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Design and Control of Hybrid Power Supply for HEV

Varsha A. Shah[1], Kriti S. Sachdev[2], Prasanta Kundu[1], Ranjan Maheshwari[3]

[1]Department of Electrical Engineering, S V National Institute of Technology, Surat, India.

[2]Department of Electrical Engineering, Sarvajanik College of engineering,Surat, India.

[3]Department of Electrical Engineering, Government College of engineering, Kota, India.

Abstract

Energy storage is a major concern in today's hybrid vehicular technology. The HEV operates with common load profile, described by relatively high peak to average power required. The complete system demands power source to be compact, lightweight and efficient with acceptable life cycle. Power source consisting of batteries which have high energy density and ultracapacitor which have high power density, specialized for the various power segments within a vehicular operating bandwidth becomes a viable solution. Ultracapacitor(UC) stored energy is directly proportional to square of terminal voltage. Under load condition terminal voltage of UC is continuously varying, so to operate DC bus with constant voltage the power electronic interface (dc-dc buck-boost converter) is needed which allows controllable power flow with better regulation of DC bus voltage. The power flow during boost mode operation is controlled by Dynamic evaluation control algorithm. This algorithm compensates all variations in the input / output voltages and load current to maintain DC bus voltage constant with a ripple of ± 2V under continuously varying load and input voltage condition. Energy saving under regeneration improves the efficiency of the complete system. The rate of transfer of energy from load to source has been controlled using hysteresis current control scheme.

Keywords: Ultracapacitor(UC), Electrical Vehicle(EV),Hybrid Electrical Vehicle(HEV),PMBLDC motor

1 Introduction

Electric vehicles are preferred over conventional petroleum based vehicles because they offer low emissions, higher efficiency, better control and an additional feature of regenerative braking [1]. Present research concerning electrical vehicle and HEV concentrates in the search for compact, lightweight and efficient energy storage system that is affordable as well as having acceptable life cycle. HEV has electrical and mechanical propulsion system which operates independently or together. Electrical propulsion is provided by electric motor through energy storage devices typically battery with power electronic devices and complex controller to control charge/ discharge of battery and electric motors.

To match with the vehicle characteristic, storage device has to handle peak power and relatively large energy demand. However, large electric energy storage in vehicles imposes several limitations [2]. Presently, energy storage units available are either having high energy density or high power density but not both. Batteries has high energy density (30-150 Wh/kg), moderate power (< .5 kW/kg), relatively short shelf life cycle (1 year w/o recharge) and relatively short cycle life (1Kcycles, deep discharge) [1], [2].Batteries are not designed to provide bursts of power over many hundreds of thousands of cycles. Batteries have high energy density but they fail to contribute to rapid energy drain/recovery associated with acceleration /braking of vehicle. On the other hand, ultracapacitors (UC) are capable of high power exchange but have limited energy storage. So, a combination of ultracapacitor and battery is proposed to meet the rapidly changing energy and power requirements.The peak power during acceleration/deceleration is supplied/absorbed by UC while battery supplies continuous power for normal driving. So by adding ultracapacitor, battery will be relived from supplying peak power, which allows battery to be optimized for energy storage. This may reduce the overall cost, volume and weight of the vehicle. Ultracapacitors have capacitance in terms of thousands of farads as it is built from highly porous double-layer carbon material. Their operating voltage is in the range of 2.3 to 2.7 volts [3]. They have energy density about 1-10wh/kg with wide operating temperature range about -40 to 65 C. UC require low maintenance, have long operating life and environmentally safe. The challenge now is the maximum exploitation of hybrid source having two different energy storage system within HEV power system architecture.

Direct connection of UC and battery causes both UC voltage and dc bus voltage to float with the battery terminal voltage. This does not allow utilization of full power capacity of UC. Also, to optimize the performance of both energy storage devices in terms of power flow from source to load and vice-versa, there arise a need for power electronic converter. Introducing a dc-dc converter between the battery and the ultracapacitor offer several advantages: 1) The ultracapacitor voltage can be different from the battery voltage, which offers flexibility with respect to the design of the battery and ultracapacitor module, 2) The power capacity can be much higher than that of the passive hybrid without exceeding the safety limit of the battery current, 3) The weight of the power source for a given peak power can be smaller than that of a passive power source for the same load, and 4) the dc-dc converter can also serve as the battery/UC charging regulator while a passive hybrid power source would require a separate battery/UC charger [4]. In this paper non-isolated half bridge dc-dc converter topology is selected.Each power source is connected to the dc bus by means of bidirectional step up (boost) or step down (buck) dc-dc converter. This converter facilitates the active control of power flow from UC and battery to load and vice-versa efficiently. Bidirectional power flow allows versatile operating modes that enhance HEV performance [5], [6].

A control algorithm needs to be developed for dc-dc converter that would control the charge /discharge rate of energy storage device to regulate DC bus voltage and current as per the load conditions .Various control algorithms have been proposed in the literature to regulate the dc bus voltage with boost converter supplied by energy storage devices as well as for buck converter. This includes sliding mode current control, hybrid control, dynamic evaluation control, adaptive fuzzy logic control, PI control, hysteresis current control and many more control algorithms. A sliding mode [7] current controller was proposed, which has faster response and lower voltage overshoot over a wide range of operation but having higher implementation cost and circuit complexity compare to peak current controller. Still problem of RPH zero may not be resolved. Hybrid control scheme [8] involving energy based switching scheme was proposed for dc-dc buck boost converter and the result shows that the transient response is quite good with respect to line and load disturbances. The main drawback of the proposed control scheme is that the converter works in discontinuous conduction mode which is not suitable for high current loads. Dynamic control algorithm turns out to be the most suitable control algorithm for controlling dc-dc boost converter operation due to its better dynamic performance [9]. The advantage is that dynamic evolution control can compensate all variations in the input and output voltages, load current and inductor current. It contributes to the better dynamic performance of the converter system. In addition, the controller also has a good response to error converging speed.

Power sharing between two energy storage devices is implemented with energy management algorithm. Efficient utilization of hybrid energy storage device requires excellent energy management algorithm so that the peak power during acceleration/deceleration is [10] supplied/ absorbed by UC while battery supplies continuous power for normal driving. The described management may reduce the overall cost, volume and weight of the vehicle. Considerable efforts have been made to address various energy management algorithms to control energy flow through multiple energy sources [10]. This includes rule based, fuzzy logic based energy management algorithm, dynamic programming, sliding mode control, neural network Control and genetic algorithm. Rule based energy management control algorithm based on the vehicle power and current requirements is designed for proper selection of energy storage devices.

The objective of this paper is to control hybrid power supply system comprising of battery-UC with buck-boost converter for EV/HEV application. The system is tested with different types of loads like pulse load and BLDC motor [11] subjected to constant load. Rule based energy management algorithm is used to select appropriate energy storage device under different load conditions. The power electronics converters/inventers are used to change the voltage levels/convert the form of electrical power. Dynamic control algorithm is used to control the operation of dc-dc boost converter to maintain DC bus voltage constant feeding the inverter. Dynamic control algorithm has a constant frequency operation as well as no compensator network is required. Hysteresis-current-control algorithm is used to control charging rate of UC through buck converter which provides better power efficiency due to absence of complex control. Energy saving being the key feature of HEVs is obtained during deceleration/braking. Kinetic energy in the rotating parts of machine is converted into electrical energy during deceleration /braking which is being used to charge ultracapacitor preferably as battery is not able to absorb power at high rate. The complete system is tested using MATLAB Simulink under different load conditions.

2 System Configuration and Operational modes

Reliable converter topologies as well as optimum dynamic control techniques are required to operate system in its best efficient mode.

2.1 System Configuration

Fig.1 shows block diagram of proposed system. The system consists of two energy storage units battery and ultracapacitor, inverter fed constant load BLDC motor, multi-switch bidirectional dc-dc converter for charging and discharging operation of ultracapacitor/battery during regeneration and motoring mode respectively.

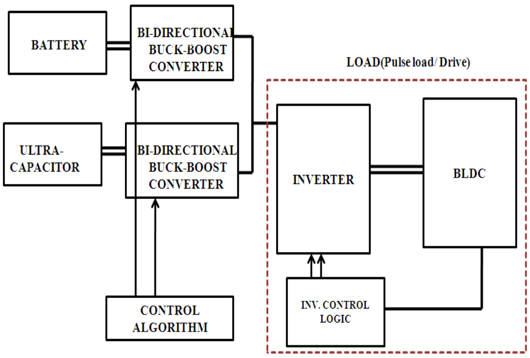

Figure 1 Basic Block Diagram

Fig.2 shows dc-dc converter topology for battery and ultracapacitor hybrid source. Both storage devices are interfaced to DC bus through individual buck boost converter.

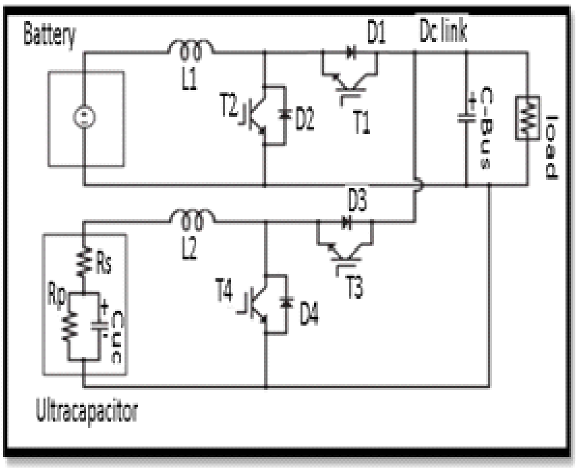

Figure 2 Buck-Boost Converter Topology

2.2 Operating Modes

The whole system operates in 3 different modes like normal mode, peak power mode, regenerative mode and charging mode with the assumption that battery and UC are 100 % charged before the operation starts.

Peak power mode - When motor is accelerated from zero speed under constant load torque requirement, the current demanded by motor is very high compared to rated current. Under this condition power is supplied by ultracapacitor through switch T4. T4 operates the converter in the boost mode and the power flow is controlled using dynamic control algorithm.

Normal mode – When the load current demand is lower than the nominal battery current, then the load current is supplied by battery only through switch T2. T2 operates the converter in the boost mode and the power flow is controlled using dynamic control algorithm.

Regenerative mode – During regeneration motor shaft gains kinetic energy due to its own inertia and load inertia. During deceleration, kinetic energy of rotating elements(BLDC motor) is converted into electrical energy. This regenerative energy is utilized to charge the ultracapacitor and battery through switch T3 and T1. T3 and TI operate with their respective converter in the buck mode and the power flow is controlled by a hysteresis control algorithm.

2.3 Energy Management Algorithm

The operating modes obtained are selected based on the load current. For the appropriate selection of energy storage device rule based [10] energy management algorithm is used. Fig.3 shows the energy management algorithm that helps in selecting the correct mode of operation of converter either of battery or ultracapacitor.

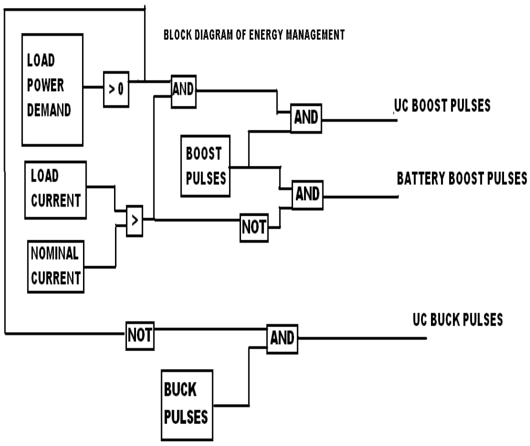

Figure 3 Energy Management Algorithm

UC and battery both storage devices have some peculiarities which needs to be kept in mind while selecting their range of operation. This range is selected in such a way that maximum efficiency is obtained without any loss of life expectancy. So, UC having a good power density as compared to the battery is allowed to handle peak demands. On the other hand battery having a better energy density as compared to UC so is allowed to handle nominal current demands.

Selection of device basically depends on power demand and the load current. Power is delivered to load which is considered as positive during acceleration or constant speed of operation [4]. Vice-versa, power stored in energy storage device during deceleration/braking is taken as negative. Now, during positive power demand the battery operation is selected if the load current demand is less than the nominal current of battery else UC supplies power to the load.when power demand is negative regenerative braking takes place and energy transfer takes place to battery/UC.

3 Control Algorithms

HEVs a suitable alternative to conventional vehicle, demands to have a proper control algorithm for an efficient, reliable and affordable converters. Control algorithms are designed to direct the system operation so that desired results are obtained. Here, two algorithms having different control aspects are discussed.

3.1 Dynamic Evaluation Control Algorithm

To maintain DC bus voltage constant under varying load conditions with continous variation in input voltage dynamic control algorithm is used. Dynamic evolution control algorithm compensates all variations in the input and output voltages, as well as the change of inductor current under load condition. Thus, it decreases rise time with steady state error in acceptable band. In addition, the controller also has a good response to error converging speed.

As the Electric Vehicles are dynamic systems in which the parameters like input voltage (specifically UC voltage), inductor current, output voltage, load current and system losses are continuously varying. Dynamic control algorithm is designed for such system in which these parameters variations are considered continuously for effective corrective action.

The basic idea of dynamic evolution control [9] is that error is allowed to follow exponential evolution path allowing it to decrease it to zero by,

$$E = Eo * e^{-mt} \qquad \textbf{(1)}$$

where, **E** is the error representing dynamic characteristic of the system, **Eo** is the initial value of E, **m** is a design parameter specifying the rate of evolution. Higher the value of m lesser will be the time taken by the error to reduce it to zero [9].
The above function can also be written as,

$$\frac{dE}{dt} + m * E = 0 \qquad \textbf{(2)}$$

Effective duty-cycle (D) equation of the converter can be generated by incorporating the effect of different parameters represented as D (Vout, Vin, iL, R). State-space average model of converter simplifies the expression of D in boost mode which can be expressed as,

$$Vin = L* \frac{diL}{dt} + Vout *[1-D] + iL*R \qquad \textbf{(3)}$$

Rewritten as,

$$Vout = Vuc + (Vout*D) - L* \frac{diL}{dt} - iL*R \qquad \textbf{(4)}$$

where,L is the inductance, R is the system resistance which is equivalent to $R_{esr} + R_L + R_D$, Vuc is the input voltage, Vout is the output voltage, D represents the duty cycle of the converter in the boost mode.

Presuming that, the selected E is a linear function of error voltage.

$$E=k*verr \qquad \textbf{(5)}$$

Where,k represents a positive coefficient, Verr is the error voltage

Taking derivative of equation (5) gives

$$\frac{dE}{dt} = k * \frac{dverr}{dt} \qquad \textbf{(6)}$$

Substituting (6) in (3) we get,

$$k * \frac{dverr}{dt} + m * k * verr = 0 \qquad \textbf{(7)}$$

Modifying equation (7) gives,

$$k * \frac{dverr}{dt} + (m * k - 1) * verr + V_{ref} = V_{out} \qquad \textbf{(8)}$$

Solving (8) and (3) the expression for duty cycle D which is the control action for the converter controller is obtained as

$$D = \frac{Vref-Vuc}{Vout} + \frac{(m*k-1)*Verr}{Vout} + \frac{k*\frac{dVerr}{dt}}{Vout} + \frac{L*\frac{diL}{dt}}{Vout} + \frac{iL*R}{Vout} \qquad \textbf{(9)}$$

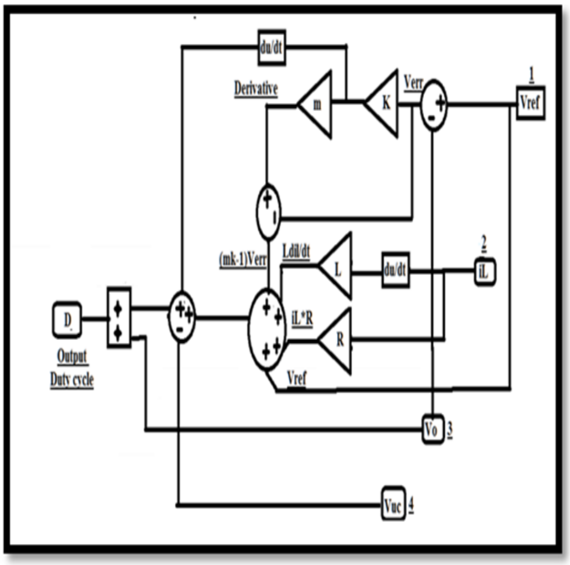

Figure 4 Dynamic Control Algorithm

It is interesting to note that the control law in **(10)** consists of five distinct parts. The first part is the feed forward term, considers input voltage variation during control action. The second and third terms are like the proportional and derivative whose gain varies with output voltage. Fourth term consists considers ripple in the inductor current. The last term considers the compensation to be applied in return to parasitic loss which leads to more of accurately compensated system. The output of D as shown in Fig.4 is used generating switching cycles according to f_{sw} (switching frequency) selection using PWM technique [9].

3.2 Hysteresis Control Algorithm

It works on the simple current feedback loop which itself gives the effective results. In this control, two current references (upper band reference), (lower band reference) are generated, one for the peak and the other for the valley of the inductor current as shown in Fig.5. According to this control technique, the switch is turned on when the inductor current goes below the lower reference and is turned off when the inductor current goes above the upper reference, giving rise to a variable frequency control. The ripple content depends on the limits that are selected in the hysteresis current band control scheme [12], giving rise to a variable frequency control.

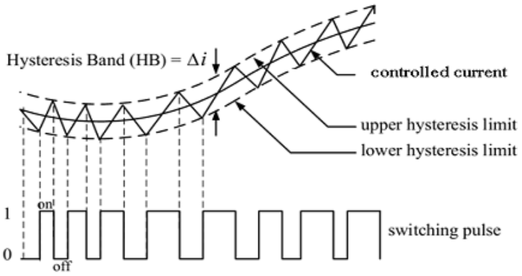

Figure 5 Hysteresis Algorithm Based Pulse Generation[12]

4 System Operation withVarying Load

4.1 Pulse Load

The EV and HEV operate with common load profile, described by relatively high peak to average power required. This type of load can be very closely represented by repetitive cycle of pulse load [4] with constant peak and average current. Battery ultracapacitor hybrid power source which is shown in Fig.2 is simulated under pulse load condition that consist of repetitive cycles of peaki and average current demand.

To test hybrid power source, battery (24V, 14A) and ultracapacitor (28V, 50F) performance under pulse load conditions, with the load having demand ranging between 4-30 A is taken.

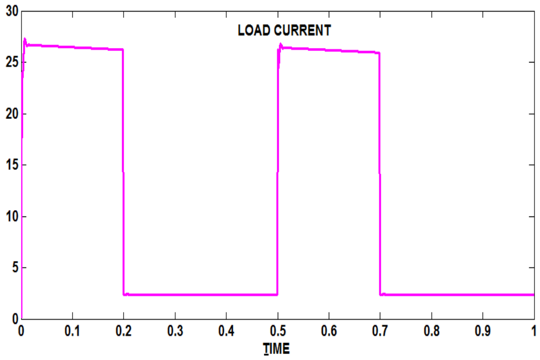

Figure 6 Load Current

The load profile which is shown in Fig.6 demands high current of 27A up to 0.2s and it demands the nominal current of 4A for 0.3s. 20kHz switching frequency is used to control boost mode operation using dynamic control algorithm.

Power sharing between two energy storage devices is implemented with energy management algorithm which is shown in Fig.3. Energy management algorithm will select appropriate energy source based on the power demand of the pulse load as well as the SOC levels of the electrical energy sources. Power flow through battery and ultracapacitor can be controlled based on their SOC levels and load current demand. Ultracapacitor provide peak current and battery provide average current and during deceleration regenerative energy is absorb by ultracapacitor as shown in Fig.7.

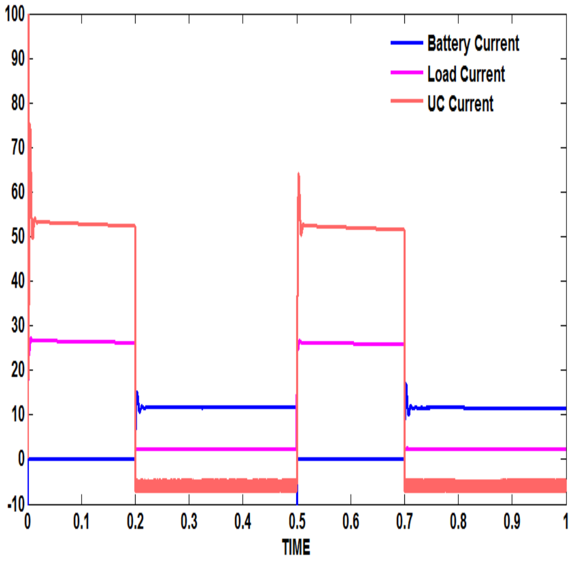

Figure 7 Current Distribution among UC and Battery Based on Load Current

Positive inductor current is the current supplied from either UC or battery. When load current demand is less than battery nominal current, then battery supplies power to the load as well as charges ultracapacitor. If load current is greater than the nominal current of battery, ultracapacitor supplies power to the load. Negative inductor current is the current responsible for charging ultracapacitor. Ultracapacitor current delivering capacity changes depending on the load requirement which in turn varies the rate of change of UC terminal voltage. Fig.8 shows the variation in UC terminal voltage under given pulse load profile. Fig.9 shows the constant DC bus voltage under continuous variation in UC input voltage due to pulsating load demand.

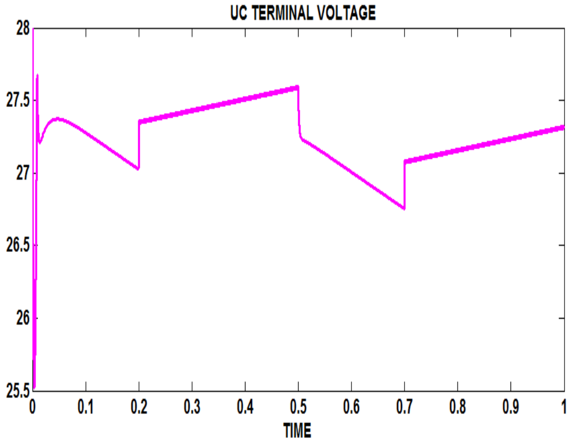

Figure 8 UC Terminal Voltage

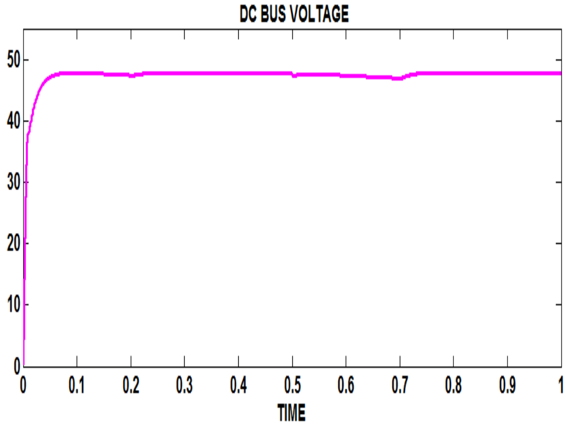

Figure 9 DC Bus Voltage

4.2 PMBLDC Drive With Constant Load Torque

PM BLDC motor drives are specifically known for their high efficiency and high power density [11]. Therefore, such drive system is used in EVs and HEVs that drive the complete system.Control of BLDC motor in both motoring mode and regenerative mode is applied with help of sensing rotor position. Speed current control loop allow motor to develop requested power and speed demanded by vehicle in both motoring mode and generating mode. Transition from motoring mode to regenerative mode requires current direction to be reversed compared to motoring mode. This is implemented with the help of rotor position sensor which provide switching information for inverter.

Vehicle always move with repetitive cycles of acceleration/deceleration and constant speed. To test the hybrid power source performance with BLDC drive with constant load torque, the required motor speed profile is shown in the Fig.10.

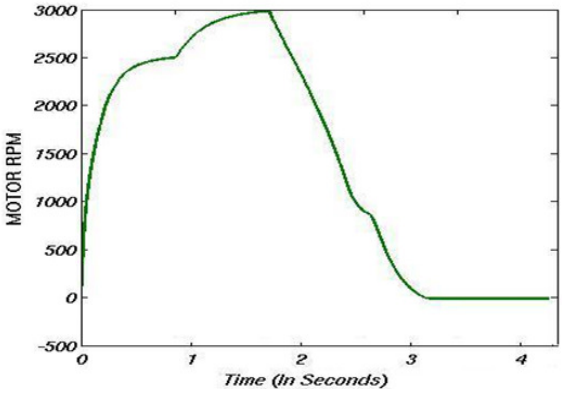

Figure 10 Motor Speed in RPM

The modes of the speed profile are: Acceleration (0-0.8s), Constant (0.8-1.7s) and deceleration (1.7-3.2s). Fig.11 shows the torque developed by motor under constant load. Positive torque is required during acceleration and negative torque during deceleration.

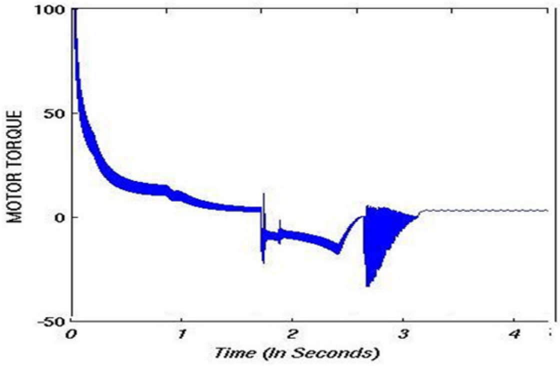

Figure 11 Motor Torque

To deliver required amount of torque and current demand of motor under suggested motor speed profile appropriate selection of energy storage device has been carried out using proposed energy management algorithm discussed in section 2.3. The current taken from the UC is treated as negative while charging current is treated as positive as shown in Fig.12. UC handles peak power demand occurring during acceleration mode for the period 0-0.8s. But battery supplies average power demanded by the load during constant speed operating mode for the period of 0.8-1.7s as shown in Fig.13. Fig.12 and 13 shows the distribution of current between UC and battery. This protects battery operation under peak power demand which enhance the battery life span and reduces the size of battery.

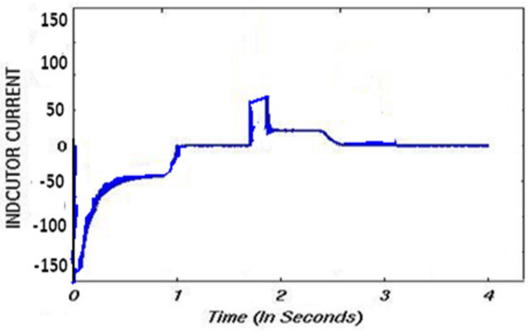

Figure 12 Inductor Current

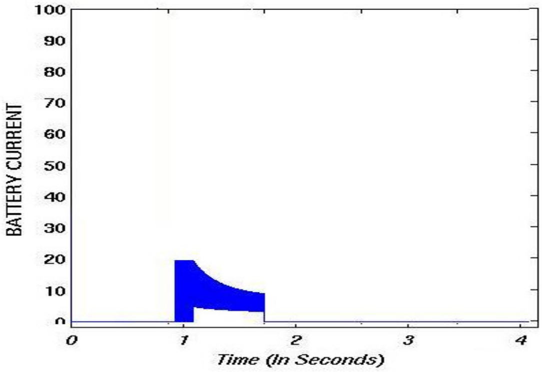

Figure 13 Battery Current

Acceleration leads to discharging of ultracapacitor while deceleration leads to charging as shown in Fig.14. During deceleration mode, regenerative braking helps in taking back the stored energy in the rotating parts of the drive system by charging the storage device. UC charging is preferred as it has fast charging-discharging capability.

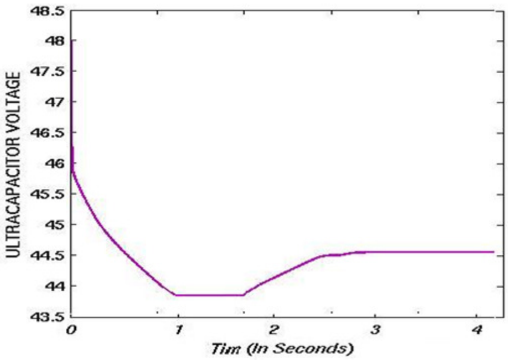

Figure 14 Ultracapacitor Voltage

5 Conclusion

The battery-ultracapacitor hybridization can bring significant benefits to hybrid electric vehicles, as hybridization of UC-battery satisfy the high peak to average power demand of vehicle. This is possible due to the complementary characteristics of batteries and ultracapacitors.This leads to reduction in weight, volume and overall efficiency of the hybrid electric vehicle. Floating point voltage in direct parallel interface of battery-UC is avoided using a power electronic converter.

The simulation studies of an active hybrid battery ultracapacitor power source have been carried out with respect to pulse load and BLDC motor with constant load using MATLAB simulink environment. Simulation results shows that DC bus voltage with a ripple of ± 2V under continuously varying load and input voltage of UC is maintained constant using dynamic control algorithm. Dynamic control algorithm has a constant frequency operation , no compensator network is required as well as computations involved are minimum which makes it suitable for real time applications. The operation of an active hybrid results in a much lower battery current with very small ripples, avoiding the deep charge-discharge of the battery and therefore a lower battery temperature and longer battery lifetime. The simulations results shows that the control system works properly, meet all the average and transient loads requirements through proper selection of UC battery with the help of rule based energy management algorithm and thus achieves the best possible utilization of all the energy sources. Under regeneration kinetic energy is absorbed by UC which improves the efficiency of hybrid storage system.

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