

HYBRID SUPERCAPACITOR-BATTERY ELECTRIC SYSTEM WITH LOW ELECTROMAGNETIC EMISSIONS FOR AUTOMOTIVE APPLICATIONS

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The present paper represents a study of a hybrid electric system that uses a battery of electrochemical double-layer capacitors (EDLC), a conventional lead-acid battery and a proprietary electronic system, designed to obtain minimum electromagnetic disturbances, with uses in automotive applications. The electronic control module offers the possibility of programming the control method of the distribution of electricity in the hybrid system. Electromagnetic compatibility assessments of the electronic were also performed according to CISPR 22 standard and the results are compared with the limits specified by the standard. Electrical tests performed on both charge / discharge cycles of the battery of supercapacitors and in combination with a reversible electric motor highlights the benefits of using EDLC in automotive applications.

Keywords: electric motor, hybrid electric system, supercapacitors, automotive

1. Introduction

The hybrid or electric vehicles are becoming slowly widely available automotive alternatives. To match the range of an internal combustion powered vehicle, the electric vehicle (EV) needs a battery capable of delivering 30–50kWh (commonly the standard capacity is 15 to 20 kWh). This is twice the battery size of a Plug-in Hybrid Electric Vehicle (PHEV which commonly has 25 to 30 kWh) and 10 times that of the Hybrid Electric Vehicle (HEV) [1]. The electro-chemical battery is not the only expense added to the EV; the power electronics to manage the battery make up a large part of the vehicle cost, thus has appeared the need of designing a relatively lower cost hybrid electric system such as the one presented in this paper. Being part of a complex electronic system with potentially high electromagnetic interference emitters, the device must also fully comply with the strict electromagnetic compatibility (EMC) requirements of the automotive industry.

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The development of lithium-ion batteries has progressed to the state that is being used in both electric and hybrid vehicles. Much of the recent battery development has been concerned with high power batteries for hybrid-electric vehicles (HEVs) and not high energy density batteries for electric vehicles (EV). Most batteries for electrical vehicles (HEV and EV) are guaranteed for eight years. To meet this long service life, the cells are optimized for longevity rather than small size and low weight, as is the case with portable consumer products. The battery manufacturers achieve this in part by using a thicker and more durable separator. To reduce stress, the battery operates in the 20–80 percent state-of-charge bandwidth, or roughly 3.5–4.0V/cell for Li-ion, rather than the customary 4.20V/cell. Another issue the battery manufacturers face and avoid mentioning is battery aging. The Lithium Ion battery loses 20% of its original capacity in the first year of operation. Capacity fade with aging will manifest itself in reduced driving distance.

Supercapacitors or electrochemical double-layer capacitors (EDLC) store energy in the chemical valence states or in the so-called "Helmholtz" double layer that exists around carbon fibers in an alkaline solution. There are presently commercially available carbon/carbon supercapacitor devices (single cells and modules) from several companies. All these companies market large devices with capacitance of 1000–5000 F. These devices are suitable for high power electric motor applications. They can provide high peak power output and can be recharged and discharged up to millions of times without damage (in contrast to batteries which have around thousands of charge/discharge cycles) [2]. Batteries are good for sustained, steady state power but not the best suited to deliver peaks of power. Supercapacitors excel at the latter, but not at the former. Thus, a so-called hybrid electric system that combines batteries with supercapacitors in an application where there are many short, sharp peaks of current (such as the start and stop of an electrical motor) is ideal for a hybrid system.

2. Proposed hybrid electric system structure

The block diagram in Fig. 1 presents the structure of an electronic module and the adjacent systems for controlling a single phase or a three-phase electric motor with electrical storage in EDLC and a battery pack (e.g. Li-Ion). The red lines represent the flow of power from the Battery Pack and the EDLC block when the electric motor is running in traction mode, while the green lines represent the flow of regenerative power from the electric motor to the EDLC when the electric motor is running in brake mode. The command of the electronic module is performed by a microcontroller through the switching power block which incorporates a high power solid state relay. It is able to detect the zero-crossing of the voltage received from the 240V inverter and performs the power

transfer to the electric motor. When the electric motor is placed under braking, the energy generated passes through an AC-DC converter to the EDLC from where it can be transferred either for charging the batteries, or reassigned to the switching block for use in supplying the electric motor. When in need, the battery pack and the EDLC pack can transfer to the switching block energy for a spontaneous surge of power. The energy needed to start a typical electric motor of 32 kW while in load can reach 200-300 A in the first seconds of operation. This top current can be drawn from the EDLC in order to reduce wear on the battery pack and also provide the system with immediate power for short term operation.

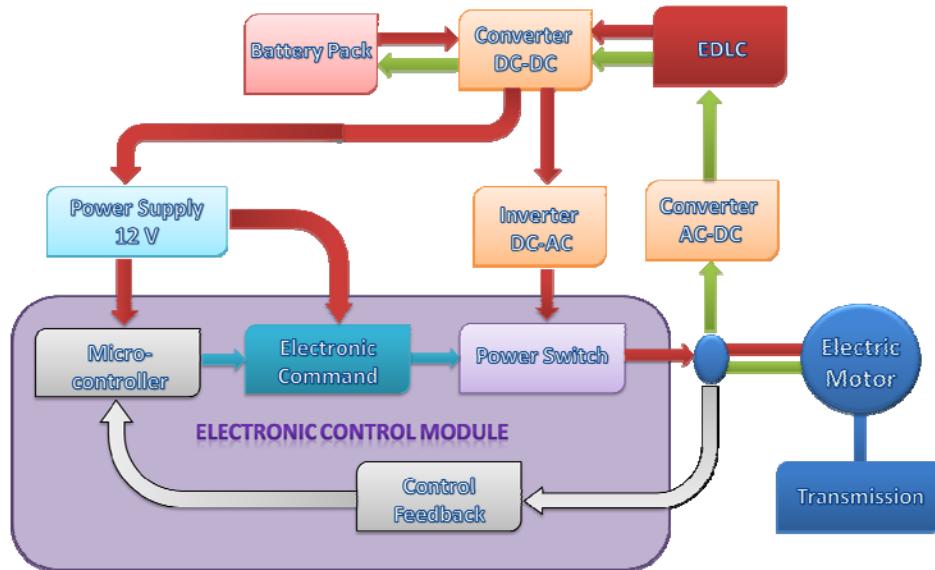


Fig. 1. Schematic diagram of the hybrid electric system

2.1. Electronic control module function

The Power Supply (12V) block, programmable Microcontroller block, Electronic Command, Power Switch and Control Feedback block form up the electronic control module. The module was designed and constructed as a prototype for controlling the energy transferred to a system with minimum electromagnetic disturbances and also being able to cope with different applications requirements. In the current development stage, the power switch block is able to support resistive and inductive loads with nominal power ratings of 3 kW.

The Microcontroller block uses a RISC micro-controller from Microchip in order to minimize the costs, the dimensions and the power consumption. Using a 4 MHz clock oscillator, which means 1 μ s per instruction, the delay between the

zero crossing and the command for the IR LED is much less than the hardware delay introduced by the SSR (500 μ s), being directly proportional to the number of instructions from the interrupt subroutine treating that request (20-25 instructions). A solid-state relay (SSR) was chosen as switching element (Power Switch block), offering an isolated interface between the high voltage AC input and the low voltage DC control circuitry. The Electric Motor block represents the load whose operating parameters values are returned to the microcontroller for analysis through the feedback loop for assessment in order to decide the next command to be given. The testing method of the command is revealed in Fig. 2 and Fig. 3.

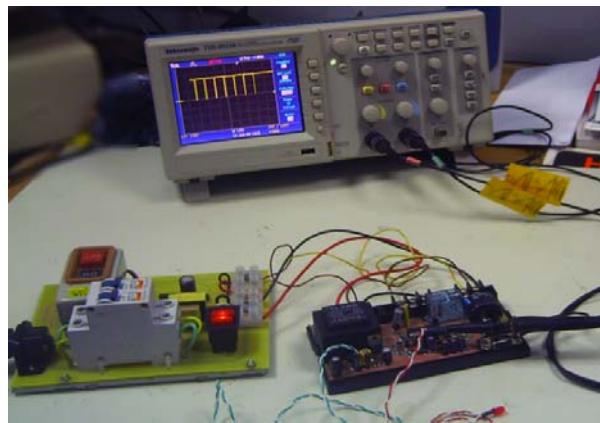


Fig. 2. Testing of the electronic module command program

An important feature of the SSR named above is the zero cross detection which has the benefit of low electromagnetic disturbances by switching only when the voltage is crossing the zero level [3]. Also the electronic module has a low pass filter included in the supply block to further diminish conducted emissions. There are two conditions necessary for a SSR to switch:

- a zero crossing of the voltage by its internal detector;
- an enable signal on its input circuit (an infrared, IR, LED and a photovoltaic detector).

In this stage, the communication between the electronic module and his operator was reduced to a data transfer between a PC and the module through RS232 serial port. This gives the possibility of programming the microcontroller to suit different parameters depending of the application (Fig. 3). Specific programs can be created using MPLAB software environment and MPLAB C18

Compiler to accommodate a wide range of applications and many types of electric motors.

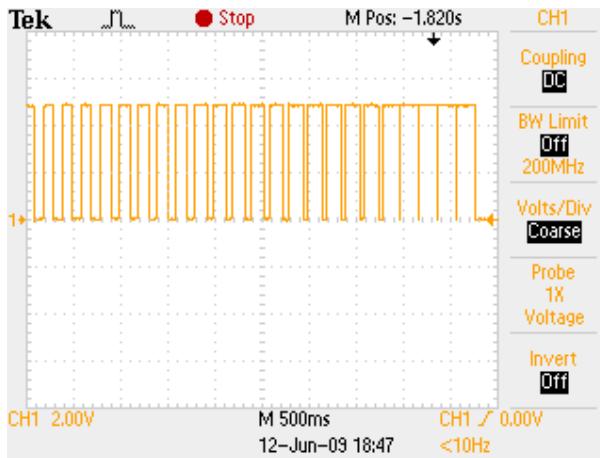


Fig. 3. Example of a command to start the electric motor

2.2. EDLC Battery function

The modern supercapacitor is not an actual battery, but crosses the boundary into battery technology by using special electrodes and electrolyte. We focus on the electrochemical double-layer capacitor (EDLC) concept. It is carbon-based, has an organic electrolyte that is easy to manufacture and is the most common system in use today.

As with all capacitors, the EDLC also has voltage limits and is confined to 2.5 – 2.7 V. Voltages of 2.8V and higher are possible but they would reduce the service life. To achieve higher voltages, several supercapacitors are connected in series. This has disadvantages. Serial connection reduces the total capacitance, and strings of more than three capacitors require voltage balancing to prevent any cell from going into over-voltage [4]. This is similar to the protection circuit in lithium-ion batteries. Table 1, shown below, compares the supercapacitor with a typical Li-ion battery used in automotive.

The charge time of a supercapacitor is about 10 seconds. The charge characteristic is similar to an electrochemical battery and the charge current is, to a large extent, limited by the charger. The initial charge can be made very fast, and the topping charge will take extra time. Provision must be made to limit the initial current inrush when charging an empty supercapacitor. The supercapacitor cannot go into overcharge and does not require full-charge detection; the current

diminishes up to the leakage current when the capacitor reached nominal capacitance.

Table 1.

Performance comparison between supercapacitor and Li-ion⁴

Function	Supercapacitor (or EDLC)	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6 to 3.7V
Specific energy (Wh/kg)	5 (typical)	100–200
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per Wh	\$20(typical)	\$2 (typical)
Service life (in vehicle)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

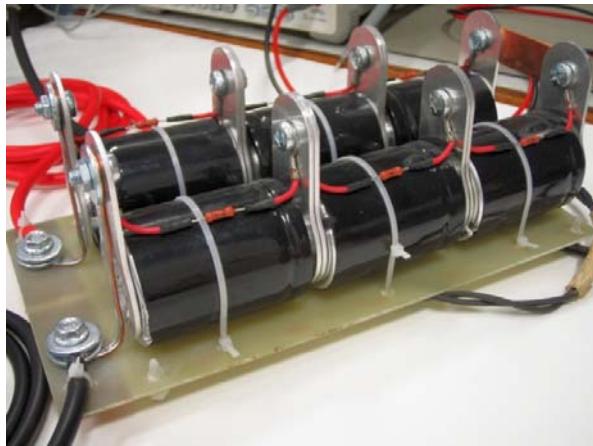
The supercapacitor can be charged and discharged virtually an unlimited number of times. Unlike the electrochemical battery, which has a defined cycle life, there is little wear and tear by cycling a supercapacitor. Age does not affect the device, as it would a battery. Under normal conditions, a supercapacitor fades from the original 100% capacity to 80% in 10 years. Applying higher voltages than specified shortens the life. The supercapacitor functions well at hot and cold temperatures. The self-discharge of a supercapacitor is substantially higher than that of an electrostatic capacitor and somewhat higher than the electrochemical battery. The organic electrolyte contributes to this. The stored energy of a supercapacitor decreases from 100 to 50% in 30 to 40 days. [5]

The Battery Pack block in the schematic diagram in Fig. 1 is intended to represent a typical lead-acid battery having a 12V voltage and 55Ah. The rapid recharging cycles and high currents needed for fast storing of the deceleration energy from the reversible electric motor would destroy the lead electrodes in standard batteries, because lead sulfate would build up on them. The new hybrid design which combines battery and EDLC can go through at least four times as many charging cycles as lead-acid batteries and crucially, would cost about a quarter of NiMH batteries. The main advantages of EDLC are long life, with little degradation over hundreds of thousands of charge cycles, it will basically outlast the lifetime of most devices, low cost per recharge cycle, good reversibility, very high rates of charge and discharge, extremely low internal resistance (ESR) and consequent high cycle efficiency (95% or more) and extremely low heating levels.

⁴ Statistic provided by Maxwell Technologies, Inc. (www.maxwell.com/ultracapacitors/)

Also they have fast, high output power, low toxicity thus, making them environmentally friendly.

Because of financial reasons we opted to use six 600F EDLC with nominal voltage of 2.5V for the energy storage block. Fig. 4 shows the six supercapacitors connected in series configuration in order to obtain the necessary voltage of 12.5V equal to that of the lead-acid battery pack. This configuration has the disadvantage that the equivalent capacitance of the EDLC pack is just $C/6=100F$. Another parameter that is influenced is the equivalent series resistance (ESR), which is



obtained by summing individual ESR of each capacitor. Also, a faulty capacitor or a high ESR influences the whole system [6].

Fig. 4. EDLC battery pack comprised of six 600F supercapacitors

3. Electromagnetic compatibility tests

For the electromagnetic compatibility tests the electronic module prototype was enlisted as class B equipment because it operates while being connected to a 230V power network and all tests were setup and performed according to CISPR 22 [7] for Information technology equipment using a 2.2 kW resistive load in order to reach nominal power output and 40W inductive load. For validation of the design and construction of the process control module the tests were initially done in a 3m semi-anechoic chamber using a Line Impedance Stabilization Network (LISN), an EMI Test Receiver, calibrated RF cables and antennas. For the mains terminal disturbance voltage tests the EUT was placed on a 0.8 meters height non-conductive table and was connected to the LISN shown in Fig. 5. Table 2 presents the recorded maximum levels of conducted emissions.

For the electromagnetic radiation disturbance tests (Fig. 7), the EUT was placed on the non-conductive table in front of the log-periodic antenna (horizontal and then vertical polarized) which measured the emissions from 3m away. The

turn-table and the antenna mast were controlled in order to record the maximum radiated emissions levels for the operating mode of the device. Table 3 compares the noted emission levels with the limits from the standard.

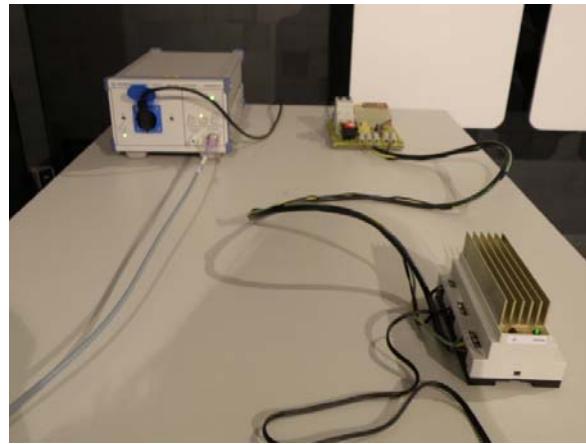


Fig. 5. View of the electronic module being tested for conducted disturbances in a semi-anechoic chamber

Table 2.

Quasi-peak levels of conducted emissions

PEAK	FREQ. (MHz)	LEVEL [dB(µV)]	LIMITS (CISPR 22)
PEAK 1	0.195	52.01	56 dB(µV)
PEAK 2	0.408	48.70	56 dB(µV)
PEAK 3	2.02	46.72	56 dB(µV)
PEAK 4	4.61	44.06	60 dB(µV)

a. frequency band from 0.15 MHz to 30 MHz
(load = 2.2kW)

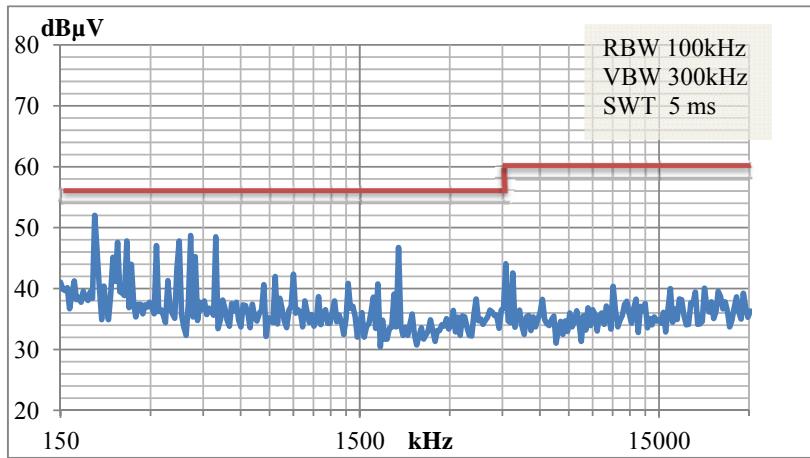


Fig. 6. Recorded conducted emissions of the electronic module



Fig. 7. View of the electronic module being tested for radiated emissions in a semi-anechoic chamber

Table 3.

Quasi-peak levels of radiated emissions

PEAK	FREQ. (MHz)	LEVEL [dB(μV)]	LIMITS (CISPR 22)
PEAK 1	4.02	32.43	40 dB(μV)/m
PEAK 2	3.64	28.43	40 dB(μV)/m
PEAK 3	4.31	27.20	40 dB(μV)/m

b. frequency band from 0.15 MHz to 10 MHz
(load = 2.2kW)

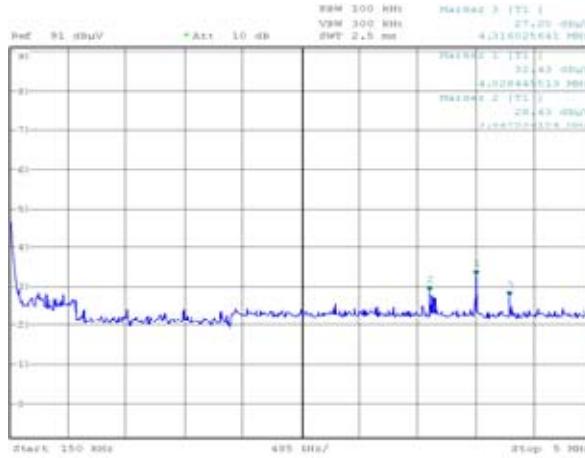


Fig. 8. Recorded radiated emissions of the electronic module

4. Electrical measurements and tests

The schematic in Fig. 9 shows the setup used in analyzing the EDLC battery pack. When used in a series connection each EDLC has to be protected against voltage overload above the nominal 2.5V value. For this purpose we used equalization resistors of $1.2\text{k}\Omega$ in parallel with each **supercapacitor**.

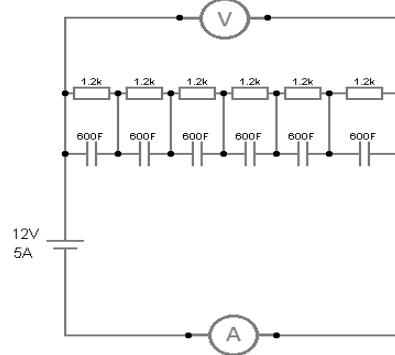
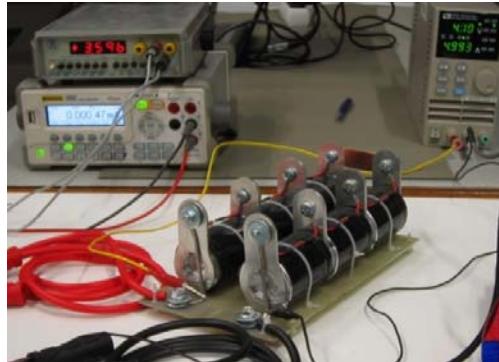


Fig. 9. Setup of the EDLC measurements and tests

When the voltage across an EDLC increases then current loss resistance decreases resulting in balancing the voltage on the supercapacitor [8]. This solution has the disadvantage that it drains the supercapacitor when the charging circuit is disabled. Using an electronic circuit eliminates this disadvantage. The power supply was configured to charge the battery of EDLC at a voltage of 12.5V and a current of 5A. The overall voltage and leakage current was noted.

The results obtained for charging the EDLC at 12.5V are shown in Fig. 10. At 5A the EDLC reached the requested voltage in 4 minute. Complete charge is obtained after 5 minutes. After more than 770 minutes the leakage current is obtained at 0.45 mA.

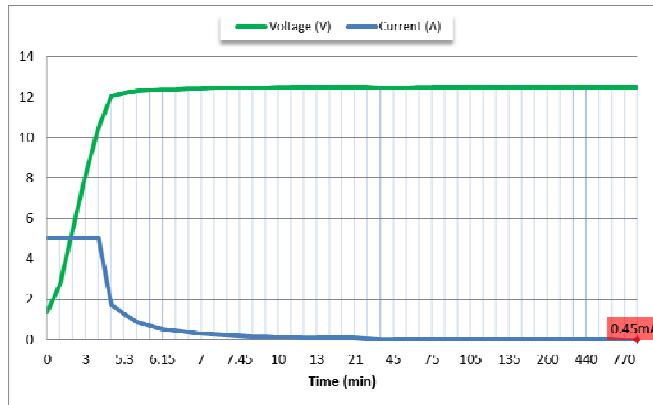


Fig.10. Charging characteristic of the EDLC at 12.5V and 5A

A DC electric motor with 12V rated nominal voltage and 6A maximum current was used to test the fast release of energy from the EDLC battery. In Fig. 11 can be seen the setup using the electric motor. Maximum rated power of the motor is 72W; nominal power is 45W at maximum 3000 rpm and maximum torque 5.35Nm.

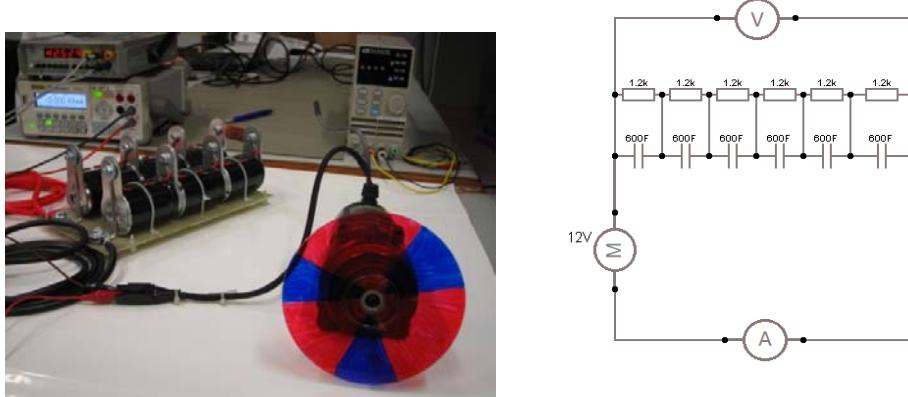


Fig. 11. Setup of the EDLC measurements using a 72 W electric motor

The electric motor was successfully started and operated for 15 minutes when the voltage from the EDLC went below 2V. Fig. 12a and Fig. 12b shows the current and voltage characteristic for EDLC discharge.

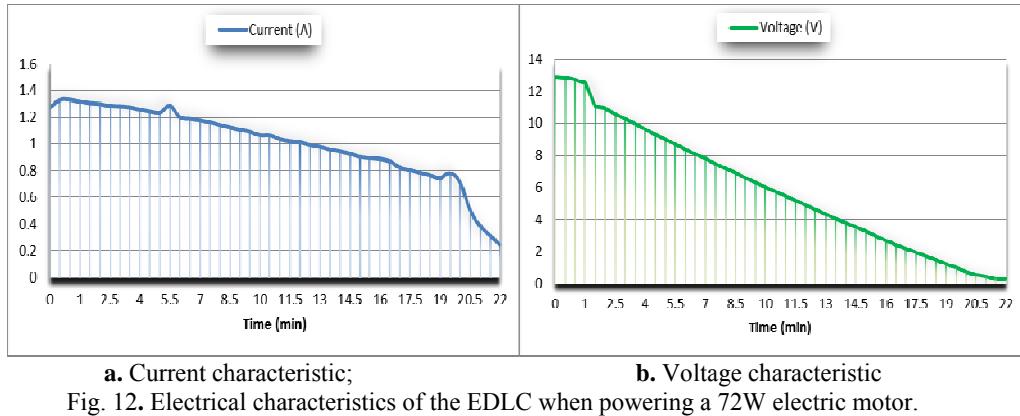


Fig. 12. Electrical characteristics of the EDLC when powering a 72W electric motor.

5. Conclusions

By combining the high power density of supercapacitors with the high energy density of batteries a hybrid electric system is obtained that can provide high power output when required, such as the start of an electric motor and keep power on through batteries for an extended period of time.

Experimental results have determined that the supercapacitors used for tests (600F at 12.5V) have increased the efficiency of the electric system when compared to using just a normal Li-Ion battery. A 72W electric motor was supplied with power from the supercapacitors for approximately 15 minutes before the Li-Ion battery had to provide power. With the EDLC battery pack as peak power unit, the main power supply system only needs to provide the average current of the load thus increasing lifecycle the of the batteries.

Supercapacitors ability for short-term storing of the deceleration energy and later transfer the recovered energy to the traction motor through the Power Switching Block reduces both the wear on the battery pack, extending application life cycle, and full recovery of the instant energy produced by the electric motor when braking. With the EDLC battery pack as peak power unit, the main power supply system only needs to provide the average current of the load thus increasing lifecycle the of the batteries.

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