Modeling and Simulation of Switched Capacitor Converters for Electric Vehicle Energy Storage Systems

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***Abstract*-This paper presents the analysis and novel controller design for a hybrid 4-quadrant (4-Q) switched-capacitor (SC) *Luo* and a conventional buck-boost bidirectional DC/DC converters, for HEV/PHEV energy storage system applications, based on power of traction motor and battery current gradient. Features of voltage step-down, voltage step-up, and bi-directional power flow are integrated into a single circuit. The novel hybrid controller strategy enables simpler dynamics compared to a standard buck converter, with input filter, good regulation capability, low EMI, lower source current ripple, ease of control, and continuous input current waveform in both modes of operation (buck and boost modes).**

***Keywords*–Battery storage, control, electric vehicles, energy storage, power electronics.**

I. INTRODUCTION

A switched capacitor converter (SCC) is essentially a combination of switches and capacitors. Different combinations of capacitors and switches result in SCC topologies producing an output voltage that may be higher (boost mode) or lower (buck mode) than the input voltage, as well as polarity reversal. The switches are controlled by capacitors that they are charged and discharged through different paths. Output voltage is proportional to input voltage. Switched-capacitor (SC) bidirectional converters, with their large voltage conversion ratio, indeed possess the potential to be one of the possible solutions for achieving high-efficiency conversion for HEV energy storage systems. At the same time, SCCs possess the ability to realize step up/down of voltage.

A novel hybrid controller strategy is developed in this paper, which enables simpler dynamics compared to a standard buck converter, with input filter, superior regulation capability, low electromagnetic interference (EMI), lower source current ripple, ease of control, and continuous input current waveform in both modes of operation (buck and boost modes) [1]-[6]. A typical system schematic is shown in Fig. 1.

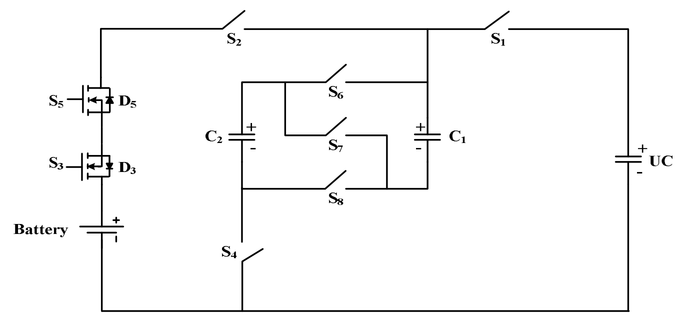

Fig. 1. Typical system schematic with hybrid energy sources and SC converter.

This paper initially discusses the controller design for SC and buck- boost converters operation, and then goes on to provide both (SC *Luo* and buck- boost) converters operating characteristics and modes and simulation results.

II.CONTROLLER DESIGN FOR SC AND BUCK-BOOST CONVERTERS

The 4-Q SC *Luo* converter is comprised of 6 switches and 2 capacitors, C_1 and C_2. Each switch consists of two MOSFETs, for current flow in both directions. For a HEV application, the high voltage (HV) side typically consists of battery modules and the low voltage (LV) side could consist of ultra-capacitor (UC) modules. In this case, the high voltage DC is at 86V, low voltage side is set at 43V, and UC initial voltage is at 22V. This type of converter operates in four quadrants (forward and reverse mode). The complete system schematics of a 4-Q SC *Luo* and buck-boost converter are shown in Figs. 2 and 3, respectively.

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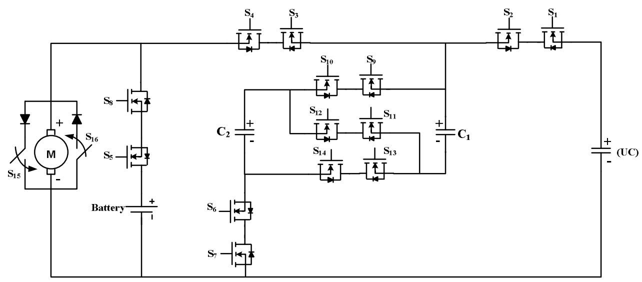

Fig. 2. Typical schematic of SC *Luo* converter with hybrid energy sources and traction motor.

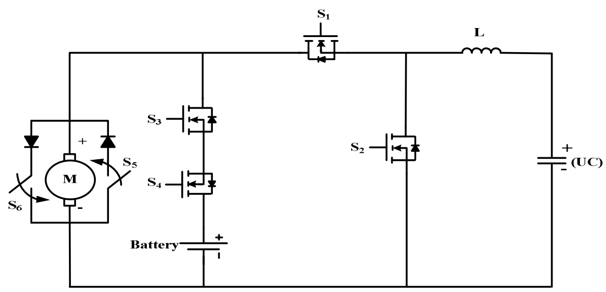

Fig. 3. Typical schematic of buck-boost converter with hybrid energy sources and traction motor.

When the converter operates in motoring mode ($P \geq 0$), two conditions are chosen: If the battery current gradient is between -2mA and 2mA, battery modules supply their energy to the load and motor side. Otherwise, UC modules supply their power to load and motor side. Secondly, during motoring mode, output power of motor (P_{out}) is compared with load power (P_L). If $P_{out} < P_L$, with attention given to battery current gradient, UC or battery modules supply their power to the motor side. Otherwise, if the battery modules need energy and fully discharge, the UC modules transfer their power to battery or HV side. If the UC modules need power and fully discharge, the battery modules deliver their energy to UC or LV side. On the other hand, when the converter operates in generating mode ($P < 0$), only the first condition is considered. In generating mode, the motor tends to give up its power; thus it is not compared with load power.

III. SC *LUO* AND BUCK-BOOST CONVERTERS OPERATING CHARACTERISTICS AND MODES

First, we consider SC *Luo* converter operating characteristics and modes, then goes on to provide buck- boost converter operating characteristics and modes.

In SC *Luo* converter, during forward motoring or quadrant I operation, voltage and current are positive. At the same time, if $P_{out} < P_L$, the UC and battery modules supply their power to motor side with attention given to the battery current gradient. Otherwise, battery or UC modules deliver their energy between each other. For better understanding of the controller, each operation mode is denoted by a specific code.

When $P_{out} < P_L$, and UC modules transfer their power to motor side, switches S_2 and S_4 are closed and D_1 and D_3 start conducting. This mode is represented with code 1, and is shown in Fig. 4 (a). However, when battery modules deliver their energy to motor side, switch S_5 is closed and D_8 starts conducting. This mode is shown by code 2, and is depicted in Fig. 4 (b).

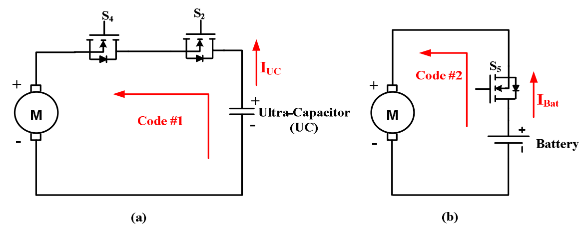

Fig. 4. Forward motoring (a) UC modules, (b) Battery modules supply power to motor side.

Now, if $P_{out} \geq P_L$, and battery modules are fully discharged, LV side or UC modules transfer their power to HV side, as a first step. Switches S_2, S_{10}, S_{14}, and S_7 are on, and D_1, D_9, D_{13}, and D_6 start conducting. Capacitors C_1 and C_2 are charged by the LV side. Also, the voltage across the 2 capacitors increases. This mode is represented by code 3. The operation mode is shown in Fig. 5 (a). Also, in both operation modes (buck and boost modes), S_{16} is on, because motor does not stop and current flows through the armature. After this operating stage, S_6, S_{11}, S_4 and S_8 are on, and D_7, D_{12}, D_3, and D_5 start conducting. Capacitors C_1 and C_2 are disconnected from LV side and transfer their stored energy to the HV side. Also, the voltage across the 2 capacitors decreases. This mode is shown by code 4. The boost mode implements the *voltage-lift technique*, because the capacitors are charged during the on-state. The input voltage (LV) appears across to the capacitors. The capacitors are discharged in series during the off-state. Hence, through this straightforward method, output voltage can be boosted by the capacitors. This operation mode is depicted in Fig. 5 (b).

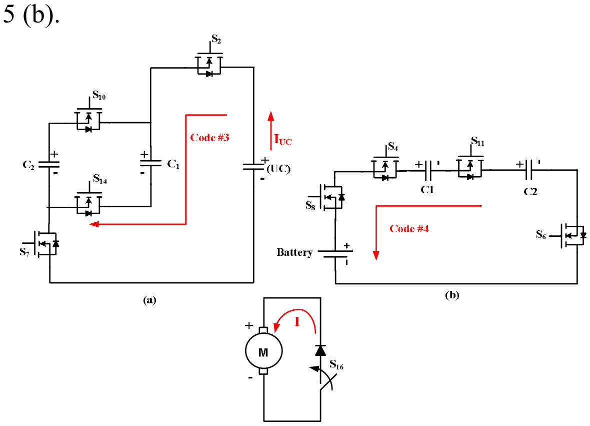

Fig. 5. Boost operation; (a) Capacitors C_1 and C_2 are charged by LV side; (b) Capacitors are discharged and are disconnected from LV side (S_{16} is on and current flows in motor).

Now, if $P_{out} \geq P_L$, and UC modules are fully discharged, battery modules transfer their energy to the LV side, as a first step. Switches S_5, S_3, S_{12}, and S_7 are on, and D_8, D_4, D_{11}, and D_6 start conducting. Capacitors C_1 and C_2 are charged by HV side. Also, the voltage across the 2 capacitors increases. This mode is represented by code 10. This operation mode is shown in Fig. 6 (a). After this operating stage, S_6, S_9, S_{13} and S_1 are on, and D_7, D_{10}, D_{14}, and D_2 start conducting. Capacitors C_1 and C_2 are disconnected from HV side and transfer their stored energy to the LV side. Also, the voltage across the 2 capacitors decreases. This mode is shown by code 11. The buck mode uses the *current-amplification technique,* because the capacitors are charged during on-state. The input current flows through capacitors. These capacitors are discharged during off-state. Therefore, the output current is amplified by these capacitors [7]-[13]. This operation mode is depicted in Fig. 6 (b).

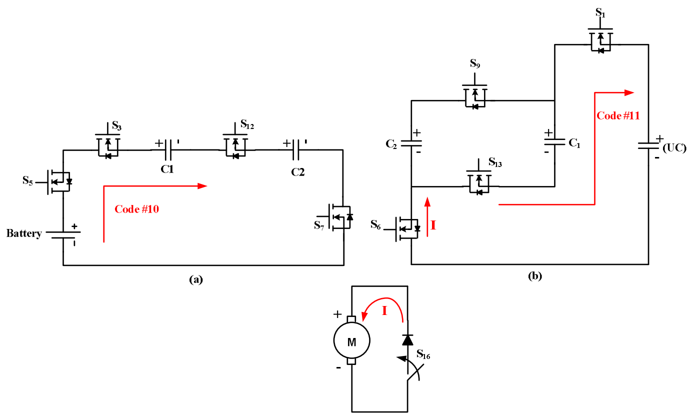

Fig. 6. Buck operation; (a) Capacitors C_1 and C_2 are charged by HV side; (b) Capacitors are discharged and are disconnected from HV side (S_{16} is on and current flows in motor).

If UC or battery modules are fully discharged, and $P_{out} \geq P_L$, then S_{16} turns on, because current flows through the motor. This mode is represented by code 9. This operation mode is shown in Fig. 7.

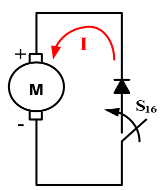

Fig. 7. Forward motoring operation; energy sources are fully discharged ($P_{out} \geq P_L$ and S_{16} is on).

In forward regenerative (forward braking) or quadrant II operation, voltage is positive but current is negative. In this operating mode, only battery current gradient is considered. When motor supplies power to the UC side and UC modules are fully discharged or half charged, then motor transfer its power to LV side and switches S_3 and S_1 are closed. D_4 and D_2 start conducting. This mode is represented by code zero, and is shown in Fig.8 (a). When the motor supplies power to battery side, and also, battery modules are fully discharged or half charged, motor transfers its power to HV side, and switch S_8 turns on. D_5 starts conducting, and this mode is represented by code 5, as shown in Fig. 8 (b). However, if hybrid energy sources (battery and UC modules) are fully charged, switch S_{15} is on, because current flows through the motor. This mode is shown by code 8, and is depicted in Fig. 8 (c).

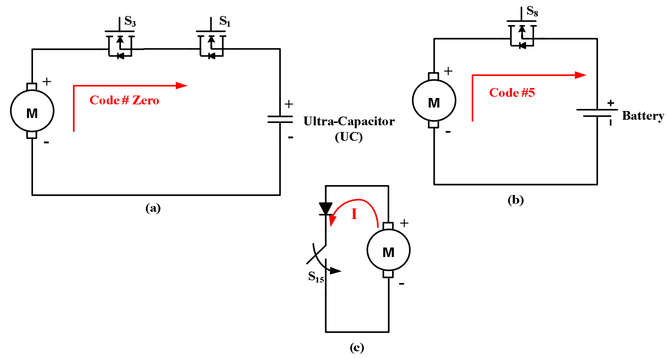

Fig. 8. Forward regenerative operation; (a) UC modules are fully discharged or half charged; (b) Battery modules are fully discharged or half charged; (c) hybrid energy sources are fully charged and current flows in motor.

Also, in buck-boost converter, during forward motoring or quadrant I operation, voltage and current are positive and during this operations mode and boost mode, UC voltage must be greater than inductor voltage. When $P_{out} < P_L$, and UC modules transfer their power to motor side, as a first step. Switch S_2 is on and inductor L storages energy. This mode is represented with code 1, and is shown in Fig. 9 (a). After this operating stage, D_1 starts conducting and inductor L transfers its stored energy to the motor side. This mode is shown by code 2 and is depicted in Fig. 9 (b).

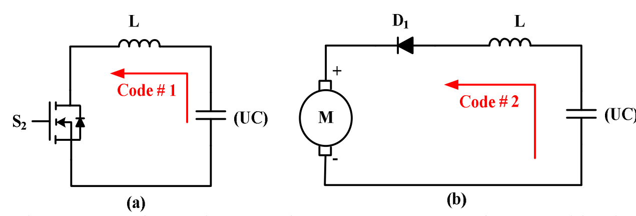

Fig. 9. Forward motoring (a) Inductor L stores energy from LV side; (b) inductor transfers its stored energy to the motor side.

Also, when $P_{out} < P_L$, and battery modules deliver their energy to motor side, switch S_4 is closed and D_3 starts conducting. This mode is shown by code 3, and is depicted in Fig.10.

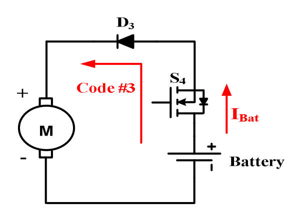

Fig. 10. Forward motoring; Battery modules supply their energy to motor side.

Now, if $P_{out} \geq P_L$, and battery modules are fully discharged, LV side or UC modules transfer their power to HV side, as a first step. Switch S_2 is on and inductor L storages energy. This mode is represented by code zero. The operation mode is shown in Fig. 11 (a). Also, in both operation modes (buck and boost modes), S_5 is on, because motor does not stop and current flows through the armature. After this operating stage, S_3 is on, and D_1 and D_4 start conducting. Also, inductor L transfers its stored energy to the HV side. This mode is shown by code 7. This operation mode is depicted in Fig. 11 (b).

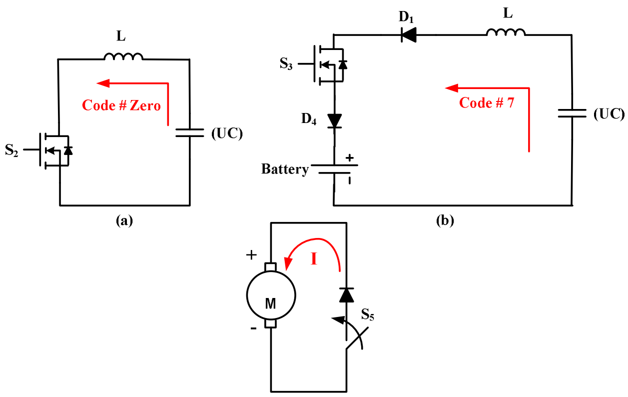

Fig. 11. Boost operation; (a) Inductor *L* stores energy from LV side; (b) inductor *L* transfers stored energy to HV side (S_5 is on and current flows in motor).

Now, if $P_{out} \geq P_L$, and UC modules are fully discharged, battery modules transfer their energy to the LV side, as a first step. Switches S_4 and S_1 are on and D_3 starts conducting and inductor L storages energy. This mode is represented by code 8. This operation mode is shown in Fig. 12 (a). During buck operation mode, battery voltage must be greater than inductor voltage. After this operating stage, D_2 starts conducting and inductor L transfers its stored energy to the LV side. This mode is shown by code 11 and is depicted in Fig. 12 (b).

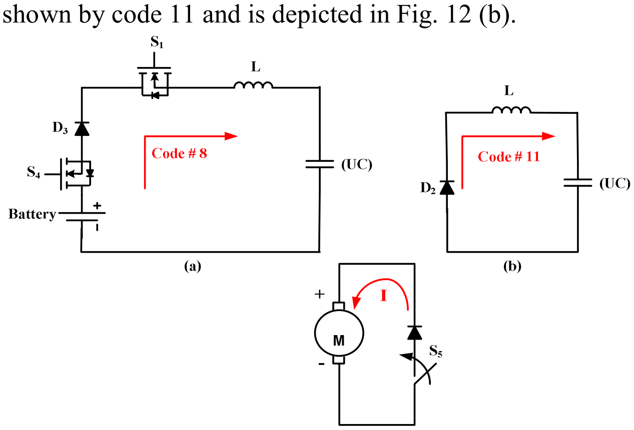

Fig. 12. Buck operation; (a) Inductor *L* stores energy from HV side; (b) inductor *L* transfers its stored energy to the LV side (S_5 is on and current flows in motor).

If UC or battery modules are fully discharged, and $P_{out} \geq P_L$, then S_5 turns on, because current flows through the motor. This mode is represented by code 9. This operation mode is shown in Fig. 13.

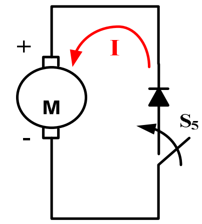

Fig. 13. Forward motoring operation; energy sources are fully discharged ($P_{out} \geq P_L$ and S_5 is on).

In forward regenerative (forward braking) or quadrant II operation, voltage is positive but current is negative. In this operating mode, only battery current gradient is considered. Also, during this operations mode and buck mode, battery voltage must be greater than inductor voltage. When motor supplies power to the UC side and UC modules are fully discharged or half charged, then motor transfers its power to LV side. In the first step, switch S_1 is closed and inductor L storages energy. This mode is represented by code 5, and is shown in Fig.14 (a). After this operating stage, D_2 starts conducting. Also, inductor L transfers its stored energy to the UC modules. This mode is shown by code 6. This operation mode is depicted in Fig. 14 (b). However, if UC modules are fully charged, switch S_6 is on, because current flows through the motor. This mode is shown by code 10, and is depicted in Fig. 14 (c).

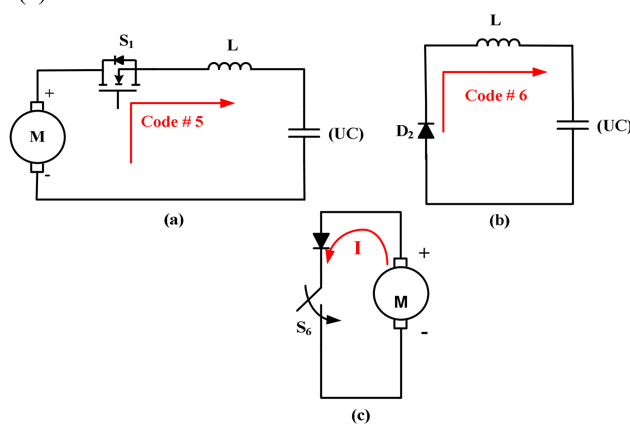

Fig. 14. Forward regenerative operation; (a) UC modules are fully discharged or half charged and inductor *L* stores energy from motor side; (b) inductor *L* transfers its stored energy to the LV side (c) UC modules are fully charged and current flows in motor.

When the motor supplies power to battery side, and also, battery modules are fully discharged or half charged, motor transfers its power to HV side, and switch S_3 turns on. D_4 starts conducting, and this mode is represented by code 4, as shown in Fig. 15 (a). However, if battery modules are fully charged, switch S_6 is on, because current flows through the motor. This mode is shown by code 10, and is depicted in Fig. 15 (b).

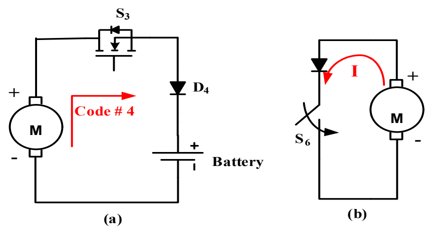

Fig. 15. Forward regenerative operation; (a) Battery modules are fully discharged or half charged; (b) Battery modules are fully charged and current flows in motor.

In both (SC *Luo* and buck-boost) converters, during reverse motoring (quadrant III) operation, voltage and current are negative. This operation mode and its codes are same as forward motoring. In reverse regenerative (reverse braking or quadrant IV) operation, voltage is negative. However, current is positive. This operation mode and its codes are same as forward regenerative.

IV. MODELING AND SIMULATION RESULTS

First, we consider SC *Luo* converter modeling and simulation results, then goes on buck-boost converter modeling and simulation results.

Fig. 16 depicts a comparison between P_{out} and P_L, load torque (T_L), battery current gradient, and voltage across of DC motor (armature voltage). In the first plot, when $P_{out} \geq P_L$, power curve is shown with value = 1. When $P_{out} < P_L$, it is denoted by value = 0. When $T_L \geq 0$, the converter operates in motoring mode (otherwise converter operates in generating mode). The third plot shows battery current gradient. As is clear, when this value is out of range (-2mA and 2mA), the UC modules supply their power to the load and motor side, in motoring mode (or motor and load must transfer their power to UC or LV side, in generating mode). As is clear from the final plot, when $V_a \geq 0$, converter operates in forward mode. When $V_a < 0$, converter operates in reverse mode.

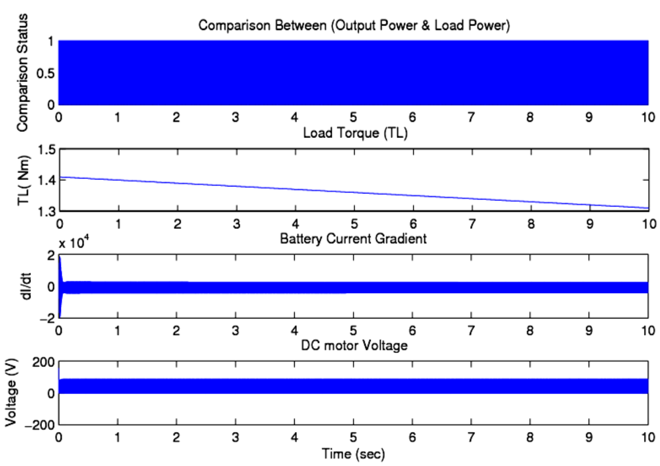

Fig. 16. Comparison between P_{out} and P_L, load torque (T_L), battery current gradient, and voltage across DC motor (armature voltage).

UC voltage is 21.5V (fully discharged) and battery voltage is 87V (fully charged). Considering the scenario when battery modules are fully charged, UC modules are fully discharged, power curve is shown with value = 1 and converter operates in motoring mode. During this interval, battery modules supply their energy to the LV side. This is shown by codes 10 and 11 in both operating modes (forward motoring and reverse motoring). However, when the power curve is shown with value = 0, with same conditions, whereby the motor needs power, UC modules supply their power to motor side, and LV side is fully discharged. In this case, battery modules, instead of the LV side, supply their energy to the motor side in both operating modes (forward motoring and reverse motoring). This mode is shown by code 2. Fig. 17 shows the charge and discharge status of the hybrid energy sources, with related converter operating codes.

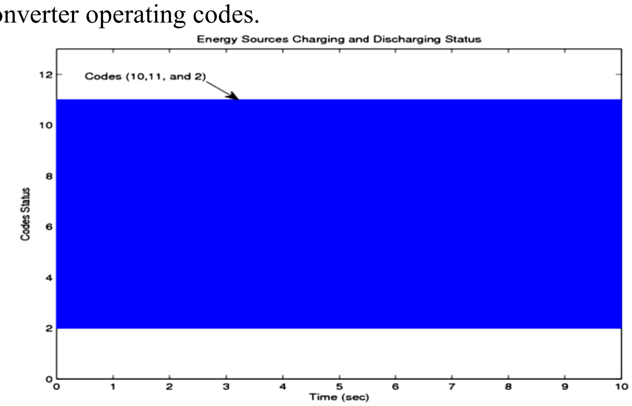

Fig. 17. Charge and discharge status of the hybrid energy sources, with codes.

Fig. 18 shows UC modules voltage and current during operation in codes 10, 11, and 2, when UC modules are charged by battery side (or when UC modules are disconnected from HV side).

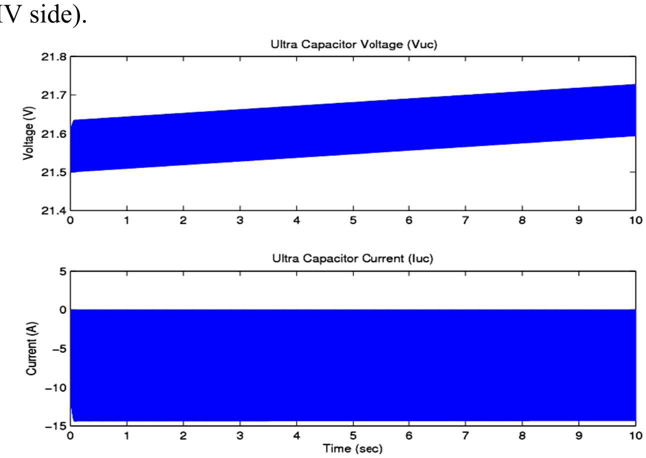

Fig. 18. UC modules voltage and current during charge (or when disconnected from HV side).

In this part, we consider buck-boost converter modeling and simulation results. Fig. 19 depicts comparisons between battery voltage ($V_{battery}$), UC voltage (V_{UC}), inductor voltage (V_L), P_{out} and P_L, load torque (T_L), battery current gradient, and voltage across of DC motor (armature voltage).

UC voltage is 21.9V (fully discharged) and battery voltage is 87V (fully charged). Considering the scenario when battery modules are fully charged, UC modules are fully discharged, power curve is shown with value = 1 and converter operates in motoring mode. During this interval, battery modules supply their energy to the LV side. This is shown by codes 8 and 11 in both operating modes (forward motoring and reverse motoring).

However, when the power curve is shown with value = 0, with same conditions, whereby the motor needs power, UC modules supply their power to motor side, and LV side is fully discharged. In this case, battery modules, instead of the LV side, supply their energy to the motor side in both operating modes (forward motoring and reverse motoring). This mode is shown by code 3. Now, if battery modules are fully charged, UC modules are half charged (UC voltage is 22V), $P_{out} < P_L$ and converter operates in motoring mode. During this interval, the UC and battery modules supply their power to motor side with attention given to the battery current gradient. When battery modules supply their energy to motor side, it is shown by code 3. When UC modules transfer their power to motor side, it is shown by codes 1and 2. At the same time, if $P_{out} \geq P_L$, battery modules supply their energy to the LV side. This is shown by codes 8 and 11.

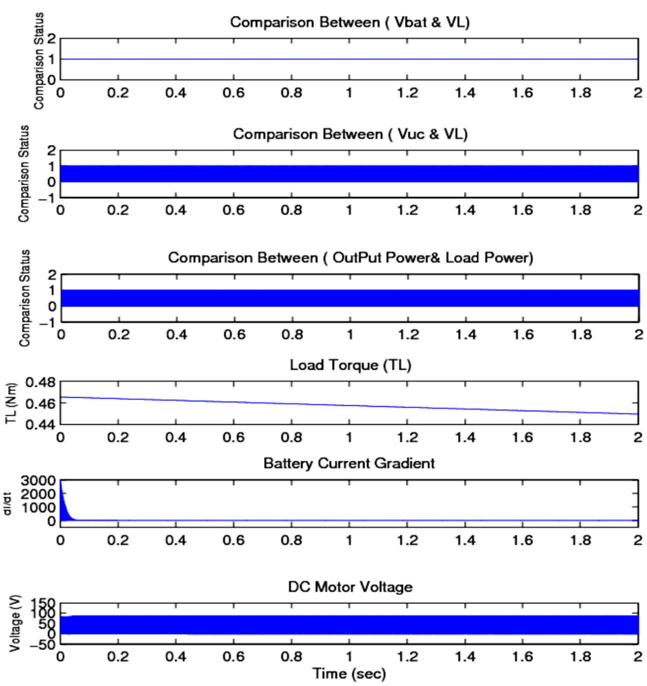

Fig. 19. Comparison between $V_{battery}$, V_{UC}, V_L, P_{out}, P_L, load torque (T_L), battery current gradient, and voltage across DC motor (armature voltage).

Fig. 20 shows the charge and discharge status of the hybrid energy sources, with related converter operating codes.

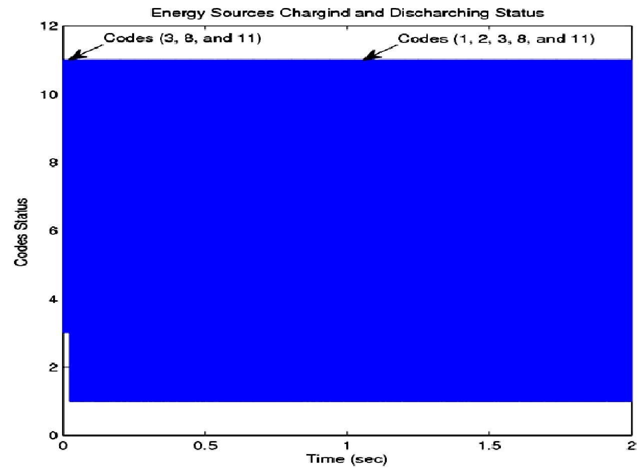

Fig. 20. Charge and discharge status of the hybrid energy sources, with codes.

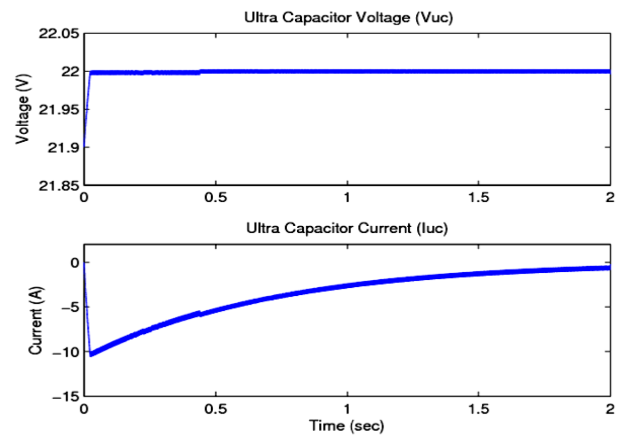

Fig. 21. UC modules voltage and current.

Fig. 21 shows UC modules voltage and current during when UC modules supply their power to motor or when they are disconnected from HV side (or when they are charged by battery side).

V. CONCLUSIONS AND FUTURE WORK

This paper presented a novel control technique for hybrid 4-Q SC *Luo* and buck- boost bi-directional DC/DC converters, applicable for HEV/PHEV ESS applications. SCCs offer essential features of voltage step-down, voltage step-up, and bidirectional power flow, associated with two or more HEV energy storage devices. Tests conducted on the proposed topology depict the following major advantages: (a) lower source current ripple, (b) simpler dynamics, (c) control simplicity, and (d) continuous input current waveform in both modes of operation (boost as well as buck). Future work includes hardware-in-the-loop (HIL) implementation of the 4-Q SC *Luo* converter topology with the proposed novel control strategy, for EV/HEV dual energy storage systems (ESS), running on various driving load patterns.

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