Design of an Experimental Setup to Study the Drives of Battery Electric Vehicles

Valery Vodovozov, Zoja Raud, and Tõnu Lehtla

***Abstract*—**This paper describes the design considerations of an experimental setup for research and exploring the drives of battery-fed electric vehicles. Effective setup composition and its components are discussed. With experimental setup described in this paper, durability and functional tests can be procured to the customers. Multiple experiments are performed in the form of steady-state system exploring, acceleration programs, multi-step tests (speed control, torque control), load collectives or close-to-reality driving tests (driving simulation). Main focus of the functional testing is on the measurements of power and energy efficiency and investigations in driving simulation mode, which are used for application purposes. In order to enable the examination of the drive trains beyond standard modes of operation, different other parameters can be studied also.

***Keywords*—**Electric drive, electric vehicle, propulsion, test bench.

I. Introduction

AUTOMOTIVE industry has turned into a primary market for electric drive and power electronic products. Accurate alternating current (ac) and direct current (dc) motor drives over a wide range of power and speed fed by power converters based on insulated gate bipolar transistors (IGBT) with complex monitoring and management systems have become an inherent part of modern vehicles [1]. This has motivated many researchers around the globe to focus on conceptualisation, design, and development of new architectures of vehicle power systems. In this a context, exploring and test platforms of a battery-operated electric vehicle (BEV) fully propelled by electrical motors are drawing today significant attention. They allow to study and to optimise vehicle performance, to reduce the number of test runs of real machines, and to provide their safety.

Many research institutions develop such kind of equipment. Also, an increasing number of engineering schools, which have initiated academic programs in advanced vehicle technologies, introduce test benches in their laboratories [2]. Severe references describe multiple kinds of experimental setups developed in different countries [3]–[10]. Most of them concern the energy management, optimal configuration, and proper combination of different energy sources of BEVs, such as batteries [3], [6], supercapacitor packs [5], [11], [12], [13], flywheels [3], fuel cells [14], etc.

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Effective platforms used for study the drives of BEVs may serve as departments of the national electromobility centres. The results of their performance affect both the choice of the drive components and the assessment of the particular drive manufacturing technologies. Their hardware and software promote comparison the different models of the propulsion drives thus helping the community in selection the car models and companies for supporting and backing and providing customers with many hidden data of the marketable electric cars. Above all, they support BEV developers by reducing the design times and costs requirements in this field.

The platforms open new possibilities in analyzing and comparison of BEV motor drives from the viewpoint of their power economical performance resulting in selection of BEVs most appropriate for regional road and climate conditions. The platforms are suitable for exploring different steady-state and dynamic modes of the motor drive performance in multiple BEV applications. Therefore, this category of the simulation and experimental techniques is effectively applied in drives working in all the possible BEV motor modes. Today, some platform-connected Web portals with social networking are open for publishing information about the BEV drives, their components, tests, reviews, and recommendations from specialists and customers As well the durability and functional tests are often requested from the test benches by the customers, including the following:

- depending on the respective prototype phase of the specimen, multiple tests are to be performed in the form of acceleration block programs, multi-step tests (speed control, torque control), load collectives or close-to-reality driving tests (driving simulation)
- main focus of the functional testing is on the measurements of power and energy efficiency and investigations in driving simulation mode, which are used for application purposes
- for highly accurate power measurement, a pool of different torque measuring procedures should be included in the platform that adopt the experimental setup and the measurement range to the tested physical values
- to enable an examination of the drive trains beyond standard modes of operation, different parameters like wheel slip (variable friction coefficient and adjustable rotational inertia of the simulated vehicle wheels), multiple wheel speed left/right, front/rear, uphill/downhill grades have to be simulated
- to support equipment test procedures, communication,

and data acquisition, highly flexible automation system are expected including the original battery simulation systems

The general configuration of the BEV involves three major subsystems – electric propulsion, energy source and auxiliary [15]. The first subsystem comprises the power converter, electrical motors, mechanical transmission, and driving wheels. The energy source subsystem includes energy sources, energy management system, and energy refuelling unit. The auxiliary subsystem consists of the power steering unit, temperature control unit and auxiliary power supply.

The motor drives, being the main components of BEVs, affect the efficiency, performances, and costs. This is the reason, why the BEV drives are of the main concern in this paper. The investigations are focused on the motors, power converters, supply chains, and transmissions, which are used in BEVs. The main objectives of the experimental setup development are as follows:

- to provide the research environment for analysis, investigation, and simulation of the marketable BEV drive systems
- to establish the assessment and verification procedures for different motor, gear, and power converter types met for propulsion
- to support commercial consulting, research and testing for enterprises
- to enlarge students' participation in corresponding research topics

The functional diagram of the discussed experimental setup is shown in Fig. 1. The testing motor system, the simulated vehicle load, and the informational environment Drive Window are implemented on the base of ACS 600/800 motor drives of ABB [16]. The system runs two motors, one working as a propulsion drive imitator and the other as a load imitator, with a physical coupling through the self-manufactured prototype of the cardan transmission.

Results obtained from the experimental setup represented in this paper could affect both the choice of the drive components and the assessment of the particular drive manufacturing technologies. They are suitable for comparison the different models of the propulsion drives from such points of view as their dynamic performance at start-up and braking, static stability on the road, energy consumption, reliability, and control suitability.

II. Considerations of the Type of Electric Drive

Different from the industrial applications, the propulsion motors have generally the following demands [2], [17], [18]:

- to offer the maximal torque of no less than four times of the rated torque for temporary acceleration and hill-climbing, while the general-purpose motors have only two for overload operation
- to support very wide speed range, achieving above four times the rated speed for highway cruising, while the general-purpose motors have only two for constant-power operation
- to be designed according to the vehicle driving profiles and driver's habits, while the general-purpose motors are usually based on typical working mode

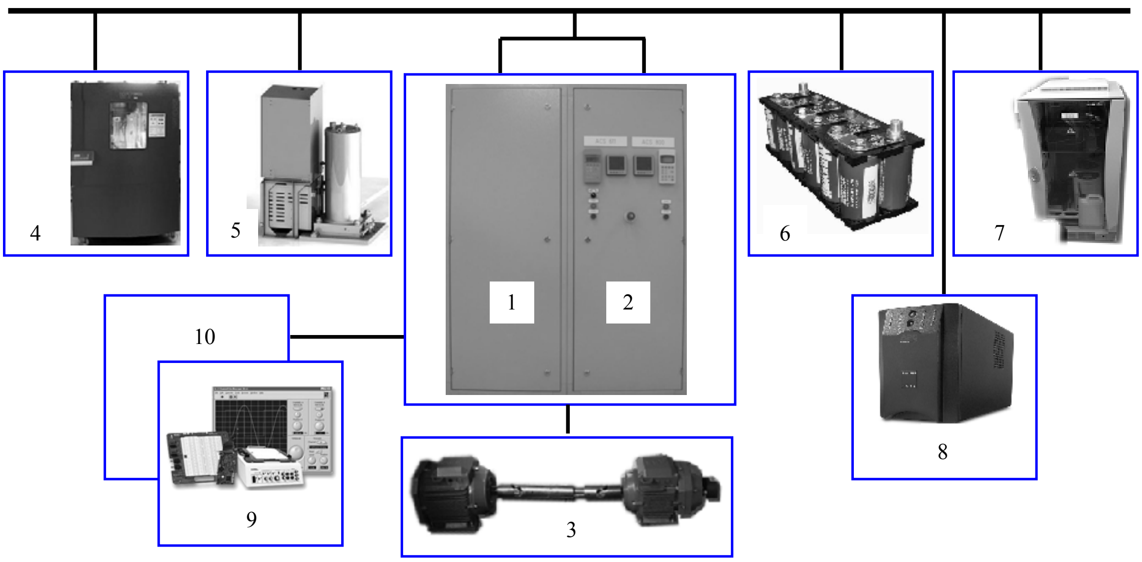


Fig. 1 Setup composition: 1 – Prototype of the propulsion electric drive; 2 – Loading electric drive; 3 – Prototype of the mechanical transmission; 4 – Traction battery; 5 – Flywheel energy storage; 6 – Supercapacitor storage; 7 – Fuel cell; 8 – UPS; 9 – LabView software and corresponding hardware; 10 – Measuring devices and instruments

- to have both high specific power and good efficiency map for reduction of total BEV weight and driving range, while the general-purpose motors generally need a compromise among specific power, efficiency, and cost optimised at a rated operating point
- to employ frequent starts and stops at high rates of acceleration and deceleration
- to provide high controllability, steady-state accuracy, and dynamic performance for multi-motor coordination
- to operate at harsh operating conditions, such as high temperature, bad weather and frequent vibration, while the general-purpose motors are generally located in fixed places

Three types of motors are used in automotive industry for propulsion, namely synchronous machines with permanent magnets (PMSM) including switched reluctance motors (SRM), induction machines, and direct current (dc) machines [19]. Considering the prototyping of BEVs, all of them could be applied in the experimental setup therefore solutions with several machine types can be found. The application of all these machines suggests that they have benefits and drawbacks of their own which render them interesting in different BEV concepts [20]. In [3], [6], [10], [19], [21], [22], the PMSMs alternate more or less effectively between motor and generator modes of operation. In [5] a dc motor is used. In [23]–[25] an induction motor is recommended. Herein, the ac drive systems are dominated today being almost equally split between induction motors from one side and PMSM and SRM from the other side [26].

Induction machines, especially squirrel cage motors, have high reliability and low manufacturing cost, but not enough high efficiency and torque density. As these demerits are not important for the experimental setup, this type of a machine was used in the discussed test platform. Unlike the PMSMs and dc motors, an induction motor has a simple design and is suitable both for the open ended and the close loop exploring. As the conventional control of induction motors, such as voltage-frequency control, cannot always provide the desired performance, the vector control was accepted along with the scalar speed adjustment [27].

For the loading imitation with movement inertia and resistance under different driving schedules, PMSMs as well as induction and dc motors can be used. In [10], an induction motor with a flywheel is proposed for this purpose. In [3], an assembly of electromagnetic brakes connected in parallel with a flywheel plays the role of the motor load, developing a resistant torque whose value is manually adjusted by an excitation current. In [5], [23], a dc machine is applied with an electrical brake controlled by the National Instrument Labview package, which allows to change the load torque through the resistive load according to various road slope simulated characteristics.

As distinct from [6] where the driven motor is connected to the utility supply via a variac allowing voltage adjustment, in the proposed solution the induction loading machine is selected supplied with the direct torque controlled dc link converter in generating region. In this way, the testing drive is in speed control mode to follow the test cycles whereas the loading drive is in torque control mode to follow a torque reference. Both systems are power reversible. By adjusting the torque, a wide range of tire/road conditions can be simulated at different slip values including system locking at 100 % slip. This is analogous to the braking process of a vehicle whose wheel can rotate freely or be locked. Due to the asymmetrical nature of induction machine characteristics, different voltages and frequencies for exciting the induction machine are simulated thus representing a variety of tire/road driving conditions on the dry, wet and icy surfaces that the BEV should overcome.

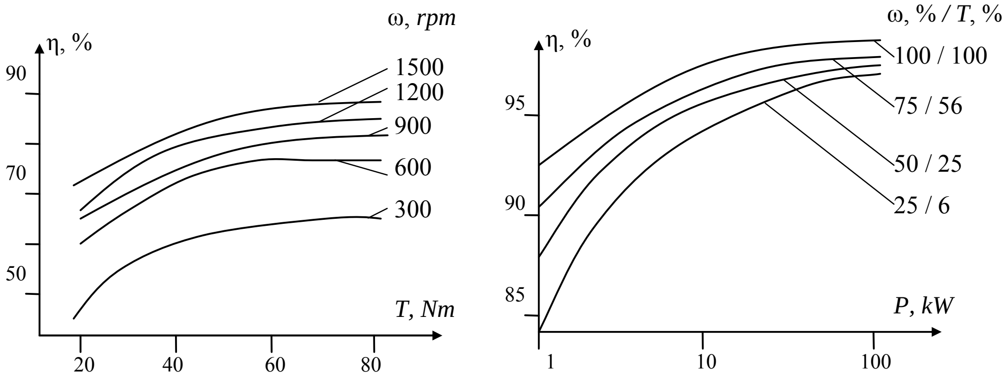
As the maximum power is to be drawn from the traction and loading electric motors, it is necessary to provide cooling of the stator and rotor windings and also of other vulnerable parts. For the test bench, an air cooling is preferable. For cooling to be effective, ducting could be employed to get the cooling air to those components which dissipate most heat. The forcing air cooling is used when the ram air is insufficient.

III. Considerations of Mechanical Transmissions

Unlike the internal combustion engine which cannot develop the peak torque until it has reached a particular speed, with all types of electrical motors an instant torque is available at any speed. The ability to start from zero speed makes it possible to eliminate the need for a clutch, and the available speed range is sufficient for elimination the need in the multispeed transmissions and in a reverse gear, thus saving the vehicle weight and making the powertrain much less complex. Under the wide torque band, especially the available torque at low speeds, the torque stays constant to the rated speed, and then it begins to slowly decrease. Along with the full absence of gear which greatly enhances smooth driving and transmission efficiency, modern BEVs frequently adopt fixed gearing with a differential. In the case of high-speed in-wheel motors, a fixed speed-reduction gear becomes useful. Electrical motors with fixed gearing can readily offer constant-torque operation for acceleration and hill climbing as well as constant-power operation for high-speed cruising.

Variable gearing is used also, involving shifting between different gear ratios which can be accomplished through a combination of clutch and gearbox. Thanks to variable gearing, multi-speed transmission is provided resulting in wide ranges of speed and torque. This approach allows a limited number of combinations. Commonly, four- or five-speed transmission is used for passenger cars, and up to 16-speed transmission for trucks.

A further step towards simplifying the drive train and eliminating the differential is taken by using two motors each connected to one of the two driven wheels. Also, a considerable amount of work is being done to develop motors suitable for in-wheel use [26].



(a) Impact of rotational speed (ω) and load torque (*T*) on efficiency (η) of a 2.2 kW induction motor driven with a frequency converter

(b) Impact of rotational speed (ω) and load torque (*T*) on efficiency (η) of frequency converters of different rated powers (*P*)

Fig. 2 Impact of rotational speed and load torque on the motor and power converter efficiencies

The mechanical transmissions incur the losses due to the meshing of gear teeth, viscous and coulomb friction of the sliding surfaces of bearings, and churning losses in air and oil those value depends on many influencing factors, such as speed, load, temperature, lubrication, etc. The representative values of the mechanical efficiencies as the ratios of the output and consumed powers are as follows [2]: clutches – 99 %, each pair of gears – 95 to 97 %, and bearings about 98–99 % resulting usually in 75–90 % totally. Typical dependencies of the gear efficiency on the output speed and torque and the transmission ratios were studied in [28].

As the energy efficiency is a very important index among the performance indices significant from the viewpoint of propulsion, it was estimated carefully on the test bench designed by the authors. Some results are presented in Fig. 2. They show that the efficiency increases with torque at constant speed and ratio, exhibiting a maximum that is more pronounced at higher speeds. Higher transmission ratios also favourably affect the efficiency. Values, some smaller than maximum, can be reached for high-load, low-speed conditions. The lowest values are typical during low-load operation.

Beyond the mechanical transmission there are further losses associated with the propeller shaft to the final drive and then through the drive shafts to the driven wheels.

In general, the efficiency in different operation modes can be found from the stationary efficiency maps. Some examples of such maps were discussed for a 32 kW PMSM and a 30 kW induction motor, respectively in [28]. Using the test bench, the similar results were obtained by the authors (Fig. 3).

The maximum torque the mover can produce is the limiting factor to the maximum traction effort of the vehicle. Such maximum torques the motors deliver under normal conditions are shown in the efficiency maps with the dash-dotted lines. These curves typically are constant up to a certain speed, and then they drop hyperbolically with the speed. Such dependencies indicate that the quantities restricted in a motor are first the current and then the power. At low speeds, the

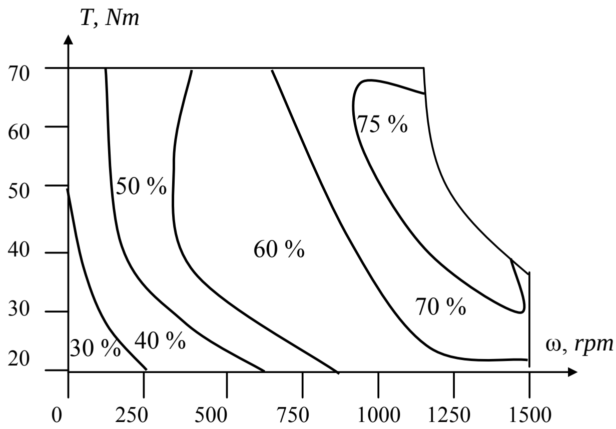


Fig. 3 Efficiency map of a BEV induction motor in torque (*T*) to speed (ω) reference frame

current limitation is active, thus the torque is constrained to be constant. Such constant torque characteristic provides high traction effort at low speeds where demands for acceleration, drawbar pull, or grade climbing capability are high. At higher speeds, the power limitation is active. This results in a constant output power while the torque declines hyperbolically with the speed.

Efficiency maps are usually well defined only for the first quadrant (motoring mode). Nevertheless, the two-quadrant efficiency maps can be available also.

In the proposed test bench solution of, a direct coupling through the long metal shaft was employed similarly to those recommended in [29]. Such a transmission has a possibility to change a slope angle thus simulating the cardan joint with

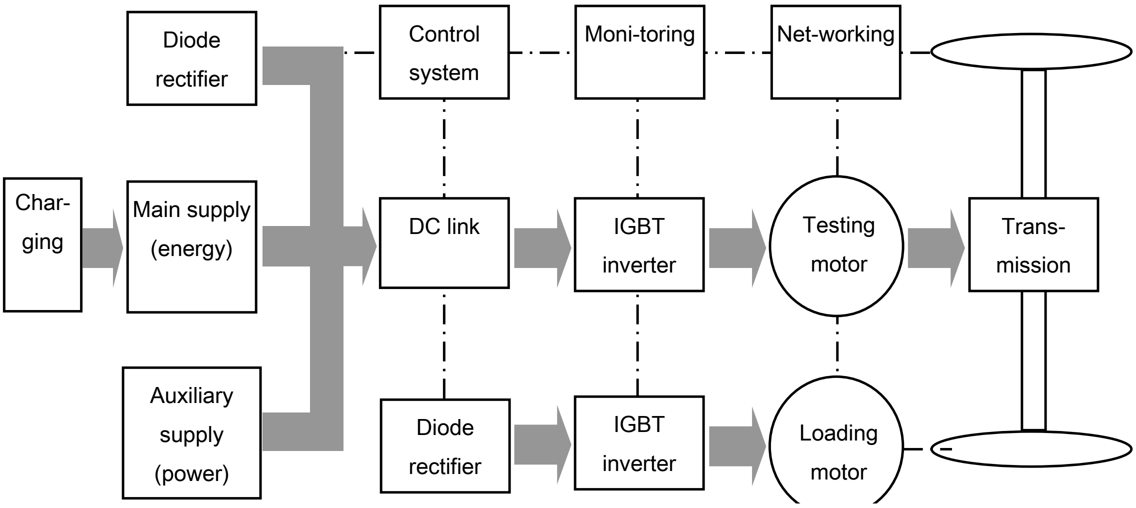


Fig. 4 Hybrid supply system of BEV

alternating transmission rigidity and moment of inertia.

IV. Considerations of Power Supply

The major part of the powertrain of an experimental setup accomplishes two power sources that feed an electric motor propelling the BEV, as shown in Fig. 4.

The three-phase network supplies the dc power bus through a rectifier. Another power source imitates an on-board energy system connected to the bus. A dc/dc converter allows the rectifier and the on-board source to have a different voltage and to adjust the power flow to fully use the energy. Usually, it is of the buck-boost configurations. Particularly, the dc/dc converter of Toyota Prius [2] boosts the battery output voltage of 206 V to the maximum dc bus voltage of 500 V using a reactor, a half-bridge IGBT stage, and a full-bridge IGBT inverter to feed the traction motor. As soon as the accelerator pedal is released, a traction machine turned by wheels acts as a generator, which voltage is converter back by the inverter freewheeling diodes, and then the booster drops this voltage back to charge the battery.

Because of the frequent stop-and-go operation, the discharging and charging profile of the on-board power source is highly varied. The average power required from the source is much lower than the peak power for acceleration and hill climbing in a relatively short duration. According to [2], [17], the ratio of the peak power to the average power can be as high as 10:1 to 16:1 for a high-performance BEV. At the same time, the amount of energy involved in the acceleration and deceleration transients is roughly 2/3 of the total amount of energy over the entire vehicle mission in the urban driving.

An important feature of the BEV is its limited range at which the vehicle could only travel in the order of 50 to 200 km on a single charge [26]. Fig. 5 built on the basis of [28] depicts the typical ranges of specific energy (energy density) and specific power (power density) of the most common energy storage systems.

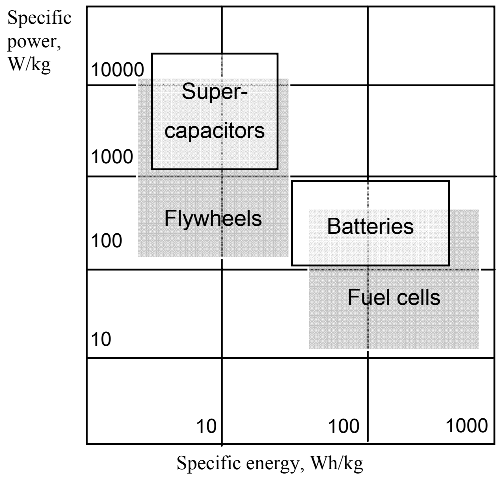


Fig. 5 Power and energy capabilities

Its analysis shows the difficulty in simultaneously obtaining high values of specific energy, specific power, and life cycle. Therefore, the power system of BEVs represents usually a hybridisation of an energy source and power source, that is, minimum two on-board supplies are to be incorporated to the experimental setup. Following [5], [6], [22], the strategy of the multi-quadrant operation provides the management at which the main supply system keeps the only moving average current whereas the auxiliary supply of high specific power (peak power source) passes the peak currents at acceleration and hill climbing.

The main supply of high specific energy, usually a battery, is optimized for the rout travelling. Typical energy

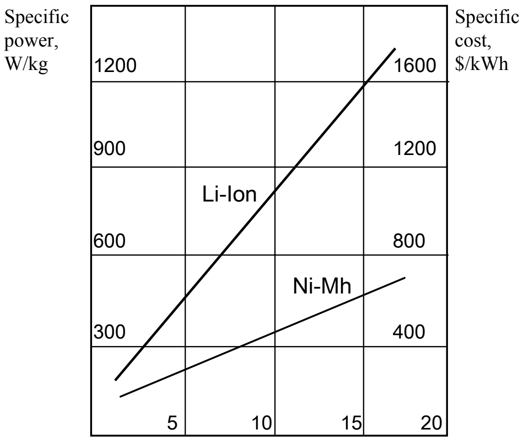


Fig. 6 Power-energy-cost ratio

consumption of BEV is about 150–300 Wh/km before the battery is fully discharged. The state-of-the-art batteries optimised for high specific energy achieve approximately 40 Wh/kg for lead-acid, 70 Wh/kg for nickel-metal hybrids, 150 Wh/kg for "hot" batteries, and 200 Wh/kg for prospective lithium-ion cells compared to a useful energy density of more than 2000 Wh/kg for gasolite. The batteries represent a reversible electrical energy storage system of enough low specific power, ranging from 150 to 350 W/kg.

As the auxiliary supply, supercapacitors (electrostatic energy), hydraulic and pneumatic reservoirs (potential energy), and flywheels (kinetic energy) can be used. The first ones can reach specific energy in order of 0.2–5 Wh/kg, the second – in order of 20 Wh/kg. At the same time, they have high specific power of 500–2500 W/kg. This parameter indicates how rapidly power can be drawn from the battery and therefore the maximum current that can be supplied to the motor to accelerate the vehicle. To select among them, the analysis of [30] can be used, which showed that the lower is the specific power to the specific energy ratio, the lighter, smaller, and less expensive energy storage system can be built (Fig. 6).

In the simplest configuration, both the main and the auxiliary supplies are connected in parallel. The BEV operates in three different modes:

- traction, i.e., the motor provides a propulsion force to the BEV
- braking, i.e., the brakes dissipate kinetic energy of the BEV while the motor can be engaged or disengaged
- coasting, i.e., the motor is disengaged and the resistant losses of the BEV are exactly matched be the decrease of its kinetic energy

During the cruising and coasting, the battery feeds the drive to provide traction. To enable the system ready for sudden power demand, this high specific energy source can precharge the high specific power source in the light-road period. During the acceleration or hill-climbing traction conditions, both the sources need to simultaneously supply the desired energy to the drive. During the braking or downhill condition, the drive operates as a generator so that the regenerative energy flows back to recharge the high specific power source. If this source cannot fully accept the regenerative energy, the surplus can be diverted to recharge the high specific energy source provided that it is energy receptive. The major disadvantage of this configuration is that the power flow cannot be actively controlled thus the peak power source cannot be fully used. To overcome this drawback, a two-quadrant dc/dc converter is placed between the main and the peak power sources. This design supports different voltages of the batteries and the peak power source and provides adjustable power flow between them.

Commonly, to feed the electrical motor during the power demand rises or to recharge the batteries when power demands come down, the supercapacitor pack is used as the high specific power source. Unlike the battery, this device stores and releases energy electrostatically, rather than electrochemically. Supercapacitors have the ability to quickly discharge high voltages and then be quickly recharged. This energy storage implements high dynamics for adding energy to motors when a vehicle needs extra power for acceleration, to overcome heavy loads, and for the regenerative braking. While the supercapacitor specific power is much higher than in batteries, its specific energy is substantially lower. In automotive applications, most of the attention has been focused on carbon-based cells with polymer electrolyte. Since the available supercapacitors for BEV application are of relatively low voltage level, an additional dc-dc converter is needed to interface between the battery and capacitor terminals.

Similar to the supercapacitors, the flywheel represents another variant of an emerging power storage device which can offer high specific power [31]. Flywheel power storage systems have storage capacities comparable to batteries in terms of specific energy a higher in terms of specific power providing faster discharge rates. The advantages of flywheels are that they contain no acids or other potentially hazardous materials, they are not affected by extreme temperatures, and they usually exhibit a longer life. There is also no limit as to how many charge and discharge cycles they can experience. Unlike other applications, the flywheel for BEVs is to be of lightweight and operate at ultrahigh speeds under a vacuum environment. This flywheel is usually incorporated into the rotor of an electrical machine which operates at motoring and generating modes when converting electrical energy to and from kinetic energy, respectively. Again, an additional dc/dc converter is needed to interface between the battery and flywheel terminals.

In the future research UPS and fuel cell applications can also be discussed, the former for the experimental setup uninterruptible supply and the latter as the main on-board supply source along with the battery.

V. Considerations of Brake Performance

The function of the vehicle braking system is to quickly reduce the speed while keeping the travelling direction stable and controllable under various road conditions. In BEV, regenerative braking, or energy recuperation, is the principal means through which kinetic energy of the vehicle is returned to electric energy storage rather than burned off as heat in the brake pads. Energy regeneration is a definite advantage of BEVs. Here, the energy can flow in both directions: from the energy source to the wheels during acceleration and cruise, and from the wheels to the energy source during braking or coasting. This reverse flow of electricity causes regeneration at which the motors convert the reduction of kinetic energy into electrical energy. Regenerative braking recovers the energy normally lost as heat when a vehicle is slowing down or braking. This performance increases a BEV range potential, especially when the vehicle speed is changing, like in city traffic where the brakes are used frequently.

In general, the regenerative braking system is activated when the BEV is decelerated for speed reduction, the accelerator pedal is released for coasting at highways, or the brake pedal is pressed for stopping. During normal speed reduction, the regenerative braking torque is usually kept at its maximum capability. When the BEV is coasting at high speeds, its propulsion drive generally operates in the constant-power mode so that the motor torque is inversely proportional to the vehicle speed. Thus, the higher the speed, the lower the capability of the regenerative braking torque will be resulted. On the other hand, when the brake pedal is pressed, the propulsion drive usually operates at low speeds. Since kinetic energy in this mode is commonly insufficient for the motor to produce the maximal braking torque, the corresponding torque capability will proportionally decrease with reduction of the vehicle speed.

According to estimates of [2], the braking energy in typical urban areas may reach up to more than 34 % of the total traction energy. In large cities with intensive stop-and-go patterns it may reach 80 %. Conventionally, there are practical limits to how much and how fast regenerative braking can be applied and it is impossible to recover full energy. On average, the amount of convertible energy is only about 30-50 % as there is significant dissipation in the road load [17], [31]. Assuming input/output efficiency of the drive train and energy source is about 70–80 % [28], the amount of energy actually returned back is about 21–35 %. This is called a regenerative braking efficiency. Additional benefit of regenerative braking concerns the decrease of the brake wear and reduction of the maintenance cost of mechanical brakes.

Converted electrical energy is stored in the battery, the supercapacitors, or the flywheel. If these receptive sources have been fully charged up, regenerative braking can no longer be applied and the desired braking effort can only be provided by the conventional braking system. Sometimes [26], they switch automatically to dynamic braking in which the energy is dissipated in resistors instead of being returned to the supply source. Mostly, the hydraulic braking system generally coexists with the regenerative braking system in BEVs and in this case, coordination between regenerative braking and hydraulic braking is a key issue [17]. To keep the BEV driver having a smooth brake feel, the hydraulic braking torque has to be controllable according to the changes of the regenerative braking torque.

In the proposed solution, the dynamic braking system performs along with the regenerative braking. To this aim, an additional dc load is connected to the dc link of the tested machine. The test bench permits simulation of the different loads to study the steady-state and dynamic modes of the BEV operation or to keep them constant for making static measurements. An energy flow generated during the braking is registered also.

VI. Conclusion

With experimental setup described in this paper, durability and functional tests can be procured to the customers as well as many other problems can be solved, such as the following:

- testing and verification the functionality of the constituent equipment
- experimental determining of the mechanical characteristics of the propulsion motors and electrical properties of their power converters
- determining the charge/discharge characteristics of the battery
- determining the charge/discharge characteristics of the supercapacitors, the fuel cell, and the flywheel
- determining the model of the traction motor and simulating the functionality of the system consisting in different combinations of energy sources and mechanical loads, in order to establish the optimal configurations for the system
- defining a procedure for an efficient management of the energy in the case of the functionality with unique sources (battery or network) and/or with hybrid sources (batteries, supercapacitors, etc.)
- studying the energy recovery processes and efficiency during the BEV braking processes

Depending on the respective prototype phase of the specimen, multiple tests can be performed in the form of steady-state system exploring, acceleration programs, multi-step tests (speed control, torque control), load collectives or close-to-reality driving tests (driving simulation). Main focus of the functional testing is on the measurements of power and energy efficiency and investigations in driving simulation mode, which are used for application purposes. In order to enable the examination of the drive trains beyond standard modes of operation, different parameters like wheel slip, multiple wheel speed left/right, front/rear, uphill/downhill grades can be studied also.

ACKNOWLEDGMENT

This research has been supported by Estonian Ministry of Education and Research (Projects SF0140016s11 and GERA1) and Estonian Kristjan Jaagi Stipendium.

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