Supercapacitor Implementation for PV Power Generation System and Integration

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***Abstract*—Novel hybrid energy storage system configuration is introduced by interleaving the supercapacitor between the electrostatically sensitive devices (ESDs) and DC-link capacitors that can handle all power demands in transient or steady state conditions, and perform the ESD functions. The new system integrates an adaptive sliding-mode DC-DC control method to address the voltage permutations and ensure the required output voltage. Bi-directional power flow, important to the continuous hybrid energy storage system operation is also fulfilled. The continuous successful operation is provided with supplemental protection controls. The operation of the proposed system is verified through simulation with Matlab/Simulink. The hybrid energy system developed in this paper can be used in several applications including electrical vehicles and grid integration of Photovoltaic (PV) systems.**

***Index Terms*—adaptive sliding-mode control, electric vehicles, grid, Hybrid energy storage, PV, supercapacitor.**

I. INTRODUCTION

Energy storage systems are becoming of greater importance due to the rising need for reliable back-up power to ensure power continuity and renewable energy power integration with potential intermittent power output. The conventional energy storage is in the form of a battery. However, an additional element is needed to provide instantaneous power for transient loads. The hybrid energy storage system has been developed to provide power for transient loads by integrating another energy storage element, supercapacitor, to overcome this challenge. Hybrid energy storage utilizes this combination of the supercapacitor and a battery to provide continuous and instantaneous demand response such as the one shown in Fig. 1 with additional PV power generation system. Hence, the hybrid energy storage system is designed to be capable of nearly all the required load responses since it has the near instantaneous response due to supercapacitor and the energy density contained within a charged battery for non-transient responses.

Hybrid energy storage has been well researched including various energy storage element combinations and configurations with several critical quantities [1-3]. It has been shown that an electrostatically sensitive devices (ESDs) and supercapacitor connected in parallel to a common dc bus is the widely used configuration for the energy storage elements [4-5]. The two energy storage elements cover the entire operational spectrum, the supercapacitor providing instantaneous response and the ESD provides steady state response [6]. Fundamentally, different demand responses are a result of the nature and design of each energy storage element type so determination of the demands nature, and differentiation thereof, expresses the required response [1-3]. Hence, the procedures and processes to achieve such a task complicates the control structure and requires additional resources.

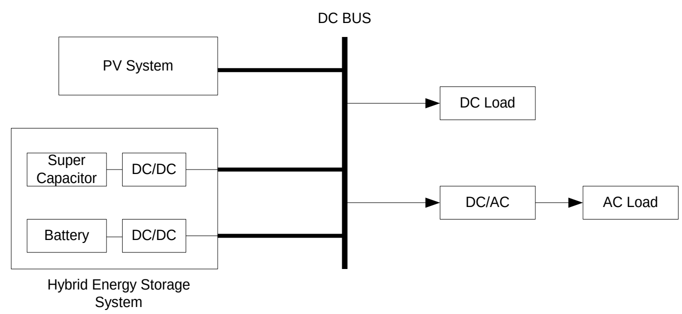

Fig. 1. Typical hybrid energy storage system.

In this paper, novel hybrid storage system configuration according to author's knowledge has been developed by interleaving the supercapacitor between the ESD and DC-link capacitor. This enables the supercapacitor to directly handle all power demands in transient or steady state conditions, and perform the ESD functions to maintain the supercapacitor charged. Furthermore, the configuration proposed eliminates the differentiation regarding the nature of the power demand and thus reduces the system's control complexity. The adaptive sliding-mode DC-DC control method [7] is integrated to the configuration to address the voltage permutations to ensure the desired output voltage. The new hybrid storage system provides bi-directional power flow which is important to the continuous hybrid energy storage system operation as well. The continuous successful operation is fulfilled with supplemental protection controls to prevent component failure. The operation of the proposed configuration is simulated and verified with Matlab/Simulink using Power Systems toolkit.

II. FORMULATION

In the proposed hybrid energy system, the bi-directional DC-DC converter is based on the cascaded buck-boost converter topology which has an intermediate stage to store energy at a higher voltage and allows the overlap between battery voltage

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and DC bus voltage in the whole operating range [8] as shown in Fig. 2.

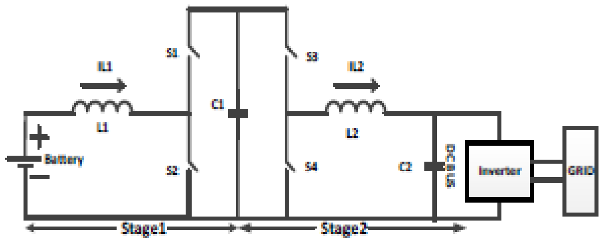

Fig. 2. Cascaded buck-boost converter topology [8].

The new hybrid system that is developed in this paper places the supercapacitor as the intermediate capacitor in this topology. It operates at a high reference voltage as the supercapacitor voltage and hence it reduces the complexity in the control scheme. This is due to fact that supercapacitor's charge is used to track its reference as power must flow through the interleaved stage throughout operation. The equivalent circuit of the supercapacitor [9] used in the system is given in Fig. 3.

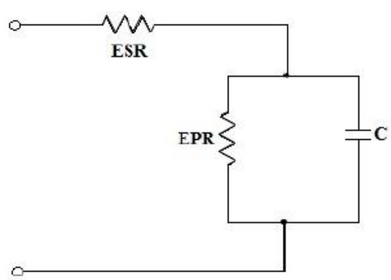

Fig. 3. The equivalent circuit of the supercapacitor.

In the equivalent circuit shown in Fig. 3, an equivalent series resistance (ESR) is used to represent charging and discharging, capacitance (C) and parallel capacitor (EPR) represent the losses during discharging [10]. The total supercapacitance and supercapacitance resistance are all described in [11].

The computational burden in regards to the nature of the power demand with the parallel energy storage configuration makes the control scheme's cumbersome. The proposed interleaved configuration with supercapacitor eliminates several challenges such as filtering to categorize the nature of the load presented and need for processing resources [1] or prior knowledge of the required load for processing [4]. The proactive adaptive sliding mode controller is integrated to the proposed design to achieve the correct response to a maximum transient load and all other transient loads of lesser magnitude. This control method also eliminates the potential need for additional computation. Proper DC-DC converter control providing bi-directional power flow allows the system to be recharged during periods of low or null demand for continuous operation. The adaptive sliding-mode controller achieves this through the use of the direction of current flow. The capability of the control to track the reference voltage ensures that the system output requirements are fulfilled. The adaptive sliding mode control for DC-DC converter used in the proposed design [7] is shown in Fig. 4.

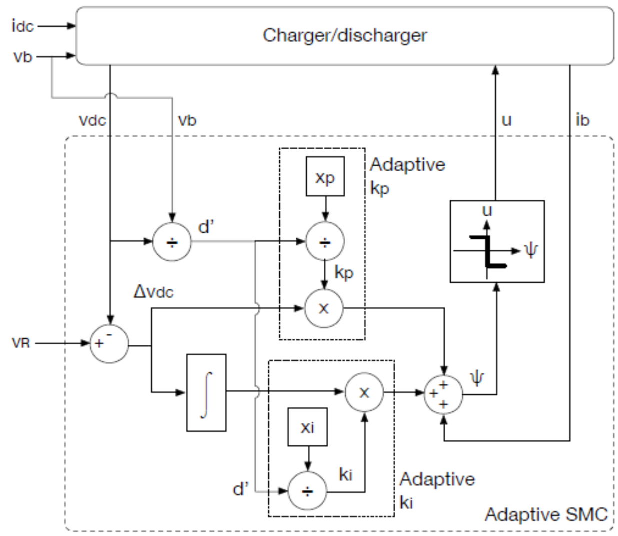

Fig. 4. The adaptive sliding mode control for dc-dc converter.

The fundamental theory governing sliding mode control defines a sliding surface, a defined value so the controlled quantity value slides around that target value. The controller in Fig. 4 triggers an opposite output once a determined threshold is away from the control variable surface of reference value. Two complementary signals, one to each switch, result which influences the DC-DC converter operation to bring the output value towards its reference. The switching function is a combination of the system state vectors and dictates a change in a control vector. The optimal condition for control vector occurs when the control function resides at the reference value. When less than or greater than the reference quantity for the control function is characterized, the switching function will reach a deviation threshold and the control will operate to reverse the systems motion.

The proposed hybrid energy system interleaving the supercapacitor is illustrated in Fig. 5. The interleaved supercapacitor in Fig. 5 operates at a voltage greater than both the ESD and output and hence provides greater available energy suitable for the transient load responses. Two DC-DC conversion stages are used to achieve this task: one to boost the voltage flowing into the capacitor from the ESD and another to buck the voltage required by the output. Maintaining the supercapacitor as the target for the boosted voltage provided by both stages allows for the fundamental control to be mirrored in regards to the boosted voltage target. With mirrored bidirectional DC-DC converters, the directions for power flow characterized by the battery current oppose each other. The second stage control only requires a scaled input and the application of a DC-DC converter duty cycle characteristic to ensure the proper power flow direction and the buck output voltage from the supercapacitor.

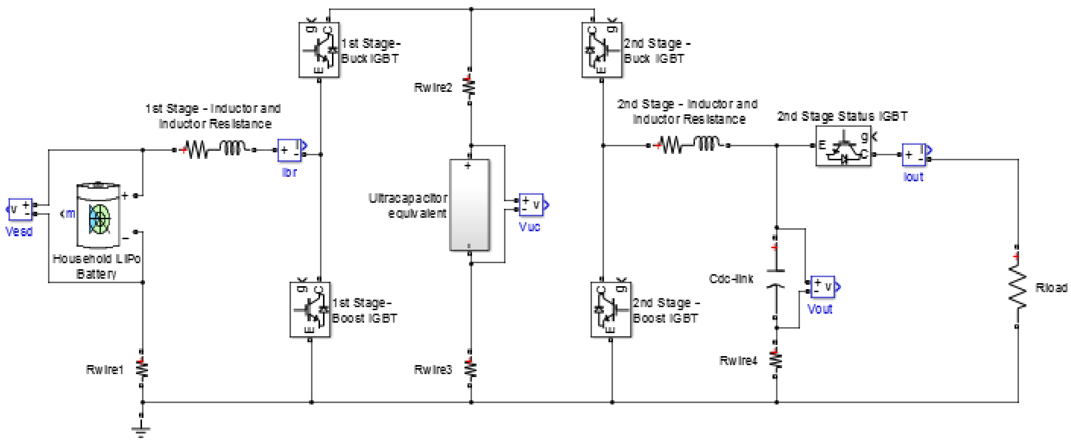

Fig. 5. The proposed new hybrid energy system.

An important property of the DC-DC converter duty cycle simplifies implementation of the adaptive sliding-mode control: the buck and boost duty cycles are complements of each other. Operation further qualifies this property: the voltage at one terminal must be greater than the other, expressing both a bucked and boosted conversion in one of the directions. The utilization of the property expressed prior with the adaptive sliding-mode control dictates that the boosted voltage for this system must be directed at the interleaved supercapacitor. The adaptive sliding mode control functions, their equations, related constraints that are used in the design are shown in Table 1 following the design process outlined in [7]. In Table 1,

- Ψ: switching function
- i_b: battery current
- i_{DC}: measured load current
- Vr: output target voltage
- V_{DC}: measured output voltage
- u: control variable/Boolean switch signal
- kp: proportional coefficient
- ki: integral coefficient.

The proportional and integral coefficients kp and ki are calculated using the equations given in Table 2 [7]. The controller stability is also addressed by analyzing closed-loop behavior presented in Table 2. Due to the discrete nature of DC-DC converter, the behavior needs to be averaged in regards to the normalized duty cycle complement, d'. The quadratic denominator clearly must not have any negative poles, verifying the range of the coefficients presented in the sections on the conditions. Furthermore, the relation between k_p and k_i can be defined. The critical values required to define the controller are the following: V_{bat}, V_{out}, element parameters, Δi_{DC}, safe response time, safe operating range. To constrain the operating frequency, a threshold value, H, must be calculated for the comparison to Ψ, resulting in the discrete control signal, u, operation which is generated using a Flip-Flop S-R and two classical comparators.

Table 1: Adaptive sliding mode control functions

	Function
Switching Function	$\Psi = i_b + k_p*(V_R-V_{DC}) + k_i*\int(V_R-V_{DC})\,dt$ ^ $\Phi = \{\ \Psi = 0\}$ (1)
Switching Function Derivative	$d\Psi = di_b/dt - k_p*V_{DC} + k_i*(V_R-V_{DC})$ (2) $d\Psi = [(V_b - V_{DC}*(1-u))/L] - k_p*[(i_b*(1-u) - i_{DC})/C] + k_i*(V_R-V_{DC})$ (3)
Power Balance	$I_b * V_B = i_{DC} * V_{DC}$ (4) $V_B = (1-d)*V_{DC}$ (5) $I_b * (1-d) = i_{DC}$ (6)
<u>Transversality</u>	Requirement: $V_{DC}/L > 0$
Condition: presence of control variable in switching function derivative	$d/du(d\Psi/dt) \neq 0$ (7) therefore $V_{DC}/L + k_p *i_b/c \neq 0$ (8) $-k_p < V_{DC}/i_b *C/L$ (9)
<u>Reachability</u>	
Control Variable Motion	$d/du(d\Psi/dt) > 0$ for u = 1 (10)
	Below Surface: $\lim_{\Psi \to 0^-} (d\Psi/dt)\vert_{u=1} > 0$ (11) $V_b/L + k_p*i_{DC}/C + k_{i*}(V_r - V_{DC}) > 0$ (12)
	Power Balance Substitutions: $(V_b/V_{DC})*[V_{DC}/L + kp*i_b/C] + k_i*(V_r - V_{DC}) > 0$ (13)
	Above Surface: $\lim_{\Psi \to 0^+} (d\Psi/dt)\vert_{u=0} < 0$ (14) $(V_b - V_{DC})/L - k_p*(I_b - i_{DC})/C < 0$ (15)
	Power Balance Substitutions: $-((V_{DC} - V_b)/V_{DC})*[V_{DC}/L + kp*i_b/C] + k_i*(V_r - V_{DC}) < 0$ (16)
Equivalent Control	$(d\Psi/dt)\vert_{u=ueq.} = 0$ (17)

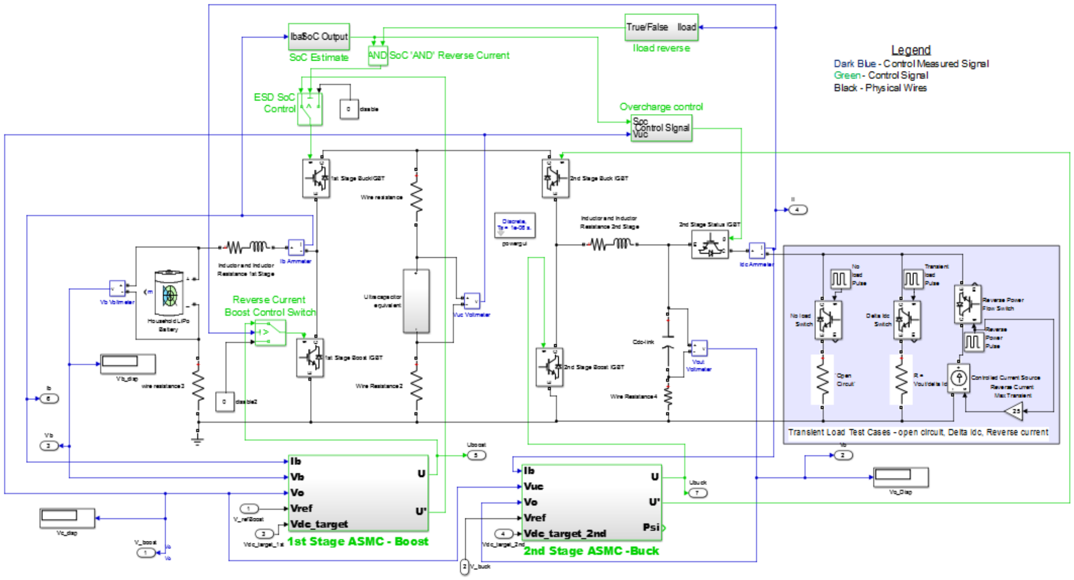

Fig. 6. The complete simulation of the proposed hybrid storage system with interleaved supercapacitor.

Table 2: Closed loop control parameters

	Equation
Closed-Loop Behavior (s-domain)	$V_{DC}(s) = [-s/(-s^2-k_p*d'*s-k_i*d'*i_{dc}(s))] + [(-k_p*s-k_i)*d']/(-s^2-k_p*d'*s-k_i*d'*Vr(s))]$ $\Rightarrow V_{DC}(s)/i_{dc}(s) = -s/(C*s^2-k_p*d'*s-k_i*d')$ (18)
Maximum Deviation	$t_{MO} = (-2*C)/(k_p*d')$ (19) $MO = [(2*\Delta i_{DC})/(k_p*d')]*\exp(-1)$ (20)
k_p	$k_p = [(2*\Delta i_{DC}) / (MO*d')]*\exp(-1)$ (21) adaptive: $k_p = x_p/d'$ (22)
	$x_p = [(2*\Delta i_{DC})/MO]*\exp(-1)$ (23)
k_i	$k_i = (-k_p^2*d') / (4*C)$ (24) adaptive: $k_i = x_i/d'$ (25)
	$x_i = -x_p^2/(4*c)$ (26)
$t_{Delta} < t_{safe}$	$\delta_{safe} = [(-\Delta i_{DC}/C)*t_{Delta}]*\exp([(k_p*d')/(2*C)]*t_{Delta})$ (27)
Hysteresis/Sw Control	$H = (1/f_{sw})*(1-(V_b/L - i_{DC}/C)$ (28)
Thresholds	Lower - -H/2; Upper – H/2 (29)

In Table 2, the parameters are defined as:

i_{DC}: measured load current
Δi_{DC}: transient load current change
V_r: output target voltage
V_{DC}: measured output voltage
d': duty cycle complement
MO: maximum overshoot
t_{MO}: maximum overshoot time
t_{delta}: time until voltage falls within MO
u: control variable/Boolean switch signal
x_p: k_p parameter unscaled by d'
x_i: k_i parameter unscaled by d'
f_{sw}: maximum switching frequency
H: hysteresis threshold

III. Simulation Results

The simulation of the proposed hybrid energy system with interleaving supercapacitor shown in Fig. 5 has been performed by Matlab Simulink using Power Systems toolkit. The verification for the operation of proposed design has been done for a household energy backup system. The AC-DC conversion is achieved using a commercially available inverter. Since the ESD and output voltage can be selected to be identical, the mirrored controller approach is implemented to a greater degree. 50 Vnom ESD was selected to have the same voltage requirements. Therefore, the adaptive sliding-mode controller parameters for both DC-DC converter stages are kept identical. The simulation design parameters are given in Table 3.

The complete system that is simulated using household energy backup system is shown in Fig. 6. The power quality requirements that are used as standards to measure the performance of the designed system are illustrated in Table 4 [12], whereas test load parameters used in the simulation are given in Table 5.

Table 3: Simulation Design Parameters

Simulated Hybrid Energy Storage Parameters	
Vb (v) and Vdc (v)	50
Vsc (v)	100
ΔIdc (A)	25
F (Hz)	95000
MO (v)	4.8
Csc (F)	5.8
Vcmax (v)	160
L (H)	.001
Cdc-link (F)	.0014
Adaptive Sliding Mode Parameters	
Xp	-3.83208
Xi	-0.63297
H	0.263135

Table 4: Power quality requirements

Nominal Voltage	$\pm$ 10%		Cycles
Voltage Sag	Below 90%		.5 – 30 cycles
Voltage Swell	Above 110%		.5 – 30 cycles

Table 5: Test load parameters for simulation of household energy backup system

	Load	Period (s)	% Active	Time (H)	Delay (s)
Open Cir	1.0E+06	.1	40	.4	.8
Δidc	2Ω (50v/25A)	2	30	.6	0.2
Reverse current	25A	2	30	.6	1.2

The voltage at one terminal must be greater than the other, expressing both a bucked and boosted conversion in one of the directions. The utilization of the property expressed prior with the adaptive sliding-mode control dictates that the boosted voltage for this system must be directed at the interleaved supercapacitor.

In the simulation, adaptive sliding mode controller is implemented as boost controller and buck controller at two stages. The controllers at the first and second stages are modeled and simulated as shown in Fig. 7 and Fig. 8, respectively. The adaptive nature of the control utilizes the difference between actual and reference voltages to maintain the sliding-mode.

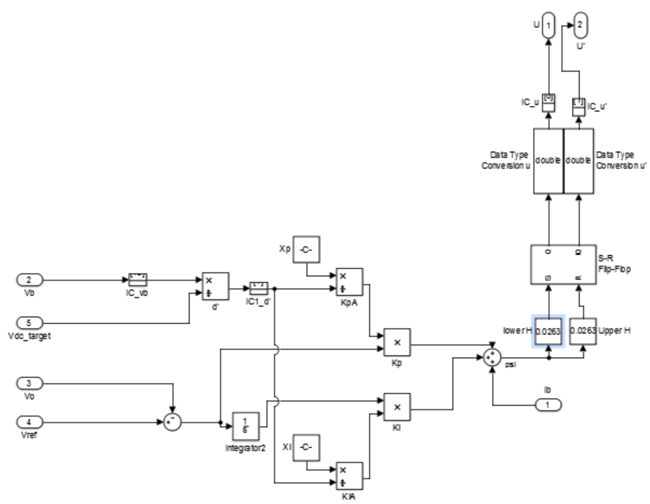

Fig. 7. 1st Stage Boost Controller Model.

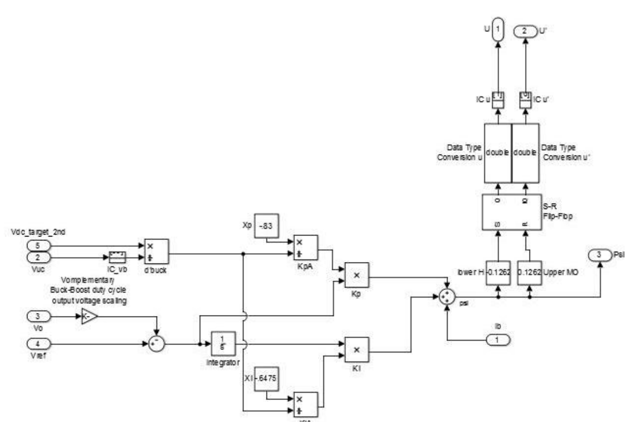

Fig. 8. 2nd Stage Buck Controller Model.

The simulation results are given in Fig. 9 and Fig. 10 for the test load parameters given in Table 5. From the system parameters provided, the output voltage, Vout in Fig. 9 (a), and output current in Fig. 10 (a) achieve the power quality definition given in Table 4. At the point of transient loading, the voltage only deviates from the nominal voltage by less than ±10% and for a period less than 0.5 cycles. The power quality requirements for household energy backup system are successfully fulfilled. Successful system operation has been achieved by providing the correct output voltage within the power quality requirements and displaying reverse power flow capabilities.

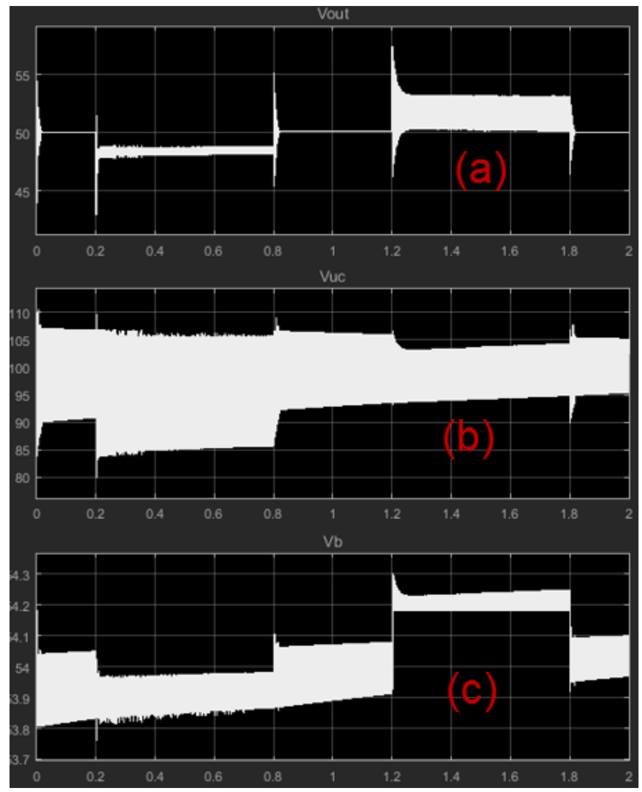

Fig. 9. Simulation results: (a) Vout, (b) Vuc, and (c) Vb.

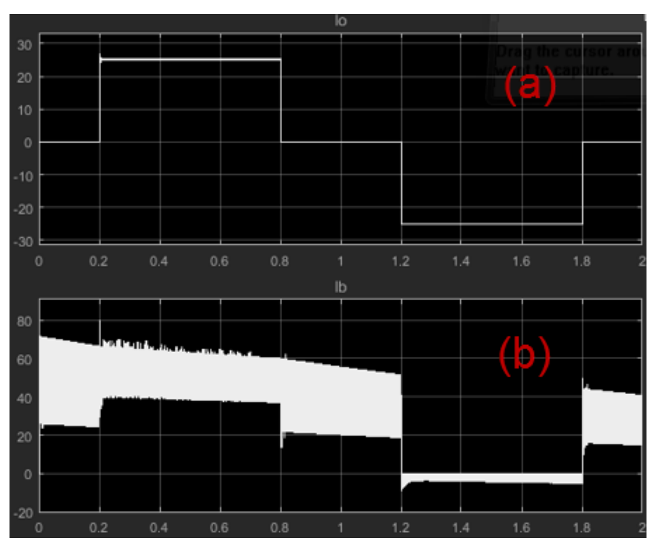

Fig. 10. Simulation results: (a) Io and (b) Ib.

It should be noted that the simulation results were attained with the initial voltage present across the supercapacitor. A large current far exceeding the ESD maximum output current and the inductor current limit threshold results without soft-start mechanism.

In summary, it has been shown that the simulation results verified the operation of the proposed interleaved hybrid energy storage system configuration using adaptive sliding-mode DC-DC converter control per the power quality requirements of the household energy backup scenario.

IV. Conclusion

In this paper, novel hybrid energy system to author's knowledge has been presented by interleaving the supercapacitor between the electrostatically sensitive devices (ESDs) and DC-link capacitors. An adaptive sliding-mode DC-DC converter control method has been adapted to have the desired bi-directional power flow and ensure the required output voltage. The simulation has been performed with Matlab/Simulink to verify the operation of the proposed design by considering the household energy backup system as the test case. Several parameters including output voltage, current and battery voltage for various load conditions has been tested. It has been shown that the proposed design with the new interleaved supercapacitor configuration met the power quality requirements as expected by minimizing the power fluctuations. The proposed design can be used in several applications including electrical vehicles (EVs) and grid integration of Photovoltaic (PV) systems.

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