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Design and Comparison of two DC/DC Converter Topologies Interfacing a Hybrid Energy Storage System to the DC Bus

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***Abstract*—The use of DC/DC converters enables the utilization of multiple energy storage systems for electric vehicles (EV) and hybrid electric vehicles (HEV). Such power converters allow controlling the power flow to or from each storage element according to the power demands of the loads. This paper proposes a system design and performance comparison between two DC/DC converter topologies interfacing an hybrid, Lithium-ion battery and super-capacitor, energy storage system to the DC link. The design of classic and three level (TL) DC/DC converter topologies is performed according to a proposed set of specifications. The appropriate design parameters of the Hybrid Energy Storage System (HESS) are identified and the proposed DC/DC converter topologies are compared. It is shown that TL topology allows reducing cost, weight and volume of the converter for the same operating conditions as it can be operated with 4 times reduced inductance for the same values of current ripples and switching frequency.**

Keywords—electric vehicles; lithium-ion battery; super-capacitor; hybrid energy storage system; three level DC/DC converters; system sizing

I. INTRODUCTION

Today, the automobile sector, one of the largest energy sectors, is currently facing huge challenges. The reducing fossil fuel reserves with their increasing price and the increasing environmental problems are pushing towards implementing efficient and clean technology alternatives for the transport sector. Currently, the transport sector is responsible for an important percentage of all the energy consumption all over the world. In order to deal with these challenges, Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have become interesting issues. One of the key concerns related to EV and HEV development is the Hybrid Energy Storage System (HESS) and its power control strategy. HESS has been an important research area for a long time [1-3]. Nowadays, HESS technologies are commercially feasible and can help maximize both power and energy densities simultaneously. Any HESS should satisfy the demands of high energy density, fast charging and discharging capabilities, long cycle life, low cost, reduced size and volume in order to improve the efficiency and performance of the vehicle power supply. HESS using battery and super-capacitor has already been widely accepted [4-9]. The impact of using battery super-capacitor HESS has been largely investigated for many vehicle applications [5-9]. All these studies demonstrated that an hybrid battery/super-capacitors storage system has improved performance in comparison with only battery system for loads that have a high to average peak power requirement. Actually, both the batteries and super-capacitors can provide power to the electric drive system during acceleration. Super-capacitors are generally used to drive high current values during regenerative braking. Adapting the voltage and current levels and controlling the energy flow between the storage elements and the other vehicle propulsion equipments, is realized through DC/DC power converters. These power converters allow the control of power flow to or from each storage device according to the power demands of the loads.

The appropriate system sizing leads to the optimal HESS in terms of effective cost and allows for the best utilization of battery and super-capacitor technologies for both high energy and high power densities. The hybrid storage system performance is already demonstrated, however deriving the appropriate approach to effectively size the HESS in terms of the best optimal system cost, weight and volume and in terms of the most adequate DC/DC converter structures interfacing the HESS to the DC link still need to be further investigated.

This paper proposes a comparison between two DC/DC converter topologies interfacing the HESS (battery module and the super-capacitors module) to the DC link. A system design of classic DC/DC converters (boost and buck/boost) and three level (TL) converters (boost TL and buck/boost TL) is performed according to a proposed set of specifications. This design allows for the appropriate sizing of the HESS components and will enable us compare between the proposed converter topologies.

This paper is organized as follows. Section 2 describes the proposed HESS along with its topology and constituting elements. Section 3 describes the design and sizing of the various system components targeting a comparison between two proposed DC/DC converter topologies. Section 4 presents results obtained from Matlab/Simulink implemented simulations for the different converter cases. Finally, conclusions are given in section 5.

II. PROPOSED HESS TOPOLOGY

To improve the efficiency and performance of an EV or HEV, the HESS should satisfy the demands of high energy density, fast charging and discharging capabilities, long life cycle, low cost, and reduced size and volume. HESS and their topologies were an important research area over the past years. The combination between battery and super-capacitor was the most examined and researched HESS. In fact, the battery/super-capacitor configuration is considered as the first step in the optimal sizing procedure. Then, the energy storage elements are each connected via DC/DC power converters to a common DC link. Through the power converters, the power flow to or from each storage device can be controlled according to the power demands of the loads. In literature, three different topologies of HESS are examined [10]. All of these topologies have the similar performance, but the design of the power converters and the choice of the energy sources modules are different [10].

One of the mostly used topologies is to combine batteries with super-capacitors. The objective of combining batteries and super-capacitors is to create an energy storage system with the high energy density attributes of a battery and the high power density of a super-capacitor. The parallel active hybrid topology shown in Fig. 1 is selected. It is composed of a unidirectional DC/DC converter connecting a battery to the DC link in parallel with a bidirectional DC/DC converter connecting the super-capacitor to the same DC link. This topology allows adapting the voltage level between the storage elements and the vehicle propulsion equipment through DC/DC converters and enables the control of the energy flow to the vehicle.

The battery generally represents the energy module of the HESS. In our case, we choose the Lithium-ion (Li-ion) batteries given their high voltage, high energy density, none memory effect and low self-discharge during storage. The battery Thevenin model [11-14] is selected due to its relative simplicity, and capability for modeling the dynamic and steady state behavior of the battery. For the super-capacitor, we choose components with high power density and rapid charging and discharging capability to provide the required power, in short-term, with charge sustaining strategy. To model the super-capacitor behavior, we selected the two RC branches proposed by Zubieta and Bonert [15].

Several researches have proposed the classic converter topologies to connect the power sources to the other vehicle propulsion equipment [16-17]. The boost and the buck/boost converters shown in Fig. 2 were basically proposed and examined for the HESS. The unidirectional converter is used for the battery module and the reversible DC/DC converter is used for the super-capacitor module. These topologies are simple in use but have many drawbacks.

For example, the boost converter suffers especially from elevated current and voltage ripples, is characterized by large weight and volume and is unable to provide a high output voltage.

In contrast, TL converters given in Fig. 3 are considered a good solution in applications with high input voltage and high switching frequency [18]. The switchers are stressed on half of the total DC bus voltage, which enables to use lower-voltage-rated switches having better switching and conduction performance than the switches rated on the full blocking voltage [19]. Several researches ensure that TL converter topology can be more efficient than the classic topologies [20-22] because of its reduced inductor size and its reduced switching frequency. We are thus aiming to examine a classic topology (boost and buck/boost) shown in Fig.2 in comparison with a TL topology shown in Fig.3. The comparison between these two converters topologies will help us conclude about the most convenient topology for the HESS in terms of cost and performance.

III. DESIGN OF THE HESS COMPONENTS

HESS systems are optimized for a given EV or HEV application. This consists in determining the optimal sizing of all its components targeting the best system performance with a reduced total weight, volume and cost. In this section, the method used to size the different components is presented. Actually, the energy storage components must be designed so that they accumulate enough energy (kWh) and supply sufficient peak power (kW) for the EV to be capable for providing the required acceleration performance with the appropriate energy capacity to meet the desired driving cycles [23].

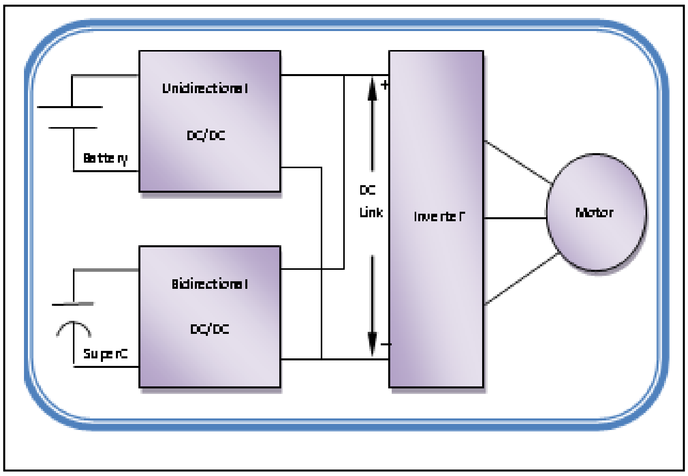

Fig. 1. Parallel configuration HESS with two DC/DC converters

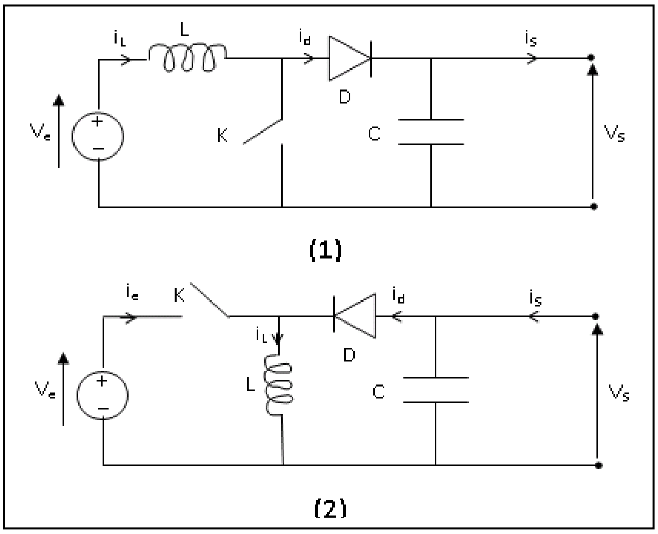

Fig. 2. Classic DC/DC boost converter (1) and classic DC/DC buck/boost converter (2).

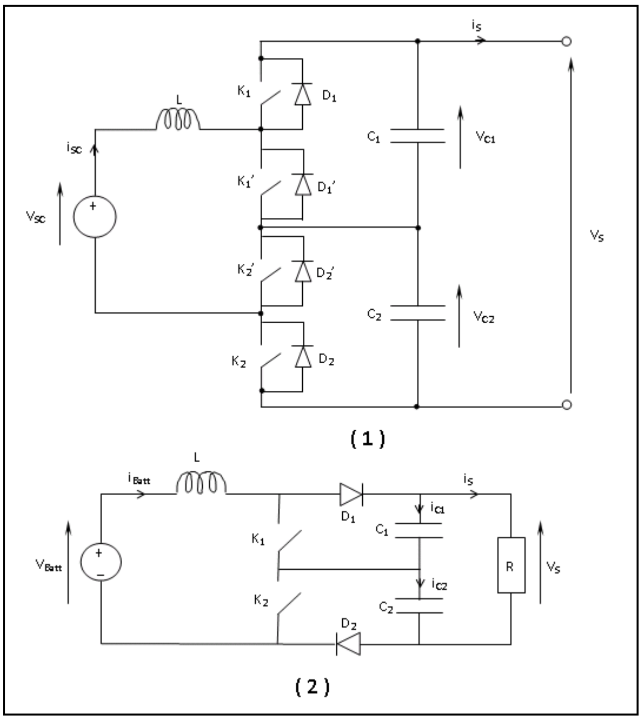

Fig. 3. TL DC/DC buck/boost converter (1) and TL DC/DC boost converter (2).

The desired power values are used for the design of super-capacitor modules given their high power densities. These power values are determined according to the required acceleration and deceleration vehicle power performances.

Given their high energy densities, battery modules are designed according to the system energy capacity values. However, the energy in the storage component cannot be utilized with 100 % efficiency because of many factors like storage leakages, number of load cycles, losses on the power electronics converters etc. For example, the average useful energy for batteries can be assumed as 50%, and for Super-capacitor as 75%, roughly including the power electronics of the converters. Given the system energy capacity requirements, and taking into account the average utilization factor of the selected technology, the total mass of commercial battery module is characterized. The number and structure of the battery module are also determined to operate within a certain voltage range.

The design and sizing of the different HESS components are shown next. We are aiming to compare between two DC/DC converter topologies. The first one is using classic DC/DC converter power interfaces (boost for battery module and buck/boost for super-capacitors). The second topology implements TL DC/DC power converters. The same energy sources are applied for both the two HESS: the same number and characteristics of the designed battery and super-capacitors modules. The obtained design parameter values are then compared to select the best HESS structure.

In this study, the vehicle specification is set as follows: capability to provide sufficient energy and power to operate 2 electric motors in front wheels with a weight of 850 kg and a top speed of 130 km/h. The vehicle is able to provide the required power to make acceleration from 0 to100 km/h in 20 s. The DC link voltage U_{DC} is 400V.

A. Sizing of the Battery Module

The battery module is the main energy source in our system. However, to estimate its parameters, we must take into account its capability to provide sufficient energy to the vehicle so it rolls to a maximum speed of 130 km / h for 1 hour. Using this number, the maximum energy capacity obtained is 35 kWh. We choose a SAFT Li-ion battery [24] designed for HEV. This proposed battery has a nominal voltage $V_{batt-nom}$ = 3.6 V and a capacity = 27 Ah (C / 3). Battery sized parameters are described in Table I.

B. Sizing of the Super-capacitor Module

To be capable of providing an acceleration of 100 km/h in 20 s, super-capacitors are calculated to provide of maximum power P_{sc} = 45kW. Designing the super-capacitors takes into account the range of the operating voltage, the maximum transferred energy, and the number of elements in series and in parallel [25]. We chose the BCAP3000 cell. For U_{DC} = 400 V we choose $U_{sc\text{-}max}$ = 200 V. In order to obtain an acceptable efficiency, the minimum voltage is given by $U_{sc-min} = \frac{U_{sc-max}}{2} = 100V$. The super-capacitor module parameters are obtained in Table II.

C. Sizing of classic DC/DC converters

Two classic DC/DC converter topologies (Fig. 2) are first used. For the battery energy source, a unidirectional DC/DC converter is implemented to boost the battery voltage and to regulate the DC link voltage. However, a bidirectional DC/DC converter is necessary to interface the super-capacitor module to the DC link. For the design of these two classic converters, the inductance L and the filtering capacitor C_f must be estimated. Values are obtained according to (1) and (2):

$$L_1 = \frac{U_{DC}}{4.f.\Delta I_{batt\_max}} \tag{1}$$

$$C_f = \frac{\alpha_{1max}.I_{1max}}{f.\Delta U_{DC\_max}} \tag{2}$$

Where $\Delta I_{batt\ max}$ and $\Delta U_{DC\ max}$ are respectively the battery current and the DC bus voltage ripples.

For the buck/boost converter, the inductance is determined by (3).

$$L_2 = \frac{U_{DC}}{4.f.\Delta I_{sc\_max}} \tag{3}$$

Where $\Delta I_{sc\ max}$ is the super-capacitor current ripple.

Using (1) to (3), the inductances and filter capacities are obtained and shown in Table III. These parameters are obtained with $\Delta I_{batt\ max}$= 2%, $\Delta U_{DC\ max}$ = 1% and $\Delta I_{sc\ max}$ = 1 %.

D. Sizing of the TL Converters

The second HESS used two TL converters (Fig. 3) as power interface with DC link. For the main energy source, a unidirectional DC/DC TL converter is used to boost the battery voltage and to regulate the DC link voltage. A bidirectional DC/DC TL converter is used with the super-capacitor module. For the design of these two TL converters, the inductance L and the two filtering capacitors C_1 and C_2 values are obtained.

For the Boost TL converter, the inductance and capacities are given by (4) and (5) (duty cycle α = 0.5).

$$L = \frac{U_{batt}}{2\Delta I_{sc-max}f}.(2\alpha - 1) \tag{4}$$

$$C = \frac{2I_{scmax}\,(\alpha_{max} - 0{,}5)}{\Delta U_{DC\_max}f} \tag{5}$$

For the Buck/Boost TL converter, the inductance and capacitors expressions are given by (6) and (7).

$$L \geq \frac{U_{DC}}{16\Delta I_{sc-max}f} \tag{6}$$

$$C \geq max\left(\frac{I_{scmax}(1-\alpha_{min})}{2\Delta U_{DC\_max}f}, \frac{I_{scmax}(3-2\sqrt{2})}{2\Delta U_{DC\_max}f}\right) \tag{7}$$

For the same voltage and current ripples as for the classic converters $\Delta U_{DC\ max}$ = 4V and $\Delta I_{sc\ max}$ ≈ 2A, the inductance and filter capacities are obtained for the TL DC/DC converters as shown in Table IV.

As shown in Table III and Table IV, the obtained inductance of the boost TL converter (extracted from (4)) represents approximately 25 % of the classic boost converter inductance for the same value of current ripple and for the same switching frequency. The same thing is concluded for the classic buck/boost converter and the buck/boost TL converter. However, we can conclude that the inductance of the TL converters represent the ¼ of the classic converters inductance. The capacitors of the TL boost and buck/boost converters calculated in Table IV have also reduced in comparison to the ones obtained for the classic converters shown in Table III. Therefore, the reduced inductance and capacitor of TL topology allow reducing the cost, weight and volume of the converter.

The appropriate sizing parameters of the two converters topologies will let us choose the optimal HESS that is more cost effective and allows for the best utilization of battery and super-capacitor technologies for both high energy density and high power density. In this case, the HESS with TL converters is selected. Next, the two system models are simulated using Matlab/Simulink in order to evaluate their behaviour with both converter topologies.

TABLE I. BATTERY SIZED PARAMETERS

Parameter	**Equation**	**Value**
Voltage U_{batt}	$(1-\alpha)U_{DC}$	120 V
Series cells N_{s-batt}	$U_{batt}/V_{batt-nom}$	30
Total current $I_{tot-batt}$	$P_{ch-batt}/U_{batt}$	250 A
Parallel branches N_{p-batt}	$I_{tot-batt}/I_{batt-nom}$	3
Total energy $E_{tot-batt}$	$N_{p-batt} \times C_{nom-batt} \times U_{tot-batt}$	26.44 kWh

TABLE II. SUPER-CAPACITOR SIZED PARAMETERS

Parameter	**Equation**	**Value**
Transferred energy $E_{max-transf}$	$P_{sc-max} \times t_a$	900 kJ
Series cells N_{s-sc}	$\frac{U_{sc-max}}{V_{ele-scmax}}$	74
Parallel branches N_{p-sc}	$\frac{N_{tot-sc}}{N_{s-sc}}$	2
Capacity C_{sc-tot}	$C_{sc}(\frac{N_{p_{sc}}}{N_{s_{sc}}})$	81 F
Resistor R_{sc-tot}	$ESR(\frac{N_{s_{sc}}}{N_{p_{sc}}})$	13.32 mΩ

TABLE III. DC/DC CLASSIC CONVERTERS SIZED PARAMETERS

Boost Converter	**Buck/Boost Converter**
L = 1.33 mH	L = 1.48 mH
C = 1.125 mF	C = 1.25 mF

TABLE IV. DC/DC TL CONVERTERS SIZED PARAMETERS

TL Boost Converter	**TL Buck/Boost Converter**
L = 0.32 mH	L = 0.37 mH
C = 1 mF	C = 0.56 mF

As shown in Table I, the calculated total energy supplied by the batteries for an hour is equal to 26.44 kWh for 3 branches connected in parallel. In order to compensate this drop of voltage and power, 4 branches of battery module are considered in the rest of the work. The second total energy calculated and obtained is equal to 34.992 kWh.

IV. MATLAB/SIMULINK SIMULATION

Matlab/Simulink is proposed to simulate the HESS models behaviors. We use the mathematical models with instantaneous equations to represent the components of the HESS [16]. For the present case, we implemented in Matlab both the classic and TL DC/DC converters models but with only the boost structures. Closed loop control is used with classic PI regulators. The main objective of the implemented control strategy is to control the power flow from the hybrid energy storage sources to the DC load. During transient power, an output voltage drop will arise so the regulator has been designed to control the deficiency of power and prevent the output voltage to drop as well as controlling the power sharing at the input side. Simulation results are obtained for the boost converter and the boost TL converter as shown in the following figures.

It is clear from Fig. 4 and Fig.6 that, the classic boost and the boost TL converters provide the 400V on the DC bus. According to Fig. 5 and Fig.7, the voltage ripples of the two topologies are low which explains the role of regulators.

Inductance current of the two converters are also described by the current curves given in Fig. 4 and Fig.6. The currents are controlled approximately to the desired value (250 A). The current ripples, shown in Fig. 5 and Fig. 7 are similar for the two converter topologies (2 % of 250 A ≈ 5 A).

This simulation result confirm the design results of table 1 ($I_{tot-batt}$ =250 A) with $\Delta I_{batt\ max}$ = 2 % as applied for the calculation of the inductance and capacitor values of the converters. In addition, the same value of current ripples is obtained for both converter topologies despite the TL boost converter is operated with 4 times reduced inductance value in comparison with the classic topology. A reduced inductor and capacitor size results in a reduced cost, weight and volume of the converter. For this reason, the TL converter topology is considered to be more cost efficient and preferable for interfacing any EV or HEV HESS system to the DC voltage common line.

The obtained simulation results confirm the design calculated values. It is also shown that the same value of current ripples is obtained for both topologies with 4 times reduced inductance value of the TL converter in comparison with the classic one. This reduced inductance and capacitor of TL topology allow reducing the cost, weight and volume of the converter and makes the TL converter topology most preferable for any EV or HEV HESS system.

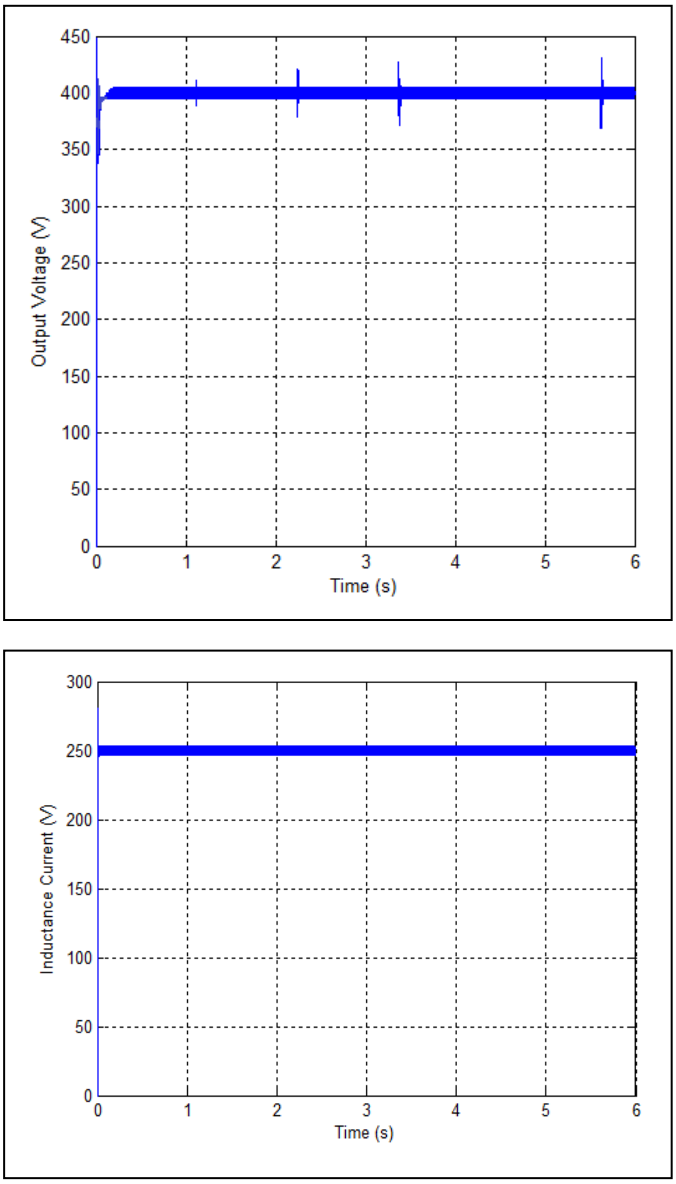

Fig. 4. Output voltage and inductance current of the classic boost converter.

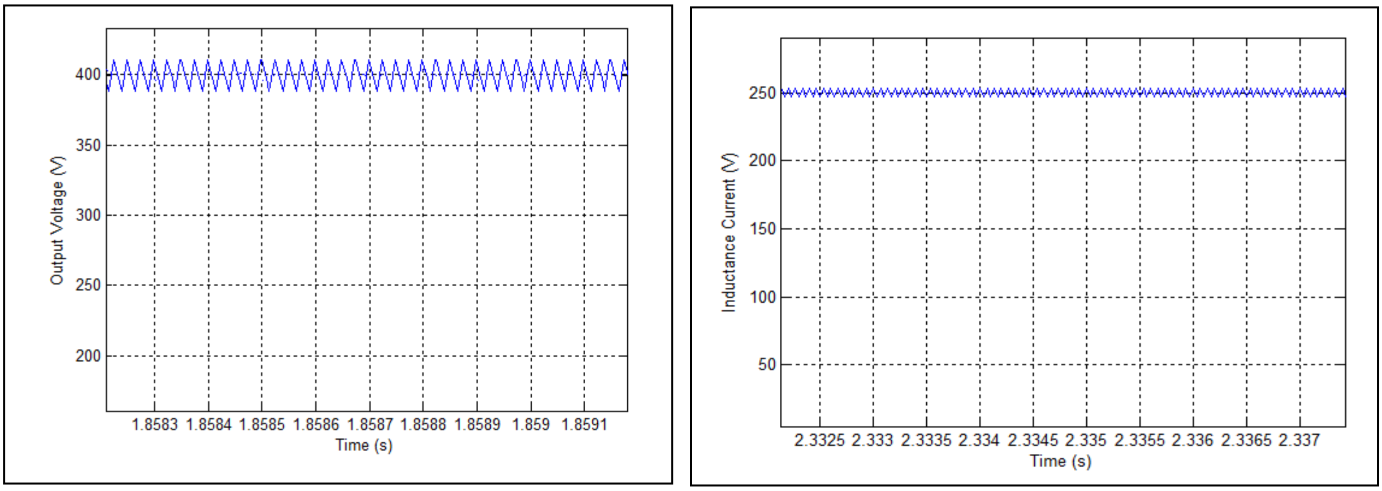

Fig. 5. Output voltage and inductance current ripples of the classic boost converter.

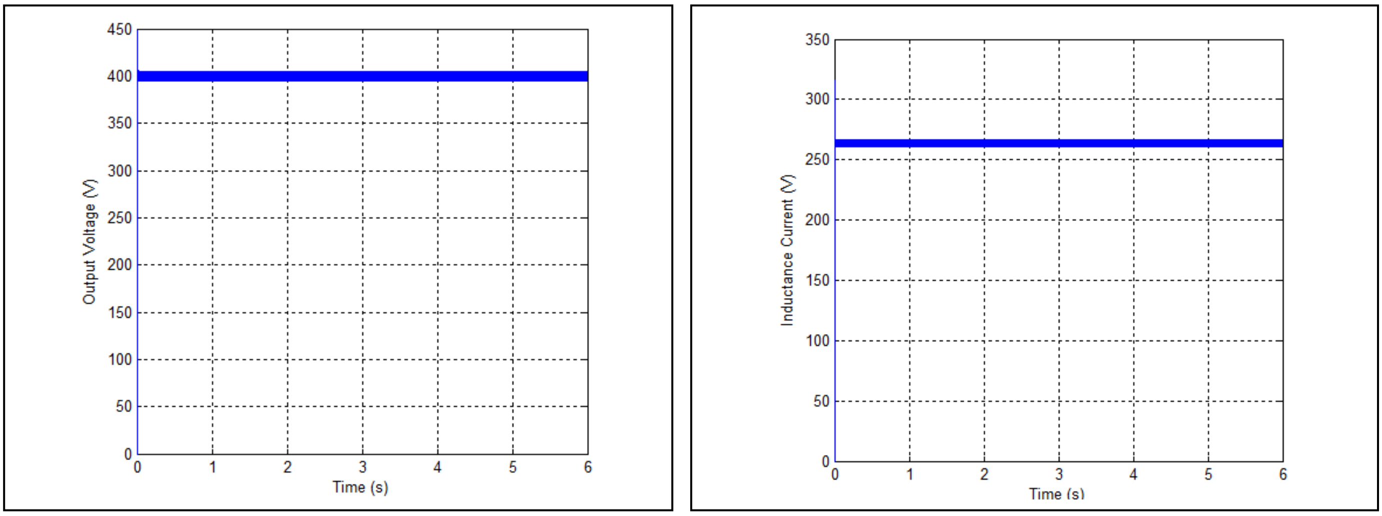

Fig. 6. Output voltage and inductance current of the TL boost converter.

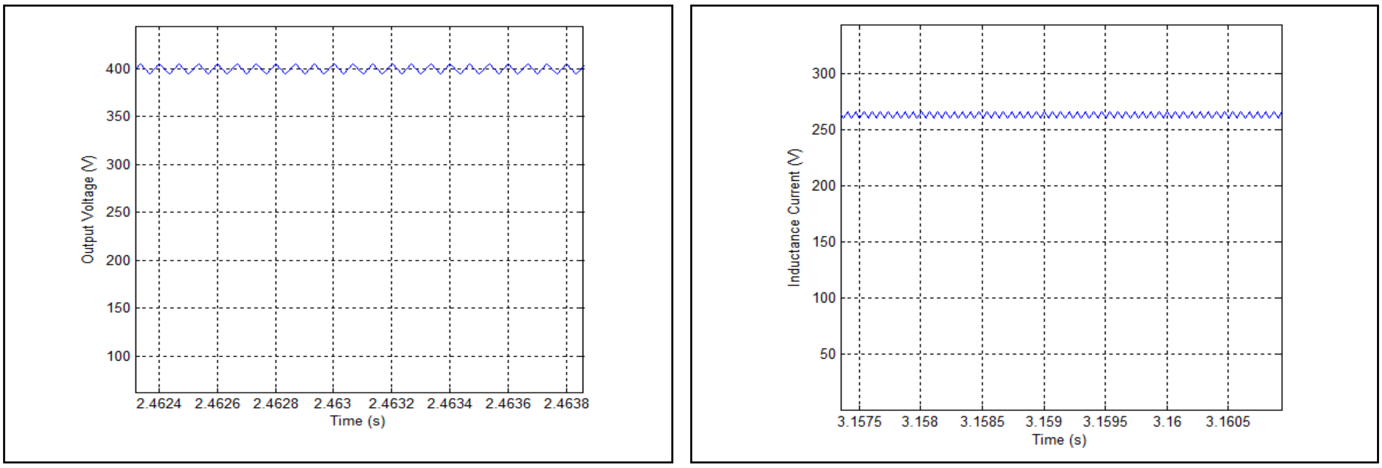

Fig. 7. Output voltage and inductance current ripples of the TL boost converter.

V. CONCLUSIONS

This paper proposes a system design and performance comparison between two DC/DC converter topologies interfacing an hybrid, Lithium-ion battery and super-capacitor, energy storage system to the DC link. Both boost and buck/boost architectures are used for both classic and TL DC/DC converter topologies. The boost unidirectional converter is performing with the battery pack and the buck/boost reversible converter is used with the super-capacitor module. The design of classic and TL DC/DC converters has been performed according to a proposed set of specifications. The appropriate design parameters of the Hybrid Energy Storage System are identified and the proposed converter topologies are compared.

Matlab/Simulink models of both boost classic and boost TL converters are simulated. For this purpose, Matlab models of these converters is implemented and PI closed loop control is performed.

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