Battery/Supercapacitor Combinations for Supplying Vehicle Electrical and Electronic Loads

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***Abstract*—In automotive vehicle, battery plays a vital role in starting /cranking vehicle engines. High power density is a key requirement for this service. The performance of lead acid battery is limited due to many factors such as number of charge-discharge cycles and temperature. The introduction of a supercapacitor supplying the high power density is expected not only to increase life of the battery but also to reduce its size, capacity and weight. In this paper, a switching technique with current limiter capability has been investigated to control the switching sequence between the battery and the introduced supercapacitor. This technique reduces the power density required by the battery as well as providing greater number of starts with lesser cracking time intervals. The starting/cranking power density has also been reduced employing the developed control technique. An efficient and more robust starting/cranking technique has been developed.**

***Index Terms*—automotive application, batteries, experimental work, switching circuit, supercapacitors, battery audit**

I. Introduction

Batteries and Supercapacitors are members of storage devices that play a vital role in wide verities of industrial applications. These applications used in low and high power applications starting from mobile phones and laptops to UPS and FACTS devices. These storage devices can be combined to form advanced power sources.

Although the two devices belong to the same family they have different performance characteristics. In battery technology, the battery can provide high energy density but limited cycle life and poor power density, whereas supercapacitor has high capacitance and provides high power density with virtual unlimited cycle life but low energy density. If these two devices are combined together they would form advanced power sources based on energy storage principles. One of the batteries applications which are wildly used is the power source of automotive vehicles. Where the battery must provide high discharge current (cranking current), which affects the battery life. A direct combination (parallel) of the lead acid battery and supercapacitor does not prevent or limit the high discharge current drawn from the battery but shared between the battery and supercapacitor, therefore, a switching converter may be used to provide switching mode between the supercapacitor/battery combinations so that the battery would provide a limited charging current to supercapacitor and as consequence, the supercapacitor would supply the cranking current. Eventually, this combination with switching converter may lead in reduction in battery size, capacity and prolongs its life cycle.

II. Battery Technology

A battery is a member of energy storage devices family which consists of a single or multi- cells. The cell (Fig. 1 and Fig. 2) is the unit where chemical reaction is taking place inside a battery, resulting in energy conversion from chemical to electrical energy. Every cell has three main parts: a positive electrode terminal (Anode), a negative electrode terminal (Cathode), and liquid or solid that separates electrodes from each other (electrolyte). When an external circuit (load) is connected to the battery, an electrical current will flow through the circuit due to chemical reaction causing positive charge (Ions) to flow in one direction and negative charge (Electrons) flow in the other direction through the external circuit. The movement of electrically charged particles causes an electrical current to flow through the cell and into the external circuit that is connected to the cell terminal. They are categorized as primary batteries which are non-rechargeable and secondary batteries which are chargeable.

Fig. 1 shows a simple single electrochemical cell. The chemical reaction is basically happen in the cell, which is the working unit that characterizes the battery.

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This reaction is divided into two parts. The first part is the release of electrons by the negative electrode (Anode), in other words oxidized, and the second part is accepting electrons by the positive electrode (Cathode), in other words oxidizing. This kind of electron immigrant causes flow of ions from one side to the other which forms the current that will supply the external circuit, hence the chemical reaction is directly converted to electrical current [1].

Fig. 2 illustrates the cell chemical reaction. The Anode and Cathode are normally immersed in the electrolyte that separates both electrodes. During the discharge, the oxidized substance is contained by the Anode (loss of electrons), whereas the oxidizing substance is contained by the Cathode (accepting electrons). As the battery is discharged, or generation of electrical current, the substance inside the cell is stat being consumed and till the point where is the cell won't be able to supply any current. To restore or replenish the substance to their origin, a direct current in reverse direction should be applied to the cell terminals, in other words charging. Therefore, batteries and their electrochemical cells are fallen into two categories according to their ability of being electrically charged [2]. They are categorized as primary batteries which are non-rechargeable and secondary batteries which are chargeable.

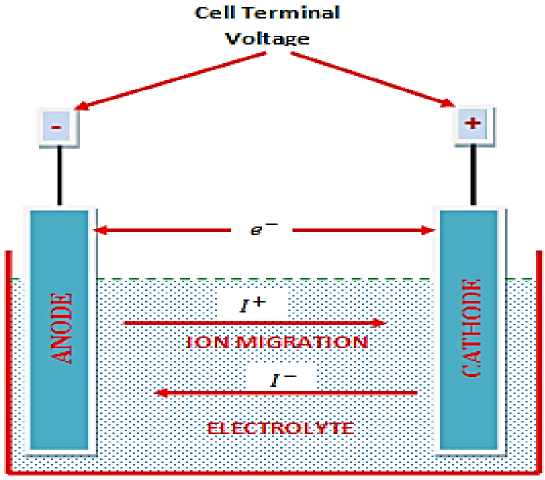

Figure 1. An electrochemical cell

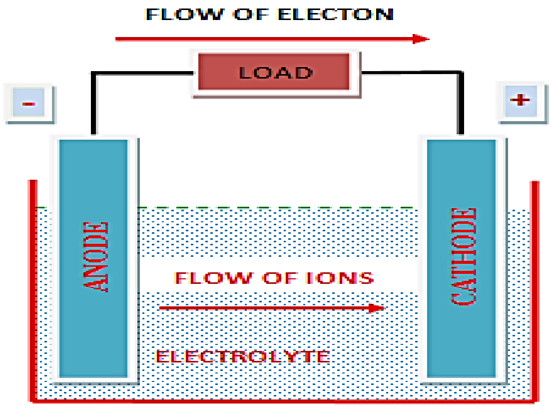

Figure 2. Cell chemical reaction

III. SUPERCAPACITOR TECHNOLOGY

Supercapacitor, also is known as Electrochemical Double-layer Capacitors (EDLC) or Ultracapacitor, is basically storage device that store and release electrical energy and is the same as conventional capacitor in terms of operational fundamental, however, the former one has high capacitance (up to 400 Farads in a single case size) compared to the latter one. In terms of construction, electrochemical double-layer capacitors are similar to the electrochemical cell; both are consist of two electrodes and separated by electrolyte. The former one is distinguished from the latter one on process of discharge/charge behavior.

The process in the electrochemical cell is accompanied by the exchange of electrons between electrodes and electrolyte which leads, as consequence, in changing cell components oxidation state, whereas, in electrochemical double-layer capacitors, the process is based on Faraday's Low and does not involve electronic exchange. This difference gives the electrochemical double-layer capacitors a lead over the electrochemical cell in terms of power densityand cycle life [1].

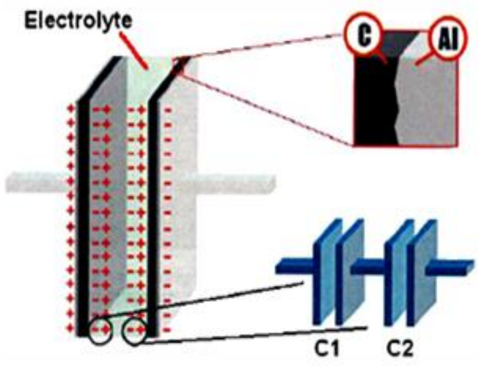

Figure 3. Electric double-layer capacitor [3]

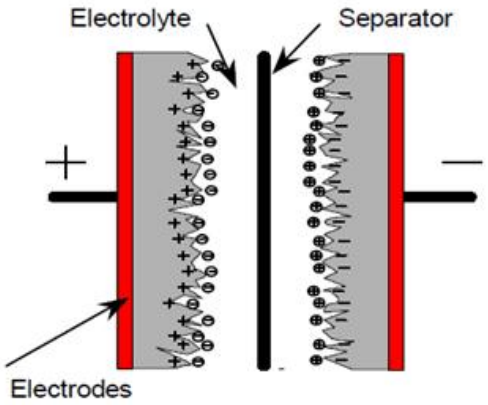

Figure 4. Inside view of EDLC [3]

The inside view of electrochemical double-layer capacitors can be expressed as two conventional capacitor connected in series as shown in Fig. 3. Supercapacitor is the same as conventional capacitor; however, the former differs from the conventional capacitor in electrodes material which is based on carbon technology. It consists of two electrodes immersed in electrolyte and separated by separator as indicated in Fig. 4.

In summary, batteries use chemical processes to store energy which can then be released as electricity. Supercapacitors on the other hand store energy through charge separation. This means that the need for chemicals is reduced, which enables a longer life length of supercapacitors [2].

The electrodes are made of conductive metal current collector quoted by activated carbon rough powder providing large specific surface area and small distance of about 10 Armstrong. The carbon powder is pressurized to increase conductivity and decrease the contact resistance between the powder and the metal collector. Since the capacitance of any capacitor is proportional to the area and inversely proportional to the distance, the carbon powder provides an electrodes area up to 3000m^2 per gram and hence maximizing the number of electrolyte ions absorbed and so is the capacitance which increases linearly up to 250F/g [4].

Supercapacitor electrolyte is a chemical liquid that containing ions or source of ions (charges). When applying voltage to the electrodes the electrical potential draws the ions into the activated carbon so that positively charged ions will be attracted to the negative electrode and the negatively charged ions are attracted to the positive electrode. The accumulation of the ions on both electrodes will form double layers inside activated carbon pores. The diameter of the ions and the size of activated carbon pores determine the double layer phenomena and hence the capacitance. Because the activated carbon is extremely pores material therefore, a very large number of ions can be absorbed into the electrodes of the capacitor resulting in high capacitance.

A separator is a barrier used as spacer between the electrodes to prevent electrodes short circuit. It blocks any electronic contact (short circuit) in the cell, but on the other hand, it allows ionic transfer between electrodes. The supercapacitor has a series of characteristics that influence and determine its performance. These factors are the capacitance, rated voltage, power and energy densities and finally its charge and discharge behaviors over the time.

IV. Experimental Work

A. Battery Audit

The battery audit is aimed to determine the energy required for cranking and to verify whether the energy needed to power the vehicle accessories is fed by the battery when the engine at idle speed and when it is accelerating. The battery is normally providing the starting current and supply the auxiliary load when the engine is in OFF state. The amount of energy consumed during the starting has to be determined for supercapacitor selection, rating and capacitance. The battery may contribute in supplying the auxiliary load when the engine at running state and accelerating state. The auxiliary load is representing all car accessories such as Front dipped beam headlamps, Front main beam headlamps, Stop lights-side lamps, etc. For battery audit, the following tests have been carried out:

1) Starting current (cranking current)

This is the current required to crank the automotive engine and supplied by the battery. The current is very large and rapidly fluctuated due to the compression of gas in the engine cylinders. Fig. 5 shows a recoded current and voltage fluctuation during cranking carried on a 4 cylinders old car by using Oscillograph. The graph is read from right to left according to the author. The top scale represents the time. The voltage curve comes next below to the time scale and shows fluctuation in battery terminal voltage. The next is the cranking current and fluctuates due to compression. The current ranges from more than 100A to more than 250A [4]. The lubricant oil viscosity plays role in minimizing the friction during the cranking and running and it increases with decrease of the temperature. The cranking current is proportional to the required torque to overcome the friction and the engine start. The latter completely depends on the oil viscosity [5]. Fig. 6 is much accurate graph than the Oscillograph but share the same results [6].

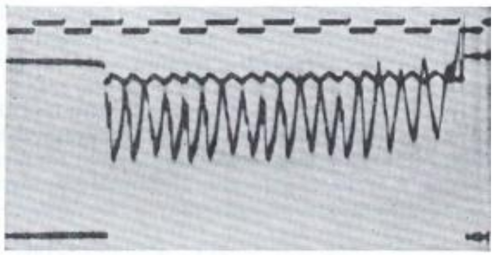

Figure 5. Oscillograph current and voltage waveform [5]

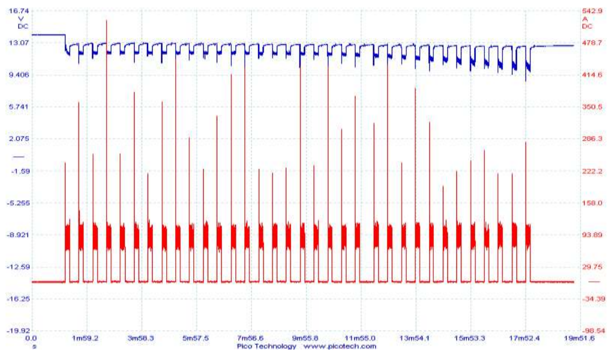

Figure 6. Current and voltage waveforms during cranking [6]

The graph obtained by Pico-Scope. It shows the same current and voltage fluctuation during cranking. The graph indicates that the instantaneous peak current fluctuate from about 500A to about 200A over a number of repeated cranking. On the other hand, the steady state peak current swings between about 80A to about 100A over every crank. Therefore, those two cases must be taking in consideration in selection and rating the supercapacitor.

2) Battery auxiliary load evaluation

The auxiliary load is all electrical loads in the car that forms an essential part of the car such as ignition circuit, main and dipped beam lighting, horn, direction signals and stop lights….etc.

It is obvious that every vehicle is equipped with an alternator, which normally big enough to supply all auxiliary loads plus charging the battery. However, the power generated by the alternator is governed by the engine revolutions, which on the other hand is governed by the acceleration of the engine. As the engine accelerates the alternator cycles increase and hence more power would be generated. However, the situation may different when the vehicle at stall or running at idle speed (not accelerating). The following tests are run to verify how the auxiliary loads are supplied during engine OFF, engine ON (idle speed) and engine accelerating.

3) OFF engine test

The test is to determine the current supplied by the battery when the engine is in off state. The car accessory loads were switched on step by step starting from the fuel pump and ending to the hazard indicator signals. Then the same sequence repeated in switching off the car accessory loads, hence the graph indicated in Fig. 7 was obtained. The maximum peak current is 52.5Amps (Red curve) and the battery terminal voltage (Goldenrod curve) dropped from 12.51V to 11.48V. The battery terminal voltage started to decrease when the load current at 7.74Amps and as the load switched on one by one the battery terminal voltage continues to drop till the point where the load current at its maximum peak.

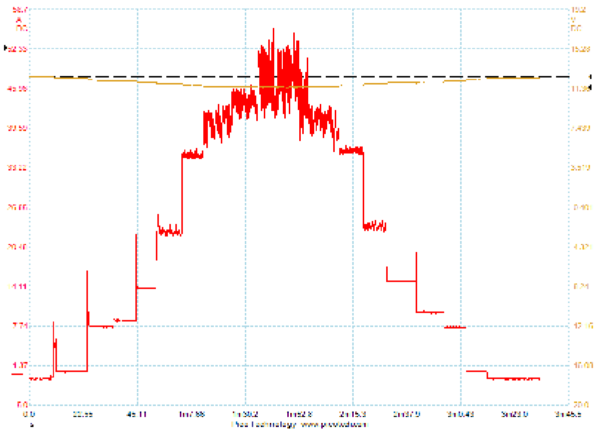

Figure 7. Car accessory current and batter voltage graphs (OFF engine)

The fluctuation in the load current at the peak is due to the changeable load such as fan, hazard signals and screen wiper. As the load current switched off one by one, the battery terminal voltage start to recover.

4) Engine running test (idle speed)

As the engine started on and run at idle speed the alternator starts to provide current to supply car accessory loads as well as the charging current, however, the alternator generates power proportional to the engine revolution. However when car accessory loads gradually switched on. The charging current starts to decline towards negative region. When the load reaches its maximum current, the battery current changes its state to negative, which means, the battery is now contributing in supplying load and hence changed its state from being receiving charging current to partially supplying the load current.

As it can be seen from Fig. 8, the load current supplied by the alternator (Blue curve) has been risen to about 58Ampswhen all loads were switched on. The battery charging current (Red curve) has switched direction from charging current of about 15 Amps supplied by the alternator to discharging current of about -4Amps supplied by the battery.On the other hand, the voltage bus (Goldenrod curve) rises from about 12.5V (battery terminal voltage) to about 14.3V (alternator terminal voltage) and as consequences, the load current goes up almost 58Amps compared to OFF engine test (52.5Amps).

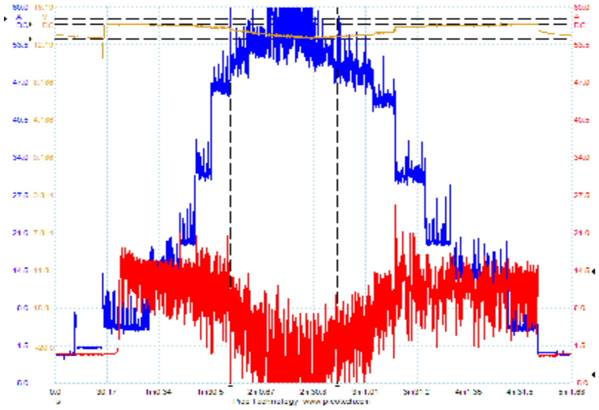

Figure 8. Car accessory current and batter voltage graphs (idle speed)

5) Engine accelerating test

While all the car accessory loads are ON, the engine accelerated up, the load current that has been shared between the battery and the alternator is now supplied by the alternator only and moreover and the battery changed states from contributing in supplying the loads to being receiving charging current from the alternator as it is shown in Fig. 9. The car accessory loads supplied by the alternator indicated by Red Graph, the charging current indicated by Green Graph and the battery voltage indicated by Goldenrod Graph.

Figure 9. Car accessory current and batter voltage graphs (engine accelerating)

The bus voltage declined from about 14V to almost 12.8V when the engine at idle speed and the load current at its peak and the battery partially supplying the load. However, when the engine accelerated the bus voltage raised to almost 14V and the alternator is now able to supply the load current along to the battery charging current.

6) Evaluation of battery audit

The tests carried above indicate that the battery does contribute in supplying the auxiliary (5A maximum) load under one condition that the auxiliary load is at its peak or is switched on towards its peak during the engine at idle speed. Because the engine was at idle speed, which on the other hand, drive the alternator which its out power depends on the engine RPM (Revaluation Per Minute), hence the battery has to compensate the lack of power demanded by the load. As the engine accelerates the RPM increases and so the alternator output power enable the alternator to supply the load demand plus battery charging current.

7) Cracking energy consumption

The energy needed for cranking and starting the engine was calculated from six starting times where the voltage and the current were recorded and exported to Excel software. The energy required per each start is calculated by applying Simpson's rule as following:

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

where, (E) the energy delivered by the battery and P is the product of the cranking current and battery terminal voltage. (t) is the starting time in seconds and (Δt) is the time increments. (P_O to P_n) is the power calculated per time increments.

The calculated energy values are shown for each test in Table I. From Table I, the energy required for every start ranges from 705.93Ws to 762.82Ws so 800 Ws can be considered as the energy required for every start [6].

TABLE I. THE CALCULATED ENERGY OF FIVE STARTING PERIODS [6]

Number of Tests	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

B. Implementation of Supercapacitor

In order to select the appropriate supercapacitor modules, the Supercapacitors specifications and rating requirements have been calculatedaccording to the recorded data indicated in Table I, 800 Ws was considered to be the energy required for every single start. To provide three starts, the energy required is 2400Ws so 3000Ws was selected as safety margin, and for battery terminal voltage of 12V, two supercapacitor modules (BMOD0058 E016 B02) in parallel were selected, forming 104 F, avoiding any damage that may happen during supply the energy required by the starter motor [6].

1) Supercapacitor cranking current

The supercapacitor was externally charged to 12.5Vand then the load was connected to supercapacitor instead of the battery. By turning on the ignition key, the supercapacitor is connected to cranking motor throughout the solenoid. Fig. 10 shows four starts provided by supercapacitor. In the first start, the supercapacitor supplied cranking current of 132A then the engine fire up within 516ms. After that the alternator charged the supercapacitor to alternator output voltage of 14V.

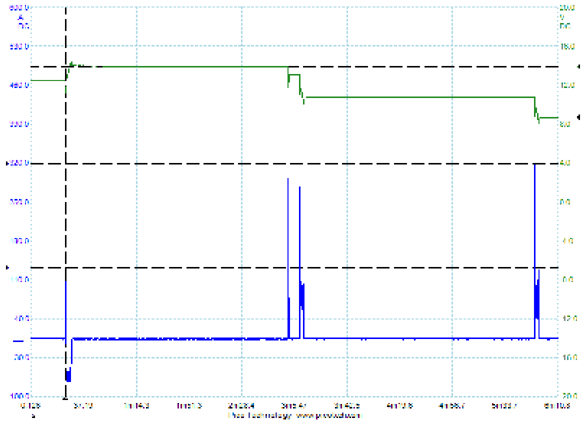

Figure 10. Supercapacitor supplying cranking current

2) Evaluation of Direct Battery/Supercapacitor Combination

A fully charged battery was providing 34 starts then fall into discharge zone where the battery unable to supply the cranking energy and has to be charged. With the supercapacitor taking place in parallel with the battery, the cranking energy was shared but not equally shared. However, there was slight improve in battery performance where the number of starts has increased by 41% with respect to the number of starts provided by the battery alone [6].

C. Developing Switching Circuit

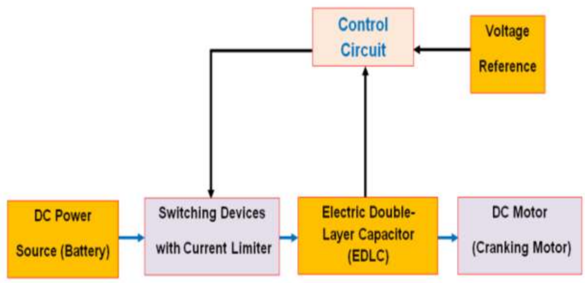

Figure 11. Switching circuit block diagram

For experimental purposes, a switching circuit to switch between the supercapacitor and the battery is needed. A block diagram is shown in Fig. 11. The DC power source, which is lead acid battery, is supplying the supercapacitor (EDLC) charging current through switching circuit with limitation of the initial charging current. Then the supercapacitor will power the Starter motor (Cranking motor). The control circuit is the device responsible to switch between the battery and supercapacitor. Assuming the initial charge of the supercapacitor is zero, the control circuit will sense zerovoltage across supercapacitor terminal and send a signal to the switching device to switch on and start charging the supercapacitor.On the other hand, it sends a signal to prohibit any start during the supercapacitor charge.

Once the supercapacitor is fully charged, the control circuit will disconnect the supercapacitor fromthe battery and connect the startermotor to the supercapacitor. After a while, the supercapacitor terminal voltage will drop to pre-determined low set point and disconnect the starter motor and reconnect the battery till the supercapacitor terminal voltage reaches the pre-determined high set point.

D. Supercapacitor Initial Charging Current Limiting Circuit

The initial charging current for zero charged and 94% charged supercapacitor is very high. This current has to be limited in some way. There are different methods in limiting the initial current by using power semiconductor devices such as power metal oxide-semiconductor field-effect transistor (MOSFET), power bipolar junction transistor (BJT) and power resistor.

E. Voltage Monitor Circuit

The supercapacitor terminal voltage gradually drops when load is connected across its terminal as it gets discharged. At certain point, the supercapacitor won't be able to drive the starter motor (cranking motor) and its terminal voltage drops down to or below the starter motor cut-off voltage. Due to this drop in voltage, the supercapacitor needs to be monitored during the whole period of testing. Therefore a simple voltage monitoring circuit was developed as shown in Fig. 12.

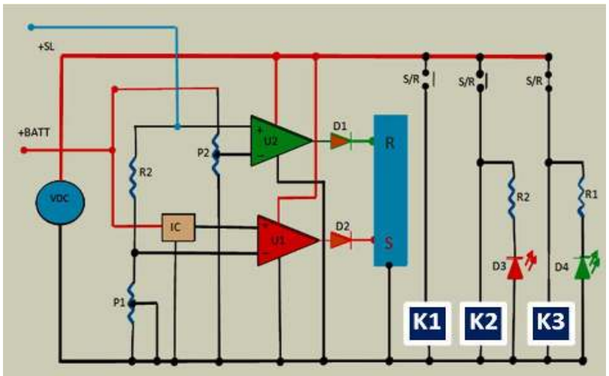

Figure 12. Voltage monitoring circuit

1) Switching circuit/current limiter coupling and testing

The voltage monitor circuit is combined with Initial current limiter circuit to represent final testing circuit but with variable power resistive load of 8.5Ω and 8.5A. A12V 24 AH (V_{BATT}) is used as well as external DC power supply (V_{DC}). The circuit in Fig. 13 shows final switching circuit with resistive load. The circuit is powered by switching on the DC power supply. The state of the supercapacitor charge is zero. PICO-Scope channels are distributed in the circuit to measure supercapacitor charge and discharge current (CH A, Blue color), supercapacitor voltage (CH B, Green color), S/R set signal (CH C, Goldenrodcolor).

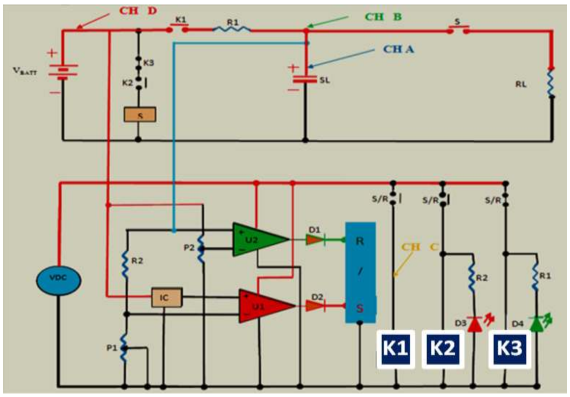

Figure 13. Switching circuit with resistive load

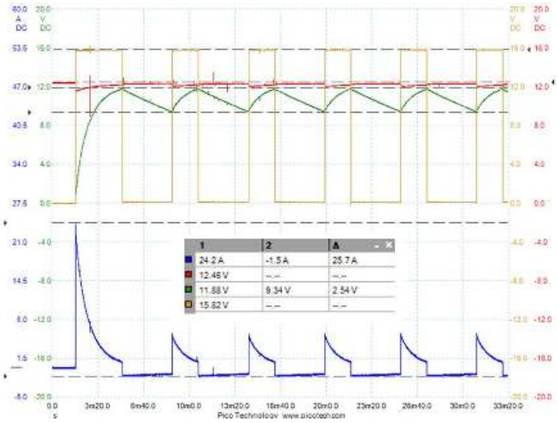

Figure 14. Current and voltage parameters of The battery and supercapacitor

When the circuit was powered, the PICO-Scope recorded the current and voltage characteristics of the battery and supercapacitor over a period of time as shown in Fig. 14. The supercapacitor starts charging from 0V to 11.88V (Goldenrod Greencolor) when the charging signal goes high (Goldenrod color) with the initial charging current being limited to about 24A (Blue color). The battery voltage drops to about 11.5V (Red color) then start to recover as the supercapacitor gets charged. When the supercapacitor reaches 11.88V, the voltage monitor circuit switches to discharge mode and the charging signal (Goldenrod color) goes low disconnecting the supercapacitor from the battery and connecting it to the load (RL).

The supercapacitor voltage start decaying over period of time till it reaches 9.34V (cut-off voltage) then the voltage monitor circuit switches to charging mode and isolates the load from the supercapacitor. The sequence continuous automatically for the rest of the test. This means that the circuit is functioning probably and ready for the main experimental test.

F. Implementation of Switching Circuit on Automotive Vehicle

The resistive load has been removed from the circuit shown in Fig. 15 and the starter motor (M) has been connected instead. The engine was disabled from fire up during the test for testing purposes as well as the car accessory load. The positive lead of the starter motor (M) is connected to the positive pole of the supercapacitor throughout the solenoid switch (S). The ignition key is also disabled and its function is now carried by the relays (K2 and K3) which can start cranking automatically.

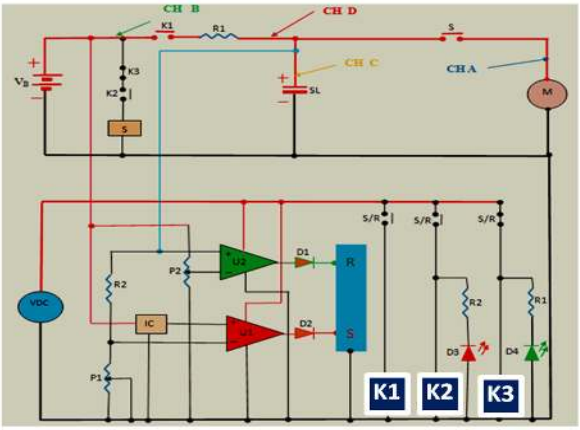

Figure 15. Switching circuit with starter motor in place

The PICO-Scope channels are distributed to measure and record the starting current (CH A, blue color), supercapacitor voltage (CH C, Goldenrod color), battery terminal voltage (CH B, green color) and finally battery current or supercapacitor charging current (CH D, red color).

The circuit is run and stopped by turning on and off theexternal DC power source (VDC). The test shall continuous automatically till the battery completely discharged. The first test carried by using the car original battery of 44AH then 24AH for the second test.

1) 44AH battery

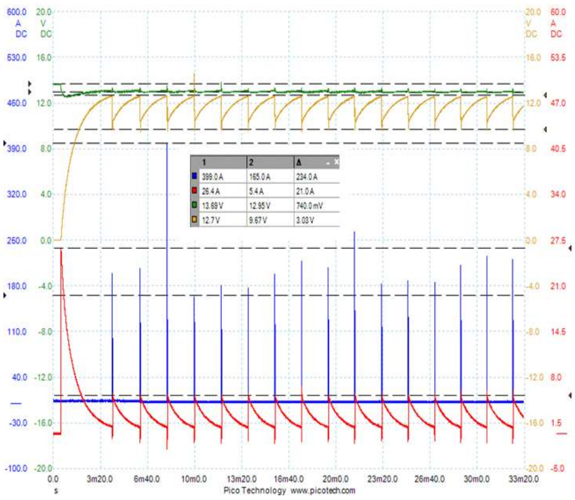

Figure 16. 44 AH battery test 1 (current and voltage parameters)

Starting with car original battery of 44AH with terminal voltage of 13.69V (battery fully charged) and the solenoid is being connected to supercapacitor so that no current will be drawn from the battery apart from the charging current, the Pico-Scope recorded seven pages of current and voltage parameters of the battery and the supercapacitor. The switching circuit detected 0V on the supercapacitor terminal and triggered the circuit to switch to charging mode then the supercapacitor voltage start rising exponentially from 0V to 12.7V. Fig. 16 and Fig. 17 show test 1 and 7 respectively.

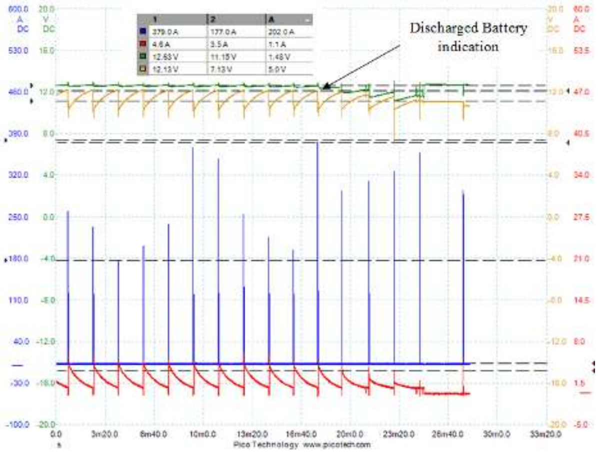

Figure 17. 44 AH battery test 7 (current and voltage parameters)

The battery voltage dropped down from 13.69V to about 12.5V then recover to 13.03Vas its delivering the supercapacitor initial charging current of 26.4A peak. This current decays exponentially with respect to the time as the supercapacitor charges up. However, the supercapacitor charging current will peak at 5A for the rest of the test as it partially discharged. When the supercapacitor reached 12.7V, the switching circuit switches to discharge mode through the starter motor and the motor start cranking over a period of time till supercapacitor voltage drops down to 9.67V (cut-off voltage) as shown in Fig. 16. The highest starter current recorded in page one was 399A whereas the lowest was 165A.The sequence of charge and discharge continuous automatically with the fall and rise of supercapacitor voltage. The number of starts recorded is 16 starts.

Six more tests have been carried out until the battery became unable to fully charge the supercapacitors modules, see Table II.

TABLE II. THE RECORDED DATA OF 44AH BATTERY-SUPERCAPACITOR COMBINATIONS

Test No.	Starter Current (A)		Battery Terminal Voltage (V)	EDLC Terminal Voltage (V)	EDLC Cut-off Voltage (V)	No. of starts
	L	H				
02	183	386	13.03	12.54	9.67	18
03	152	418	13.03	12.46	9.75	19
04	185	398	12.87	12.46	9.75	19
05	171	405	12.38	12.38	9.75	19
06	184	392	12.62	12.3	9.75	20
07	177	379	11.15	12.13	9.75	12

2) 24AH battery

The vehicle original battery 44AH is now replaced by smaller lead acid battery of 24AH. Due to battery capacity dropped almost by half which affects the energy stored in the supercapacitor, therefore the switching circuit in Fig. 15 is modified so that the solenoid current is now driven by the battery instead as shown in Fig. 18. The PICO-Scope channels distribution remains the same. The battery terminal voltage is 12.46V (battery fully charged) at the beginning of the test. Four more tests have been carried out and tabulated in Table III.

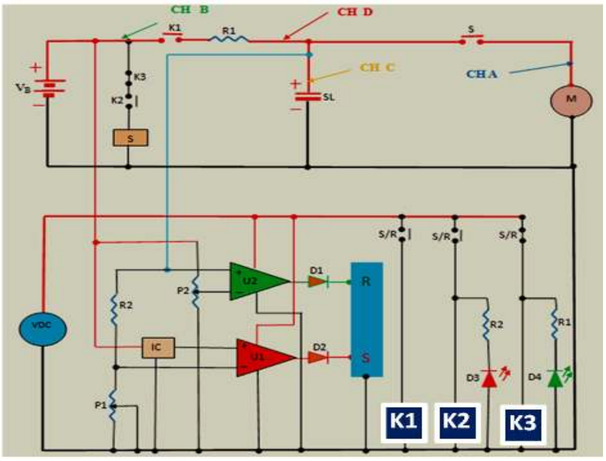

Figure 18. Switching circuit with starter motor in place (24AH battery)

TABLE III. THE RECORDED DATA OF 24AH BATTERY-SUPERCAPACITOR COMBINATIONS

Test No.	Starter Current (A)		Battery Terminal Voltage (V)	EDLC Terminal Voltage (V)	EDLC Cut-off Voltage (V)	No. of starts
	L	H				
02	398	180	12.38V	11.89V	9.83	21
03	388	171	12.2	11.86	9.75	18
04	367	165	12.12	11.78	9.83	17
05	382	183	11.95	11.61	9.24	9

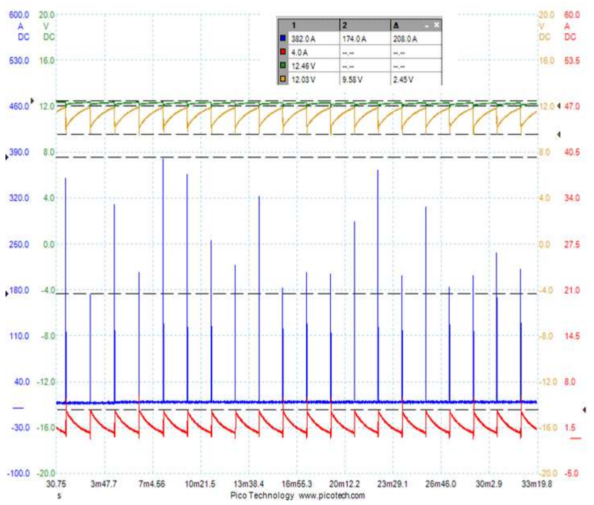

Figure 19. 24 AH battery test 1 (current and voltage parameters)

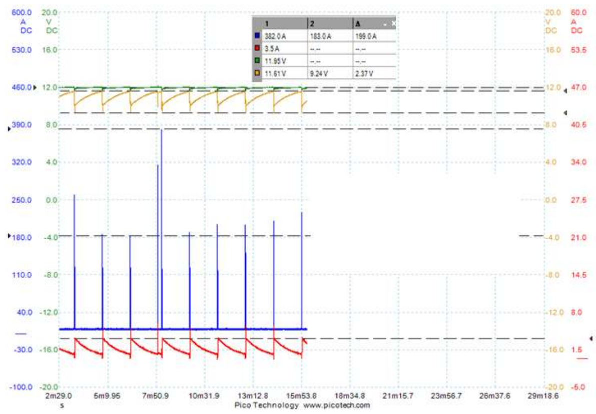

Figure 20. 24 AH battery test 5 (current and voltage parameters)

Starting with first test, the battery delivered charging current to top-up the partially charged supercapacitor to 12.03V at charging current of 4A peak, as shown in Fig. 19. At voltage level the switching circuit switches from charging mode to discharging mode (cranking). During the first cranking, the supercapacitor voltage drops to 9.58V (cut-off voltage).The sequence shall carry on automatically till the battery become unable to deliver enough energy to supercapacitor. Fig. 19 and Fig. 20 show test 1 and 5 respectively.

V. EVALUATION OF BATTERY/SUPERCAPACITOR COMBINATION

The cranking current fluctuated from 382A peak to 174A peak over of the number of starts in the fifth test. The number of starts achieved in the first test is 20 starts. Four more tests have been carried and recorded, see Table III. To evaluate the results obtained, five highest peak cranking current of each test are averaged. This covers previous results from previous work of battery supplying cranking current and direct battery/supercapacitor combination along with results obtained from battery/ supercapacitor switching. The results are tabulated in Table IV.As indicated in Table IV, the battery being the only supply of cranking current provided number of starts of 34 starts. This number of starts is a reference for the number of starts achieved over direct battery/supercapacitor combination (44AH//SL) and battery/supercapacitor switching combination (44AH/SL). The average peak cranking current was 441A in case of battery only. However, with a supercapacitor being directly connected to the battery, the number of starts improved by 41% (with respect to the only battery number starts) and the average peak cranking current fallen down to 242A.

TABLE IV. NUMBER OF STARTS AND AVERAGE PEAK CRANKING IN EACH COMBINATION

	44AH	44AH//SL	44AH/SL	24AH/SL
Batt. I_{av} (A)	441	242	5	4
SL I_{av} (A)	0	58	400	383
NOS	34	48	123	86

In case of 44AH with switching circuit, the number of starts increased by 261% (with respect to the only battery number starts). The average peak cranking current is 5A. Unlike the direct battery/supercapacitor (44AH//SL), the cranking current was totally supplied by the supercapacitor.

Finally, when 44AH battery replaced with 24AH battery, it has indicated improvement on the number of starts by 155% (with respect to the only battery number starts). The average peak cranking current supplied by the batter was 4A. Fig. 21 illustrates the number of starts achieved and the average peak cranking current in each case. When considering the cranking period, the time interval taken during cranking to fire up the engine was 930ms in case of the only battery supplying cranking current. However, the time taking for engine to cranks and fires up is shorter with period of 540ms with cranking current being supplied by the supercapacitor only.

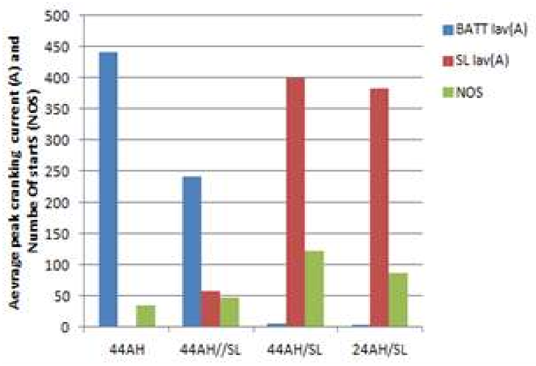

Figure 21. Average peak cranking current and number of starts over each case

VI. Conclusion

In conclusion, the energy stored and released in electrochemical cell is based on exchange of electrons. Furthermore, the energy and power densities provided by an electrochemical cell are determined by a number of factors such as size and temperature. The life cycle is inversely proportional to the number of charge and discharge. A long time is time is required in charging electrochemical cell. The supercapacitor is advanced storage technique based on Faraday's low where the charges are physically stored. It has high capacitance and a virtually charge-discharge cycle. Moreover, it requires short charging time and able to deliver high power density but lower energy density than electrochemical cell. Furthermore, the life cycle is unlimited and the operating temperature range is very wide. The battery audit showed that the alternator takes over in supplying vehicle's accessory loads after the engine is ignited. Moreover, the battery contribution in supplying the case of engine at idle speed and all loads are ON. The capability of the alternator increases as the engine accelerates providing enough power tovehicle's accessory loads as well as battery charging current. The 104 F supercapacitor initial charging current is considerably high at fully and partially discharged. The power resistor provided a limit to the initial charging current but does not maintain a constant current. The voltage monitor circuit provides a monitoring window on the supercapacitor terminal voltage and control the switching between the battery and supercapacitor. Furthermore, it runs automatic engine ignition.

The results obtained from implementing the switching technique between the battery and supercapacitor has resulted in elimination of starting/cranking current and reduction of battery capacity by 46% which on the other hand, leads to reduction of battery size and weight. Furthermore, the starting/cranking time interval has improved as well as the life cycle of the battery. The number of starts achieved from 24AH/SL is greater than the required number of starts by 2.5 times. The battery contribution was 10% (5A) in supplying the vehicle's accessory load. This indicates that the capacity of the 24AH can be reduced further down so is the size and weight.

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