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ANALYSIS, MODELLING AND IMPLEMENTATION OF A SWITCHING BI-DIRECTIONAL BUCK-BOOST CONVERTER BASED ON ELECTRIC VEHICLE HYBRID ENERGY STORAGE FOR V2G SYSTEM

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ABSTRACT

This paper presents a switching bi-directional buck-boost converter (SBBBC) for vehicle to-grid (V2G) system. The topology can provide an energy bi-directional flow path for energy exchange between the Li-battery/supercapacitor (SC) hybrid energy storage system (HESS) of the electric vehicle and the grid. This topology not only has buck-boost capability, but also has the function of energy management. In this paper, the state-space averaging method is used to analyse the stability of the topology in boost and buck modes. The control strategy is given according to the state of charge (SOC) of the energy storage system to ensure that the output voltage and current are stable. And the Li-battery is charged in constant current (CC) and constant voltage (CV) mode. In addition to a soft switched DC-DC conversion, the circuit also facilitates an additional output which makes the system capable of supporting multiple applications. The circuit under discussion uses fuzzy logic for the closed loop operation which has better overall performance compared to other conventional converters. Finally, the electrical feasibility of the topology, the suitability of the design controller and control strategy are verified by simulation and experiment.

1. INTRODUCTION

Electric vehicles have been widely used because of their cleanliness and low impact on the environment [1]. Li-batteries are of critical importance part in energy storage systems of electric vehicle [2]. Although Li-batteries with high energy densities can provide enough energy during steady-state operation, the power densities of Li-batteries are too low to meet the peak power demand [3], [4]. Combining Li-batteries and supercapacitors (SC) to form a hybrid energy storage system (HESS) can solve the problem. The reason is that SC with higher power densities can provide the transient power required by the load [5]–[17]. Since output voltage peak of the voltage source inverter is less than the dc-link side voltage, it is necessary to use the dc-dc converter to raise the Li-battery voltage [18]. Figure 1 shows the block diagram of HESS. The SC is directly connected to the inverter, which can increase the dynamic response of the HESS during transient peak power demand, while the Li-battery is connected to the DC-link by a bi-directional DC/DC converter [19]. The effect of the bidirectional dc-dc converter in the HESS is to transfer the energy and keep the dc bus voltage stability. Moreover, the converter should provide bi-directional power flow because the energy storage system and the grid require energy AHESS topology is mentioned in articles [3] and [5].

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In the topology of [3] and [5], the Li-battery can be connected to the SC via a bi-directional dc-dc half-bridge or directly to the DC bus via a diode. This two-stage converter can make full use of the power capacity of the SC but the boost ratio is low. A buck-boost converter for a plug-in hybrid electric vehicle is proposed in paper [21] and [22], respectively. However, the converter mentioned in the paper [21] cannot achieve a bidirectional flow of energy between the grid and the energy storage device. The converter mentioned in the paper [22] has many switching devices, large losses and complicated control. A high voltage gain bi-directional dc-dc converter is given in article [23]. This topology can operate under zero voltage switching conditions and reduces switching and conduction losses. However, this topology has many switching states and the operation is complicated. In [13] and [24], hybrid energy storage systems for electric vehicles based on Z-source inverters (ZSI) and quasi-Zsource inverters (qZSI) were proposed. These two topologies have the boost capability, and provide a bi-directional energy flow path. Moreover, the reliability of the hybrid energy storage system is enhanced due to the characteristics that allow the inverter to shoot-through. These two topologies can increase power density [25].

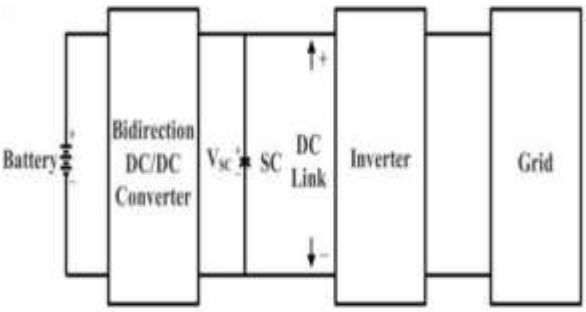

FIGURE 1. The block diagram of HESS.

The control strategies proposed in [13] and [24] are complex, and the topologies have multiple passive components between the SC and the DC bus, which will greatly increase the size of the device. This paper proposes a switching bi-directional buck-boost converter (SBBBC) and its appropriate control strategy, which is used in the HESS for vehicles-to-grid (V2G) system. The converter allows shoot-through of two switches of any phase, with anti-electromagnetic interference capability. Meanwhile, since there are three switches in the DC side, the SC and Li-battery can fulfill bi-directional power flow. Furthermore, the small-signal model of the topology is established by state space averaging method and the stability of the system is analyzed. The control strategy is given according to the state of charge (SOC) of the energy storage system and the operating state of the circuit. The performance of the proposed converter and control strategy are verified through simulation and experimental results.

2. POWER CONVERTERS

2.1 INTRODUCTION TO POWER CONVERTERS:

In this project, a hybrid photovoltaic- fuel cell PV/FC system for grid connection is proposed. PV and Fuel cells produces low voltage dc output. Grid interconnection of PV/FC system requires power converters to meet the grid requirements like voltage amplitude, frequency, and phase angle. First convert the low voltage dc into high voltage dc by using boost dc-dc converter and then convert this dc voltage into ac by using inverters and finally connect the whole system to grid. This type of system (dc-dc and dc-ac conversion) is called two stage conversion systems. For two stages conversion of hybrid system requires following power converters.

1. DC-DC CONVERTERS
2. INVERTERS (DC-AC CONVERTERS)

3. CONTROLLER IN ELECTRICAL ENGINEERING

3.1 INTRODUCTION:

Control theory is an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems. The desired output of a system is called the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

The usual objective of control theory is to calculate solutions for the proper corrective action from the controller that result in system stability, that is, the system will hold the set point and not oscillate around it.

3.2 COMPARING OPEN-LOOP CONTROL WITH CLOSED-LOOP CONTROL:

A. CLOSED-LOOP CONTROL

- shows a closed-loop action (closed control loop);
- can counteract against disturbances (negative feedback);
- Can become unstable, i.e. the controlled variable does not fade away, but grows (theoretically) to an infinite value.

B. OPEN-LOOP CONTROL

- shows an open-loop action (controlled chain);
- can only counteract against disturbances, for which it has been designed; other disturbances cannot be removed;
- Cannot become unstable - as long as the controlled object is stable.

4. MATLAB/SIMULINK

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include-

Math and computation
Algorithm development
Data acquisition
Modelling, simulation, and prototyping
Data analysis, exploration, and visualization
Scientific and engineering graphics

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows solving many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or FORTRAN.

The MATLAB system consists of six main parts:

(a) Development Environment

This is the set of tools and facilities that help to use MATLAB functions and files. Many of these tools are graphical user interfaces. It includes the MATLAB desktop and Command Window, a command history, an editor and debugger, and browsers for viewing help, the workspace, files, and the search path.

(b) The MATLAB Mathematical Function Library

This is a vast collection of computational algorithms ranging from elementary functions, like sum, sine, cosine, and complex arithmetic, to more sophisticated functions like matrix inverse, matrix Eigen values, Bessel functions, and fast Fourier transforms.

(c)The MATLAB Language

This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both

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"programming in the small" to rapidly create quick and dirty throw-away programs, and "programming in the large" to create large and complex application programs.

(d) Graphics

MATLAB has extensive facilities for displaying vectors and matrices as graphs, as well as annotating and printing these graphs. It includes high-level functions for two-dimensional and three-dimensional data visualization, image processing, animation, and presentation graphics. It also includes low-level functions that allow to fully customize the appearance of graphics as well as to build complete graphical user interfaces on MATLAB applications.

5. TOPOLOGY AND MODULATION OF THE PROPOSED SWITCHING BI-DIRECTION BUCK-BOOST CONVERTER

A. PROPOSED TOPOLOGY

Figure 2 shows the proposed SBBBC with HESS, which consists of five parts: Li-battery, switching bi-directional buck-boost circuit, SC, full bridge inverter and gird. The switching bi-directional buck-boost circuit has an inductor, a SC and the additional three switches (SD1, SD2, SD3). Since the gate signals of switches SD2 and SD3 are the same and complementary to the gate signal of switch SD1, one gate signal can control these three additional switches. This unique SBBBC network allows the system work on the buck and boost modes, and it can provide bi-directional power flow.

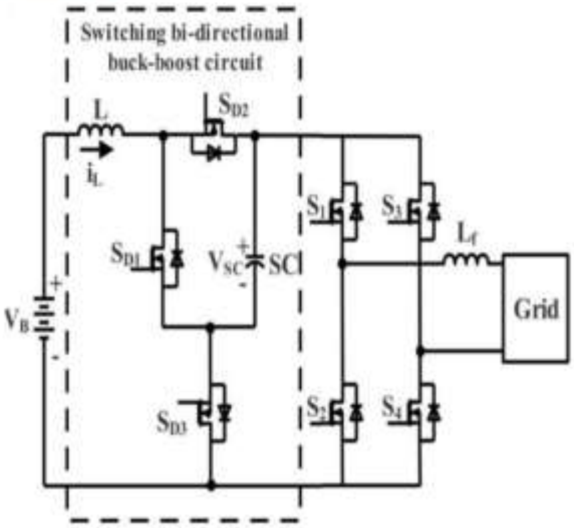

FIGURE 2. The proposed SBBBC.

TABLE 1. Switch combination and inverter output voltage.

N	U_{AC}	S_{D1},S_{D2},S_{D3}	S_1,S_3	S_2,S_4	state
1	0	0 1 1	0 0	1 1	zero state
2	0	0 1 1	1 1	0 0	zero state
3	$-U_{SC}$	0 1 1	0 1	1 0	active state
4	U_{SC}	0 1 1	1 0	0 1	active state
5	0	1 0 0	1 1	X X	shoot-through state
6	0	1 0 0	X X	1 1	shoot-through state

Note:X is 0 or 1.

6. EXISTING CONTROLLER

6.1 CONTROL STRATEGY AND CONTROLLER DESIGN

A. CONTROL STRATEGY

The control strategy diagram of the proposed converter is shown in Figure 12. The control scheme includes four controllers. The SC voltage controller PI1 outputs a duty cycle d1 for controlling the SC voltage. The Li-battery current controller PI2 and the Li-battery voltage controller PI3 are two parallel controllers for controlling the charging current and voltage of the Li-battery. The controller PI2 outputs a duty cycle d2, and the

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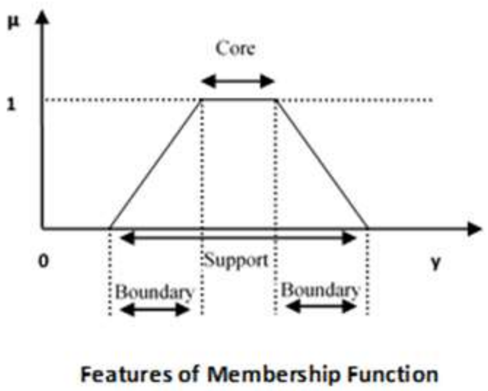
controller PI3 outputs a duty cycle d3. The grid current controller PR outputs a duty cycle d4. The PR controller can track the sinusoidal reference of the grid current [32]. The proposed controll strategy has two operation modes which are vehicles-to-grid (V2G) and gridtovehicles (G2V).

$$E_c = \frac{1}{2} C V_c^2$$

From equation (28), when the capacitor voltage VC is charged to 50% of the maximum voltage of the capacitor VC_max, the capacitor stores only 25% of the energy. If the voltage closed loop stabilizes the capacitor voltage at 80% of the capacitor's maximum voltage, the capacitor store 64% of the energy. The reason for choosing the 80% voltage charging ratio is that the DC bus voltage will not drop greatly when the capacitor supplies power to the grid, and there is enough capacity to achieve voltage regulation of the DC bus.

Fig 3: Features of Membership Function



SIMULATION RESULTS

The SBBBC was simulated to verify the feasibility and dynamic performance. The simulation parameters are shown in Table 2.

TABLE 2. Design parameters

Parameter	Value	Unit
Li-battery voltage V_B	100	V
SC voltage V_{SC}	200	V
grid voltage V_G	100	V
grid voltage frequency	50	Hz
inductor L	2	mH
filter inductor L_f	2	mH
supercapacitor SC	2	F
parallel capacitance of the Li-battery C_l	470	μF
parasitic resistors R_L	800	mΩ
parasitic resistors R_C	25	mΩ
parasitic resistors R_{Cl}	51	mΩ
internal resistance of the Li-battery R_B	100	mΩ
switching frequency f_s	5	kHz

Figure 19 shows the simulation waveforms when the SBBBC is operating in boost mode. To make the grid current clear, the amplitude of the grid current is amplified 10 times. The current injected into the grid is in phase with the grid voltage to achieve a unit power factor. As shown in Figure 19(b), when the shoot-through duty cycle ds is 0.25, the proposed converter boosts the 100V Li-battery voltage to 200V SC voltage, which meets the voltage gain given by equation (5). At t = 0.5, the reference current IG_ref of the grid current controller changes from 4A to 5A. At this time, the Li-battery current increases and the output power of the Li-battery increases, which can achieve a fast response of the grid current.

Simulink Block Diagram

Fig 4: SBBBC is operating in Boost Mode:

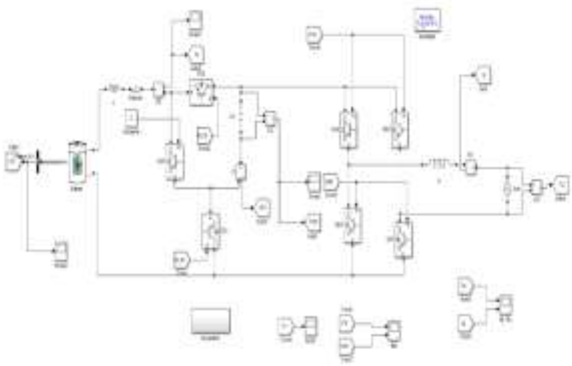
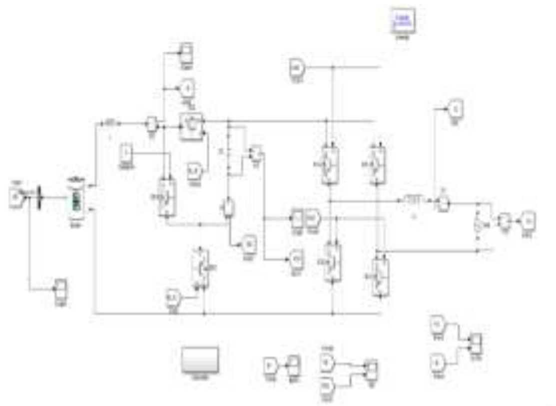


Fig 5: SBBBC is operating in Buck Mode:



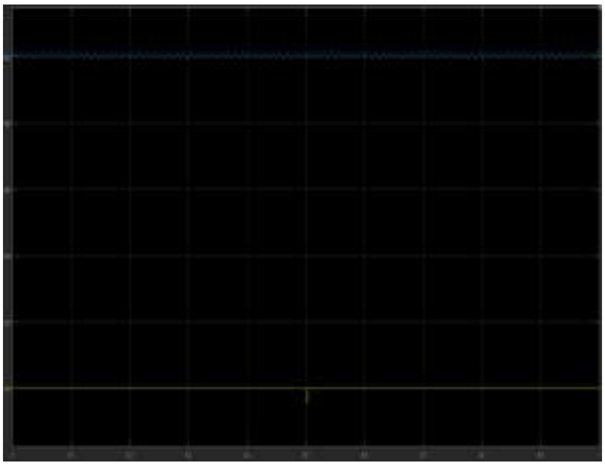


FIGURE 20(b). Simulation results of the existing system. (b) Battery charging current.

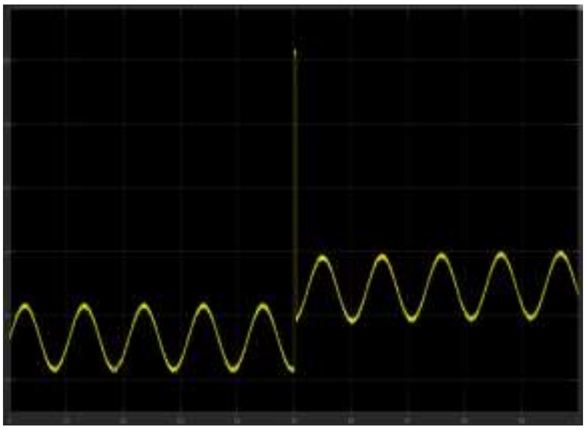
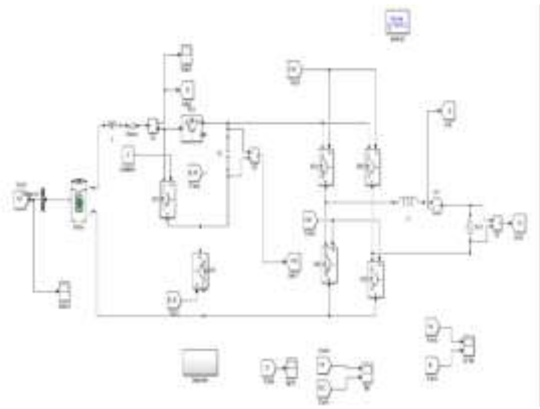


FIGURE 20(c). Simulation results of the existing system. (c) SC voltage.

Figure 20 shows the main waveforms when the SBBBC is operating in buck mode. To make the grid current clear, the amplitude of the grid current is amplified by 10 times. The grid current is in reverse phase with the grid voltage, so the energy flows from the grid to the HESS. At this time, the grid charges the energy storage system. At t = 0.5, the amplitude of grid voltage drops from 100V to 95V. As shown in Figure 20(a), when the grid voltage decreases, the grid current can quickly reach a stable state under the action of the grid-connected controller. The Li-battery charging current waveform is shown in Figure 20(b). It can be seen that the charging current of the Li-battery remains constant. Asshown in Figure 20(c), the SC outputs energy to the Li-battery.

Fuzzy

SBBBC is operating in Boost Mode Using Fuzzy Logic:



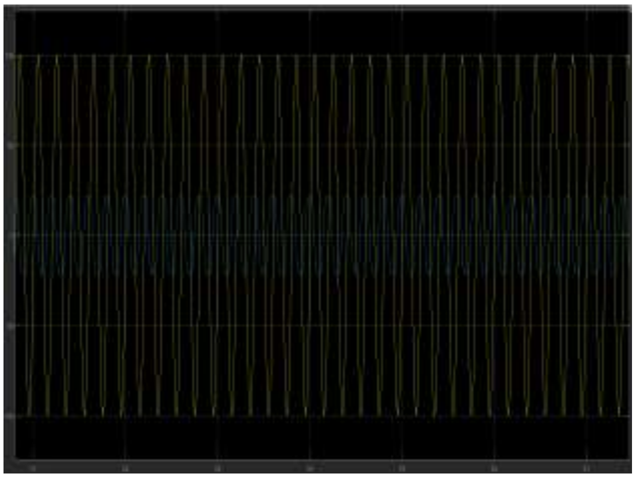


FIGURE 21(a). Simulation results of the proposed system. (a) Grid voltage and grid current

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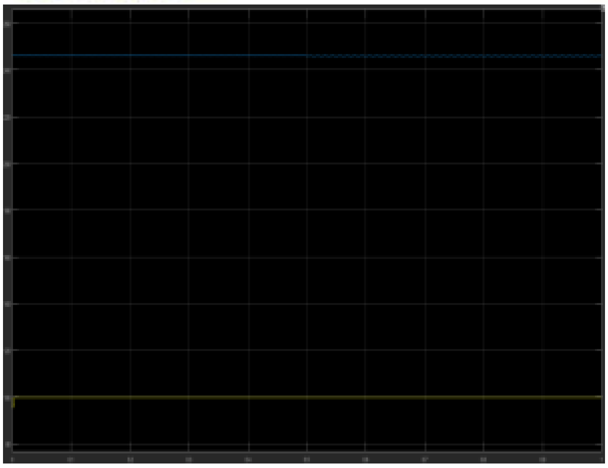


FIGURE 21(b). Simulation results of the proposed system. (b) Battery discharge voltage and SC voltage.

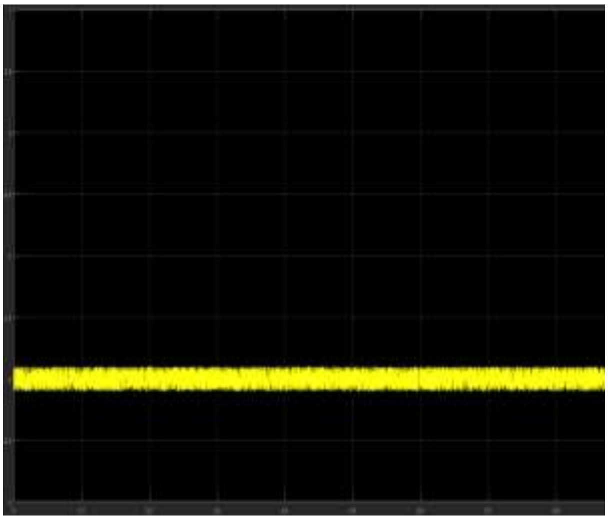
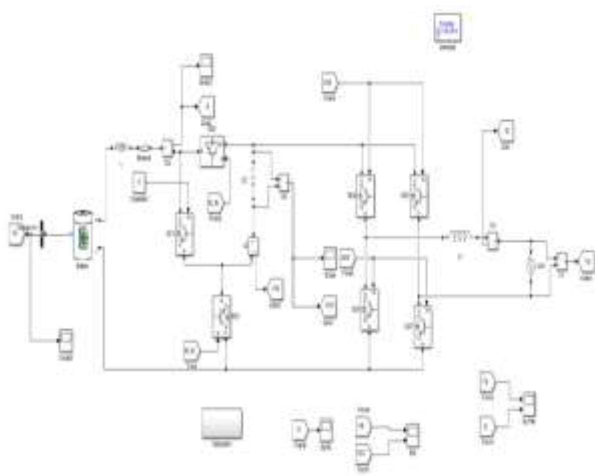


FIGURE 21(c). Simulation results of the proposed system. (c) Battery discharge current.

SBBBC is operating in Buck Mode Using Fuzzy Logic:



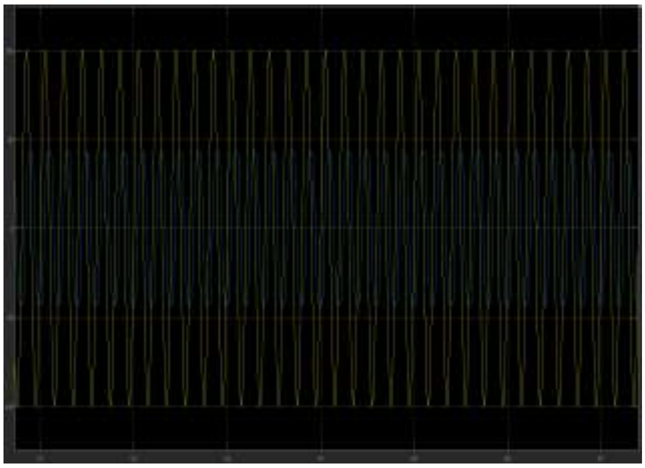


FIGURE 22(a). Simulation results of the proposed system. (a) Grid voltage and grid current.

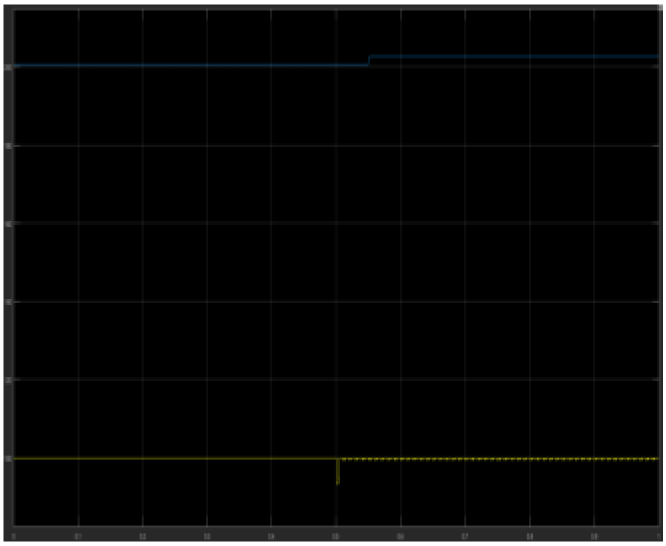


FIGURE 22(b). Simulation results of the proposed system. (b) Battery charging current.

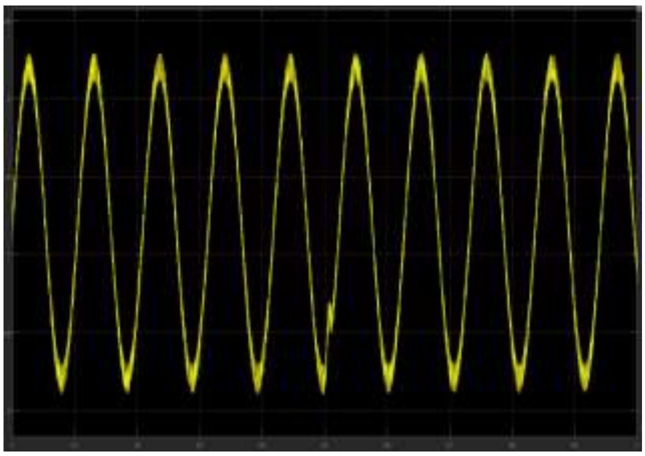


FIGURE 22(c). Simulation results of the proposed system. (c) SC voltage.

CONCLUSION

This paper presents a SBBBC for V2G system. The proposed converter not only has high voltage gain and immunity to electromagnetic interference, but also provides a bidirectional energy flow path. In this paper, different working modes of the SBBBC are discussed in detail and the small signal model of the converter is established. The zero-pole diagram of the system was drawn, the dynamic characteristics of the system were analyzed and its stability was proved. This paper proposes control strategies for V2G and G2V modes, which implement energy management of the HESS. Apart from the advantage of higher efficiency achieved by implementing soft switching, the mentioned topology provides an extra benefit of multiple outputs, thus reducing the complexity as well as the expense of the circuit. The waveforms corresponding to closed loop and open loop circuit has been mentioned in the above sections. The closed loop circuit has been simulated for a 15% of load change. As discussed earlier multi output converters are capable of supporting two different applications simultaneously as well as for applications which require two different voltage levels like multilevel inverters etc.

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