Impact of Variable Hysteresis Control in Evaluating the Performance of an Ultra-Capacitor Configured Energy Storage System for Electric Vehicles

Shrikant Misal [1] B.P. Divakar [2]

Abstract– Uncontrolled frequent charging and discharging of batteries is of great concern to Electric Vehicle manufacturers. The idea wherein the battery is made to supply a constant base load with an energy buffer taking care of transient load is gaining acceptance. Ultra-capacitor can undergo several charge-discharge cycles and absorb/deliver energy for short durations such as during acceleration and deceleration. Because of this property, hybrid energy storage system concepts have been developed by interfacing ultra-capacitors and batteries. There are many ways in which the hybrid energy storage system can be configured in electric vehicles. In this study, a topology wherein, the ultra-capacitor is interfaced with the battery through a bi-directional converter is considered and analyzed. The performance of the hybrid system in which the capacitor voltage is controlled with hysteresis control is studied in detail and several limitations with the control have been brought out. Results reveal that there is a need for adjusting the hysteresis window, so as to control the power being delivered from or to the battery. The study aids sizing of capacitor in the hybrid system.

Keywords– Electric vehicle (EV), battery, ultra-capacitor (UC), hybrid energy storage system (HESS), bidirectional DC-DC converter, hysteresis window

I. INTRODUCTION

Energy Storage System (ESS) is one of the most important components of an electric vehicle that play a vital role in improvising the overall performance of the complete drivetrain configuration. A conventional battery-based ESS possess several limitations which are needed to be worked upon like: i) Low power density ii) Thermal Management iii) Cell Balancing iv) Frequent charge-discharge cycles leading to deterioration v) Size and cost. In a typical urban driving condition, owing to sudden acceleration and braking actions of an Electric Vehicle (EV), batteries are subjected to transient loads very often. Research works have already proved that the batteries when subjected to a constant load profile perform more efficiently and can last longer. Hence to overcome these limitations of a conventional battery based energy system as highlighted above, different Hybrid Energy Storage System (HESS) configurations integrating battery and ultra-capacitor (energy buffer) have been suggested in literatures [1-4], [6] and [7]. Interfacing the battery and an ultra-capacitor through a controlled dc/dc converter results in battery size reduction and better overall performance [1], [3] and [6].

There are few configurations for HESS design proposed in literatures [1-8] and [10-12] wherein battery and ultra-capacitor are configured uniquely to share the load. Some of the prominent configurations are i) Ultra-capacitor/Battery configuration having UC at the input of dc/dc converter and Battery at its output. The advantages associated with this configuration are: a) The battery which is directly connected to the DC link yields a rather constant DC link voltage and b) The UC energy can be used in a wide range by controlling bi-directional dc/dc converter. The disadvantages associated with this configuration are: a) there is no means to protect the battery from transients and b) the bi-directional converter should be rated to handle the UC power in addition to the load demand. ii) Battery/Ultra-capacitor configuration having battery at the input and ultra-capacitor at the output of dc/dc converter. The advantages associated with this configuration are: a) requires battery with lower voltage rating b) better utilization of the energy stored in UC because the UC voltage is allowed to swing in a wide range. The only limitation associated is that the design calls for optimization of UC and converter size for better utilization of energy. iii) Cascaded configuration implements two dc/dc converters in cascade in such a manner that second converter is connected at the output of first. This is an extended version of Battery/UC configuration. A major advantage associated with this configuration is that UC voltage can be further controlled in much more efficient and precise manner to meet the variable load requirements. The only disadvantage associated with this configuration is the overall cost since two converters are implemented. iv) Multiple Input Converter configuration permits series connection of converters for high voltage application. The advantages associated with this configuration are: a) High voltage implications of dc link can be efficiently met since both the energy buffers are not unduly stressed and b) The UC energy is fully utilised resulting in battery size reduction. Few disadvantages associated with this configuration are the complexity of the system as well as the challenge of optimizing the sizes of both battery and UC to meet the requisite power demands. v) Multiple Converter configurations paralleling the output of two converters instead of cascading [1]. The advantages associated with this configuration are the use of two dc/dc converters with input from energy buffers helps in effective optimization of energy associated with each buffer resulting in reduced stress on the battery. The disadvantages associated with this configuration are increased cost and complexity.

The configuration, in which a bidirectional converter is interfaced between a battery and an ultra-capacitor, is the widely preferred topology [12-15]. Even though this design alleviates the peak power seen by the battery, the battery is still subjected to frequent charge and discharge

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[1] Department of Electrical and Electronics Engineering, M.S. Ramaiah University of Applied Sciences, Bangalore, E-mail: shrik88@gmail.com
[2] Department of Electrical and Electronics Engineering, REVA Institute of Technology and Management, Bangalore, E-mail: eebpdiva@hotmail.com

operations. A Battery/Ultra-capacitor configuration is implemented in [1] where the ultra-capacitor is directly connected across the load so as to meet the power demanded by the load. This configuration has the advantage of flexibility in varying the dc link voltage in accordance with frequent charge and discharge operations of the ultra-capacitor.

Organization of the paper

The HESS configuration presented in [1] is introduced in II, significance of hysteresis window in III, mathematical modeling of the bidirectional converter in IV, simulation of mathematical model in V and various simulation studies in VI, inferences drawn from simulations in VII followed by concluding remarks in VIII.

II. ULTRA-CAPACITOR CONFIGURATION

A. *Operation Of Battery/Ultra-Capacitor HESS Configuration :*

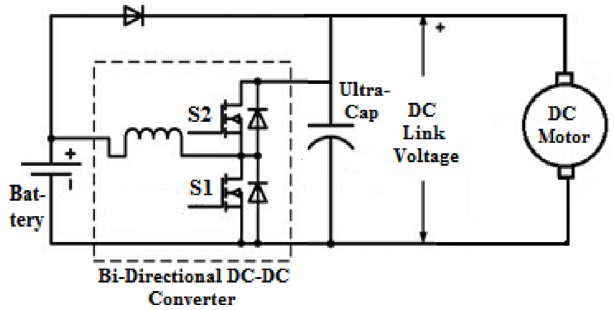

Fig.1: Battery/Ultra-Capacitor Configuration [1]

An ultra-capacitor based energy storage system configuration is as shown in Fig.1 wherein the battery is interfaced with the ultra-capacitor through a bidirectional dc-dc converter that acts as a boost converter in the forward mode and buck converter in the regenerative mode.

The function of the capacitor is to transfer and absorb transient energy thereby making the battery see a stable load. Thus it protects the battery against frequent charge/discharge cycles thereby extending the life of the battery. Since the battery voltage is stepped by boost action, this configuration requires less number of batteries in the string.

B. *Control Strategy :*

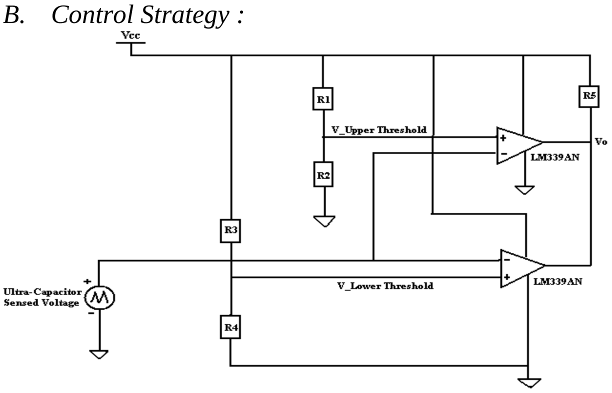

Fig.2 Circuit Diagram of Window Comparator

The capacitor is expected to deliver or absorb energy as and when required by the load so that the battery supplies a steady load. As the energy supplied or absorbed depends on the difference of the square of the maximum and minimum voltage of the capacitor, the voltage swing of the capacitor has to be monitored and controlled for effective operation of the system. In present scheme, the well-known hysteresis method, in which the capacitor voltage is maintained within an upper and lower limit, has been employed. The band width plays a significant role during forward and regenerative mode of the bidirectional converter. Hence the main focus of this paper is to present various options for choosing hysteresis band and their effectiveness in satisfying the energy requirements. Fig.2. shows the schematic of the window comparator wherein two op-amps compare the capacitor voltage with upper and lower reference value respectively.

C. *Generation of PWM Signals for Lower and Upper Switch:*

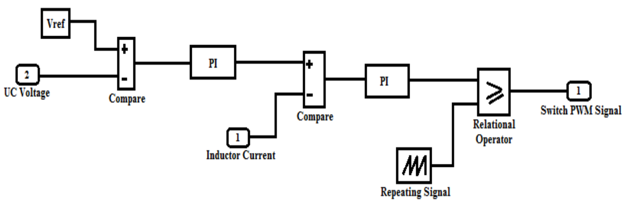

Fig.3 Block diagram of PWM Sub-system

The operating mode of the motor load: forward or regenerative, influences the switching action of the dc-dc converter. The gate signal generation scheme is incorporated using a PWM subsystem as shown in Fig.3 above. Here current mode control has been employed for controlling the battery current during forward and regenerative modes.

The current in the inductor is sensed and compared with a reference signal which is produced from the PI controller to which the error between the sensed capacitor voltage and the reference is fed. The error between the sensed inductor current and the commanded value is again passed through the second PI controller and compared with the ramp signal for controlling the switches. Through the pulse steering circuit, the generated signals are applied to the appropriate switches depending on the mode of converter operation.

III. SIGNIFICANCE OF HYSTERESIS WINDOW

The energy stored in an ultra-capacitor is a function of the magnitude of capacitance value and the square of the hysteresis band/window as shown in Eq. (1).

$$E_{UC} = (1/2)\, C\, (V^2_{max} - V^2_{min}) \tag{1}$$

where

E_{UC} = Energy stored by ultra-capacitor
V_{max} = Upper threshold voltage level attained by capacitor
V_{min} = Lower threshold voltage level attained by capacitor

And

$$E_{UC} = P_O\, T_D \tag{2}$$

$$E_{UC} = P_{IN}\, T_C \tag{3}$$

where,

P_O = Output power delivered by the ultra-capacitor
P_{IN} = Input power absorbed by the ultra-capacitor
T_D = Discharge time of ultra-capacitor
T_C = Charging time of ultra-capacitor

From Eq. (1) one can observe that the energy stored and released by the capacitor depends on the two thresholds. Similarly from equations (2) and (3) one can observe that the power delivered or absorbed by the capacitor varies inversely with the respective discharging or charging period of capacitor. Hence it can be concluded that the energy stored or released by the ultra-capacitor can be controlled by controlling the hysteresis band or the charge/discharge period.

IV. Mathematical Modeling Equations Of Bi-Directional Converter

Mathematical model of the bi-directional converter for both boost and buck mode of operation can be realised based on the operation of motor load connected at its output i.e. boost operation for motoring mode and buck operation for regenerative mode. The equations governing this bi-directional operation of the converter are:

Buck Mode:

$$(di_L/dt) = [V_g - (1\text{-}D)V_o] / L \qquad (4)$$

$$(dV_o/dt) = [\, i_L - i_o \,] / C \qquad (5)$$

Boost Mode:

$$(di_L/dt) = [(1\text{-}D)V_o - V_g] / L \qquad (6)$$

$$(dV_o/dt) = [\, i_o - i_L \,] / C \qquad (7)$$

where,

i_L = Current through Inductor
i_o = Converter Output Current
V_g = Input Voltage of Converter
V_o = Output Voltage of Converter

Since the inductor current (i_L) and the output voltage (V_o) of the converter are responsible for determining its overall performance hence equations (4) to (6) have a significant role in developing a mathematical model for implementing the simultaneous boost and buck operation of the converter. Eq. (4) governs the boost operation of the converter with a duty cycle '*D*' while Eq. (6) governs the buck operation of the converter.

V. Simulation of Mathematical Model For Converter Circuit

The Fig.4 below shows a complete mathematical model of the bi-directional converter depicting the cyclic forward and regenerative operation of the motor load.

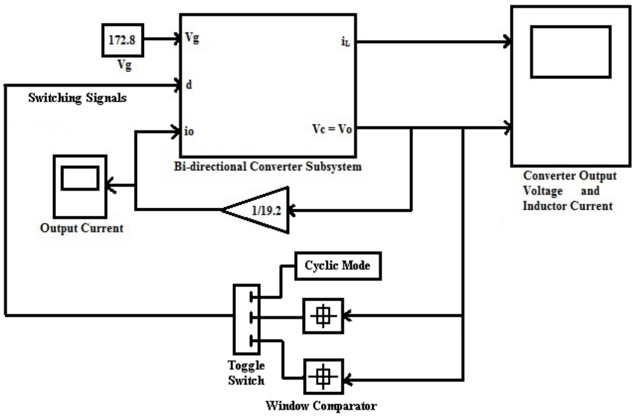

Fig.4: Bi-Directional Converter Mathematical Model

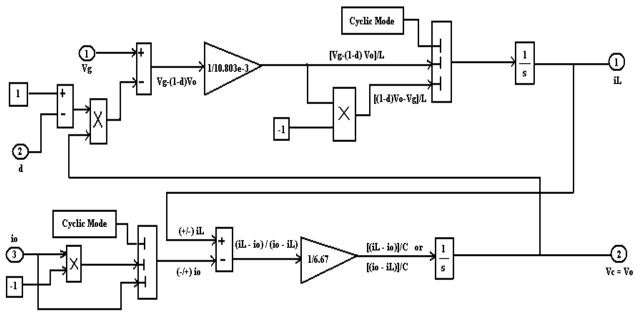

Fig.5: Bi-Directional Converter Sub-system

Fig.5 represents the bi-directional converter sub-system realizing equations (4) to (7) for its respective boost and buck operation as discussed in the previous section. The model has been developed to depict the bidirectional features of the system simultaneously.

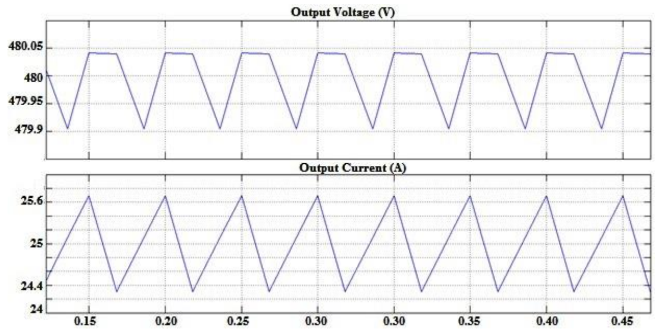

Fig.6: Simulation Results in Boost Mode. Top: Capacitor Output Voltage and Bottom: Output Current

The simulation results from the model shown in Fig.4 are shown in Figures 6 and 7 for the forward mode (generation mode or boost mode) and regenerative mode (buck mode) respectively. During forward mode, the output voltage is tightly regulated at 480V for an input voltage of 172.8V from the battery. The capacitor voltage almost remains constant at 480V because of the 0.15V hysteresis window. The inductor current of the boost converter has an average value of 25A with a ripple content of 1.4A. The on period is indicated by the up-slope of the inductor current while the off period is indicated by the down-slope of the inductor current. The capacitor discharges during the on time and support the load till the switch is turned off. During the off period, the energy stored in the inductor is used to charge the capacitor and to supply the load.

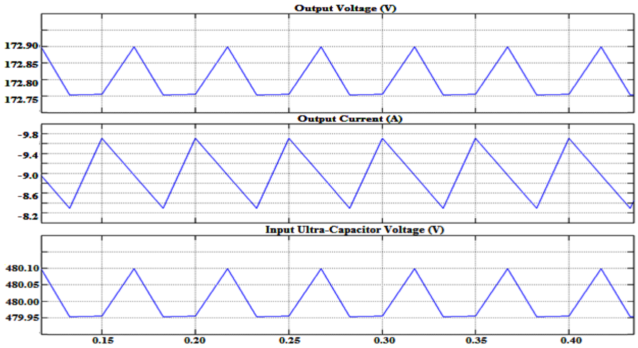

Fig.7: Simulation Results in Buck Mode. Top: Rated Battery Voltage. Middle: Battery Charging Current and Bottom: Input Capacitor Voltage

The bidirectional model can also describe the operation during regeneration in which the capacitor is made as the source and battery as the sink. In the regenerative mode, the load current is reversed and the capacitor is made as the source feeding the bidirectional converter which now is operated in the buck mode.

In the regenerative mode, the capacitor's voltage as before is controlled within a hysteresis band of 0.15V. The plots shown in Fig.6 confirm the bidirectional capability of the mathematical model.

VI. HESS Circuit And Simulation Results

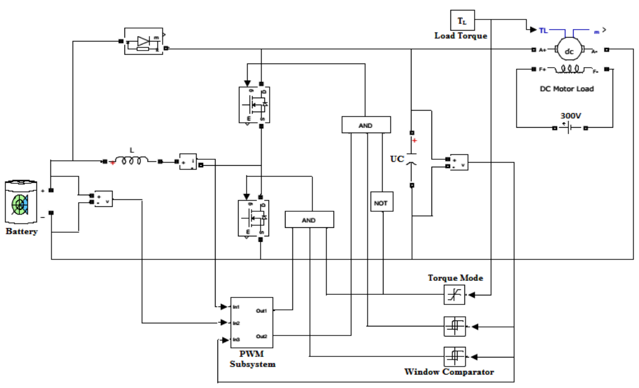

Fig.8: Complete Simulation Circuit of a Battery/Ultra-Capacitor HESS Configuration

The complete simulation model at the circuit level is depicted in Fig.8 and the simulation specifications are shown in Table I. As mentioned earlier, control of capacitor voltage influences the system's performance; hence several strategies highlighting their pros and cons are considered and discussed below.

Case I: Normal Window of Hysteresis

a) Forward Operation: With a Band (450 – 480)V for Load Torque (T_L) = 150Nm

In this mode of operation the capacitor voltage is allowed to vary between 450V and 480V. The characteristic of this mode is that the load is being supplied mainly by the battery and partly by capacitor as indicated by its discharge profile. The energy lost by the capacitor will be replenished by the battery in every cycle.

Table 1: Typical Ratings and Characteristics of the Components Used in Simulation

	Ni-Mh Battery	Ultra-Capacitor	DC-DC Converter	DC Motor Load
Specifications Used	172.8V, 180Ah	6.67F, 500V_{max}	Constant Efficiency, 12kW Continuous	100HP Max., 500V, 1750rpm
Nominal Cell Voltage (V)	1.25	2.5-2.7		Armature Parameters: $R_a = 0.1968\ \Omega$ $L_a = 0.00342H$ Field Parameters: $R_f = 58.82\ \Omega$ $L_f = 7.267H$
Energy Density (Wh/Kg)	60-120	5-30		
Power Density (W/Kg)	220	4000-10000		
Charge/Discharge Cycles	300-500	Upto 1000000		
Operating Temperature (°C)	-20 to 65	-40 to 65		

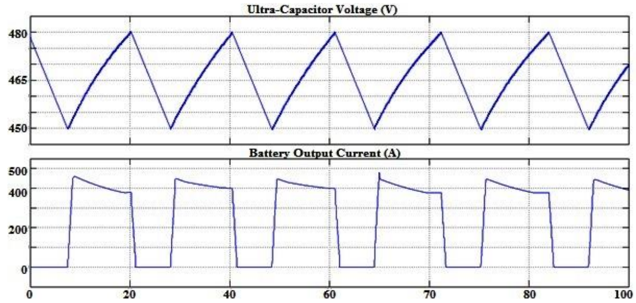

Fig.9: Simulation Results in Forward Mode for Normal Window. Top: Ultra-Capacitor Voltage and Bottom: Battery Current

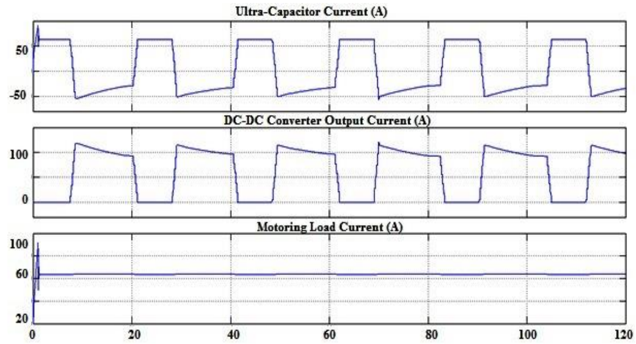

Fig.10: Simulation Results in Forward Mode for Normal Window. From Top: Ultra-Capacitor Current, DC-DC Converter Output Current and Motoring Load Current

Various plots are given in Figures 9 and 10 from which one can determine ratings of various devices. A 150 N-m of motor load will demand a peak current of 400A from the battery and that will translate into 100A peak of output current from bi-directional converter.

Hence the conducting switches S_1 and D_2 will see a peak current of 400A in the forward mode of operation. Because of the nature of the hysteresis band, the capacitor is allowed to discharge thereby the entire load of 63A is met by the capacitor alone. Thus the battery does not contribute during the time when the capacitor is able to meet the load demand on its own. As can be seen, the battery current is a series of high pulses which will reduce the life of the battery. Therefore, it can be inferred that the capacitor voltage should be properly regulated by dynamically adjusting the width of the window thereby allowing the battery to supply a constant base load.

b) Reverse Operation: With a Band (480 – 500)V for Load Torque (T_L) = -150 Nm

This case study pertains to the regenerative mode in which the regenerative load of 150Nm is considered and a hysteresis band of (480-500)V is taken. The upper limit has been increased to 500V with an intention of storing higher energy in the capacitor, which can be utilized when the demand arises.

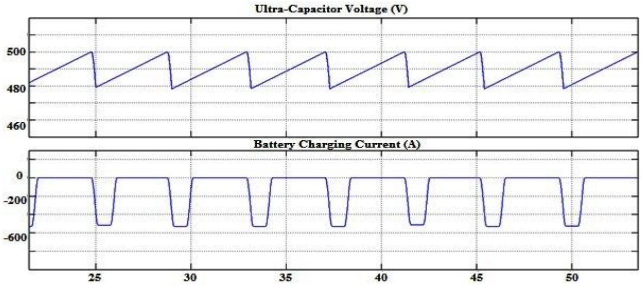

Fig.11: Simulation Results in Regenerative Mode for Normal Window. Top: Ultra-Capacitor Voltage and Bottom: Battery Current

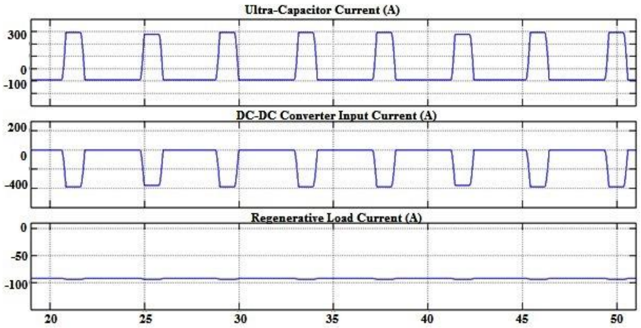

Fig.12: Simulation Results in Regenerative Mode for Normal Window. From Top: Ultra-Capacitor Current, DC-DC Converter Input Current and Regenerative Load Current

In the forward mode, 90A of regenerative current and 300 A peak from the capacitor are translated into 390A peak current at the input of the bidirectional converter. Hence the battery will be charged with a peak current of 530A due to buck operation. In this mode, switch S_2 and diode D_1 will be in conduction.

The capacitor is mainly responsible for absorbing the sudden inrush of regenerative power from the load and once it reaches the upper threshold of 500V, it discharges until the lower limit of 480V before the start of the next cycle. The simulation highlights hidden aspect of the window comparator. It helps the capacitor to store and discharge as much energy as desired depending on the hysteresis width. However, it will result in high discharge current from the capacitor during regeneration if measure is not taken to prevent unnecessary discharge by the capacitor.

c) Combined Forward and Reverse (Cyclic) Operation: For Load Torque (T_L) = 150 Nm and -100Nm

In this case the simulation is carried out with alternate forward and regenerate mode cyclically to test the validity of the model. Accordingly the cyclic mode of operation has been implemented for a fixed hysteresis voltage window of (450-480)V during forward torque and (480-500)V during regenerative mode. Here both the upper and lower limits are changed according to the mode of operation for effective utilization of capacitor energy. The switching signals for switches S_1 and S_2 are generated as per the mode of operation with the help of the mode detection block.

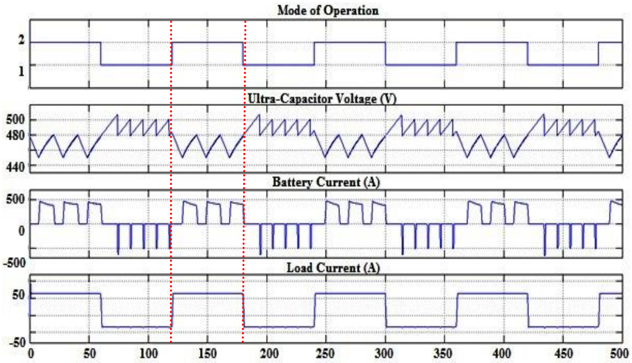

Fig.13: Simulation Results in Cyclic Mode From Top: Mode Signal, Ultra-Capacitor Voltage, Battery Current and Load Current

The simulation results for cyclic operation are shown in Fig. 13. The mode of operation is detected by the direction of the load current shown by the bottom trace. The positive polarity shows the forward mode while the negative polarity indicates the regenerative mode. In the forward mode, both the upper and lower limits of the hysteresis band are lowered to allow the capacitor to meet the sudden demand. Thus at the start of forward mode, the capacitor discharges until it reaches the lower limit from there it begins to charge from the battery towards the upper limit. Therefore from the start of the forward mode up to the point of lower limit, the battery remains idle. Similarly when the mode changes from forward to regeneration as indicated by the second vertical line, the upper and lower hysteresis windows are increased so as to permit charging of the capacitor thereby protecting the battery from sudden inrush power.

Case II: Increased Window of Hysteresis

a) Forward Operation: Hysteresis Window of (400 – 480) V for Load Torque (T_L) = 150Nm

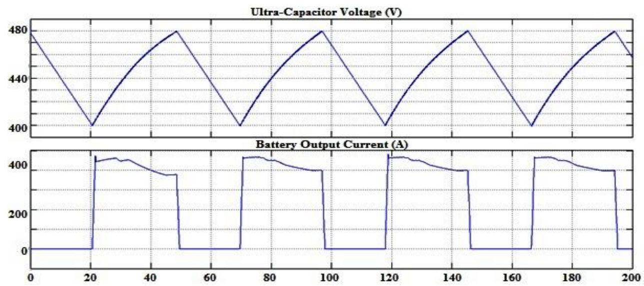

Fig.14: Simulation Results in Forward Mode for Increased Window. Top: Ultra-Capacitor Voltage and Bottom: Battery Current

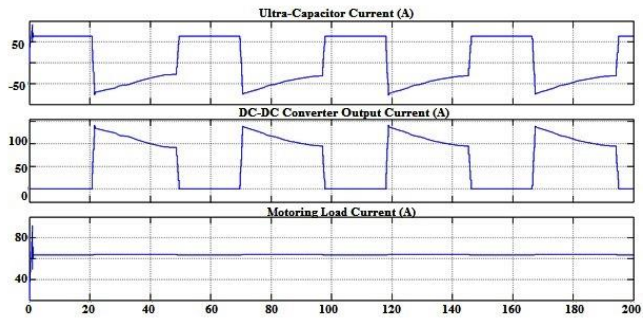

Fig.15: Simulation Results in Forward mode for Increased Window. From Top: Ultra-Capacitor Current, DC-DC Converter Output Current and Motoring Load Current

The simulations are carried out with an increased window of (400–480)V. This increased window has naturally increased the time taken to discharge the capacitor and has increased the energy stored by 1.52 times as compared to Case I. This increased energy will mitigate the sudden change in future power requirements.

b) Reverse Operation: Hysteresis Window of (450 – 500) V for Load Torque (T_L) = -150Nm

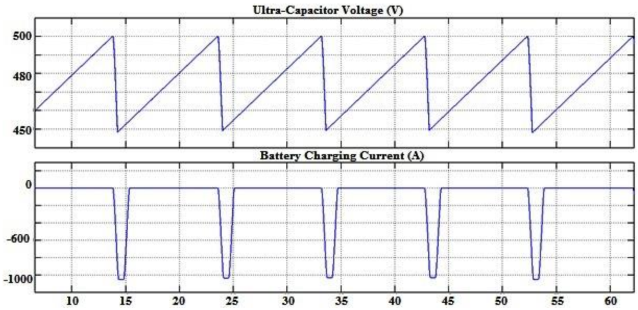

Fig.16: Simulation Results in Regenerative Mode for Increased Window. Top: Ultra-Capacitor Voltage and Bottom: Battery Current

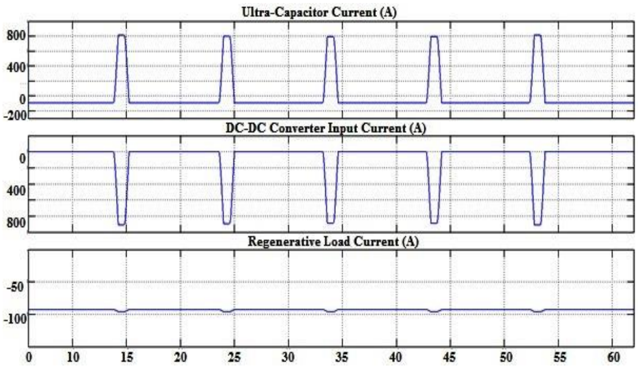

Fig.17: Simulation Results in Regenerative Mode for Increased Window. From Top: Ultra-Capacitor Current, DC-DC Converter Input Current and Regenerative Load Current

This case is similar to case I but with higher hysteresis window. The increased window permits storage of more regenerative energy in the capacitor thereby protecting the battery against inrush power.

c) Combined Forward and Reverse Operation: for Load Torque (T_L) = 150 Nm and -150Nm

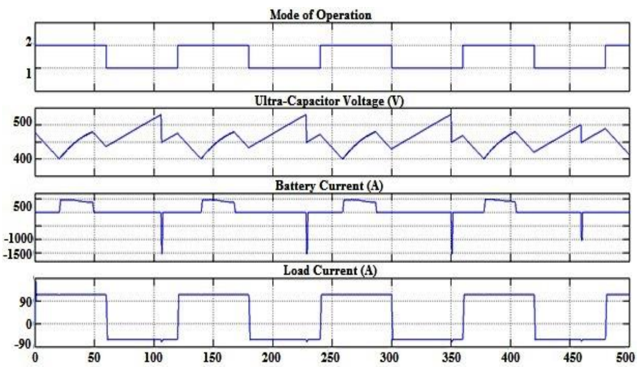

Fig.18: Simulation Results in Cyclic Mode from Top: Mode Signal, Ultra-Capacitor Voltage, Battery Current and Load Current

A simulation of combined forward and regenerative mode of operation is carried out as seen in Fig.18. During forward operation the upper limit is fixed at 480V while the lower limit has been decreased to 400V. The basic intention behind increasing the window is to make the UC discharge deeper so as to meet the load requirements for longer duration of time. Similarly for the regenerative operation the lower limit is fixed at 450V while the upper limit has been changed to 500V with intent to make UC store more regenerative power compared to Case I.

Case III: For Reduced Hysteresis Window Control

Simulation studies pertaining to the first two cases have brought out one basic drawback with the present control strategy that hysteresis window not only causes frequent charging-discharging of the ultra-capacitor but also of the battery. Because the capacitor is connected across the load and supplied by the battery, discharge of the capacitor can cause the battery to replenish the lost charge. If hysteresis control is employed with a large window, the battery will see a pulse load required to charge the capacitor.

Thus there is a serious limitation associated with this topology wherein the capacitor is directly connected across the load and made to meet the change in load demand. Taking account of above situation, the desirable option would be to maintain a steady voltage across the capacitor for constant power loading which can cause the power delivered from the battery to be constant for constant load thereby extending the battery life.

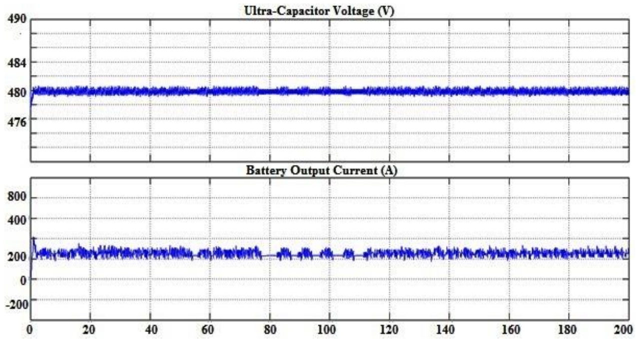

Fig.19: Simulation Results in Forward mode for Reduced Window Top: Ultra-Capacitor Voltage and Bottom: Battery Current

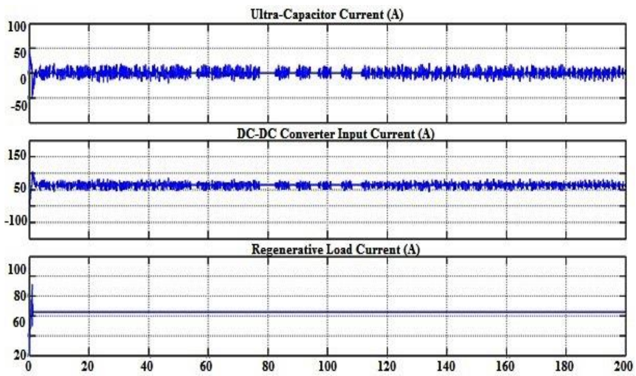

Fig.20: Simulation Results in Forward mode for Reduced Window from Top: Ultra-Capacitor Current, DC-DC Converter Output Current and Motoring Load Current

So considering these aspects, a case study with a very small window of Hysteresis i.e. (480-479.8) V for the forward operation and (499.8-500)V for the reverse operation of the motor load has been carried out. During forward operation as shown in Figures 19 and 20, an average battery input of 225A will be responsible for charging the capacitor at a constant current of 63.75A through Boost operation of converter. Similarly for regenerative operation shown in Fig. 21 and 22, a constant regenerative current input of 93A will be charging the battery at a constant current of 200A through buck operation.

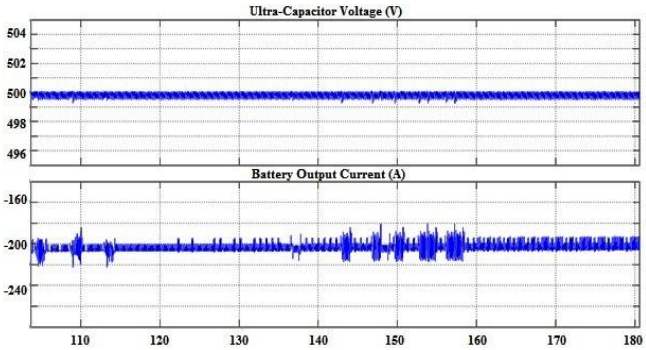

Fig.21: Simulation Results in Regenerative Mode for Reduced Window. Top: Ultra-Capacitor Voltage and Bottom: Battery Current

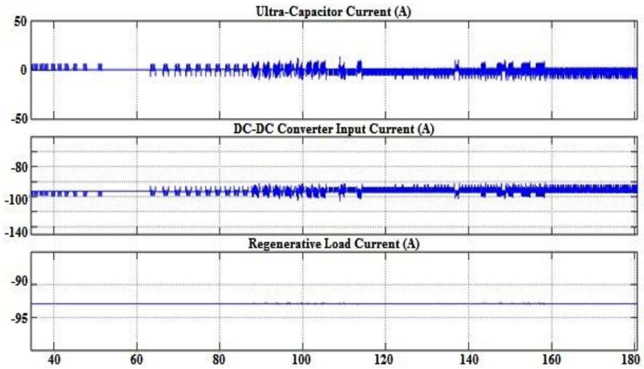

Fig.22: Simulation Results in Regenerative Mode for Reduced Window. From Top: Ultra-Capacitor Current, DC-DC Converter Input Current and Regenerative Load Current

With the reduced window, the capacitor voltage has been confined within a smaller band resulting in tighter control over charging and discharging of the capacitor. From the view point of longevity of capacitor this profile is very much favorable but it will not permit the capacitor to either discharge during sudden change in the load as happens during acceleration of motor load or to charge during regeneration.

Case I, II and III considered simulation under various windows and highlighted their advantages and limitations. For cases I and II, the battery is subjected to pulse currents of high magnitude. On the other hand the simulation with reduced window as in case III overcomes the above limitation but it does not allow the capacitor to share the load during forward and regenerative modes. So the desirable feature is to have the windows dynamically changed with respect to the mode of operation as well as the load thereby letting the capacitor to participate actively in load sharing with the battery.

A simulation study is therefore carried out with dynamically changing windows during forward and regenerative modes. In this study, four cycles lasting for 125 sec are considered. The first two cycles are for the forward operation with increased and reduced windows respectively. The next two cycles are for the regenerative mode with increased and reduced windows respectively. The results are depicted in Figures 23 and 24.

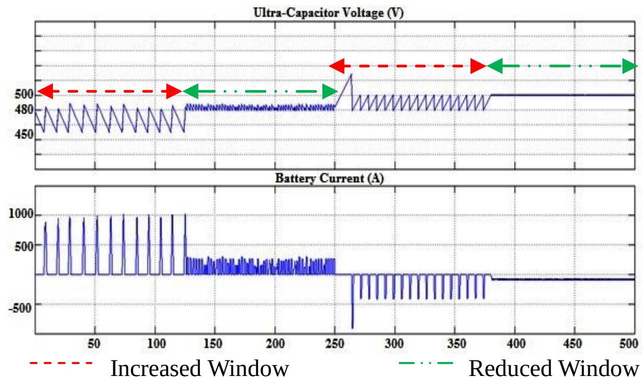

Fig. 23: Simulation Results for Combined Mode with Variable Window; Top: Ultra-Capacitor Voltage and Bottom: Battery Current

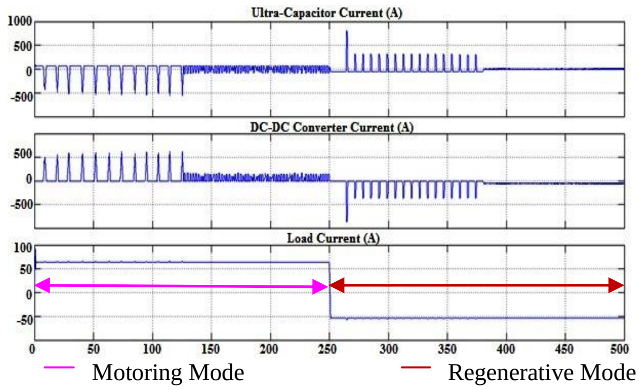

Fig. 24: Simulation Results for Combined Mode with Variable Window. From Top: Ultra-Capacitor Current, DC-DC Converter Current and Load Current

From 0-125 sec, the capacitor voltage is controlled with a larger window. Thus the capacitor is able to discharge its energy into the load from the instant voltage reaches the upper limit. After the capacitor reaches its minimum limit, the energy is supplied by the battery. Thus the battery supplies both the load as well as the capacitor. This mode of operation is not beneficial for the battery which has to supply high peak pulses. From 125-250 sec, the capacitor voltage is confined to a smaller window. As a result, the peak current from the battery has decreased. The next two sections from 125-375 sec and 375-500 sec show the result for regenerative mode with increased and decreased window.

Thus from the simulations it can be seen that by dynamically adjusting the hysteresis window, it is possible to control the charge and discharge rate of the battery.

VII. Summary Of Simulation Results

The power delivered or absorbed by the capacitor for the operating period to support the given load, the influence of hysteresis window and the magnitude of capacitances used are depicted in bar graphs discussed below. Figures 25 to 28 show the plots of output power delivered or absorbed versus time in forward mode and regenerative mode respectively for different values of capacitors.

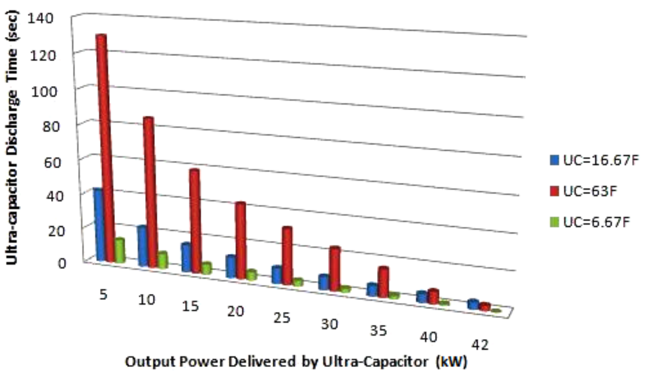

Fig.25: Ultra-Capacitor Output Power Delivered Vs Time for Normal Window of Hysteresis Control

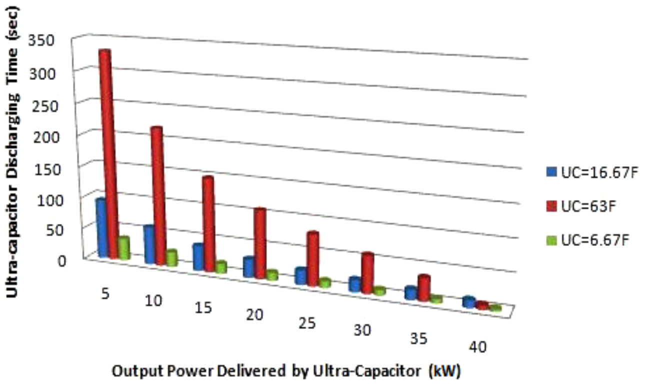

Fig.26: Ultra-Capacitor Output Power Delivered *Vs* Time for Increased Window of Hysteresis Control

Figures 25 and 26 show the plots for the normal (450V-480V) and increased (400V-480V) hysteresis control bands. Different capacitor ratings of 6.67 F, 16.67F and 63F are considered for the study. For normal window, it can be seen that the capacitor with large rating of 63F is able to deliver a large burst of 30-40kW quite amicably for almost 10-20 sec as against 4-8 sec from the smaller capacitors. As expected from the studies made in the previous sections, the increased window causes the capacitors to discharge more power into the load compared with the normal window. Hence, when burst of power is needed for acceleration, the window may be increased by lowering the lowest threshold.

Similarly the increased window allows the capacitor to discharge deeper such that the power demand is met for a sustained period of 20-50 sec.

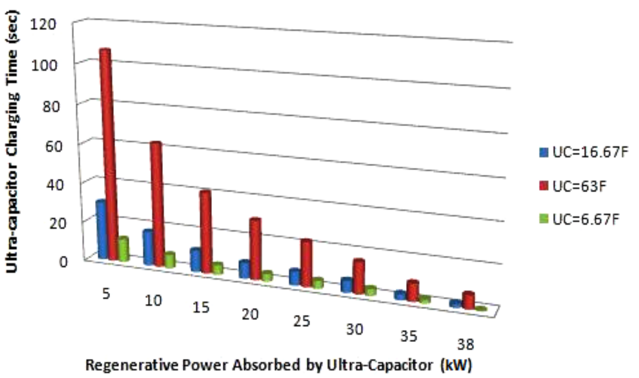

Fig.27: Regenerative Power Absorbed by Ultra-Capacitor *Vs* Time for Normal Window of Hysteresis Control

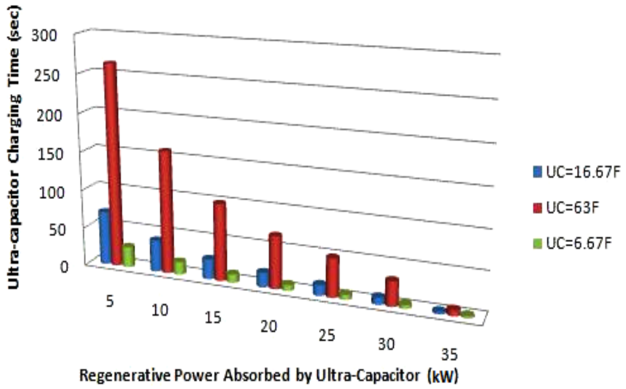

Fig.28: Regenerative Power Absorbed by Ultra-Capacitor Vs Time for Increased Window of Hysteresis Control

The regenerative power absorbed versus time plots for normal (480V-500V) and increased window (480V-500V) are shown in Fig. 27 and 28 respectively. The plots confirm that the energy stored is directly proportional to the value of the capacitor as well as the window width. The study shows that by proper selection of window size and capacitor, the battery can be protected against sudden bursts of regenerative power. Through the plots one can select appropriate windows and capacitor so as to absorb or deliver the required energy.

VIII. CONCLUDING REMARKS

In the present simulation study, the impact of hysteresis window on the performance of a hybrid system wherein the ultra-capacitor, fed by a bidirectional converter directly connected across the load is discussed. The simulation study was mainly carried out for various cases in the forward as well as regenerative modes of the motor load pertaining to different capacitances and different hysteresis windows. From the simulation results it can be seen that the smaller hysteresis window will prevent frequent charge-discharge cycles of the capacitor and does not allow the capacitor to deliver or absorb sudden thrust of power. On the other hand, the larger hysteresis window causes charge-discharge cycles but permits discharging of capacitor to meet the sudden demand. Thus the load seen by the battery during forward and regenerative mode can be controlled by controlling the hysteresis window. Hence there is a need for a variable window controller that will adjust not only the window but also the upper and lower limits in accordance with the modes of operation. In all the previous literatures, there is no discussion on varying the upper and lower limits of the hysteresis band. The simulation study clearly depicts that the energy management of ultra-capacitor is very vital for the operation. The present paper has shown that the capacitor energy can be better managed by making the upper and lower limits variable depending on the operating modes. The paper has thoroughly analyzed the variable window control supplemented by the model of the bidirectional topology. The simulation study helps in the selection of the capacitor and the hysteresis band.

IX. FUTURE WORK

In the battery/ultra-capacitor HESS configuration discussed above, a control mechanism needs to be implemented which according to the speed of operation during either acceleration or deceleration should be able to maintain the charge on the ultra-capacitor for supplying variable load or absorbing the regenerative power for charging the battery. Hence a variable window of the hysteresis control is desired which according to the load requirements and the mode of operation can automatically shift the lower threshold limit of the capacitor voltage conveniently.

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BIOGRAPHIES

Shrikant Misal obtained his B.E (Electrical) degree from Nagpur University, India in 2010 and M-Tech (Power Electronics) degree from Visvesvaraya Technological University, India in 2013. He worked as a Teaching Assistant in Electrical Engineering department of Visvesvaraya National Institute of Technology, India from 2010-2011. He later joined M.S. Ramaiah University of Applied Sciences, Bangalore, India as an Assistant Professor in 2013. His areas of interest are ultra-capacitors, energy storage systems for electric/ hybrid/ plug-in hybrid electric vehicles and bi-directional dc-dc converters.

B.P. Divakar received the M.E. degree in Power Systems from Annamalai University, India in 1991 and the Ph.D degree in Power Electronics from the Hong Kong Polytechnic University, Hong Kong in 1998. He worked as RA/RF/Staff in the Electrical Engineering department of The Hong Kong Polytechnic University from 1998-2009. He later joined REVA ITM, Bangalore, India as Professor in 2009. His research interests include soft-switching, power factor correction, BMS, HID and LED lightings, multilevel inverters. He is guiding six research scholars and is also the PI of a funded project on BMS.