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# Integration of Ultra-Capacitor and Battery as Hybrid Energy Storage with Intelligent Controller for Effecient Electric Vehicle Application

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**ABSTRACT**

In this paper a novel combination of Ultra-Capacitor, Battery and Intelligent Controller are presented and its application for electric vehicle is highlighted. The proposed system has significant findings through its ability to supply power to load with good saving. By using an intelligent controller, at the start of the system, priority for the ultra-capacitor is set and it gives a burst of power, providing maximum current to the load. In addition, by using the tremendous property of an ultra-capacitor, fast current draining from the battery is rectified which makes the battery discharge quickly and improve battery life. Finally, the proposed system is applied in the future hybrid vehicle which will contribute to energy saving, green environment and a step toward the power and efficiency.

***Keywords:*** Ultra-Capacitor; Battery; Intelligent Controller; Electric Vehicle

## 1. INTRODUCTION

The hybrid electric vehicle is a vehicle that uses more than one types of energy in a system to run the load. Research on hybrid electric vehicles (HEV) began in 1970s after the first crisis of oil, but declined in the 1980s [1]. In 1997, with increasing concern about air quality and energy security of HEV was first launched in the Japanese market as the Toyota Prius. Since then, automotive makers in the United States have also begun to manufacture the HEV. Now, several countries are competing to lead HEV and development of electric vehicles, including Brazil and China [2].

Rapid deployments of hybrid system in electric vehicle are limited by high life cycle cost. The main contributor to the high life cost is the battery bank, which is used to store energy and delivers power to the load. All combinations regardless of their arrangement of circuitry either in series or parallel arrangement, they have limitations in terms of maximum power and energy density, charging and discharging time of the battery, maximum range of currents and voltages and regenerative braking power management [3]. However, in most cases battery is used as the primary power source, where the battery has to operate in conditions that it is not designed for. For example, it is often operates in deep-discharged and overcharged states where continuous exposure to the rapid charge/discharge profiles will degrade the performance of the battery and reduce its lifetime [4,5]. The reduced battery lifetime leads to frequent replacement, thereby increasing the overall life cycle costs. Apart from that, due to limited energy capacity of battery, as the power demand increases, the batteries need to be oversized for high power applications. And thus, creates problem for space constrained applications when high discharge rate, the battery lifetime is reduced significantly.

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Studies have shown that ultra-capacitor could generate much higher power densities and thus make it a candidate to improve the traditional battery systems [6,7]. Ultra-capacitor and battery parallel configuration has mainly been considered by the automotive industry for hybrid electric Vehicle (HEV) and electric Vehicle (EV) because of its potential in reducing the size and volume of the overall hybrid electrical system. The usage of ultra-capacitor also decreases the current load on battery system thereby it may improve the battery lifetime [8,9]. Due to the advantage, further investigation on the battery-ultra-capacitor configurations for hybrid electrical vehicle (HEV) application is highly needed to improve power efficiency and management in the system.

In this work, a design of an electrical system for the hybrid electrical vehicle applications, which can improve power and energy density, enhance usage of power range and efficiency and utilize regenerative breaking is presented. The proposed system, which is used to empower motor of an electrical vehicle, consists of lithium-ion battery and ultra-capacitor with improved circuit arrangement, built-in intelligence for power source selection and power management of regenerative braking power. The proposed system is expected to improve the maximum power and energy density, and maximum range of currents and voltages. Thus, the usage of the ultra-capacitor will enhance the peak power of the energy storage system, reduce internal losses and extend the discharge life of battery.

## 2. GENERAL ARCHITECTURE

Figure 1 gives the overview of the proposed system. The system consists of motor which serves as a load to the system; The DC to DC converters consists of inverter plus rectifier arrangement acts as current boost converters; Voltage sensor module is designed in the system to sense the voltage across ultra-capacitor and it is fed into PIC microcontroller to control the selection of the power sources being supplied to the load during its operation. Relays are used in the circuit for switching and controlling the power flow direction. The relay conditions during the start of operation are shown in Table 1 below

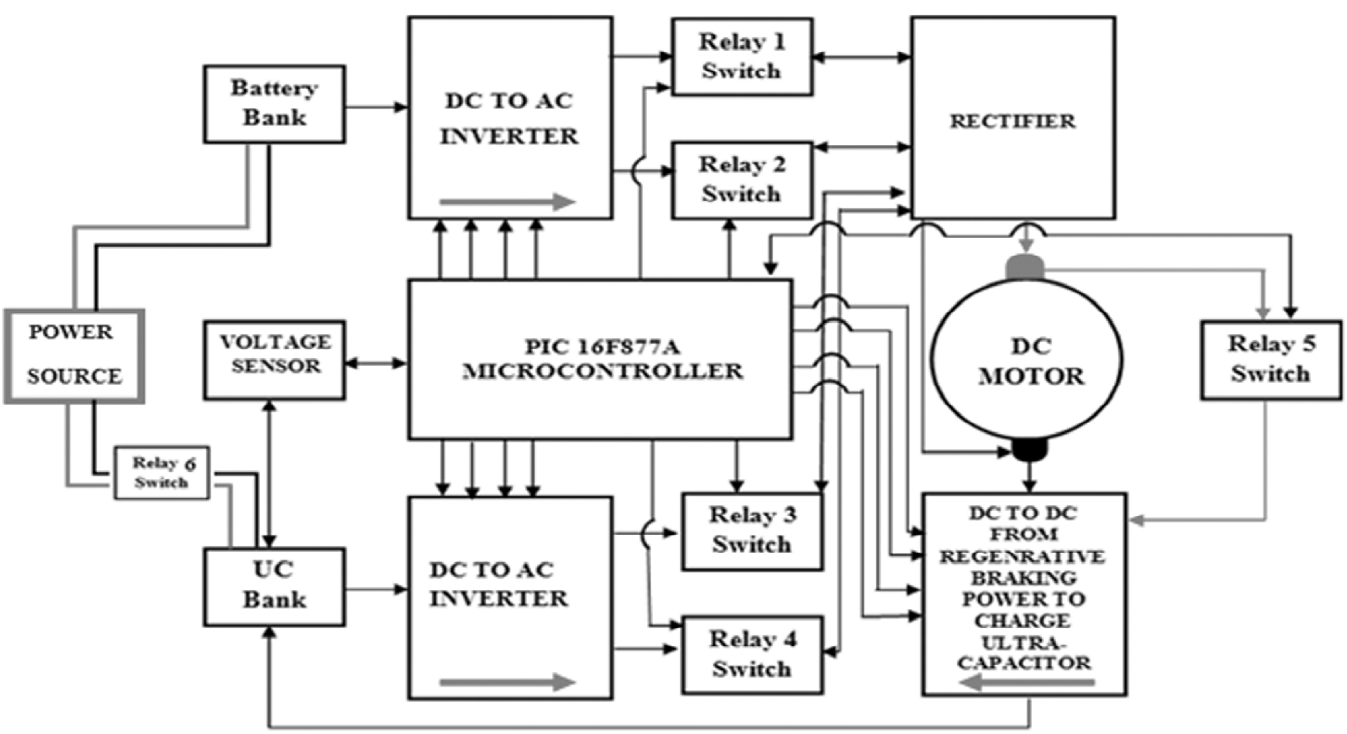



**Figure 1: Block diagram system showing the overall circuit design (red colour shows the direction of power)**

**Table 1**
**Relay conditions set at begging of the system operation**

| *Relays* | *Ultra-capacitor Charging* | *Battery Power Supply to Load* | *Ultra-capacitor Power Supply to Load* | *Regenerative Braking Power for Charging Ultra-capacitor* |
|---|---|---|---|---|
| Relay 1 | ON | ON | OFF | OFF |
| Relay 2 | ON | ON | OFF | OFF |
| Relay 3 | OFF | OFF | ON | OFF |
| Relay 4 | OFF | OFF | ON | OFF |
| Relay 5 | OFF | OFF | OFF | ON |
| Relay 6 | ON | ON | OFF | ON |

The system consists of 12V, 5A battery and ultra-capacitor, which can also produce the same ranges of voltage and current as battery. The external power source which is used for charging both battery and the ultra-capacitor is assumed to provide maximum voltage and current even during intermittent condition which is approximately 12.3V and 5 to 5.5A such that minimum charging period of the energy storages can be carried out. The charging rate capability of ultra-capacitor is fast that it take up to 54sec to store charge from the threshold voltage level to the maximum voltage level where in the case of battery, normal charging time is considered.

The battery bank used in the system is lithium ion battery, which is easily available in the market plus cost versus power efficiency is the best among other batteries. Ultra-capacitor bank (Maxwell BMOD0058 E016 B02) is also used in this system as energy storage, which is equivalent to the capacity of the battery bank. Both of the energy storage components are connected to an external power source, which could be solar panel that is used as a power source to charge the battery and ultra-capacitor banks during the operation of the system. However, in this work, the solar panel circuitry is not being studied and it was treated as a constant power source supply to the system.

The battery and ultra-capacitor are arranged in parallel configuration to provide maximum energy and power density as the battery or ultra-capacitor may provide the required power according to the load demand. In this system ultra-capacitor is considered as primary source of power to the load. This is good for the system because power can be provided in robust condition, in this case at the start of motor where the motor draws large current of which ultra-capacitor has the capability to provide large current.

Motor used in this system is a DC motor and it also acts as electromotive force (emf) generator. When the coil inside the motor is being turned, an emf is generated. The generation of emf depends upon several factors such as the torque of the load, vehicle size, running speed and generated magnetic field inside the motor. The generated emf during the stopped condition of the DC motor is used as regenerative braking power to charge the ultra-capacitor in this work.

The reason to charge the ultra-capacitor with regenerative voltage is due to high spikes that may produced at the time on regenerative braking of which could damage the battery. This is because battery has constant voltage and current carrying capability but the ultra-capacitor can bear high voltage and current spikes. The second reason is due to the amount of regenerative braking voltage is comparatively small and generated within a short interval of time. Considering the characteristic of charging time of the ultra-capacitor, ultra-capacitor can benefit from this emf because it has the capability to charge quickly in comparison to the battery.

General operation of the circuit will be discussed next. Referring to the Figure 2, battery power bank is connected to the single directional DC to AC inverter in a current booster arrangement circuit, it increases the average value of current, which is triggered by the PIC microcontroller. Relay 1 and relay 2 are operated by the microcontroller to allow power to pass to the load through a rectifier. The rectifier converts the AC to DC. This rectified output of DC to DC will have some spikes and in order to nullify the spikes, a capacitor across the load to obtain stable DC voltage across the load is applied.

Ultra-capacitor is also connected via single directional DC to AC inverter in which the circuit inputs are triggered via microcontroller. Relay 3 and relay 4 are controlled by an PIC controller to deliver the power to load after passing AC to DC rectifier. The regenerative braking effect is also operated via PIC controller that cuts off the power supply from the battery via relay 1, relay 2 as well as from the ultra-capacitor via relay 3, relay 4. It will then turn on the relay 5 which is connected to the DC to DC converter to charge the ultra-capacitor.

The priority of the circuit is set such that the circuit will start using ultra-capacitor to supply power via relay 3 and relay 4 to the load until it reaches the threshold voltage limit, which is 5.6V. The voltage of the ultra-capacitor is monitored by a voltage sensor circuit, which serves as an input to the microcontroller. Once it reached the threshold voltage limit, the priority of supplying power to load changes to the battery bank by turning off relay 3 and relay 4 and turning on relay 1 and relay 2 until the ultra-capacitor fully charged via relay 6 from the external power source. The decision-making flow is programmed into the PIC microcontroller(PIC 16F877A). Figure 2 shows DC to DC on PCB board, switching circuitry and testing with microcontroller after the hardware is assembled.

## 3. SIMULATION RESULT

The PIC microcontroller that produces outputs to trigger the opto-couplers in order to switch the power transistors in the circuit are simulated using a function generator in the Multisim 13.0 and 12.0, software from National Instruments. The inputs are triggered according to phase shift, angle and frequency that are set inside the generator for each input separately. The switches are controlled manually in this simulation.

Figure 3 shows the simulated output of the function generator to trigger opto-coupler of which will switch on or off the TIP142 Power Transistor in the DC to AC inverter block. Three cases were simulated

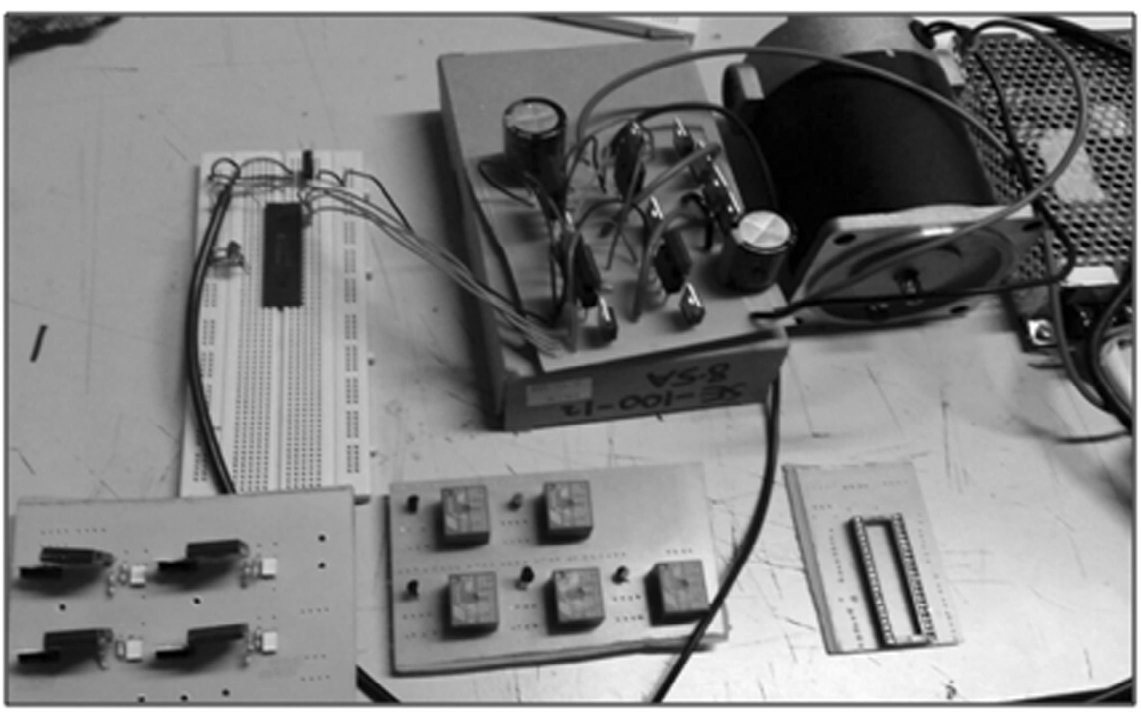
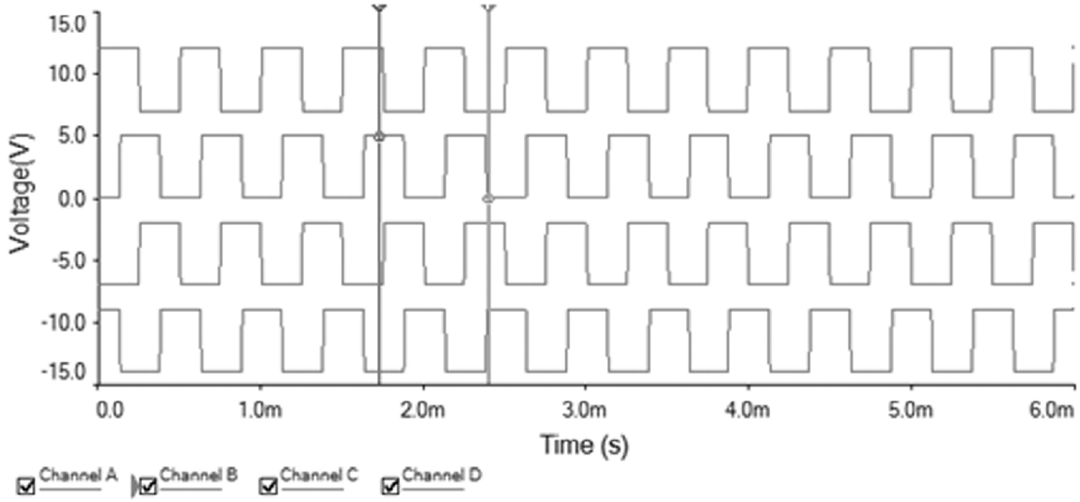
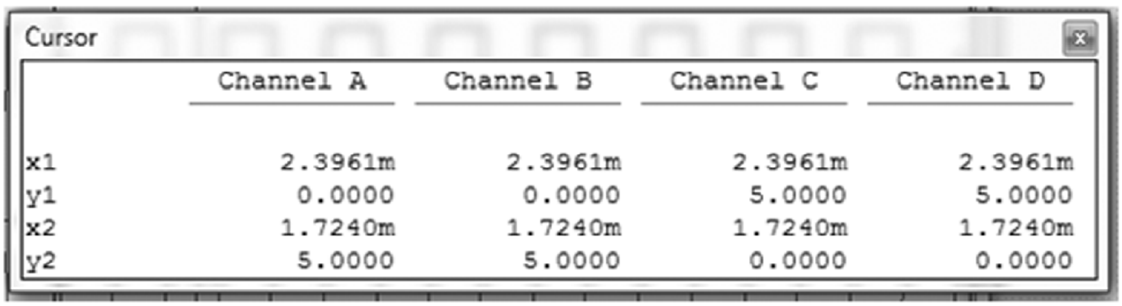


**Figure 2: Hardware built on printed circuit board for testing**



Cursor

| | Channel A | Channel B | Channel C | Channel D |
|---|---|---|---|---|
| x1 | 2.3961m | 2.3961m | 2.3961m | 2.3961m |
| y1 | 0.0000 | 0.0000 | 5.0000 | 5.0000 |
| x2 | 1.7240m | 1.7240m | 1.7240m | 1.7240m |
| y2 | 5.0000 | 5.0000 | 0.0000 | 0.0000 |

**Figure 3: Output Triggering Signals from Function Generator to Power Transistors**

where case 1 battery to load single directional DC to DC converter, case 2 from ultra-capacitor to load single direction DC to DC converter and case 3 regenerative braking. Gate terminals of the TIP142 power transistors are triggered at firing angles of 00, 1800, 2700, 900 via four channels A, B, C, D from the function generator. Figure 4 shows the combined output signals generated from the four channels to trigger four power transistors alternatively. The x1, x2 represents time and y1, y2 represents the voltage value for each triggering input taken at two random points.

Figure 4 shows the AC inverted output voltage generated from the DC to AC inverter when transferring power from battery bank to the load. The AC output is operated at 2KHz frequency. The purpose of using 2KHz frequency is to make the voltage and current spikes in control so that, it can be rectified before feeding it to the load. Operating at this frequency gives a smooth and linear output of voltage and current after rectification. After the voltage drop across AC circuit voltage is shown in the Figure 5, the voltage increases gradually until it reaches a stable value which is between 9.1V to 9.2V peak to peak. When the ultra-capacitor power is cut off from load as shown in the figure at the start of the simulation, the battery gives output voltage of 11.8V peak to peak approximately.

It can be seen from the Figure 5 that during the switching of the power sources (ultra-capacitor to battery) to the load, the output peak to peak voltage shown at cursor y1 was 11.789V and then, the output peak to peak voltage gradually reaches a stable peak to peak voltage value at y2 at 9.2V. Variable dy shows the difference in the value between maximum peak to peak voltage before switching and stable peak to peak voltage value after running load at the two selected time points x1 and x2, the difference is approximately -2.5v. Variable dx represents the time difference between two points.

Figure 5 shows the DC-AC inverter output voltage when supplying power from ultra-capacitor to the load. The frequency is same as discussed in the case of battery. After the voltage drop across AC circuit, which represents the power cut-off from battery and ultra-capacitor starts supplying the power to the load,

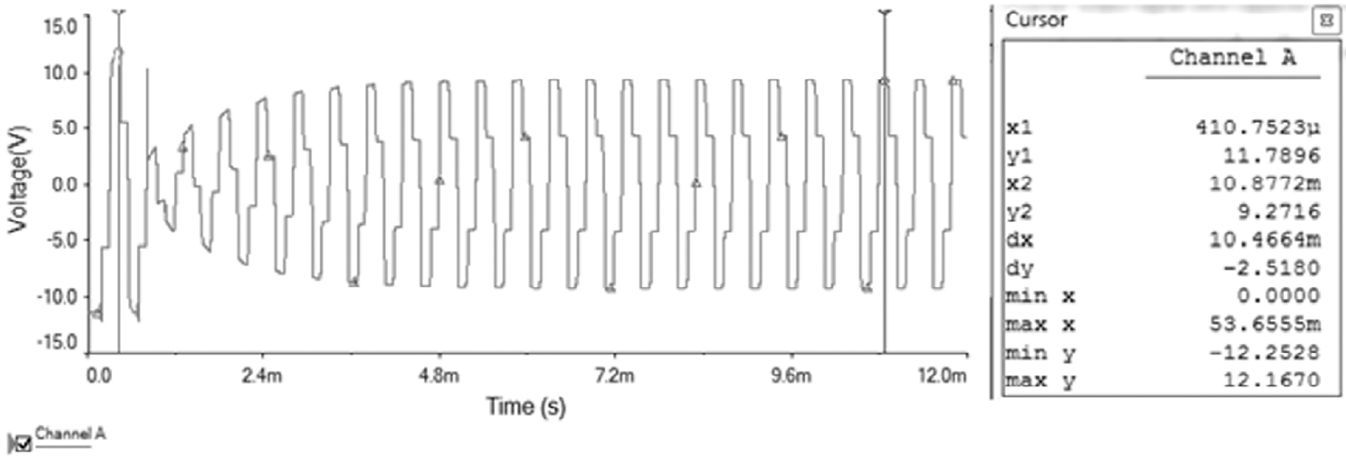



**Figure 4: Simulated DC-AC inverter output signalbattery to load**

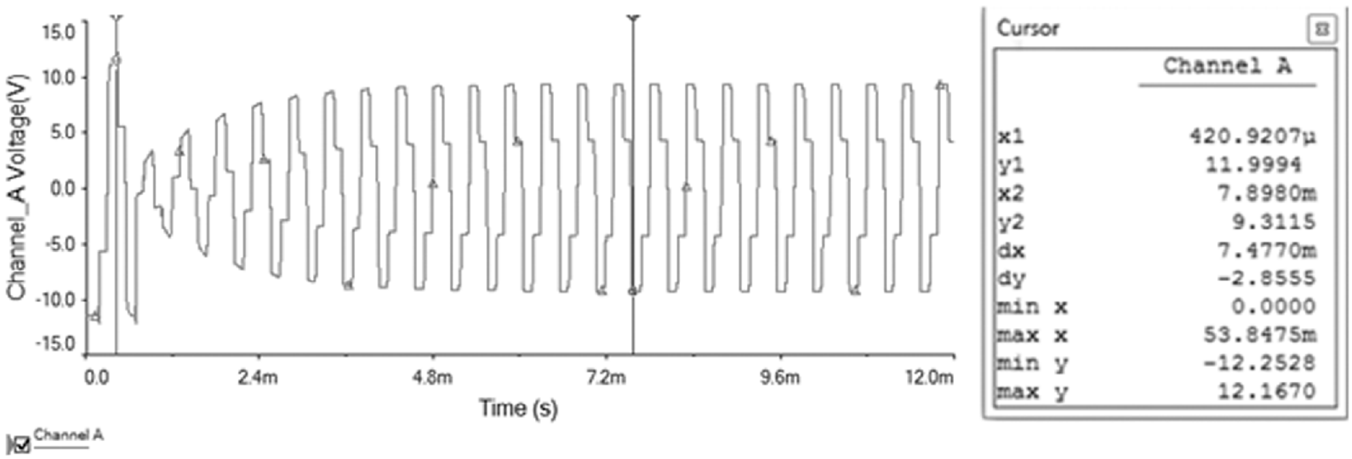



**Figure 5: Simulated DC-AC inverter output signal ultra-capacitor to load**

the simulated output peak to peak voltage is at 11.99V. Then, the output peak-to-peak voltage gradually reaches its stable value, which is in between 9.2V to 9.3V peak to peak.

The output voltage of the inverter from ultra-capacitor shows a slightly greater value than the battery. Due to higher voltage is produced by the ultra-capacitor at the start of the motor; it can prove that the ultra-capacitor can provide the burst of power with more power density during power demand. Figure 6 shows the DC output voltage across the load. The output supply voltage to the load after nullification of ripples is at 7.8V peak to peak. This voltage is being fed to the load. Initial voltage value across load at voltage point y2 is at 194.6mV at the time point x2, and at y1 is 7.8v at x1. Variable dy shows the difference between the initial voltage value and the maximum voltage value which is is approximately -7.61V. While the dx represents time difference.

Figure 7 shows the triggering inputs to the TIP142 Power Transistor to turn on the circuit for regenerative braking in opposite direction, so that generated braking could be used for charging ultra-capacitor. The inputs of TIP142 power transistors for the regenerative breaking circuit are triggered at the firing angles of $0^0$, $180^0$, $270^0$, $90^0$ via four channels A, B, C, D from function generator. The following graph shows the combined output signals generated from the four channels to trigger four power transistors alternatively. The x1, x2 represents time and y1, y2 represents the voltage value for each triggering input taken at two random points.

Figure 8 shows the simulated output of generated regenerative voltage. The regenerative effect cannot be simulated in the simulator due to nonexistence of motor exact model. Input voltage of 2V is assumed to

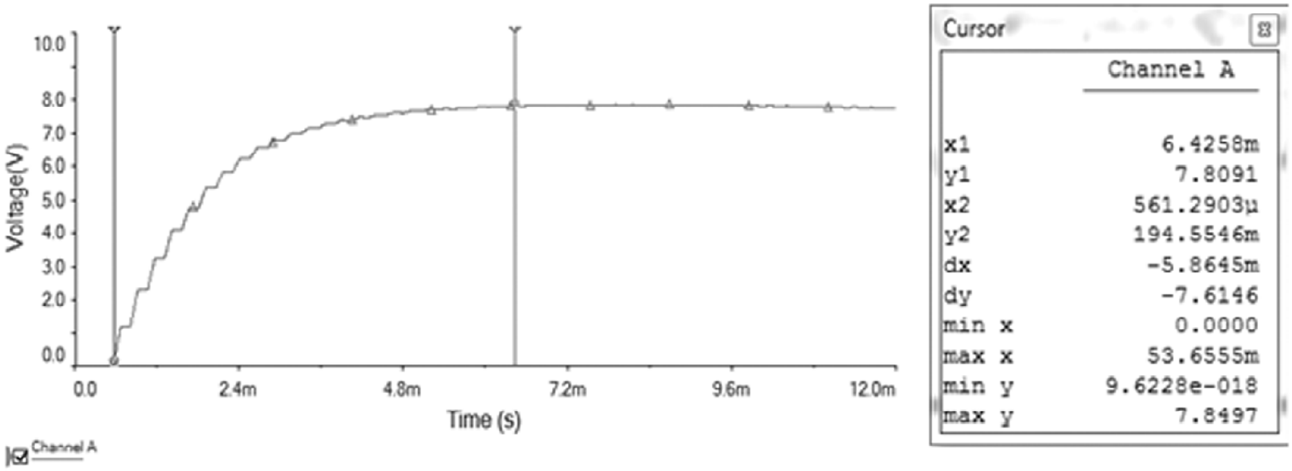



**Figure 6: Simulated DC output signal across load**

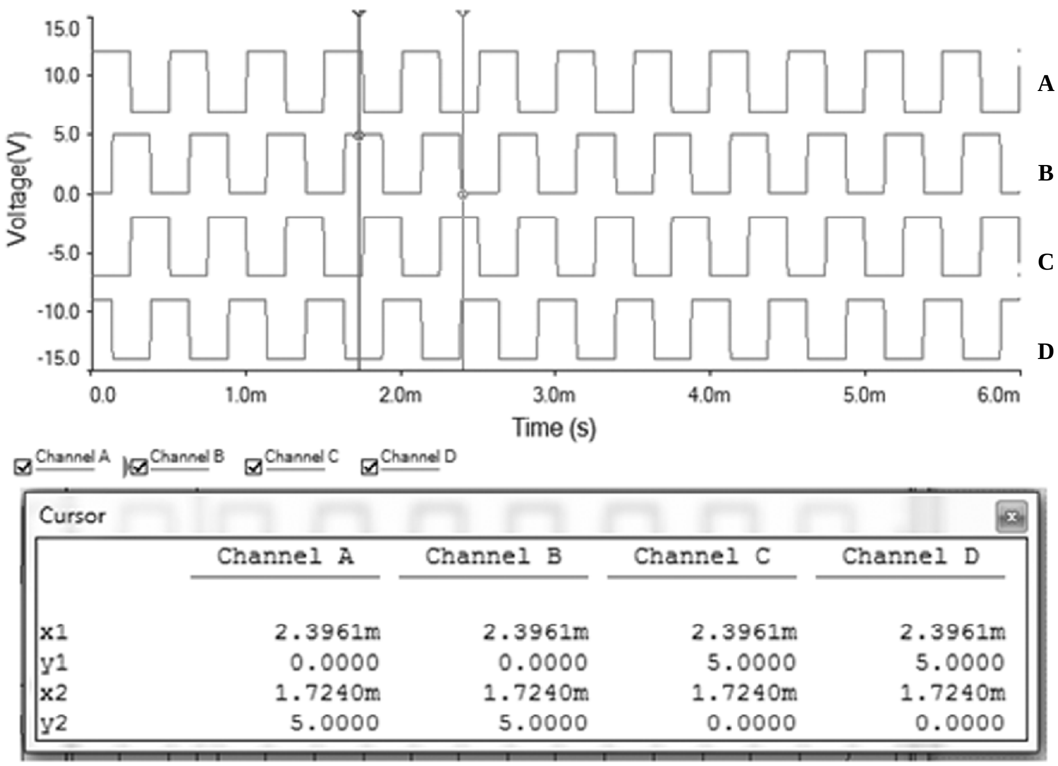



**Figure 7: Triggering inputs for Regenerative Braking to power transistors**

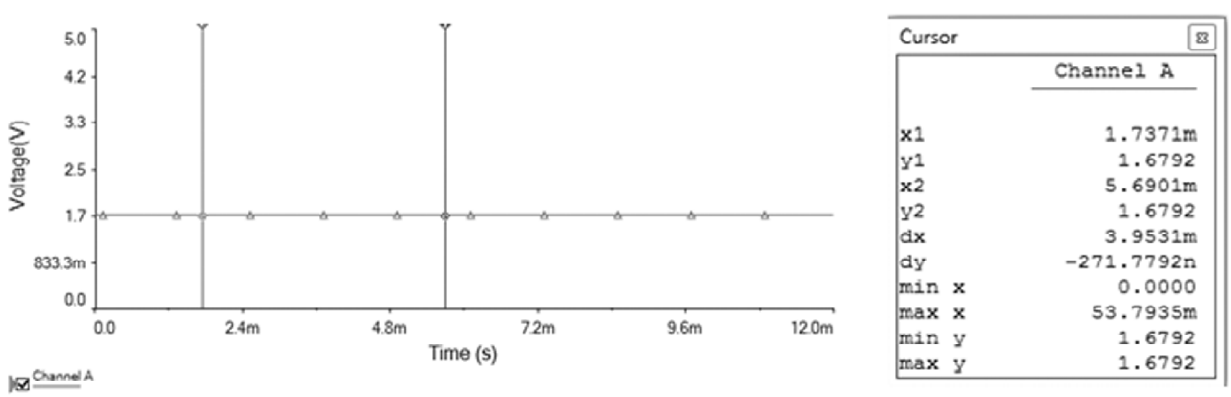



**Figure 8: Triggering output for regenerative braking Circuit**

replicate the regenerative voltage from the motor and this is regarded as another power source to charge ultra-capacitor in real circuit. The regenerative voltage from the load is 1.67V as marked at y1 and y2 and the difference between the peak voltage at two selected time, at points x1 and x2 is approximately -271.77nV. While the dx time difference between two values taken, minimum and maximum value of time and voltage also can be seen in the Figure 8.

The regenerative braking voltage value decreases from 2V to 1.67V due to conversion losses of DC to DC voltage where during the conversion, there are some losses occur which lower the value of generated voltage slightly.Ultra-capacitor charging output waveform is shown in Figure 9. It shows the property of fast charging and discharging of ultra-capacitor. With respect to time, ultra-capacitor voltage goes higher value and current will become a limiting factor. At the start of charging ultra-capacitor simulation, the produced current is in KA range which is not practice in real. When external power source is allowed to charge the ultra-capacitor, the voltage at y1 is 1.28mv and value at y2 is 11.9964v. The voltage varies from zero to 11.99v. Variable dy shows difference in the value between peak voltage and initial charging voltage at two selected time points x1 and x2, the difference is approximately 11.9951v. While the dx time difference between two values.

Discharging of ultra-capacitor starts as the load draws power from the ultra-capacitor as shown in the Figure 9. The simulation result shows that the charging and discharging time of the ultra-capacitor almost remains same. Moreover the discharging rate of the ultra-capacitor depends on the load size. The graph shows that the voltage is decreasing with the time where at y1 voltage of 11.992V is observed at time point x1, it discharge to a value at y2, which is 2.98V at x2.

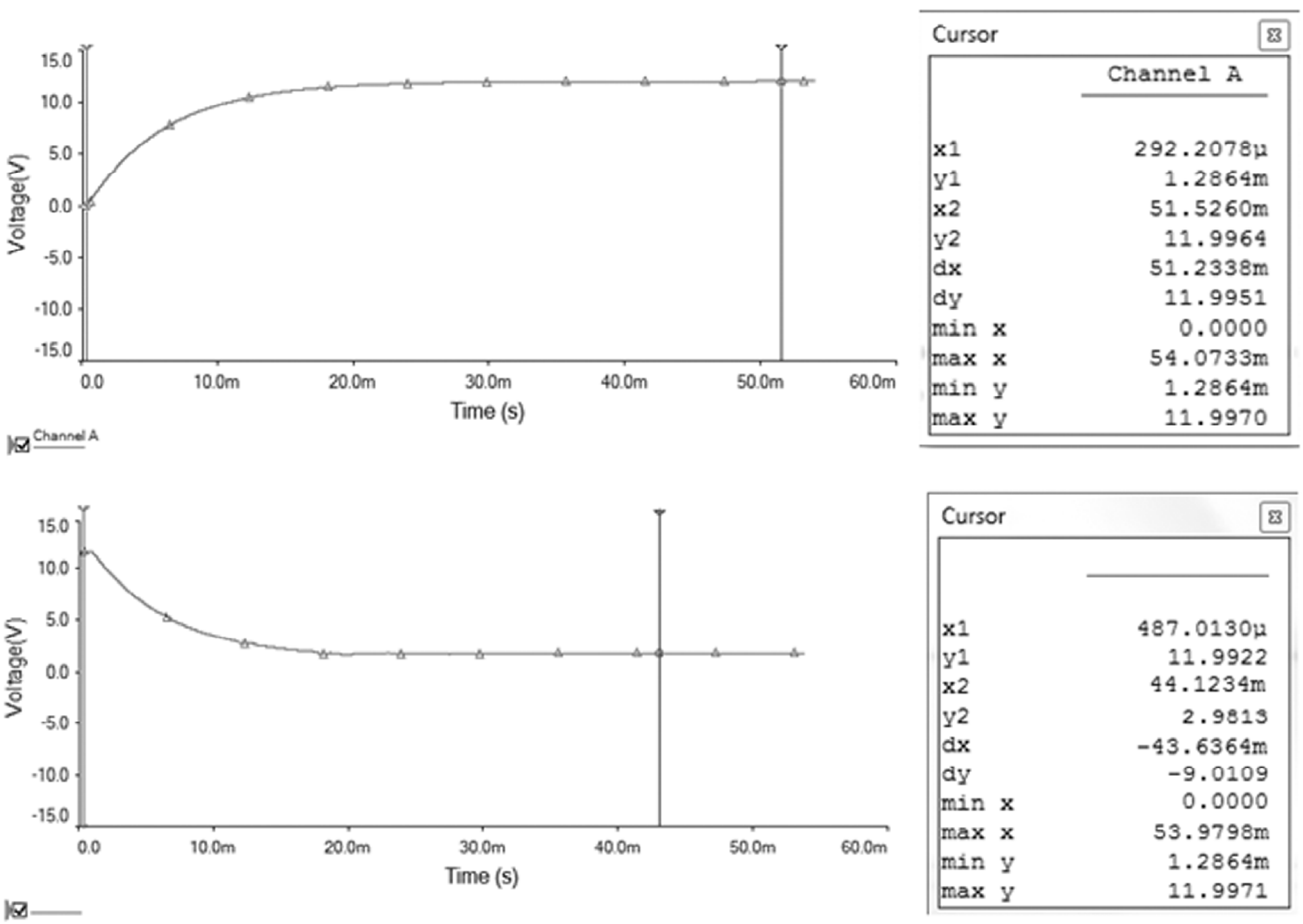



**Figure 9: Ultra-capacitor charging (above) and discharging (below) rate**

## 4. EXPERIMENTAL RESULT

The Figure 10 shows a sudden drop in voltage across the battery during normal operation when load is running via battery at the start. This will make the current from the battery to drain faster. Thus, this explains the advantage of giving priority to ultra-capacitor upon running load with battery at the start. Using the ultra-capacitor at the first priority of transferring power to load may increase the lifetime of the battery of which will result in longer running time and longer distance travelled in the case of electric vehicle application.

Voltage and current values at different time points across the load were taken and shown in Table 2 The difference in the voltage values across load is due to the capacitance difference in simulated and real ultra-capacitor because the property of ultra-capacitor cannot be fully simulated in the simulator. In simulation normal capacitor is used with enhanced values, so that nearly equal functionality can be seen. The experimental values are greater than simulated values due to the capacitance of the ultra-capacitor is greater in real time operation than the simulated capacitor values.

Figure 11: Voltage value with respect to time during shifting of power sources measured at ultra-capacitor, battery and load.

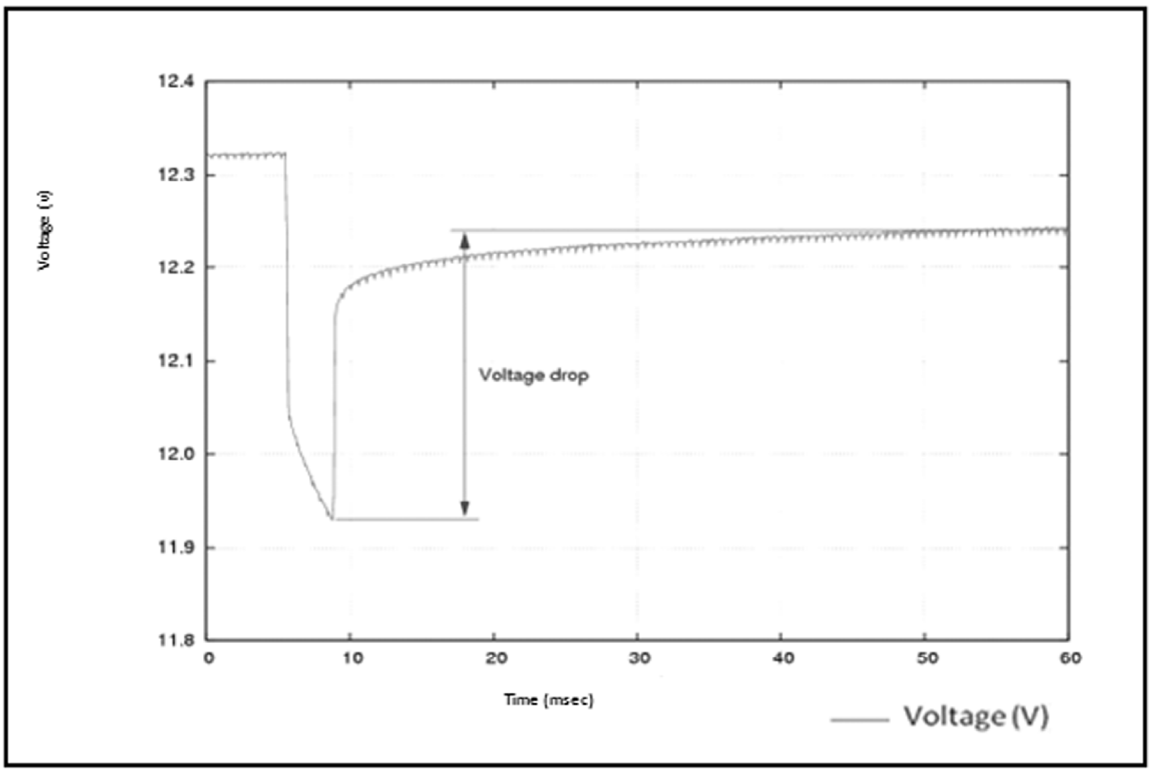



**Figure 10: Battery voltages with respect to time a load is attached (without ultra-capacitor)**

**Table 2**
**Comparison of Voltage and current across load between simulation and experimental results**

| *Time (Sec)* | *Experimental Voltage (v)* | *Experimental Current (A)* | *Simulated Voltage (v)* | *Simulated Current (A)* |
|---|---|---|---|---|
| 1 | 8.41 | 6.93 | 7.92 | 6.817 |
| 5 | 7.99 | 6.85 | 7.87 | 6.805 |
| 10 | 7.65 | 6.55 | 7.5 | 6.79 |
| 15 | 7.3 | 6.11 | 7.0 | 6.77 |

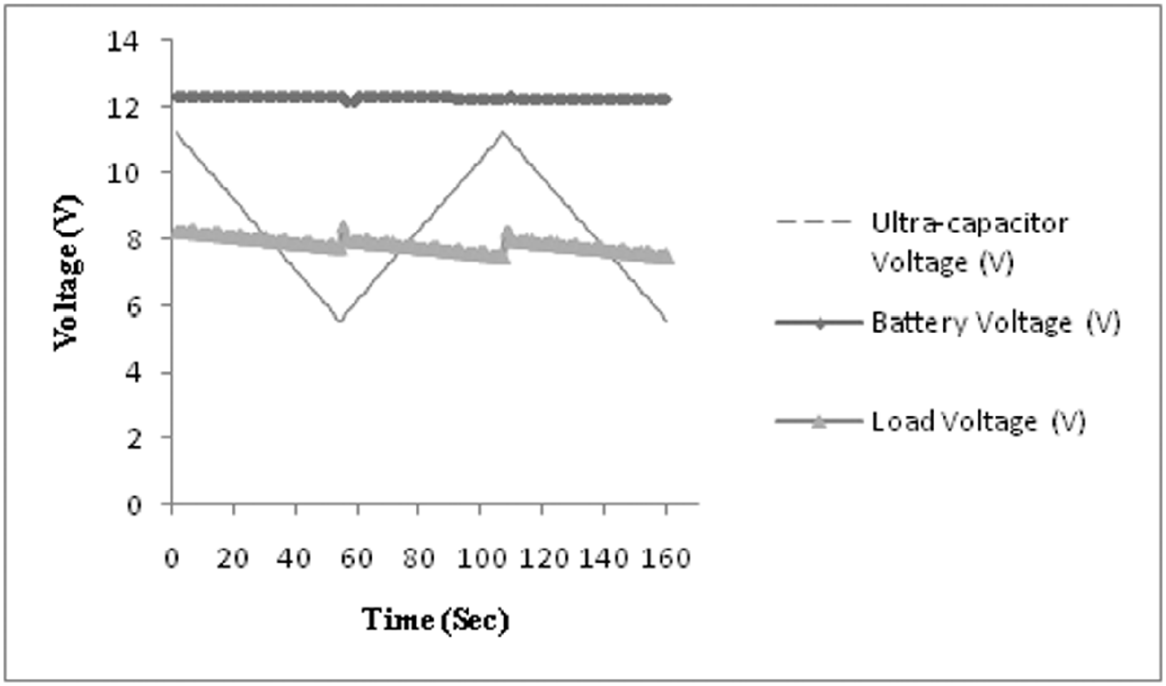



**Figure 11: Voltage value with respect to time during shifting of power sources measured at ultra-capacitor, battery and load.**

The experimental values are taken during the shifting of power source during running of the load shown in Figure 11. It is observed that at the start ultra-capacitor provides full power to the load as the voltage remains almost constant the current goes lower for short interval of time then it comes to the normal linearly. While shifting load to battery from ultra-capacitor it is observed that the battery gives its maximum voltage value and current value without any fluctuation of voltage or current, it is because the load is running during shifting of source. During the shifting of power source from battery to ultra-capacitor the capacitor linearly discharges by giving power to load, it is observed that while discharging ultra-capacitor voltage decrease and current increases to maintain the power across load. The Figure 11 explains the advantage of giving priority to ultra-capacitor upon running load with battery at the start. It makes battery to run for longer time and cause the enhancement of power and energy density.

## 5. CONCLUSION

This paper presents the integration of intelligent energy storage system designed for electrical vehicle (EV) applications which has rapid power transmission, high energy and power density, increased battey life, efficent power management, with high protection circuitry and also regenerative braking power storage capability in comparison to traditional designs. The PIC controller is used to select priority of the power sources to transfer power to load and control the direction of the power flow at each point. By using the sensing module for volltage and current across the ultra-capacitor, the ultra-capacitor is allowed to be used for the maximum effective power limit. Both power sources which are the battery and ultra-capacitor are operated at a wide range of current and voltage. Moreover, this design provides a lower cost with efficent performance, environment friendly with zero carbon emission, better power management whereby electromotive force is being utilised in the system to charge the ultra-capacitor and hence the system could last longer than other designs for electric vehicle applications.

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