Application of Supercapacitorsto Automotive Applications

Abdeladim A Gazwi

Abstract---The paper discuses the introduction of supercapacitors, also known as Electrochemical Double Layer Capacitor (EDLCs) in automotive application to improve the battery performance and extent its life span. The energy storage technologies such as lead-acid batteries and supercapacitors were presented. In order to investigate to what extent the performance of the battery can be improved; the battery was directly connected in parallel with supercapacitor modules, forming Direct Power Source (DPS). According to the energy audit of the application, two parallel connected of 15V, 52F supercapacitor modules BPAK0052B01 manufactured by the Maxwell Company were experimentally selected. The relative merits of the power source are also discussed.

Keywords--Automotive Application, Batteries,Experimental Methods, Power Source, Supercapacitors**.**

I. Introduction

ELECTRIC energy storage devices such as batteries and supercapacitors have a vital importance in a wide number of applications. These applications range from low power applications (Mobile phones, Laptops, etc.) to high power applications (Transportation, UPSs, Submarines, FACTS devices, etc.). One important area where there is immediate application is the automotive sector. These storage devices can be combined to form advanced power sources. Compared to power sources based on oil, the power sources based on these storage devices have a number of advantages in terms of environment, pollution, cost, availability, etc.

Supercapacitors are one of the advanced storage devices that have very high capacitance in a range of few up to thousands Farads. Compared with existing battery technologies, supercapacitors have higher power density, virtual unlimited cycle life and higher charge/discharge efficiency. However, the main disadvantage of supercapacitors is that their energy density is lower than batteries. Although, their advantages are more than their drawbacks, they need to be connected to an additional energy storage system such as a lead acid battery, forming Battery- Supercapacitor Power Source (BSPS).

In this paper, batteries and supercapacitors are investigated including their principles, characteristics, applications, etc. Particularly, the supercapacitors shall be used in automotive applications so as to find to what extent the performance of a 12 V lead-acid battery can be improved.

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II. Battery Technology

A battery is an electrochemical device which is used for the storage of electrical energy. This energy can be released or stored in the battery according to the electrochemical reactions between the active material of its electrodes and the solution. It consists of one or more electrochemical (galvanic) cells. Basically, a cell comprises two electrodes; electrolyte solution and a separator (see Fig. 1). The electrodes are made from different metals and divided into anode (positive) and cathode (negative) [1].

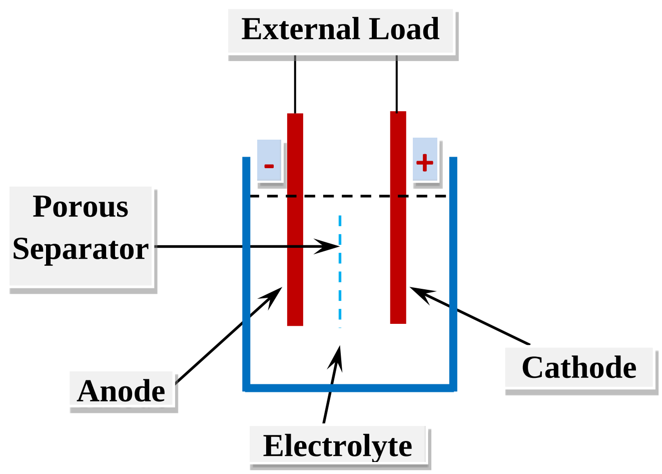


Fig.1An Electrochemical cell

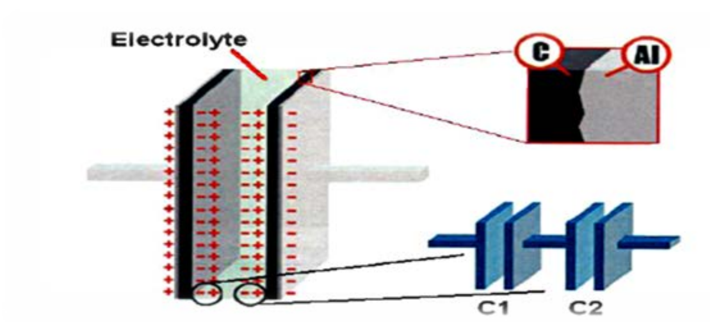
Typically, batteries are classified as rechargeable (secondary) or non-rechargeable (primary), where first type can be recharged but the second cannot be. When a battery is charged or discharged, electrical energy is stored or released respectively. When an electrical circuit is connected to a cell or a battery, an electrical closed loop is made allowing electrons, which are released due to the chemical reactions within the cell, to flow in the circuit, resulting in an electric current. The ions transport from the positive electrode to the negative electrode. Chemical reactions include two cases, reduction and oxidation. Reduction reactions take place between the attracted electrons and the active materials of the positive electrode causing the charge to flow through the electrolyte to the negative electrode [1]. This charge reacts with the active material of the negative electrode in oxidation reactions that donate extra electrons to the external circuit. Depending on the battery cycle life, the active materials of both electrodes become completely depleted after a period of time, as a consequence, the current stops flowing. In order to recharge the battery, the load needs to be replaced by a dc power supply (charger) to give current to the battery. Hence, the active materials can be restored by reversing the chemical reactions [1]-[2].

III. SUPERCAPACITOR TECHNOLOGY

Supercapacitors are also known as Electrochemical Double-Layer Capacitors (EDLCs), Electrochemical Capacitors (ECs), or Ultracapacitors. The EDLCs are electrochemical energy storage devices that are able to either store or release charge when they are charged or discharged respectively. The EDLCs can be used in a wide range of applications. EDLCs have a number of advantages over other energy storage devices in terms of the efficiency, power density, charging / discharging speed, range of operating temperature, cycle life and environmental issues [4]. However, their disadvantages are low rated terminal voltage and energy density. The name of Double or Dual Layer Capacitor is because the EDLCs can be considered as two traditional capacitors connected in series, where there is acapacitor between each electrode and the electrolyte as shown in Fig.2.

Fig.2Electric double-layer capacitor [3]

As stated previously, the energy storage devices such as lead-acid batteries and EDLCs have advantages and



disadvantages in terms of power density and energy density. Consequently, these energy storage technologies may need to be combined together, forming battery-supercapacitor power sources (BSPSs). In addition, if the battery isolates from severely high load current transients, its cycle life and performance may be improved [5]- [6]. This case may be done by connecting the load with the EDLCs in parallel while the battery is isolated from them through a current limiter or a switch mode converter (Fig. 4). Furthermore, it may be useful to distribute the load current between the battery and the EDLC by connecting them with the load directly in parallel as illustrated in Fig.3.

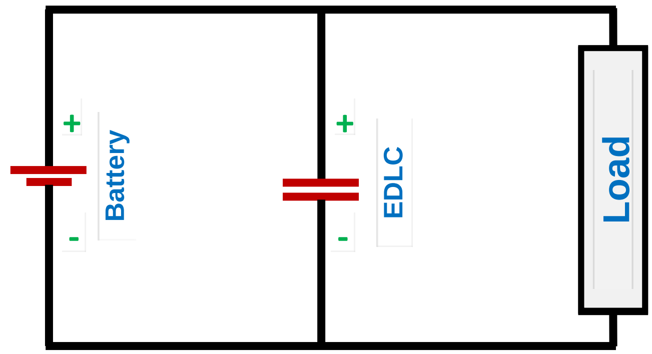


Fig. 3 The Direct Battery-supercapacitor power source (DBSPS)

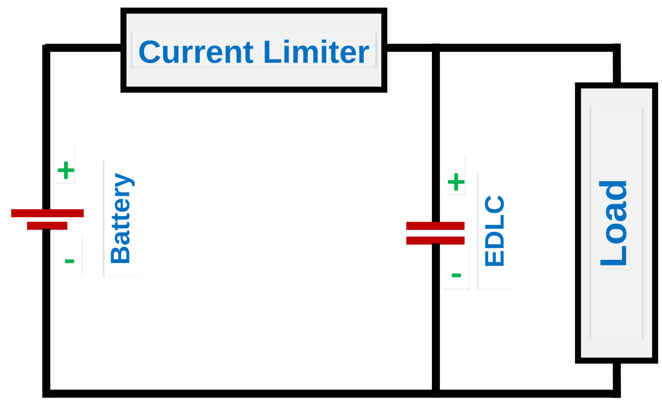


Fig. 4 The Indirect Battery-supercapacitor power source (IBSPS)

IV. SPECIFICATIONS OF EDLC MODULES FOR AUTOMOTIVE APPLICATIONS

In order to determine the specifications of EDLC modules, the starting current taken by the starter motor and the terminal voltage of the 12 V lead-acid battery need to be measured as shown in Figs. 5 and 6. Accordingly, the amount of energy delivered by the battery during starting up the engine can be calculated. The starting current and terminal battery voltage were measured and recorded five times using the PicoScope Oscilloscope as illustrated in Fig.7.

Fig. 5 Picture of testing the battery without the EDLC modules

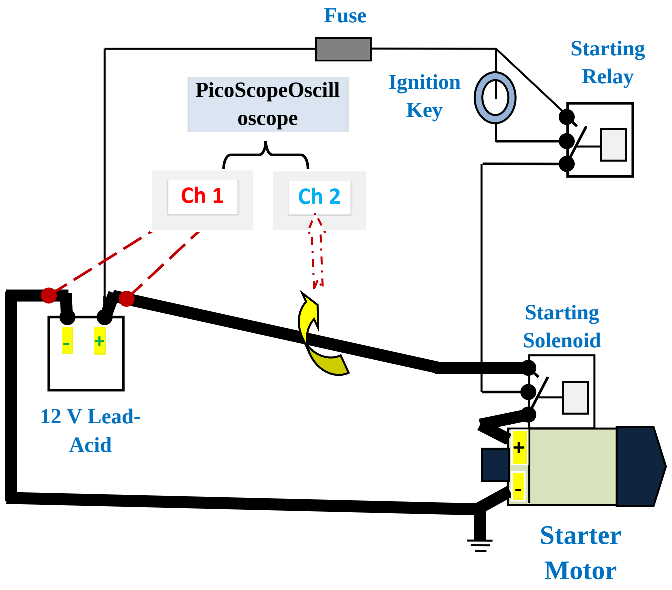


Fig. 6 Measuring the starting current and the battery voltage

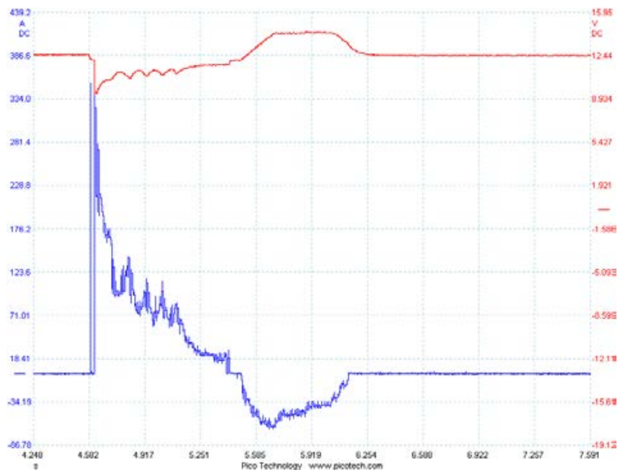


Fig. 7 PicoScope capature of starting current and terminal voltage waveforms of test 1

The voltage and current data was exported to excel and energy supplied by the battery was calculated by (1).

$$E = \int_0^t P(t)dt \approx \frac{\Delta}{2} * (p_0 + 2p_1 + 2p_2 + \cdots + 2p_{n-1} + p_n) \quad (1)$$

Where, "E" and "P" are the energy (in WS) and power (in W) delivered from the battery respectively, "t" is the starting period in seconds,"Δt" is the amount of increments and "P_o up to P_n" are the calculated power for every individual numerical value. The calculated energy values were tabulated for each test as shown in Table I.

TABLE I
THE CALCULATED ENERGY OF FIVE STARTING PERIODS

Test No.	Starting Period (s)	Energy (Ws)
Test 1	0.809045	720.79
Test 2	0.766303	705.93
Test 3	0.796833	762.82
Test 4	0.744932	721.74
Test 5	0.793781	762.59

For rating purposes let us assume that the EDLC should be able to cater for three operations without recharging. From Table I, a conservative figure for the energy required for one starting operation can be taken as 800 Ws. Therefore for three starting operations 2400 Ws is required. For initial experimental work, in order to have some spare capacity in had it was decided to take 3000 Ws as the rated energy of the EDLC.The energy stored in a capacitor is given by (2).

$$E = \frac{1}{2}CV^2 \quad (2)$$

Assuming a rated voltage of 12 V the above equation gives a capacitance value of 42 F. In addition, the EDLC must be able to withstand the maximum measured peak current of about 400 A. Additionally, the following specifications need to be taken into account:

1- maximum operating voltage,
2- maximum instantaneous peak current,
3- maximum continuous current,
4- Maximum short circuit current.

The existing Maxwell EDLC module"BPAK0052 P015 B01" has the following specifications:

1- capacitance = 52 F,
2- rated voltage = 15 V DC,
3- maximum instantaneous peak current (for 1 sec) 80 A,
4- maximum continuous current = 20 A,
5- Short circuit current is 1500 A.

The measured maximum instantaneous peak current is less than the rated value although the short circuit current is very high which can be considered as the rated maximum instantaneous peak current. However, for more safety it may recommend to connect two of the above modules in parallel, resulting in the rated specifications may be doubled.

V. TESTING THE BATTERY AND THE BATTERY-SUPERCAPACITOR POWER SOURCES (DBSPS & IBSPS)

In order to see the benefits and advantages of using the battery-supercapacitor power sources over only using a 12 V lead-acid battery in automotive applications, the power sources and battery were experimentally tested. The EDLCs were connected close to the starter motor and in parallel with it.

For each test, the engine cranked (not started up) for 10 seconds and stopped for 20 seconds. This test was regularly repeated many times until the battery became unable to crank the engine properly over 10 seconds. The tests are as follows:

- ✓ The first test is only for the battery (Fig. 6) including one test lead (Ch 1) for measuring the terminal voltage of the battery and one 600 A clamp meter (Ch 2) for measuring the starting current.
- ✓ The second test is for the direct battery-supercapacitor power source (Figs.8 and 9) including one test lead (Ch 1) for measuring the terminal voltage of the battery, one 600 A clamp meter (Ch 2) for measuring the current supplied by the battery and two 60 A clamp meters (Ch 3 & Ch 4) for measuring the current of the EDLCs.

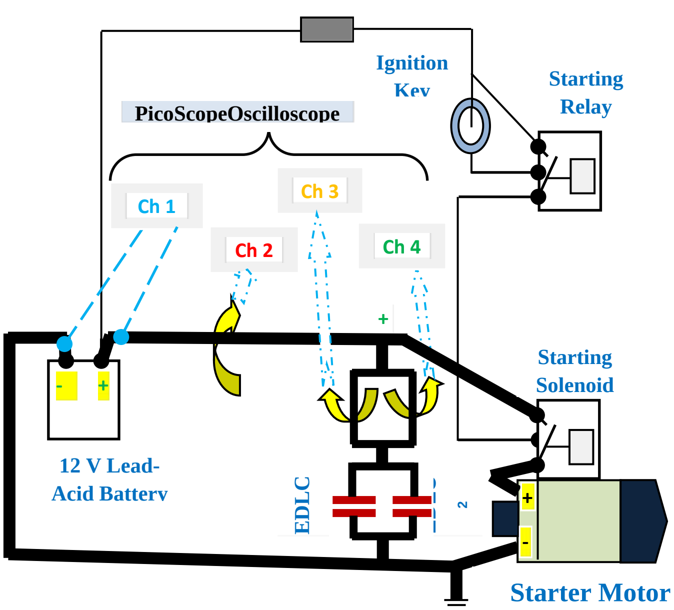


fig.8 Testing the Direct Battery-Supercapacitor Power Source (DBSPS)

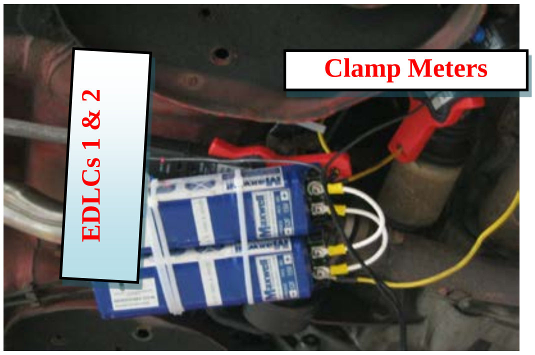


Fig.9 Picture of testing the Direct Battery-Supercapacitor Power Source (DBSPS)

Note: During testing, this clamp meter gave error readings because when the location of the clamp meters swapped, the same error occurred. Therefore, the reading of the other clamp meter will be multiplied by 2.

VI. Evaluation Of Using The EDLC Modules In Automotive Application

In order to evaluate the performance and the cycle life of the 12 V lead-acid battery, the battery with and without using the EDLC modules were experimentally tested. Accordingly, the results of the battery as illustrated in Fig. 10.

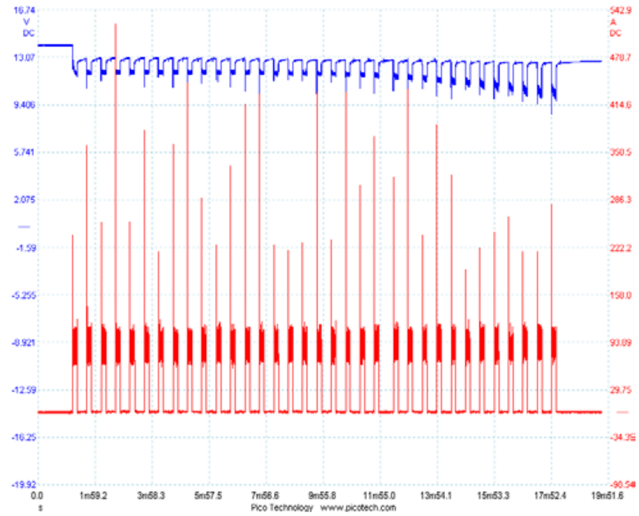


Fig. 10 PicoScope capature of the current and voltage waveforms of the battery without the EDLCs

After simplifying the waveforms illustrated in Fig. 10, the peak currents varied from about 200 A to 525 A during 34 cranks. However, the steady state current during the first crank (as a sample) varied from about 60 A to 120 A and its average was about 88 A. In addition, the instantaneous peak voltage of the battery dropped to 12.18 V during the first crank and it dropped to 8.68 V during the last crank.

Also, the results of the Battery-Supercapacitor Power Source (DBSPS) was evaluated according to the Picoscope capture of the waveforms of current and voltage of this test as shown in Fig. 11.

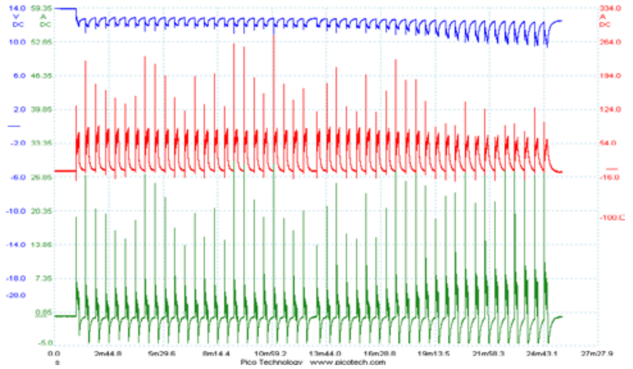


Fig. 11PicoScope capature of the current and voltage waveforms of the DBSPS

According to the waveforms shown in Fig. 11, the peak currents varied from about 68 A to 280 A during 47.The continuous current during the first crank (as a sample) varied from about 32 A to 87 A and its average was about 64 A. The load current was supplied by the battery and EDLCs but it was not equally shared. Finally, the instantaneous peak currents supplied by the EDLCs during 47 cranks were in the range of 30 A to 60 A and the continuous current varied from about 1.94 A to 7.95 A and its average was about 1.2 A.

The EDLCs supply current during cranking, therefore, when the engine is stopped, the EDLCs were recharged from the battery by instantaneous peak currents in the range of 7.15 A to 13.87 A. This means that the discharging current is more the charging current of the EDLCs, resulting in a parentage of the load current is supplied by the EDLCs. The peak voltage of the battery was 12.61 V during the first crank and it dropped to 9.79 V during the last crank.

VII. Battery Performance Evaluation

The performance and cycle life of the battery with and without the EDLCs are compared and evaluated in terms of the battery terminal voltage and the number of cranks provided by the battery. The instantaneous peak currents supplied by the battery when tested without the EDLCs were higher than the peak currents supplied by the battery with the EDLCs because the load current was distributed between the battery and the EDLCs. Consequently, the number of cranks increased from 34 to 47. Also, during the last crank, the battery voltage without the EDLCs dropped to 8.68 V, however, with the EDLCs it dropped to 9.79 V. It can also be noticed that the battery voltage with/without the EDLCs are different. This is due to the fact that the internal resistance of the battery without the EDLCs is higher than that of the battery-supercapacitor combination (DBSPS).

VIII. Conclusion

The performance and cycle life of the battery were improved by adding the EDLCs because the load current was distributed between the EDLCs and battery but without using the EDLCs, the entire load current was only taken from the battery. In other words, when the battery is not severely discharged, its performance can be improved. However, the main disadvantage of the DBSPS is that the current supplied by the EDLCs is relatively small compared with the current supplied by the battery, resulting in the performance of the battery still requires improvement. In order to overcome the disadvantage, it may also recommend connecting the battery and EDLC indirectly but using a switching mode converter to switch between these storage devices. .

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