromagnetic compatibility, EMI simulation.

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TO STUDY PROPULSION DRIVES

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TEST BENCH WITH SUPERCAPACITOR STORAGE

This paper describes a test bench developed to study and monitor the propulsion drives of electric vehicles at Tallinn University of Technology. The composition and performance of the setup are explained. The charging process of the supercapacitor bank is described as an example of the test bench application. The developed simulation model of the supercapacitor bank is presented and discussed.

Key words: Electrical vehicle, test bench, supercapacitor, propulsion, electrical drive.

INTRODUCTION

An electric vehicle (EV) represents a transport facility, such as a bicycle, a car, or a train propelled by an electric motor. The EV is a rather complex system for accurate mathematical description, monitoring, and validation. However, today much attention is paid to the studies of EVs and their test platforms. The test bench, combining advantages of software models and real equipment, contributes to the reduction of the number of vehicle test runs and safe maintenance. Reports on the test benches developed in different research centres cover energy management [16], [7] optimal configuration [12], [1], [4] and combination of different energy sources of EVs [11], like the batteries [8], supercapacitor packs [2], [3], [5], flywheels [11], and fuel cells [17].

The focus in this paper is on the EV propulsion electrical motor drives, which are the main components of EVs that define their energy efficiency, distance, speed and acceleration performances, and cost. Results received from the proposed test bench could affect the choice of the propulsion drive components and the assessment of the particular drive manufacturing technologies. They suit for the comparison of different models of the propulsion drives in terms of their dynamic performance at start-up and braking, static stability on the road, energy consumption, reliability, and control suitability. Such

solutions may help researchers in the selection of the car models and companies to support and in providing customers with many hidden data of the marketable electric cars.

TEST BENCH DESCRIPTION

The test bench described in this paper facilitates analysis and comparison of EV motor drives from the viewpoint of their power economical performance resulting in the selection of EVs most appropriate for regional road and climate conditions. The platform is suitable for exploring different steady-state and dynamic modes of the motor drive performance in multiple EV applications. The developed simulation and experimental techniques could be effectively applied to the drives working in many EV motor modes.

The major part of the powertrain of the experimental setup is shown in Fig. 1. The test bench incorporates two electrical drives, the testing drive ABB ACS 800 and the loading drive ABB ACS 611. Every drive is equipped with a squirrel cage induction motor and AC/DC and DC/AC converters coupled via an intermediate DC link. The shafts of the motors mounted on the single base are mechanically coupled through a cardan transmission to provide their joint rotation. The testing drive is equipped with a speed pedal to imitate the regular driver's habits in the case of the vehicle application. Electrical equipment is installed within a cabling cabinet the front panel of which is occupied by the remote control buttons, control panels, sockets, and measurement devices [18].

The test bench enables four quadrant smooth load variation of the testing drive, which can be explored within all possible running and braking modes. By adjusting the loading torque, a wide range of different EV motion conditions can be simulated on the test bench at different slip values including the vehicle locking. This is analogous to the braking process of a vehicle whose wheel can rotate freely or be locked. By applying different loads and slip gains, a variety of driving conditions on the dry, wet, and icy surfaces can be studied. The testing drive can be supplied with variable voltages and frequencies both in open and the closed loop DTC (Direct Torque Control) control modes. The loading drive operates only in the DTC control mode to provide smooth transition between the forward and the reverse torques. Using the ABB software DriveWindow, it is possible to track, save and analyze the parameters of the booth drives of the test bench. In addition to the ABB equipment, the test bench is supplied with the speed sensor and the input energy analyzer.

The testing drive can be calibrated to obtain the speed-torque characteristics of its static and dynamic performances. To this aim, at the beginning of experimentation an active DC load is applied to the testing drive to provide an energy flow during the regenerative braking. In this way the test bench is calibrated correctly for further studies, particularly to study the propulsion efficiency aiming to reduce the drive losses. To explore dynamic EV performance, the standard urban driving cycle ECE-R15 is used, which represents an alternating speed of the vehicle in the predefined time intervals. The testing drive based on the ABB ACS 800 has the internal logical controller that allows many speed testing programs to be designed under adaptive DriveAP programming software.

Diagrams in Fig. 2 were plotted using the DriveWindow toolbox at the constant load of 21 Nm. The ECE-P15 speed set-point diagram is shown by the dashed lines (Fig. 2.a). The set of speed timing traces shows that the measured speed values correspond to the speed set-point values. Some inaccuracies in the corners could be explained by the normal open loop system operation. Inaccuracy during the constant-speed motion is due to the induction motor slip. Both errors can be eliminated by the transition to the close-loop operation. Other timing diagrams display the current (Fig. 2.b), power (Fig. 2.c), and active torque (Fig. 2.d) throughout the driving cycle. The power peaks at acceleration could be reduced using the fast operated storage systems such as supercapacitors.

Results obtained from the test bench can be used to choose the drive components and to assess the particular drive manufacturing technologies. They are suitable for the comparison of different models of the propulsion drives in terms of their dynamic performance at start-up and braking, static stability on the road, energy consumption, reliability, and control properties.

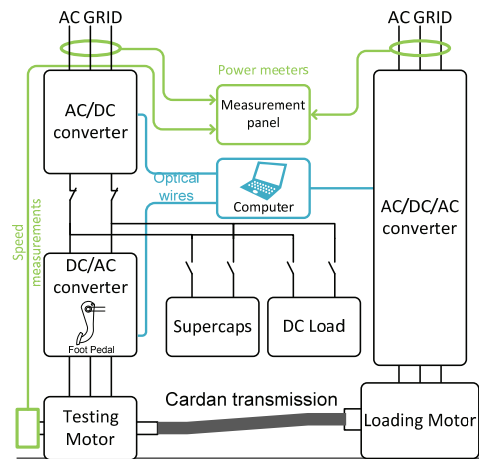


Fig. 1. Basic circuit of the test bench

TESTING AND SIMULATION OF THE SUPERCAPACITOR BENCH

The possibilities of the test bench could be expanded with the help of additional setups, like supercapacitor bank storage with an adjustable DC/DC converter that allows comparing different charging/discharging modes and optimal tuning of the EV supercapacitor energy storage.

An electric double-layer capacitor (EDLC), or just a supercapacitor is a capacitor with high power destiny, with a capacitance up to kilofarads and high-rate charge/discharge characteristics. The EDLC uses solid porous carbon on either side of a porous membrane containing a dilute sulphuric acid electrolyte which is dispersed and is in intimate contact with the high surface area electrode material [15]. Such high surface area and small charge separation highly increase the supercapacitor capacitance relative to the conventional capacitors. The electric charge stored in the layer is proportional to the surface area of the electrode and reversely proportional to the thickness of the double layer. Optimizing the pore-size distribution of the electrodes improves the high-rate charge/discharge characteristics [9].

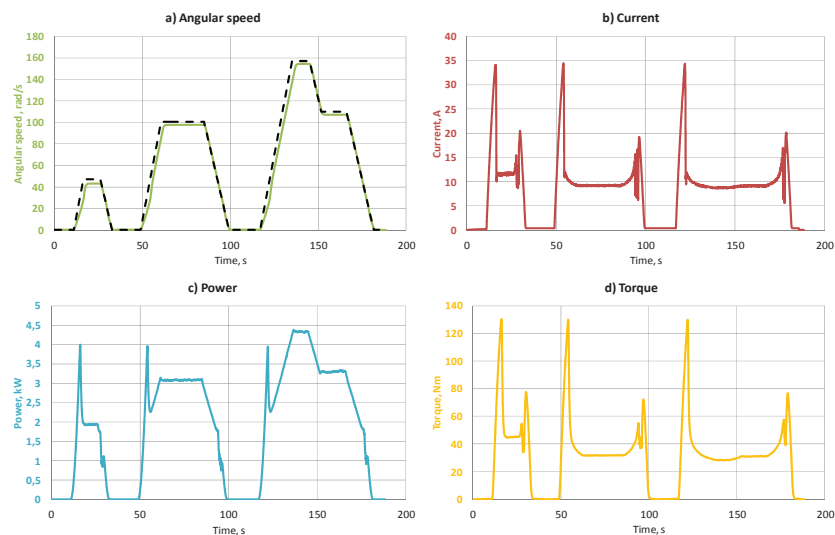


Fig. 2. Sample urban driving cycle ECE-R15 applied to the loaded testing motor

The main benefits of supercapacitors are high specific power and high efficiency, low self-discharge, long lifetime, and low cost per cycle. The main drawbacks of supercapacitors are: low voltage of a single device; to increase the voltage several capacitors should be connected in series which decrease the total capacity [13]. Supercapacitors are now being used in many applications where higher power densities are required. Among them, the load levelling in EV and hybrid EV, telecommunications built on the short high-power pulses, and power smoothing in elevators [6].

The developed supercapacitor bench consists of a supercapacitor bank, a bidirectional buck-boost DC converter and an LC filter. The supercapacitor bank consists of three Maxwell 48V/165F modules connected in series with a total capacitance of 55F and voltage of 144V. According to [6, 14], from the viewpoint of efficiency, stability and failure modes tolerance, the dual bidirectional buck-boost interface topology of the DC/DC converter is more suitable for applications like EVs. The buck-boost converter is used to decrease DC-link voltage to the supercapacitor range and to limit the charging current. To reduce the ripple factor, an LC filter is used.

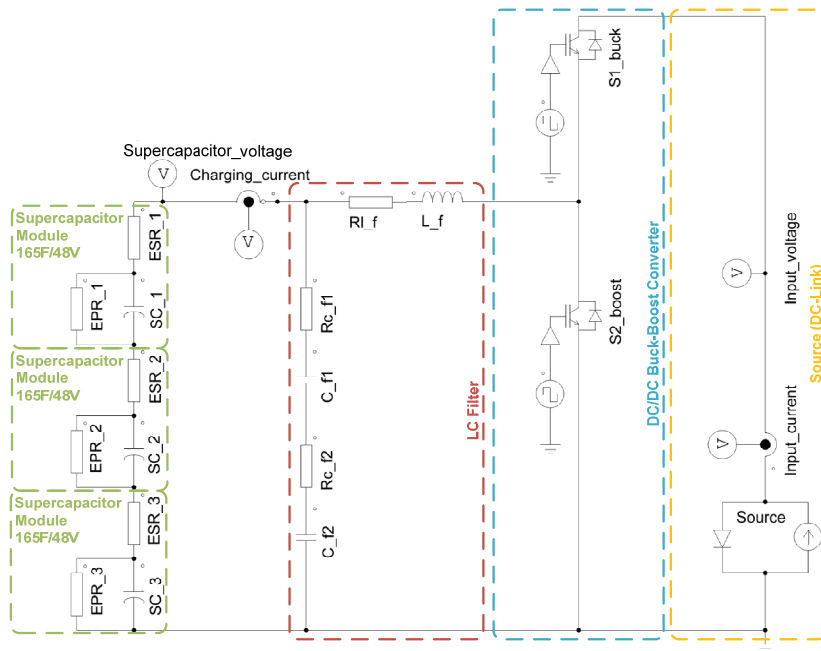


Fig. 3. PSIM simulation scheme of the supercapacitor bench

Many supercapacitor models have been published based on the material structure of the supercapacitor and their limitations. One of the classical equivalent circuits suitable for slow charge-discharge applications (Fig. 3) was used in this study [6, 14]. It includes the supercapacitors (SC), equivalent series resistors (ESR) to emulate the internal resistances that occur during charging and discharging, and equivalent parallel resistors (EPR) to represent the path of the leakage charge which, for supercapacitors, has a long-term effect.

The diagram in Fig. 4 shows the charging process of the supercapacitor bench supplied from the DC link with constant duty cycle. As the diagram reveals, it takes about 300 s to charge the superapacitor banks from the half-rated level to 97%. The normalized voltage swing (U_{min}/U_{max}) at open circuit for supercapacitors is 0.2. It is limited by the electronic circuitry, which does not allow the supercapacitor depth of discharge (DOD) to exceed 80 % [10]. It means that in real applications the charging/discharging time is shorter.

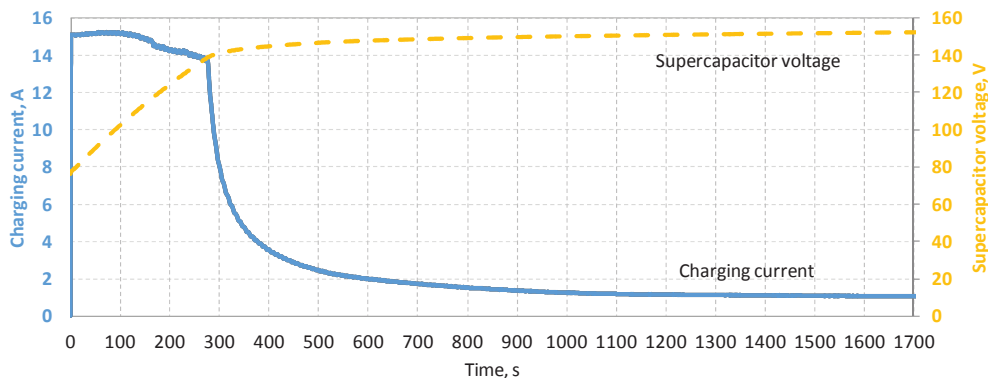


Fig. 4. Voltage and current responses obtained during the supercapacitor charging

Although the model is widely used, it fails to simulate all the dynamics of the supercapacitor cell. That is because the capacitance of a supercapacitor is generally not constant, and the charging process strongly depends on the terminal voltage [6]. Therefore, more accurate supercapacitor dynamic models are to be used for short-term modelling.

Figure 5 presents some results obtained from the measurements during the charging of the supercapacitor bank and those from the PSIM modelling of this scheme Fig. 5. Experimental and modelling results.

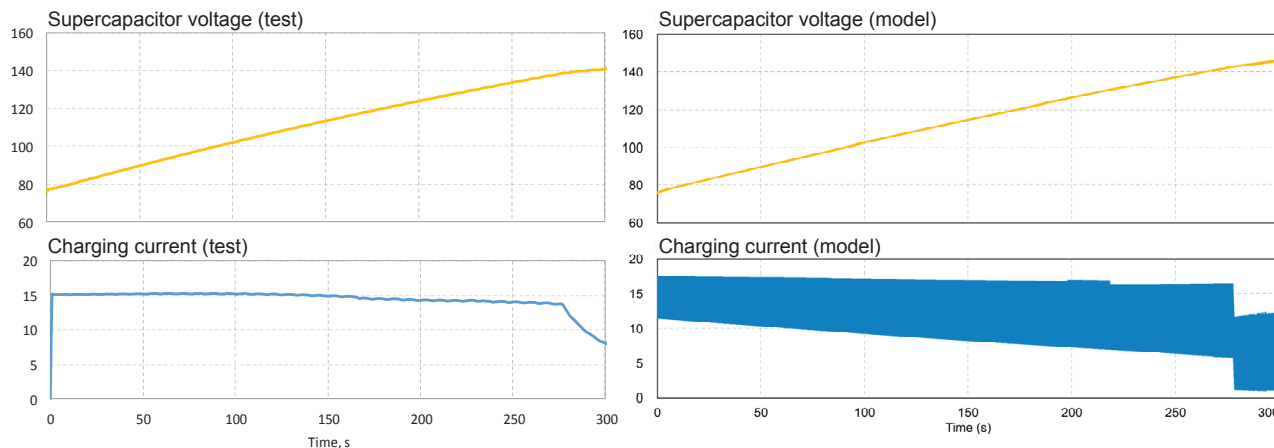


Fig. 5. Experimental and modelling results

CONCLUSION

The platform described in this paper provides durability and functional tests to the customers and helps to solve many other propulsion problems. The results received from the charging tests of the supercapacitor bank could be used for correct choice, verification and tuning of the real EV with a supercapacitor. The designed PSIM software could be used for computer simulation of different supercapacitor charging conditions.

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АНАЛІТИЧНЕ ПРЕДСТАВЛЕННЯ ВЕКТОРНОГО КЕРУВАННЯ МАТРИЧНИМ ПЕРЕТВОРЮВАЧЕМ З ВИКОРИСТАННЯМ КОВЗНОГО РЕЖИМУ

Объектом исследования является матричный преобразователь с управлением в скользящем режиме. Векторное управление позволяет обеспечить высокое качество выходного напряжения с уменьшенным количеством переключений и приближенную к синусоидальной форму потребляемого из сети тока. Получены аналитические соотношения, позволяющие построение цифровых моделей для исследования электромагнитных процессов и практическую реализацию распределителя импульсов с использованием одного и того же математического описания.

Ключевые слова: матричный преобразователь, скользящий режим, векторное управление, конечно-автоматное представление, булевы векторы состояния, элементы переключающей матрицы

Об'єктом дослідження є матричний перетворювач з керуванням у ковзному режимі. Векторний підхід до синтезу ковзного режиму забезпечує високу якість вихідної напруги з мінімальною кількістю комутацій та форму струму мережі, наближену до синусоїдальної. Отримано аналітичні співвідношення, що дозволяють побудову цифрових моделей для дослідження електромагнітних процесів та практичну реалізацію розподільників імпульсів МП за використання одного й того самого математичного опису.

Ключові слова: матричний перетворювач, ковзний режим, векторний метод, кінцево-автоматне представлення, булев вектор стану, елементи комутаційної матриці.