Review of Ultracapacitor Technology and its Applications

V.A. Shah, Jivanadhar A. Joshi, Ranjan Maheshwari and Ranjit Roy

Abstract— **An efficient electrical energy storage media are essential and are considered as a short term and an enabling infrastructure power technology. Energy storage technologies do not represent energy sources but they provide value added benefits to improve system stability, power quality and reliability of supply. As batteries technologies are low cost ,well established and widely used technology offer disadvantages like volume, weight, poor power density, high internal resistance, poor transient response, they are not suitable for some transient application or where volume and size are an important issue. On the other hand due to advancement in the material and other technology, Ultracapacitors offers high power density, fast transient response, low Wight, low volume and low internal resistance which make them suitable for pulsed load application. In this paper we will review some of the present application of the Ultracapacitor(UC) in the field of low power and high power applications like telecommunication devices, automatic meter reading system, load leveling on the electrical power system, maintaining continuity of power during outages, improving profitability in high energy system, enhance transmission capacity of the transmission grid in high power application, various power quality and backup related uses such as UPS system and power stabilization, to improve reliability of wind turbine pitch system. Simple ultracapcitor and battery model with pulse load is simulated in MATLAB-SIMULINK without and with DC to DC buck boost converter to prove ultracapacitor as a peak power supply device.**

***Index Terms*—Equivalent series resistance (ESR), Ultracapacitor (UC), UPS.**

I. INTRODUCTION

ELECTRICAL system is designed with energy storage device as a secondary energy source. Recent developments and advances in energy storage elements and power electronics technology provide significant benefits to utilities and other power applications. Viable energy storage elements include batteries, ultracapacitors(UC), flywheels[1] and superconducting energy storage systems (SMES). The specification for various storage devices are given in terms of Wh/kg, W/kg, life cycle, size, weight and initial cost. Base on the application, particular energy storage device must meet above requirement. Usually at the time of designing any system, primary source must be sized in such a manner that it can provide peak demand even though it occurs only for few seconds or minutes as compared to continues or average demand.

Sizing[2] whole system based on peak demand in place of average demand is very costly and inefficient as we are unable to utilize its full capacity all the time. But if we design system by storing electrical energy from primary source to some other energy storage device and then delivering that stored energy to the load in forms of burst of power in a controlled manner whenever peak demand occurs for a period of time ranging from fraction of seconds to several minutes, we can improve operation of system significantly. The most common technology in energy storage is battery for primary energy source and storage/peak power delivery as it can store large amount of energy in a relatively small weight and volume. But batteries have many limitations like low power density, poor low temperature performance, can't be charged or discharged at high rate over many hundreds of thousands cycles, requires repeated replacements throughout the life of system . Environmental problems are another great concern related to battery. They create many design challenges for engineers. Even with this, still people are using this technology mainly due to low cost and may be a lack of an efficient alternative.

Above mentioned limitation of batteries are overcome by new storage technology i.e. double layer capacitor also known as 'Ultracapacitor'. It is 100 years old technology enhanced by modern material technology. UC provides simple and highly reliable solution to bridge the short term power mismatches between power available and power required. This device reduces system size and cost,[2,3,4] improves performance and reliability and provide burst of power over many hundreds of thousands of cycle. They have much higher power density, extremely longer cycle life, wide temperature range (-40 to +65 degree) but low energy density. UC modules can be designed for harsh condition of vibration, temperature and humidity. Even in harsh climate like hot deserts with wide temperature swings and high humidity condition maintenance requirement is low. To increase power capability of UC, a tradeoff between energy density and RC time constant of UC is required. They are available as a low voltage cells (2.5 to 3.0 volts range) .To satisfy the energy storage, power delivery demand and higher voltage level required by large system, they are available in modules which consist of multiple numbers of cells (15 to 390 volts by Maxwell Company). Flywheels can be used to store energy in rotating mass of a rapidly spinning flywheel. The main advantages of flywheel

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storage systems are large energy storage capacity and high power density. The problems are its complex power and control electronics and potential for catastrophic failure. SMES devices store energy in the magnetic field generated by a loop of endless current passing though a zero-resistance coil with superconductivity. Selection of each storage devices is based of their application, but for certain applications, it is possible to achieve the best performance by combining different energy storage elements to gain the advantages of each while avoiding the disadvantages. The most popular combination is UC and batteries. UC can completely absorb and release a charge at high rate and in a virtual endless cycle with little degradation. Due to this they are used in electrical hybrid vehicle system along with battery. The ultracapacitor can deliver energy during period of high current surge, such as engine start, acceleration and recaptured energy through regenerative braking. This allows battery to be used only for long duration loads, optimizing its energy storage and extending its life. Thus a combination of UC and battery can built a energy storage device offering high power density and high energy density. Power system applications for UC are wide-ranging and will revolutionize the use of short-term storage for power control and power quality enhancement. Load swings on the arc furnaces and rolling mills are very large and very rapid. This load swing cannot be met by generator instantaneously. The generator will try to supply extra energy, which will cause to decelerate its rotor. So large scale fast acting energy storage device is required to meet the load swings. Industrial plants relay on adjustable drive for critical process applications. They are accepected to power disturbances like voltage sags and momentary interruptions within the time interval of 2 seconds to 2 minutes. This will trigger the protection system of electrical drive. Tripping of drive in process plants is very costly. This can be mitigated by use of ultracapacitor. It is used in wind turbines as a reliable energy storage, which are usually located in remote and even offshore places. During interruption in the grid the pitch of turbine can be steadily controlled even in high wind condition due to power back up system provided by ultracapacitor.

II. WHAT IS ULTRACAPACITOR?

Ultracapacitor is an electrochemical device which stores energy via electrostatic charges on opposite surfaces of the electric double layer which is formed between each of the electric and electrolyte. No chemical reaction takes place during [3] charging and discharging even though it is electrochemical device

UC construction is same as that of battery having to non reactive porous electrodes immersed in an electrolyte solution separated by an electronic barrier such as a glass paper.

Electrodes are fabricated from porous carbon material (activated carbon fiber material) deposited on metal foils having a pores in the nanometer range and very high surface area (1000-2000 cm^2/gm) the properties of the double layer capacitor strongly depends on how porous carbon activated material is and how small the electrolyte ions are. Activated carbon electrodes used in ultracapacitor have a large specific surface area and charge separation distance is in the order of 10 Armstrong or less. This allows ultracapacitor to store large amount of energy [3] Fig. 1 shows schematic of ultracapcitors with module and cell.

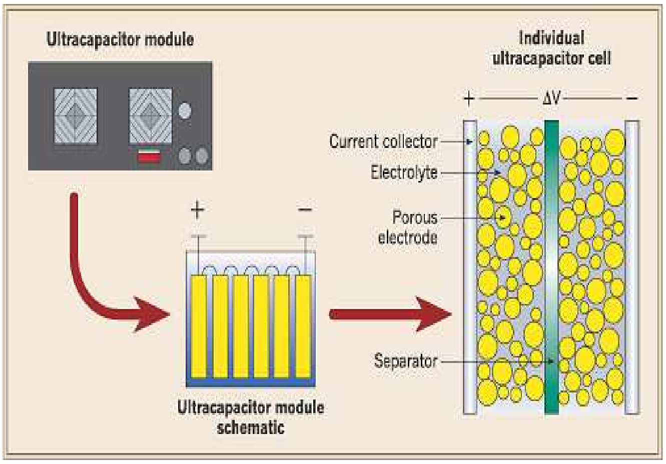

Fig. 1. Schematic of ultracapacitors.

During charging the positive and negative ions of electrolyte are drawn to electrodes of opposite polarity where they accumulate into layers inside the activated carbon pores. The penetration of electrolyte ions is governed by pore size of activated carbon. The double layer phenomenon is strongly determined by the activated carbon pore size and electrolyte positive and negative ions diameter. Electrolyte ions diameters are of the order of 1 nano meter. If the average pore diameter is 3 nanometer good capacitance value exists for both organic and aqueous electrolytes when it is less than or equal to 2 nanometer, good capacitance value exist for only aqueous electrolyte and if it is below 1 nano meter no double layer capacitance exists.

The specific capacitance for ultracapacitor for aqueous electrolytes is in the range of 75 -175 F/gm and for organic electrolyte 40-100 F/gm. This because of larger size of ions in organic electrolyte. If larger the ion size less penetration of ions into pores of activated carbon.The cell voltage of the ultracapacitor is dependent on electrolyte used and the maximum voltage is limited by the insulating ability of the electrolytes. For aqueous electrolyte the cell voltage is about 1 V and for the organic electrolyte the same voltage is about 3-3.5 V. UC offered some resistance, as conductivity of organic electrolyte is low it has higher ESR then aqueous electrolytes.

As charging and the discharging of the ultracapacitor do not involve any chemical reaction they can be cycled with almost no deterioration. UC can withstand more than 1 million charge and discharge cycle. As the capacitance offered by UC is very high, energy density UC is also very high (10 times) compared to conventional capacitor and the power density is very high (10 times) compared to battery. A comparison of conventional storage technologies is shown in Table I.

Table I: A comparison of conventional storage technologies [4]

Available Performance	Lead Acid Battery	UC	Electrolytic Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10-3 to 10-6s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10-3 to 10-6s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1,000	>500,000	> 500,000

Specific Power (W/kg)	<1000	<10,000	> 100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	> 0.95

To compare relative matrices of UC energy storage technology against batteries and others, it is to place them on a ragone plot. The plot is between Wh/kg against the W/kg and it shows that how energy density decreases for increase in the power density. They are good means of qualifying an energy storage system and to size the storage system for variety of application. Extracting energy from an UC is more demanding on the inverter (static power converter) than in the case of a battery system. This is because the DC voltage input into the inverter will vary over a much larger range than it will with a battery. With a lead-acid battery, voltage decreases about 20% between full-charge state and essentially 100% discharged state. In an UC, extracting 75% of the energy requires a 50% decrease in the capacitor voltage.

III. UC APPLICATIONS

A) Transmission line: The need for energy storage in the power system is mainly due to the variation in electric power demand. The novel ultracapacitor technology is also extended up to power transmission level. A transmission ultracapacitor[5](TUCAP), based on emitter turn-off (ETO) thyristor technology at the device level, modular VSC based on cascade multilevel converter (CMC) technology for the converter system and UC as the energy storage is a state of the art FACTS for utility high-power applications from power quality enhancement, voltage and frequency stabilization, power transfer limit improvement to renewable energy and distributed generation support. It is expected that integrating TUCAP technology in FACTS will result in extremely fast response and that is less costly per kW/ kVA than any other FACTS based on traditional storage/ power electronics technology.

B) Combined UC and battery UPS: By combining an UC with a battery-based UPS[6] system, the life of the batteries can be extended. The UC provides power during short-duration interruptions and voltage sags. The batteries provide power only during the longer interruptions. This reduces the cycling duty on the battery and extends its life.

C) UC UPS: For critical loads needing only a few seconds or tens of seconds of ride-through, an UC system with no batteries is feasible and should have very low maintenance costs.

D) Area voltage stabilizer/power conditioner: Larger-scale UC systems could provide brief bursts of energy to filter voltage sags on the distribution system.

E) System frequency and stability control: The ability to absorb and reject energy [6] quickly can make UC useful for system stability control and as a frequency-regulation tool. They can accept power at a far greater rate than batteries

F) Micro grid micro generation: Ultracapacitor is used as an energy storage device in a micro source system connected to micro grid. [7] Inertia offered by such a system is zero or very low. Any instantaneous mismatch in active power may disturb stability of the system. To ensure stable operation under any mismatch energy storage device is interfaced through power electronics device with grid.

G) Mitigation of voltage sag problem: Voltage sags can be delivered from the grid,[8] however in most cases, sags are generated on the load-side of the meter. In case of residential installations, the most common cause of voltage sag is the starting current drawn by motors in refrigerators and air-conditioners. In industrial applications, the numerous motors, compressors etc. and their large size, generate many voltage sag events everyday. Electronic equipment with fast response times like PLCs, adjustable speed drives and switching power supplies lack sufficient internal energy storage to tolerate severe sags in the supply voltage. Ultracapacitors are ideally suited as an energy storage solution for hardening sensitive equipment against voltage sag. The key factors for UC to serve as hardening devices are extremely long life, flexible voltage, very high pulse power.

H) Wind turbine system: The deficiencies of battery storage systems are varied and they create many design challenges for pitch system. Batteries have a known low temperature performance in addition to a life cycle under extreme conditions. Batteries require repeated replacement throughout the life of the wind power plant and they are not designed to satisfy the most important requirements [9] of pitch system power source which is to provide bursts of power in the seconds range for rotor blade adjustments over many hundreds of thousands of cycles. With no moving parts, ultracapacitor provide a simple, solid state, highly reliable solution to buffer short-term mismatches between the power available and the power required. When appropriately designed with a systems approach, they offer excellent performance, wide operating temperature range, long life, flexible management, reduced system size and are cost effective as well as highly reliable. *I) Telecommunication:* To achieve high reliable operation of telecommunication system, usually they are supported by “hot standby system” like battery back up, parallel type UPS[10] and redundant DC-DC converter. Even if they have very good response, there is some power consumption in the standby unit. Recently, it becomes a serious problem because power saving is an important issue. So we require cold standby device like diesel generator set, fuel cell etc. But their response time is large. They are under operation during line outage and the output voltage of the system may be interrupted in this starting time. The solution is to use UC which operates in a shorter time as soon as any interrupt occurs in a system.

J) Cold starting of diesel fueled engine: Diesel fueled engines are more difficult to start at cold temperature (up to -40°C). Due to dropping of engine lubricating oil temperature below 0°C, the viscous friction level increases which require high cranking torque with decrease in temperature. Lead acid batteries are used in engine cranking.

At low temperature resistance offered by battery is high which affect the high current discharge of a battery necessary to crank a cold engine. Again lead acid battery ages, the internal resistance further increases and current discharge capability further reduces. [11] These two factors contribute to reduce cold cranking current and reduce ability to sustain this current during extended engine start. To overcome above difficulty UC bank is used with battery to supply cranking current to cranking motor via three phase inverter as shown in Fig. 2. The battery is not directly providing cranking current surge so its life time can be considerably improved and its cold cranking ampere rating reduces. When the engine is running the direction of power flow reverses and is used to charge the battery and to supply the vehicle electric load.

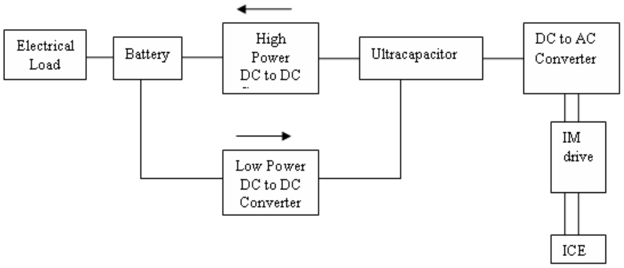

Fig. 2. Schematic of cold starting of diesel fueled engine.

K) Hybrid electric vehicle: In case of hybrid electric vehicle, if battery alone is used to drive the vehicle through inverter and motor, the life of battery get affected under transient operating condition like acceleration and deceleration because battery can not be charged or discharged at high rate. If along with battery which is rich in [12]energy density, ultracapacitor rich in power density is used together, the transient requirement, i.e., pulse of current during acceleration is supplied by UC and during deceleration or braking the energy will be returned back to the UC. So, appreciable amount of energy used during acceleration will be regained. This way life of battery can be saved and the rating of battery with UC will greatly reduce. So, size, volume and weight and cost of overall system will greatly reduce.

IV. MODELING AND SIMULATION OF HYBRID ENERGY STORAGE DEVICE

Hybrid energy storage device is built with parallel combination of UC and battery. If we have battery alone as a source and if it is connected with a pulse load, then battery has to supply the total demanded pulse load which occurs only for short period of time. This will greatly affect [13, 14] the battery life and battery terminals voltage if battery of rated current rating is used. With hybrid storage device above problem can be solved.

Fig. 3 shows the passive hybrid storage system which supplies power to the pulse load of 20% duty cycle. The UC is modeled as a capacitor in series with equivalent resistance, battery is modeled as a constant voltage source in series with equivalent resistance, and pulse load is modeled as load resistance along with electronic programmable switch with required pulse width in MATLAB-SIMULINK. The load current is shared by battery and UC based on their equivalent series resistance. The equivalent series resistance of UC is small compared to battery. So UC will supply maximum amount of load current.

The circuit shown in fig. 3 has following specifications. Battery equivalent resistance = 10 milliohms, Battery voltage=16V, Ultracapacitor equivalent resistance = 2.4 milliohms, UC capacitance = 500 Farad, UC voltage=16V, Pulse load with resistance of 2 ohms and the pulse frequency of 1 Hz and 20% duty cycle and 0.1 Hz and 20% duty cycle.

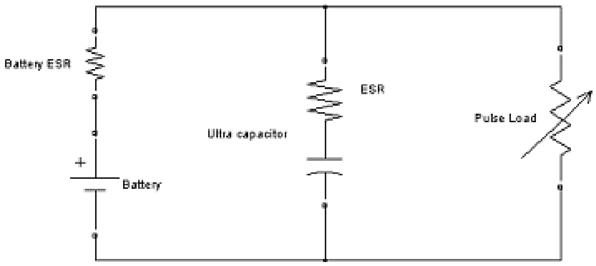

Fig. 3. Passive hybrid circuit with pulse load.

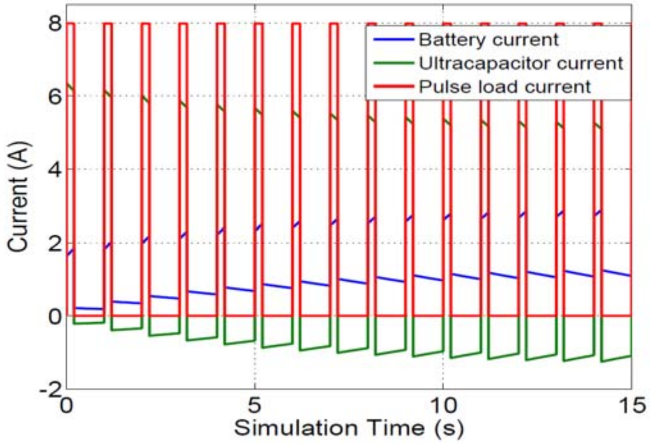

Fig. 4. Simulation results of the current waveforms of passive hybrid with load frequency 1 Hz and 20% duty cycle.

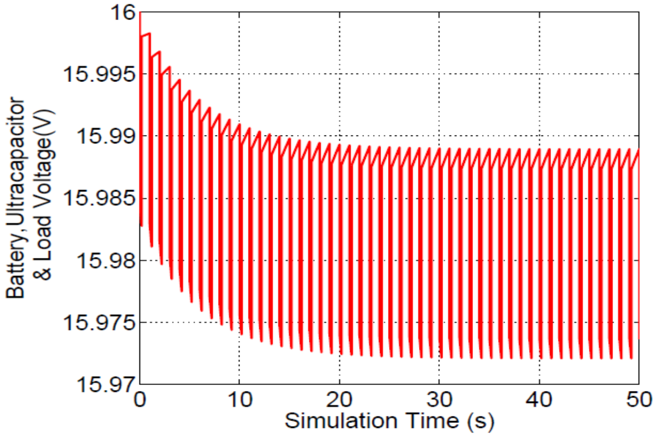

Fig. 5. Simulation results of the voltage waveforms of passive hybrid with load frequency 1 Hz and 20% duty cycle.

However, the direct connection of UC & battery has some limitations. The UC voltage & load voltage both float with the battery terminal voltage. This does not allow utilizing the full power capacity of ultracapacitor. Due to this the upper limit of UC voltage can not be selected randomly. The current sharing between the UC and the battery depends on their equivalent series resistance. So the required power enhancement is achieved based on minimum value of UC equivalent series resistance. Hence the choice of series-parallel connection [18] of UC cells depends on voltage level of the battery and the required power enhancement. The terminal voltage of the of

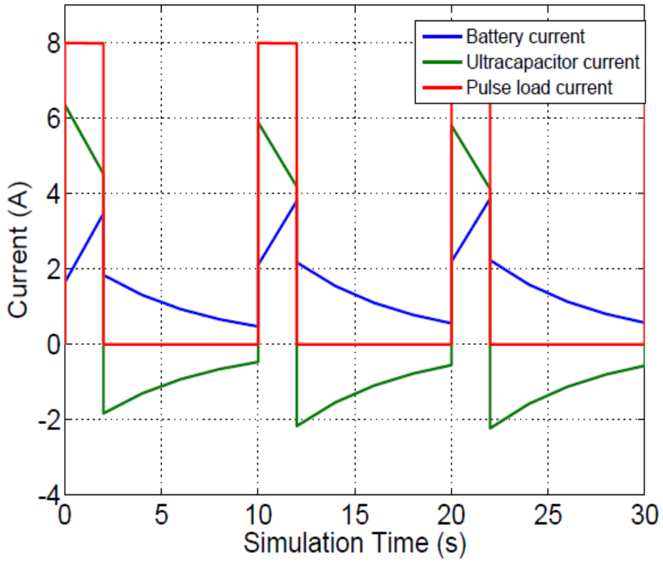

Fig. 6. Simulation results of the current waveforms of passive hybrid with load frequency 0.1 Hz and 20% duty cycle

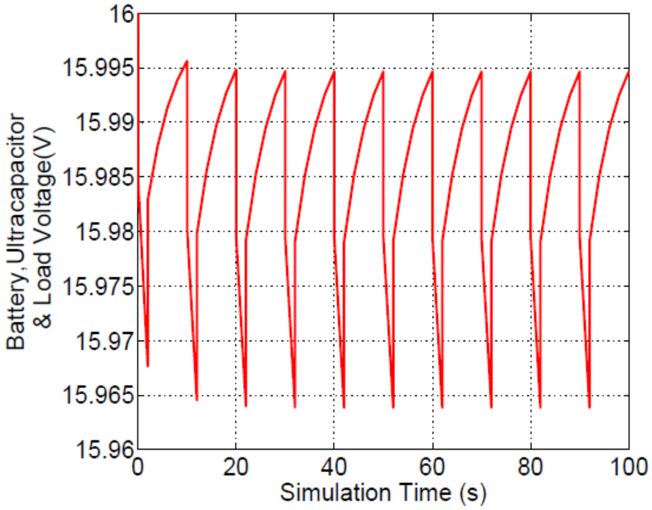

Fig. 7. Simulation results of the voltage waveforms of passive hybrid with load frequency 0.1 Hz and 20% duty cycle

UC cells depend on voltage level of the battery and the required power enhancement. The terminal voltage of the passive hybrid is not regulated as shown in Fig.5 and 7 , but instead follows the discharge curve of the battery. By inserting the DC-DC converter in above scheme as shown in Fig.8 has several advantages:

1. The load terminal voltage can be kept almost constant, which was varying with out use of converter. This is implemented with feedback from dc bus [15] to adjust the duty cycle of DC converter.

2. The UC voltage can be different from the battery. This partially removes the limitation of adding series cells of UC to the upper limit set by maximum allowed ESR. The maximum limit of ESR is set by required power enhancement ratio as mentioned in the previous discussion.

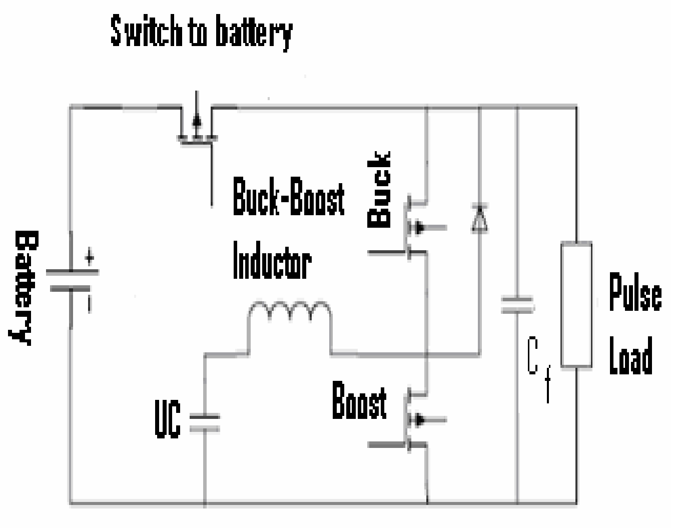

Fig.8. Active hybrid energy storage system with buck boost converter

The circuit shown in Fig.8 is simulated in MATLAB with the following specifications: Parasitic resistance of inductor=0.0001 ohm, Boost inductance L= 500 micro Henry, Output filter capacitance=500 microfarads, equivalent series resistance of filter capacitance=0.001 ohms. Switching frequency of converter is 50 KHz. The remaining circuit parameters are same as in Fig. 3.

Under the peak load condition, the load is supplied only by ultracapacitor through boost converter & battery is in idle state. As UC discharges, its voltage reduces from it's fully charged state under constant power operation. DC bus is always operating under constant DC voltage. So boost converter will adjust it's duty cycle to maintain DC bus voltage constant & to provide required current under constant power condition. The UC is allowed for it's maximum discharge up to half maximum voltage of UC bank, so that at least ¾ th of the total stored energy can be utilized. Switching of UC is controlled by boost converter by adjusting it's duty cycle through PI control algorithm. PI algorithm is implemented based on reference voltage set inside is compared with output dc bus voltage.

When the load current becomes nominal & UC voltage has dropped to certain value, the UC is charged from battery through buck converter. Maximum charging current & voltage level of UC is controlled by adjusting the duty ratio of buck converter.

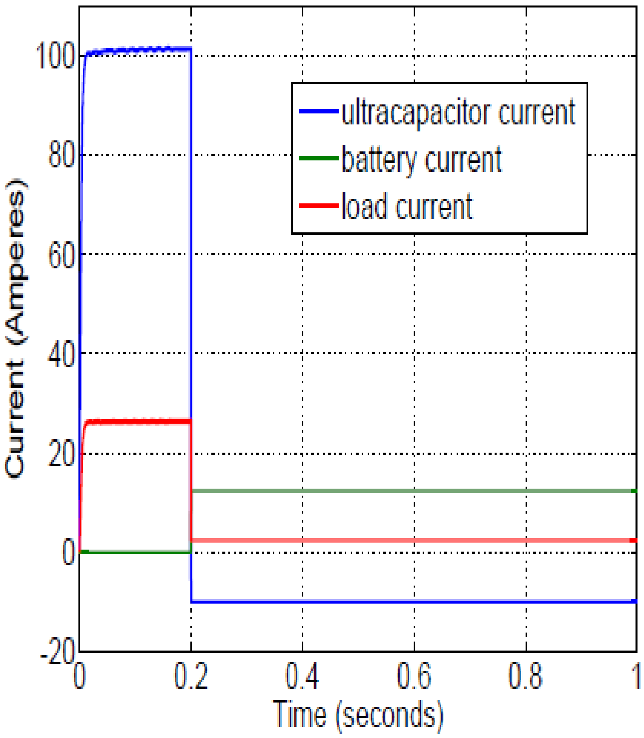

Fig. 9. Simulation results of the current waveforms of the active hybrid

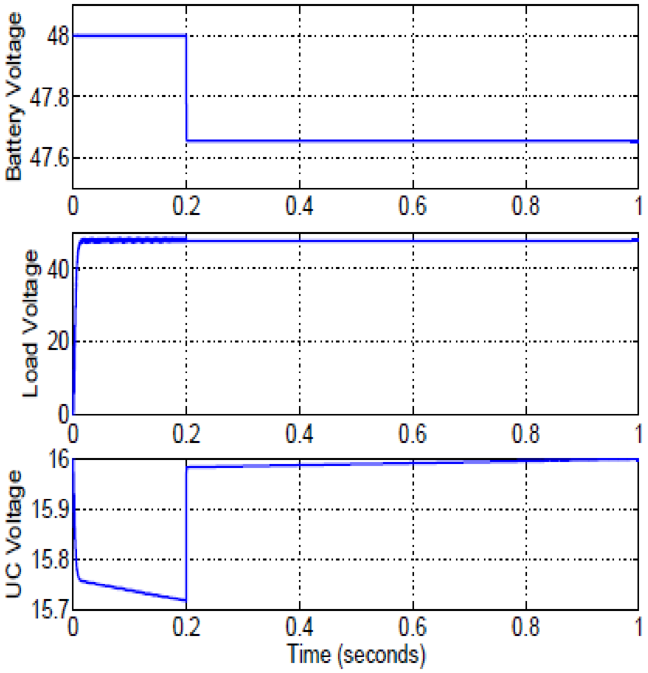

Fig.10. Simulation results of the voltage waveforms of the active hybrid

V. CONCLUSION

The simulation shows that with the help of buck-boost converter we can utilize optimum value of energy stored in UC. Current sharing of battery can be drastically reduced with small ripple during peak power demand compared to passive model of UC & battery. The sizing of battery for the same load can be optimized. The current drawn from battery is small which results in to lower temperature rise & increased life. By this, UC is claimed as possible best candidate for developing hybrid energy storage system for various applications.

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