Design and Small Signal Modelling of Battery-Supercapacitor HESS for DC Microgrid

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***Abstract*—This paper presents the small signal modelling and Control of Battery- Supercapacitor energy storage system in DC microgrid. Growing interest in Renewable energy sources (RESs) and the introduction of new loads like electric vehicles leads to more investigation in DC systems. The main issue with RES is its intermittent nature and an attractive solution for the above issue is the use of additional storage devices. Battery storage is able to regulate the output for a long time however unable to discharge during sudden disturbances in the system. On the other hand, supercapacitors are higher power density devices that can supply energy for a short duration. System need to control both transients as well as a steady state power flow and single device cannot able to help. Hence hybrid energy storage systems are introduced to meet the requirements. This paper discuss the Battery - Supercapacitor hybrid energy storage system modelling and control in detail. The analysis is verified through simulation study.**

***Index Terms*—Hybrid Energy Storage system, DC microgrid, Bidirectional Converter.**

I. Introduction

21^{st} century faced many drastic changes in the electricity scenario and its growing day by day. One of the biggest change is the introduction of new sources such as which converted the old fashioned- source centred power system to scattered distributed power system. This lead to the introduction of user-dependent distribution systems called AC Microgrid (ACMG) and DC Microgrid (DCMG) [1]. If the total source power is converted to AC, then its called ACMG and if it is DC, its called DCMG. Earlier, ACMG got more attention due to already developed ancestor network and most electrical loads are considered as AC. However due to the development of loads like Electric Vehicles (EVs), LED-based Lighting systems and much electronic equipment's demands DC power, which helps the growth of DCMG.

Hexagonal representation DCMG with different sources and load are shown in fig:1. The hexagon represents the transmission system and incoming arrows represent the source connections. The main sources are Photo voltaic plants (PV plants) and wind power generation plants. AC-grid can consider as a back up for the DC system. In the load side, industrial loads, data centres, electric vehicle (EV), home applications and hospital are considered separately based on the power level and application[2]. Industrial loads and data centres can be considered as continues periodic loads while home and electric vehicle loads are non-periodic loads. Compared with other loads, home and EV will consume less power. Industries, hospitals and technical centres like data centres have a different type of loads. Operation theatre in hospital, control rooms in industries, radar equipment's related to national security and flight navigation, control systems such as SCADA systems in hydro-electric power plants are some of the main loads (critical loads) that require continues DC power supply. They need continues uninterrupted power supply and must be free from transients and voltage variations [3].

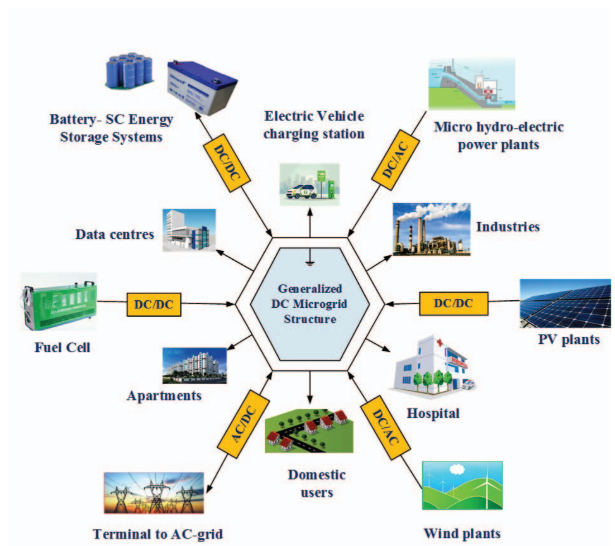

Fig. 1. Generalized Hexagonal representation of DC transmission system

Due to the unpredictable nature of RES, DCMG always face output voltage variations and sudden transients due to source disturbances. An attractive solution presented for the above issue is the use of additional energy storage's to supply power during various disturbances [4]. On account of different energy storage devices, battery got more attention due its low cost high power density. Recently supercapacitor also got the attention because its quick response towards variations. This result in the combined operation of battery and SC towards DCMG stabilization called Hybrid Energy Storage Systems (HESSs). Battery will help to mitigate the steady state

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variations and transient disturbance is mitigated with the help of Supercapacitor. Different control strategies are introduced in literature [5-10]. However the control system is designed based on common boost converter voltage- current transfer function to connect between $\hat{i_L}$ and $\hat{V_0}$. This will affect the independent operation of battery and SC [8-10]. Hence in this paper, detailed modelling and control strategy analysis for Boost converter based HESS is proposed based on small signal modelling. Outer loop for the converter is designed by considering total load current. Also deign and simulation study are explained in detail. In this paper, HESS configurations are explained in section II. Control Strategy and design explained in section III. Section IV presents the simulation results and in the V^{th} section, conclusion and remarks are presented.

II. System Configuration

HESS is an integral part of DC microgrid. In large DC system, Load side operations can be individually consider as DC microgrids and their operations can be analyzed separately. From the literature it is relevant that ES are main supporting structure for DCMG. Based on the mode of connection, HESS are classified in to three. Which are (i) Passive configuration, (ii) Semi-active configuration and (iii) Fully active configuration, and is shown in Fig.2.

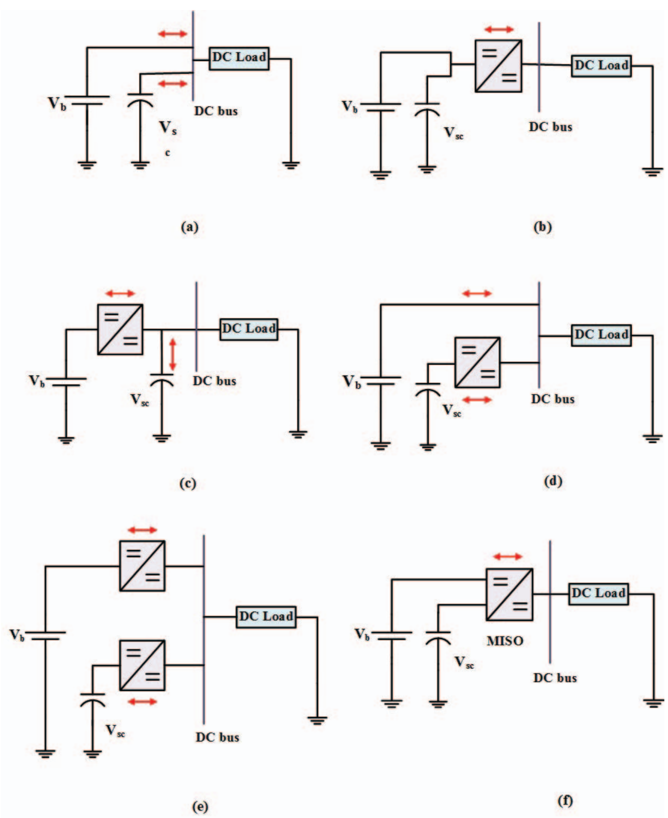

Fig. 2. Different HESS configurations. (a),(b) represents passive configuration.(c),(d) represents semi-active configuration and (e) & (f) represents active HESS configuration

In Fig 2, (a), (b) represents Passive configuration of HESS. Figure:a is simplest of all, where battery and supercapacitor (Bat- SC) system directly connected to the load. This configuration will help to reduce the power variations but there is no control over battery and SC. Hence this method suffer with lack of accuracy and vulnerable to external noise. Fig.2 (b) also represents passive connection, because there is no control over the charging and discharging of storage devices. Fig.2 (c) and (d) represents semi active HESS configuration kin which one storage connected through dc-dc converter and the other storage directly connected to DC bus. it can provide partial control over power though its not efficient. Fig.2 (e) and (f) configurations are active HESS connections. Fig.2 (f) shows a Multi Input Single Output (MISO) configuration for HESS. However these converters face high size and losses. In Fig.2(e) battery and SC connected to DC bus through independent dc-dc converter. The main advantage of this configuration is independent control is applicable and increased modularity in the system. This paper mainly focus on (e) configuration and its analysis.

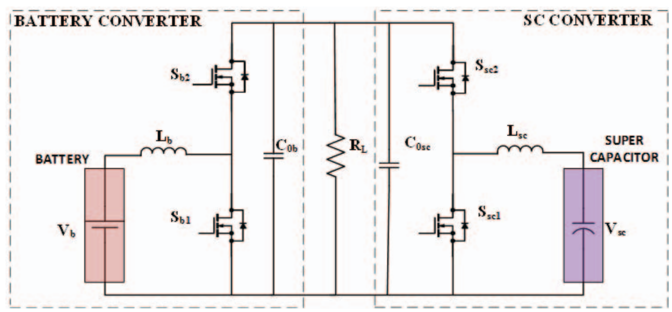

Fig. 3. Battery- supercapacitor HESS system

Fig: 3 shows the presented Bat-SC system connected to the load through two bidirectional boost converters. Battery converter have two operation modes via charging and discharging mode. Any steady state deficiency in the DC bus will be supplied by battery. Due to the right hand zero instability effect of boost converter, bidirectional converter is designed based on boost converter characteristics. SC converter will also allows bidirectional power flow depends on DC bus transients. If load increases, SC will supply the transient power because battery will take more time to discharge. Similarly if load is reduced, the additional current will used by the SC to charge. The converters are using Mosfet switches with inbuilt internal diodes which helps them to conducts in both direction. Output capacitance of the converters can be consider as single capacitor since they are connected in parallel across the load

III. Control Strategy and Controller Design

In this section, controller design for both battery and supercapacitor is explained. The function of battery is to supply slow varying power demand and SC will supply the complimentary power. To achieve this requirement,control system is designed such a way that the reference for battery indicate the steady state value and SC indicate the high frequency component of the load. The figure shows the control circuit for Bat- SC system. The controller consist of two loops, via inner current loop and outer voltage loop. The criteria for power sharing between battery is designed based on LPF [5]. LPF output of outer voltage controller split the current reference into low and high frequency component. The high frequency component is for the SC.

A. Design of Boost Converter for HESS

The boost converter design equations were obtained from bib5. The converter operation is assumed to be continues. Inductor L_b and L_{sc} of both bidirectional converter can be calculated from following equations.

$$L{=}\frac{V_0 D}{\Delta i_{in} f_{sw}} \tag{1}$$

Where f_{sw} is the switching frequency and D represents the duty ratio. Inductor current ripple Δi_{in} choose to be 5%.Similarly capacitor can be designed by the equation.

$$C = \frac{V_0 D}{\Delta V_0 R_L f_{sw}} \tag{2}$$

V_0 andΔV_0 output voltage and allowable output voltage ripple. In this analysis ΔV_0 is choose to be 2%. The converter is designed considering the worst conditions. The HESS system is designed for handling 144W power and providing output voltage is 48V. Battery input voltage is taken as 24V and output designed for 48V. The design values are given in table-1. The C_0 combines the total effect of both battery output capacitor$C_0 b$ and SC output capacitor $C_0 sc$.

TABLE I
DC-DC CONVERTER PARAMETERS

Sl.no	parameters	values
1	Battery input voltage, V_b	24 V
2	SC input voltage, V_{sc}	16 V
3	Load resistance, R_L	16 Ω
4	Battery boost converter inductance, L_b	4 mH
5	SC boost converter inductance, L_{sc}	3.5 mH
6	Total output capacitance, $C_0 = C_{0sc} + C_{0b}$	180μ F
7	Output Power, P_{out}	144 W
8	Switching frequency, f_{sw}	20 KHz
9	Output voltage, V_0	48 V

B. Small Signal Modeling of Boost Converters

Since the operation of both converters are complimentary in nature, the analysis is valid for both boost converters. The averaged equations of inductor and capacitor of boost converter over one switching period is given by

$$L\frac{di}{dt} = v_s - (1-d)v_c \tag{3}$$

$$C\frac{dv_c}{dt} = (1-d)i_L - \frac{v_c}{R_L} \tag{4}$$

Based on the inductor and capacitor equations, state space equations obtained as

$$\begin{bmatrix} \dot{i_L} \\ \dot{v_c} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-d)}{L} \\ \frac{1-d}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_s \tag{5}$$

where v_c and v_s represents the instantaneous values of output capacitor voltage and source voltage. v_s is choose indicate both battery and supercapacitor voltage. d represents the duty ratio.The output equation is given in equation 6. Since there is no direct feed forward path, the transition matrix D value will be zero.

$$\begin{bmatrix} i_s \\ v_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + DV_s \tag{6}$$

Introducing perturbations to the above equations by replacing $v_c = V_c + \hat{v_c}$, $v_s = V_s + \hat{v_s}$, $i_L = I_L + \hat{i_L}$ and $d = D + \hat{d}$. After perturbing the steady state values in the state space equation become zero since $\dot{i_L}$ and $\dot{V_c}$ will be zero at steady state. The resulting small signal equations are

$$\begin{bmatrix} \dot{\hat{i_L}} \\ \dot{\hat{v_c}} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-D)}{L} \\ \frac{1-D}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} \hat{i_L} \\ \hat{v_c} \end{bmatrix} + \begin{bmatrix} \frac{V_c}{L} \\ \frac{-I_L}{C} \end{bmatrix} \hat{d} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \hat{v_s} \tag{7}$$

The equation 7 is useful in calculating different transfer functions for the converter[7]. The voltage control transfer functions is derived as

$$G_{Vd} = \frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{(1-D)V_0 - LI_s s}{LCs^2 + \frac{L}{R_L}s + (1-D)^2} \tag{8}$$

Also the current control transfer function is calculated as

$$G_{id} = \frac{\hat{i}_s(s)}{\hat{d}(s)} = \frac{CV_0 s + 2(1-D)I_s}{LCs^2 + \frac{L}{R_L}s + (1-D)^2} \tag{9}$$

Output transfer impedance for the converter can be derived from 8 and 9

$$G_{vi} = \frac{\hat{v}_0(s)}{\hat{i}_s(s)} = \frac{(1-D)V_0 - LI_s s}{CV_0 s + 2(1-D)I_s} \tag{10}$$

C. Design of proposed control strategy for HESS

The proposed control strategy for Bat- SC HESS is represented in Fig: 4.The power sharing between battery and SC is achieved by using a Low Pass Filter (LPF) [5]. G_{ibd} and G_{iscd} are the current control transfer function of battery and SC, which will regulate the current through inductors.

In designing, of the inner loop, band width (BW) also place an important role. For the fast response of Super capacitor, BW of SC boost converter made more than BW of battery boost converter. In this paper BW of SC converter is selected as $16krad/sec$ and that of battery converter is $10krad/sec$. Also the phase margin for inner current loop and outer voltage loop are selected as 60^0 to meet the stability[8]. There are three PI controllers are used to tune the feed back system. the general representation PI is given as

$$PI_x = K_{px} + \frac{K_{ix}}{s}$$

where x represents b, sc, and v. b and sc represents inner PI loop controller and v represents outer loop voltage PI controller. H_1 and H_2 are feed back transfer function and taken as unity in this case.

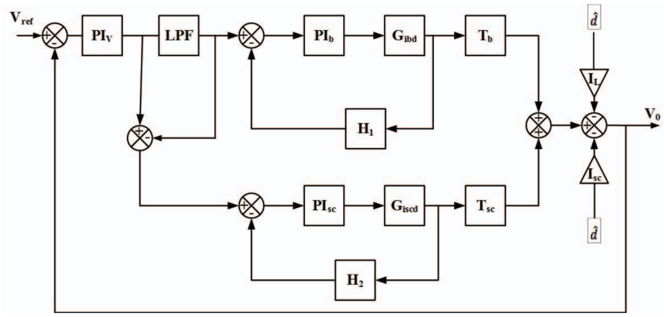

Fig. 4. Small signal model of presented HESS

In previous works, G_{vi} is used to convert $\hat{i_L}$ with $\hat{v_0}$. Since both converters operations are complimentary, those methods leads to error. Using small signal modelling of the converters, $\hat{i_L}$ with $\hat{v_0}$ related by using new transfer function T_b and T_{sc}. The relation can be modelled by perturbing load equations found in [11].

Battery boost converter current can be given as

$$\hat{i_{0b}}(s) = (1 - D_1)\hat{i_{Lb}}(s) - I_{Lb}\hat{d}(s) - \hat{v_0}(s)sC_{0b}$$

SC boost converter current can be given as

$$\hat{i_{0sc}}(s) = (1 - D_2)\hat{i_{Lsc}}(s) - I_{Lsc}\hat{d}(s) - \hat{v_0}(s)sC_{0sc}$$

Total load voltage during the interval can be given as

$$\hat{v_0}(s) = (\hat{i_{sc}}(s) + \hat{i_b}(s))R$$

From above equations, $\hat{v_0}$ can be solved as

$$\hat{v_0}(s) = \hat{i_{Lb}}(s)T_b + \hat{i_{Lsc}}(s)T_{sc} - \hat{d}(s)(I_{Lb} + I_{Lsc})$$

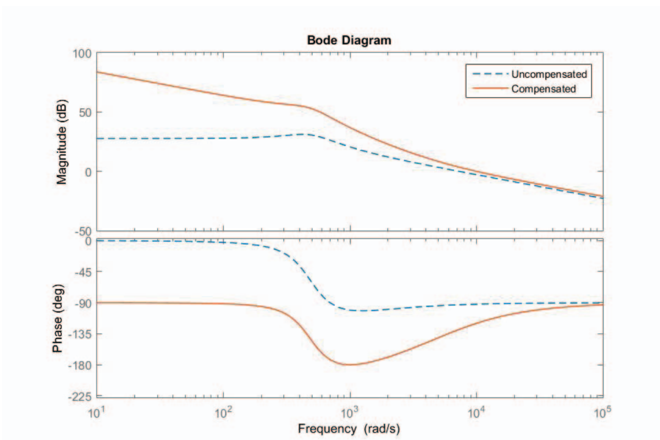

Fig. 5. Bode diagram for inner battery current control loop

where T_b relates $\hat{i_{Lb}}(s)$ and $\hat{v_0}(s)$ and is given by

$$T_b = \frac{R(1 - D_1)}{1 + s(C_1 + C_2)R}$$

and T_{sc} relates $\hat{i_{Lsc}}(s)$ and $\hat{v_0}(s)$ and is given by

$$T_{sc} = \frac{R(1 - D_2)}{1 + s(C_1 + C_2)R}$$

Based on above equations, over all system can be modelled and designed for specified band width and phase margin, shown Fig. (5) and (6).

The PI values derived for inner current control loop of battery and SC is by using G_{id} with the help of SISO tool. The PI values obtained for battery current loop is $K_{pb} = 1.22$ and $K_{ib} = 3403.3$ and for SC current loop is $K_{psc} = 1.68$ and $K_{isc} = 6403.7$. Outer loop is designed from over all transfer function calculated from Fig: 4 with the help of Matlab and SISOtool. $K_{pv} = 25$ and $K_{iv} = 0.1$. Due to high band width of SC, high frequency output voltage variations are mitigated. So the steady state error in output voltage also reduced. That's the reason why, K_{iv} value is very low compared to K_{pv}.

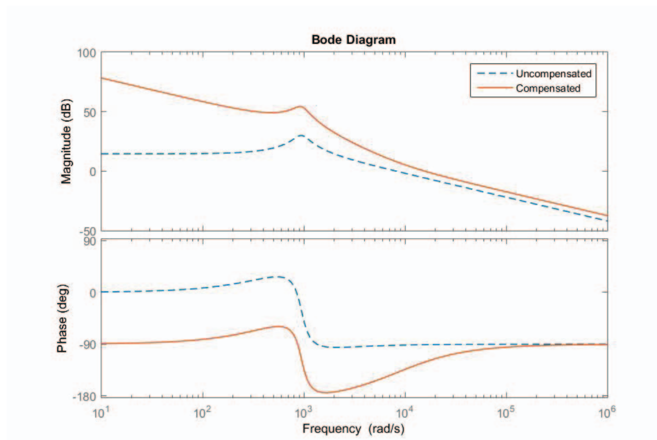

Fig. 6. Bode diagram for inner SC current control loop

IV. Simulation Results

To verify the design of Bat- SC system, simulation study is done using MATLAB/ Simulink. Battery- supercapacitor HESS is simulated for 144W and component ratings and design requirements are shown in Table I. The controller is verified through introducing input and output variations in the circuit and by changing the output voltage reference. Initially, at 0.1 sec load variation introduced by increasing load by 16% and circuit able to mitigate those effects without allowing transients. At 0.2 seconds, supply variation is introduced by varying supply voltage by 30% and the resulting transients occurred with in permissible range.

Fig. 7 represents the output voltage variations during disturbances. Maximum transient is at the time of turn on, which is about 0.5 V. Load voltage is setting at 48 V with minimum ripple, because of the action of supercapacitor.

Fig.8 represents the load current variation with different disturbances.Its clear that for 0.5A disturbance (16% of rated output current), the load current variation limited to 0.03A (1% of rated output current). Total power will be the product of load voltage and load current, and its given in Fig. 9.

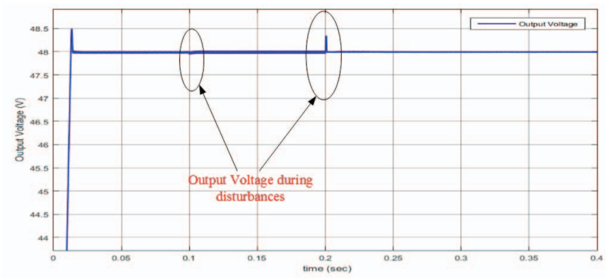

Fig. 7. Load voltage variations during different disturbances

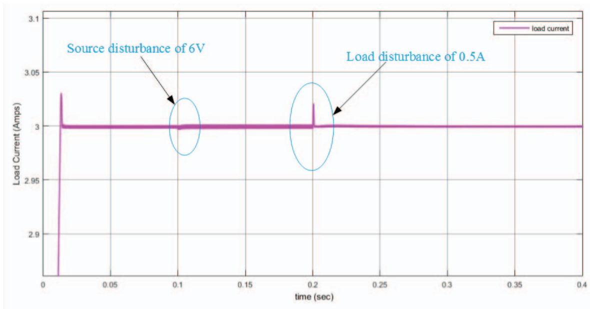

Fig. 8. Load current variations during different disturbances

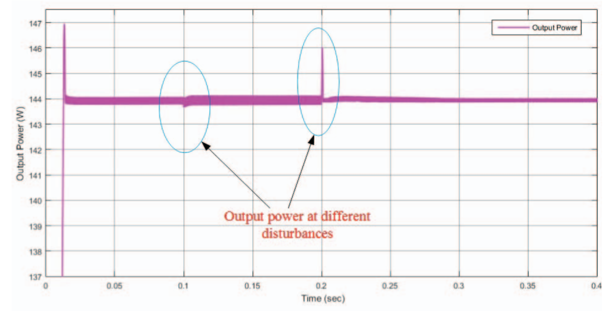

Fig. 9. Load power variation with respect to different variations

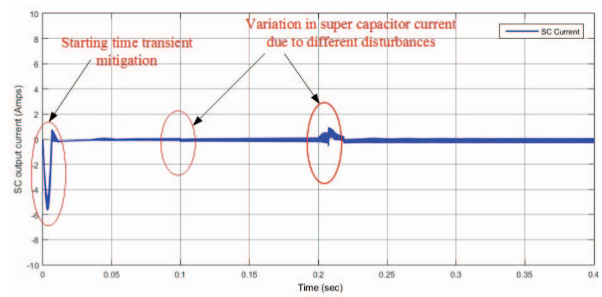

Fig. 10. SC current during all disturbances

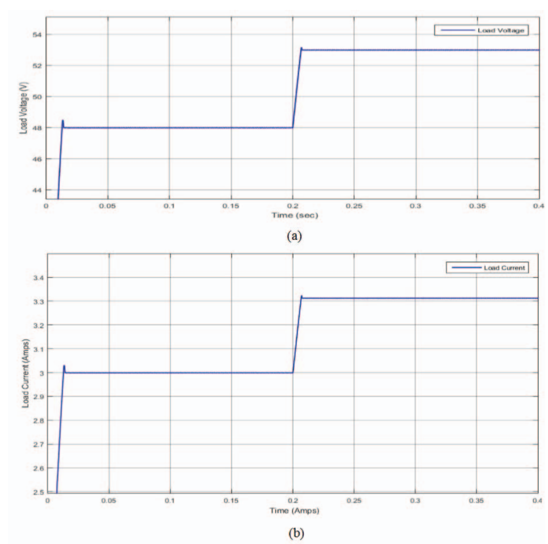

Fig. 11. (a)Load voltage variation with 5V reference change. (b) Load current variation with 5V reference change.

Fig.10 presents the supercapacitor current during the operation. Here discharging of SC current taken as negative and charging of SC current taken as positive.

The initial high transient is the discharge during turn on period due to slow response of battery. And at 0.2 sec, load power increases and the additional energy is absorbed by the SC. Very small ripple current in the SC is shows its ability to respond with small variations in the load side. SC responds to all high frequency variations and as a result the load side ripple is reduced. Total performance of the system improved with SC. Fig.11 shows the load voltage and current variations when the reference change to 48V to 53 V. The controller able to eliminate the transients and SC eliminates the ripple voltages.

V. Conclusion

This paper analyses the functioning of Battery- supercapacitor hybrid energy storage system in DC microgrid. From the small signal model, it is clear that the battery is supplying the steady state power and supercapacitor supplies the transient power. By using a supercapacitor, the transient current handled by the battery is reduced and hence it enhances the life of the battery. Also from the Matlab simulation, it is seen that input, as well as output variations is mitigated using battery supercapacitor system. In all cases, load current and voltage maintained in the permissible limit. Due to the presence of right hand zero in the voltage control transfer function, outer loop bandwidth and phase margin have to made some trade of during design. From the analysis Battery -supercapacitor system improves the overall load performance. The transients and ripple voltages in the load voltage and current limited to an acceptable value. As an extension of this work, the controller needs to modify considering both SOC and RES integration.

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