International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 15, No. 2, June 2024, pp. 913~924
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v15.i2.pp913-924

Power converters analyzed in energy storage systems to enhance the performance of the smart grid application

Md Jahidur Rahman[1], Tahar Tafticht[1], Mamadou Lamine Doumbia[2]
[1]Department of Engineering, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada
[2]Department of Electrical and Computer Engineering, Université du Québec à Trois-Rivières, Trois-Rivières, Canada

Article Info

Article history:

Received May 3, 2023
Revised Oct 28, 2023
Accepted Nov 7, 2023

Keywords:

Battery performance
Conduction losses
DC converters
Smart grid
Storage system

ABSTRACT

This paper implements and compares the existing power supply converters for an energy storage system to determine the best suited for the smart grid application. A survey of different DC-DC converters is carried out to analyze the battery's overall performance. The main objective is to identify this application's most appropriate energy storage device. The advantages of this technology have high efficiency and reliability, which can connect various energy sources and reduce conduction losses in the power converters. Through the converter control, reference currents are imposed to charge the battery. The battery nominal voltage needs to change to see which type of converter is the most suitable and robust. Simulation results show that the operating ranges of boost-buck, buck-boost, and buck-boost converters with negative output voltage enhance the efficiency of battery and renewable energy sources and compared the DC converters to know the functional voltage for the energy storage system. The power converter's efficiency and control facility will allow us to link the energy storage system with the power grid. The overall installation is established using MATLAB/Simulink software.

Corresponding Author:

Md Jahidur Rahman
Department of Engineering, Université du Québec en Abitibi-Témiscamingue
445 Bd de l'Université, Rouyn-Noranda, Québec, J9X 5E4, Canada
Email: mdjahidur.rahman@uqat.ca

1. INTRODUCTION

The techniques for designing and producing power converters are mainly based on the association and assembly of discrete components. Thus, a converter can be seen as a set of passive and active components interconnected to perform the desired function for a given specification. Each component must then be chosen according to the constraints that will be imposed on it by these specifications. This approach, therefore, requires a specific study for each function to be performed, which will have several consequences [1]. Each new application corresponds to a new converter, which systematically reviews and redesigns new conversion structures and proves costly in terms of time and money. Eventually, this can lead to specific technological developments that also affect the cost of developing power converters solutions [2], [3]. Regulating the conversion functions and the complex coupled electrical, magnetic, thermal, and mechanical phenomena involved in the operation of a power converter requires an excellent knowledge of power electronics reserved for specialists in this field only. Moreover, with the current integration process, this point becomes more critical. The three preceding points induce significant development times and costs, thus limiting the generalization of a power converter with high conversion efficiency in consumer and industrial applications [4], [5]. This leads to reducing the penetration of power converters in mass applications, which would reduce our consumers' energy bills.

Energy sources in local settings are excluded from use in low or medium power applications, including micro-grids and industrial areas situated at higher power ranges [6], [7]. These regionally distributed energy sources present opportunities for enhancing load balancing among various power supply modules. Their operation relies primarily on the communication channel, resulting in a heightened risk of failures, reduced load regulation, and intricate implementation, all of which contribute to elevated manufacturing and maintenance expenses. Nonetheless, the progress of photovoltaic systems has drawn attention to numerous factors that have a direct impact on the performance of this technology [8], [9]. The power converters and storage devices (battery) are the disciplines in which we seek to design and analyze an electrical system ensuring the transfer of power from an energy source to a receiver and guaranteeing the highest possible energy efficiency while limiting losses as much as possible [9], [10]. The power converter is a device composed of electronically controlled switches. This commute, i.e., oscillates between an on-state and an off-state. The frequency of these switching is generally relatively high, of the order of a few kilo-Hertz, or even a few tens of kilo-Hertz. Such a converter is commonly called a static converter because it does not include any moving mechanical component. Static converters are used to shape an electrical wave. They allow, for example, to modify the voltage or current waveform to adapt it to the receiver's needs. The power dissipated during the transfer has a loss due to the imperfections of its components which make up using the converters [9].

Many research have been done on a multiple-power converter based on distributed power systems in other systems to handle multiple input sources. Most system configurations adopted from previous research rely solely on localized converters with extensive communication capabilities or on a decision agent mechanism technique, described in [11], [12]. Multi-converter systems designed for communication and battery applications exhibit exceptional load regulation and robust load-sharing capabilities [13], [14]. However, this particular system is specialized and tailored for specific tasks, rendering it unsuitable for the all-encompassing performance requirements of smart energy systems. The universal input converter emerges as an optimal choice for distributed generation and smart grid infrastructures, as it can seamlessly integrate and process energy sources and storage into a unified global unit. The universal keying technology topology boasts advantages such as cost-effectiveness, higher power density, and simplified management.

Extensive research conducted over the past decade has yielded a wide array of topologies for multi-input converters. Broadly, multi-input converters can be categorized into two groups: magnetic coupling converters (MCC) and electrically coupled converters (ECC). Doncker *et al.* [15] pioneered the initial literature on single-output topologies after [16], [17] reached a consensus on an idea that applies to other topologies and multi-input versions. The tri-port converter employs various power flow control strategies [5], [18]. Nevertheless, the magnetic energy transfer method is sensitive to circuit parameters and may lead to potentially inaccurate performance, making current disposal capacity a critical consideration when interfacing with renewable energy sources like fuel cells.

Alternatively, energy transfer methods not only focus on current regulation but primarily emphasize power flow control. MCCs offer higher power density and flexible output voltage levels, facilitated by strong and soft switching techniques. However, MCC circuit devices entail a complex load-sharing implementation compared to other energy sources and storage elements. On the other hand, ECCs are straightforward and typically operate with less than 10 kW of power [19]. ECCs are often associated with non-isolated converter topologies, such as buck, boost, and buck-boost. Their power flow control is relatively simple, and the peripheral circuitry is generally uncomplicated. ECC systems feature less flexible output voltage, a modular structure, and lower manufacturing costs, rendering them advantageous in various applications like automotive and communication systems.

In this context, we explored various implementations of multi-input topologies. Zientarski *et al.* [20] grouped diverse sources together to achieve high output voltage and employed a time-domain switching scheme for these channels with multiple inputs, offering a multiplex or a combination of multiplexing and simultaneous switching topology based on the boosted cell with stack input voltage. Mira *et al.* [21] introduced a step-down topology based on the multi-input ECC code, operating with a time-multiplexed switching model. Kumar *et al.* [8] investigated sources with varying input levels and proposed a topology featuring mix-boost and buck-boost switching cells as a front-end application for microgrid conversion. The combination of Buck and Boost switching cells is integrated into a single unit to share power, with a bank of battery sources included for the negative output of the buck-boost switching cells. Mira *et al.* [22], the use of mixed switch mode and charge pump topology results in a multi-input ECC with all subsystems having a common point, enabling bi-directional power flow due to inductive coupling. This approach provides several benefits, such as the ability to transmit power individually or simultaneously from PV and wind turbines directly to the grid, the capacity to implement maximum power point tracking (MPPT) for solar systems and wind power, and an extended variable input voltage range for renewable energy power systems [23], [24]. Zapata *et al.* [2] also concurred that similar boost cells could constitute a multi-input converter system suitable for immobilizer systems, mobile applications, and switch cells capable of supplying power to various sources. Canciello *et al*. [25] approached to operate a buck-boost converter as a bidirectional regulable power bridge between low and high-voltage buses. As a result, the battery's charge can be utilized and handle overload situations. A flexible and sustainable power generation scheme is proposed in [26] using flexible fuzzy goal programming to increase the capacity of renewable sources and reduce emission levels on Earth. The optimal cost solution and flexibility of power demand are achieved by switching to renewable energy sources.

The DC–DC converters are presented in most applications of low, medium, and high voltage or current. Researchers in every sector are launching new research technology aiming to improve and solve many issues related to power converters to enhance new technology associated with challenges and requirements which have been brought recently in the power converters applications. Power electronics and converters always help to solve problems of industrial and residential power losses and support energy development, opening the gap for new opportunities and improving the quality of power supply. Thus, it is a reality that power converters and their technologies can be a major considerable research topic in power system engineering. In this paper, we present the study of the different types of existing converters and batteries to choose the most suitable for the smart grid system and can solve the problem of intermittency of the operation of renewable energy sources. We compared the different operating ranges of boost-buck, buck-boost, and buck-boost with negative output voltage using MATLAB simulation. Then we studied the DC-DC converters capable of feeding the battery storage. Each converter's control strategy is determined and chosen for the best topology.

The primary contributions of this paper can be summarized as: i) Devising a control scheme for switched-mode converters aimed at facilitating rapid energy storage and delivery to batteries while meeting desired energy levels; ii) Analyzing the operating ranges of boost-buck, buck-boost, and buck-boost ($-V_{out}$) converters to enhance the efficiency of battery and renewable energy sources; and iii) Comparing the DC converters to know the functional voltage for the energy storage system. The rest of the paper is sorted as: i) Section 2 studies the converters used in an energy storage system; ii) Section 3 described the operational technique of different DC converters; iii) Section 4 presents the simulation results of the proposed research work; iv) Section 5 summarized the functional voltage of the converters for the energy storage system; and v) Section 6 concludes the paper.

2. STUDY OF CONVERTERS USED IN ENERGY STORAGE SYSTEMS

DC converters play a vital role in energy storage systems (ESS) by facilitating efficient power conversion and bidirectional energy flow between storage devices and the grid. As the demand for renewable energy integration and grid stability increases, the importance of energy storage systems and their associated DC converters becomes more significant. Energy storage systems have gained prominence as a crucial element in modern power systems due to their ability to mitigate renewable energy intermittency, support grid stabilization, and enhance overall system efficiency. DC converters serve as an interface between energy storage devices (e.g., batteries, supercapacitors) and the AC grid, allowing for efficient energy conversion and optimal power management. They are essential for converting the DC output of energy storage devices into usable AC power for the grid or vice versa. These converters enable bidirectional power flow, allowing energy to be stored in the system when there is excess generation or to be released to the grid when demand exceeds supply. A study has been done to compare the existing power supply converters for an energy storage system to determine the best suited for our application. This technology has many advantages [27], such as high efficiency and reliability, connecting various energy sources, and reducing conduction losses in power switches. The main disadvantages of this technology are magnetic losses, eddy current losses, and losses in passive components. Despite its losses, switched-mode power supplies have an efficiency of between 65% and 90%, while linear power supplies reach between 35% and 55% [28]. Through the converter control, reference currents are imposed to charge the battery. We will also change the battery's nominal voltage to see which type of converter is the most suitable and robust.

3. OPERATIONAL TECHNIQUE OF DIFFERENT DC CONVERTERS

3.1. Operational equations of the boost-buck converter

The DC-DC converter utilized in this system functions as a switching power supply capable of both stepping up and stepping down the output voltage. This converter is integrated with a Li-ion battery. The battery model is linked to a DC voltage source through a series resistor. The equivalent circuit and the configuration of the bidirectional boost-buck converter can be observed in Figure 1. In its operation, the converter shifts into boost mode for discharging and switches to buck mode when charging the battery.

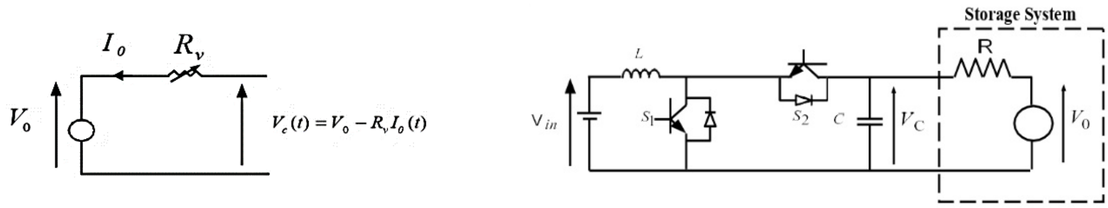

Figure 1. Equivalent circuit diagram of a battery with bidirectional boost-buck converter

In a boost-buck converter, the control source voltage typically refers to the voltage that controls the duty cycle of the switch in the converter. This voltage is often derived from a feedback mechanism to regulate the output voltage. The precise formula for the control source voltage in a boost-buck converter depends on the control strategy used, such as voltage mode control or current mode control. In this approach, the precise formula for control voltage $V_C(t)$ is introduced in (1).

$$V_C(t) = A \exp\left(-B \int_0^t I_0 dt\right) + V_0 - R_V I_0 - K \frac{Q}{Q-\int_0^t I_0 dt} \tag{1}$$

Where V_0 is the nominal voltage, I_0 is the nominal current, and K is the bias voltage of the battery. The following relationship represents the control source of voltage shown in (2).

$$V_C = A \exp\left(-B \int_0^t I_0 dt\right) + V_0 \tag{2}$$

Where A is the exponential voltage and B is the exponential capacity of the battery, and (3) represents the variable resistor.

$$R_V = \mathrm{R} = R_i + k \frac{Q}{Q-\int_0^t I_0 dt} \tag{3}$$

Where R_i is the number of resistors and Q is the capacity of the battery. We will now establish the equations with the fixed resistor R to extract the control law [29] by analyzing in (4)-(34). This converter comprises switches and diodes, each of which can be on or off. When the switch is on, the voltage V_{in} is entire across the inductor. When S_1 and S_2 are on:

$$V_{in} = L \frac{dI_L}{dt} \tag{4}$$

$$\frac{1}{L} V_{in} = \frac{dI_L}{dt} \tag{5}$$

$$\frac{1}{R}(v_c - V_0) - C \frac{dv_c}{dt} = 0 \tag{6}$$

$$\frac{dv_c}{dt} = \frac{1}{RC}(v_c - V_0) \tag{7}$$

Then, we get the state model

$$XA_1 + UB_1 = X \tag{8}$$

With:

$$U = \begin{bmatrix} V_{in} \\ V_0 \end{bmatrix} \tag{9}$$

$$X = \begin{bmatrix} I_L \\ v_c \end{bmatrix} \tag{10}$$

This allows us to establish the following matrix:

$$\begin{bmatrix}\frac{dI_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix} = \begin{bmatrix}V_{in}\\ V_0\end{bmatrix}\begin{bmatrix}\frac{1}{L} & 0\\ 0 & -\frac{1}{RC}\end{bmatrix} + \begin{bmatrix}I_L\\ v_c\end{bmatrix}\begin{bmatrix}0 & 0\\ 0 & \frac{1}{RC}\end{bmatrix} \quad (11)$$

When S1 and S2 are closed, the current flows through the circuit shown in Figure 2.

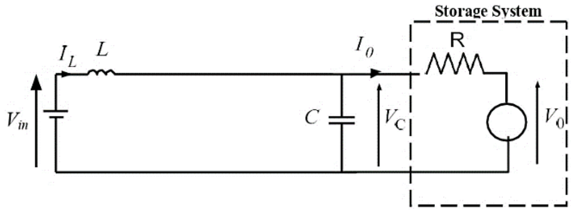

Figure 2. Diagram of the boost-buck converter when the switch is blocked

When S is blocked and D on:

$$V_{in} = v_c + L\frac{dI_L}{dt} \quad (12)$$

$$\frac{1}{L}V_{in} - \frac{1}{L}v_c = \frac{dI_L}{dt} \quad (13)$$

$$\frac{1}{R}(v_c - V_0) + C\frac{dv_c}{dt} = I_L \quad (14)$$

$$\frac{1}{RC}(V_0 - v_c) + \frac{1}{C}I_L = \frac{dv_c}{dt} \quad (15)$$

Then we get the state model:

$$XA_2 + UB_2 = X \quad (16)$$

This allows us to establish the following matrix:

$$\begin{bmatrix}\frac{dI_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix} = \begin{bmatrix}V_{in}\\ V_0\end{bmatrix}\begin{bmatrix}\frac{1}{L} & 0\\ 0 & \frac{1}{RC}\end{bmatrix} + \begin{bmatrix}I_L\\ v_c\end{bmatrix}\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix} \quad (17)$$

The following equality is used to determine the mean of the state model in (18):

$$XA + UB = \dot{X} \quad (18)$$

As well:

$$A = d.A_1 + (1-d)A_2 \text{ and } B = d.B_1 + (1-d)B_2 \quad (19)$$

Where *d* is the duty cycle of the converter. We use the two matrices previously determined to obtain A and B in (20):

$$A = (1-d)\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix} + d\begin{bmatrix}0 & 0\\ 0 & \frac{1}{RC}\end{bmatrix} \quad (20)$$

and:

$$B = (1-d)\begin{bmatrix}\frac{1}{L} & 0\\ 0 & \frac{1}{RC}\end{bmatrix} + d\begin{bmatrix}\frac{1}{L} & 0\\ 0 & -\frac{1}{RC}\end{bmatrix} \quad (21)$$

Therefore, we obtain:

$$A = \begin{bmatrix}0 & -\frac{(1-d)}{L}\\ \frac{(1-d)}{C} & -\frac{1}{RC}\end{bmatrix} \quad (22)$$

and:

$$B = \begin{bmatrix}\frac{1}{L} & 0\\ 0 & \frac{1}{RC}\end{bmatrix} \quad (23)$$

This can be written as:

$$V_{in} - (1-d)v_c = L\frac{dI_L}{dt} \quad (24)$$

$$\frac{1}{RC}V_0 + \frac{1-d}{L}I_L - \frac{1}{RC}V_C = C\frac{dv_C}{dt} \quad (25)$$

We will only focus on current regulations in (26) so we will use the dynamic current equation.

$$V_{in} - (1-d)v_c = L\frac{dI_L}{dt} \quad (26)$$

To maintain current regulation, a proportional-integral (PI) controller is employed. The new input, denoted as *u* and representing the regulator's output, is defined in (27).

$$u = L\frac{dI_L}{dt} \quad (27)$$

By employing the Laplace transform, the following expression is derived in (28).

$$u = S.L.I_L \quad (28)$$

Consider *G* as the open-loop current transfer function, defined in (29).

$$G = \frac{1}{SL} = \frac{I_L}{u} \quad (29)$$

The controller will produce the boost command based on the signal representing the difference between the setpoint I_{Lref} and the inductor current I_L. The transfer function of the controller is expressed in (30).

$$Cs = \frac{K_i}{S} + K \quad (30)$$

The transfer function in the closed-loop system of the controller linked with the PV system is defined in (31).

$$\frac{I_{PV}}{I^*_{PV}} = \frac{\frac{K_i+K_PS}{L}}{\frac{K_i}{L}+S^2+S\frac{K_P+R_C}{L}} = \frac{\frac{K_i+K_PS}{L}}{\omega_i^2+S^2+2S\omega_i\zeta} \quad (31)$$

In this context, I_{PV} stands for the current error, while I^*_{PV} represents the reference current for the PV system. This process facilitates the identification of the coefficients K_p and K_i:

$$K_P = 2L\omega_i\xi - R_c \quad (32)$$

and:

$$K_i = L\omega_i^2 \quad (33)$$

The control law is analyzed in (34) and (35).

$$L\frac{dI_L}{dt} = V_{in} - (1-d)v_c = u \quad (34)$$

$$d = \frac{u - V_{in}}{v_c} + 1 \quad (35)$$

The PWM modulation method is employed for producing trigger pulses to manage the converter switch. The control schematic of the boost-buck converter is depicted in Figure 3. Through the utilization of the controlled voltage source V_{in}, the boost-buck converter is controlled by comparing the real-time current with the reference current, which can assume values of 10 A, -10 A, -20 A, and 20 A. The battery undergoes discharging when the reference current is negative and charging when the reference current is positive. Four simulations were carried out with this converter. For each simulation, the nominal voltage of the Li-ion battery used in the MATLAB software, with the modified value V_{bat} = 250 V, V_{bat} = 350 V, V_{bat} = 500 V, and V_{bat} = 650 V. The input voltage V_{in} is fixed at 500 V. The components of the boost-buck converter have the value of L = 10 mH and C = 4500 μF.

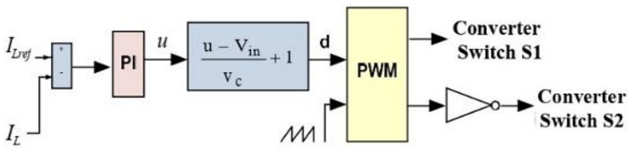

Figure 3. The control scheme of the boost-buck converter

3.2. Operational equations of the buck-boost converter

The DC-DC converter in use serves as a bidirectional switching power supply, capable of both stepping down and stepping up the output voltage as needed. This converter is paired with a Li-ion battery, with the battery model connected to a DC voltage source via a series resistor. Figure 4 provides a visual representation of the equivalent circuit and the configuration of the bidirectional buck-boost converter. In its operational modes, the converter charges the battery in buck mode and discharges it in boost mode.

The method employed here is PWM modulation, which generates the trigger pulses to manage the converter switch. Figure 5 illustrates the control diagram of the buck-boost converter. Utilizing the controlled voltage source V_{in}, the buck-boost converter is adjusted by comparing the real-time current with the reference current, which can assume values of 10 A, -10 A, -20 A, and 20 A.

Charging occurs when the reference current is positive, while discharging takes place when the reference current is negative. Four simulations were carried out with this converter. For each simulation, the nominal voltage of the Li-ion battery used in the MATLAB software, with the modified value V_{bat} = 250 V, V_{bat} = 350 V, V_{bat} = 500 V, and V_{bat} = 650 V. The input voltage V_{in} is fixed at 500 V. The components of the buck-boost converter have the value of L = 10 mH and C = 4500 μF. The control law of the buck-boost converter using (35) is given in (36).

$$d = 1 - \frac{-u + V_{in}}{v_c} \quad (36)$$

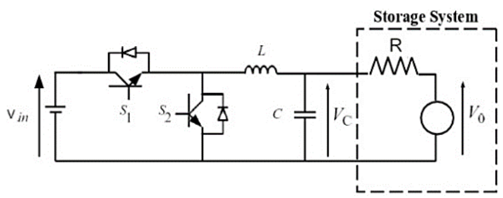

Figure 4. Circuit diagram of the buck-boost converter

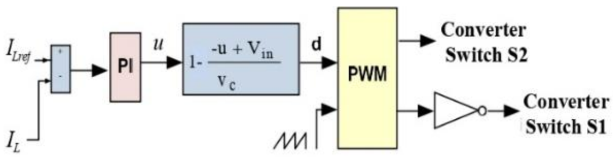

Figure 5. The control scheme of the buck-boost converter

3.3. Operational equations of the buck-boost converter with negative output voltage

Figure 6 depicts the general topology of the buck-boost converter with a negative output voltage. The control law in (36), which was previously analyzed for the buck-boost converter, is applied in this configuration. This control strategy ensures efficient regulation of the converter's output in the presence of a negative voltage requirement.

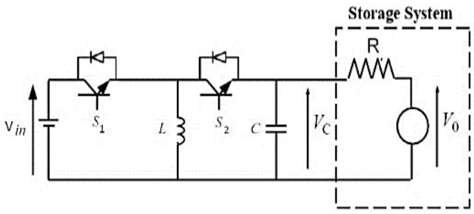

Figure 6. Circuit diagram of the buck-boost converter with negative output voltage

4. SIMULATION RESULTS

4.1. Simulation results using the boost-buck converter

The simulation results indicate that the boost-buck converter is unable to charge or discharge the battery when the nominal battery voltage is set at 250 V and 350 V, as depicted in Figures 7(a) and 7(b). However, the converter exhibits the capability to charge or discharge the battery effectively at a nominal battery voltage of 500 V and 650 V, as illustrated in Figures 7(c) and 7(d). The total simulation is run for 0.7 s.

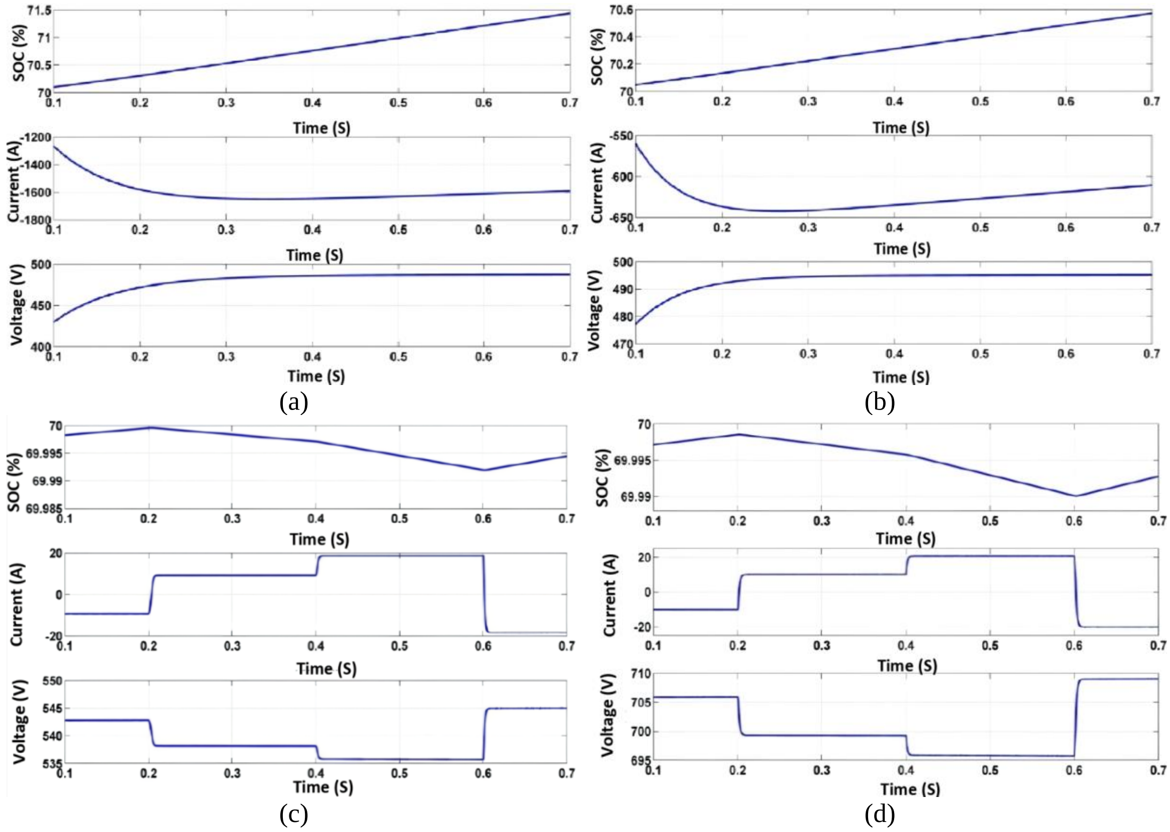

Figure 7. Battery states of charge with boost-buck converter for (a) 250 V, (b) 350 V, (c) 500 V, and (d) 650 V

4.2. Simulation results using the buck-boost converter

The simulation results demonstrate that the buck-boost converter is capable of charging or discharging the battery when the nominal battery voltage is set at 250 V and 350 V, as depicted in Figures 8(a) and 8(b). Conversely, the converter exhibits an inability to charge or discharge the battery at a nominal battery voltage of 500 V and 650 V, as shown in Figures 8(c) and 8(d). The total simulation is run for 0.7 s.

4.3. Simulation results using the buck-boost converter with negative output voltage

The simulation results show that the buck-boost converter with negative output voltage has the capability to charge or discharge the battery at all the nominal battery voltages of 250 V, 350 V, 500 V, and 650 V shown in Figures 9(a) to 9(d). The battery current has been changed to observe the system-on-chip (SOC) conditions. The total simulation is run for 0.7 s.

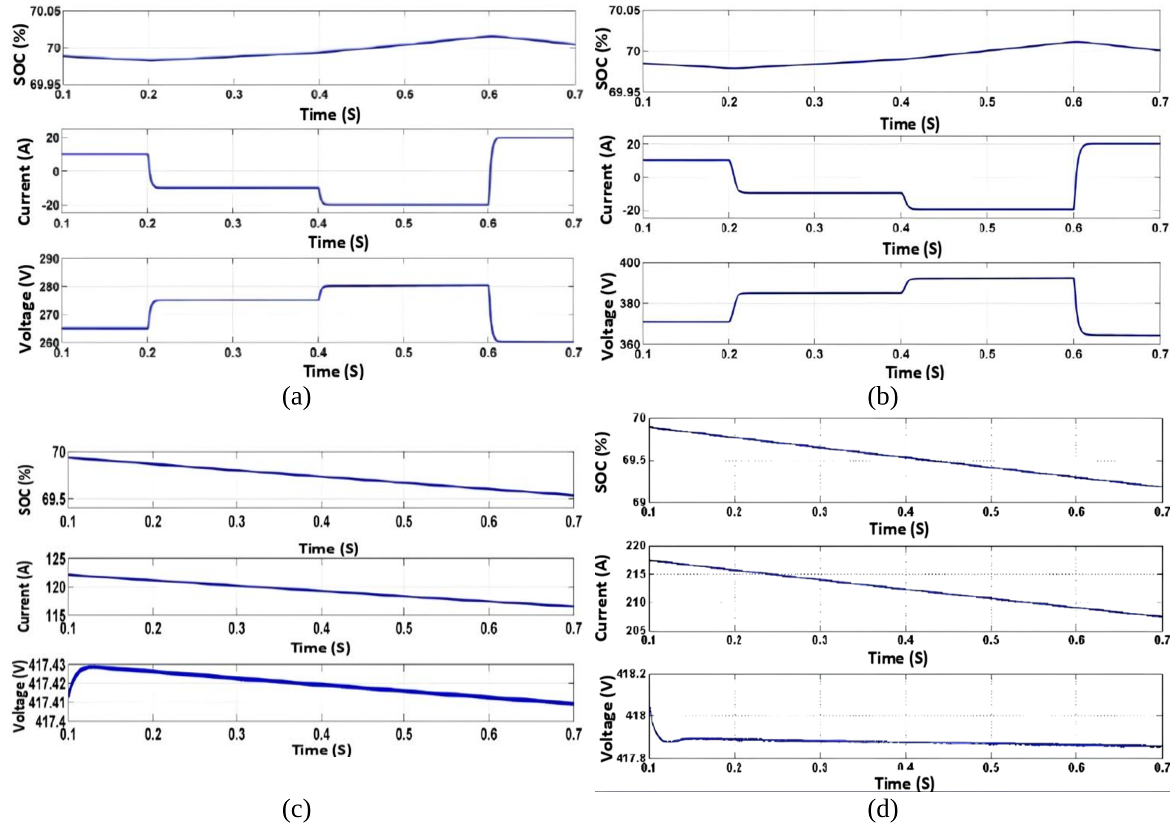

Figure 8. Battery states of charge with buck-boost converter for (a) 250 V, (b) 350 V (c) 500 V, and (d) 650

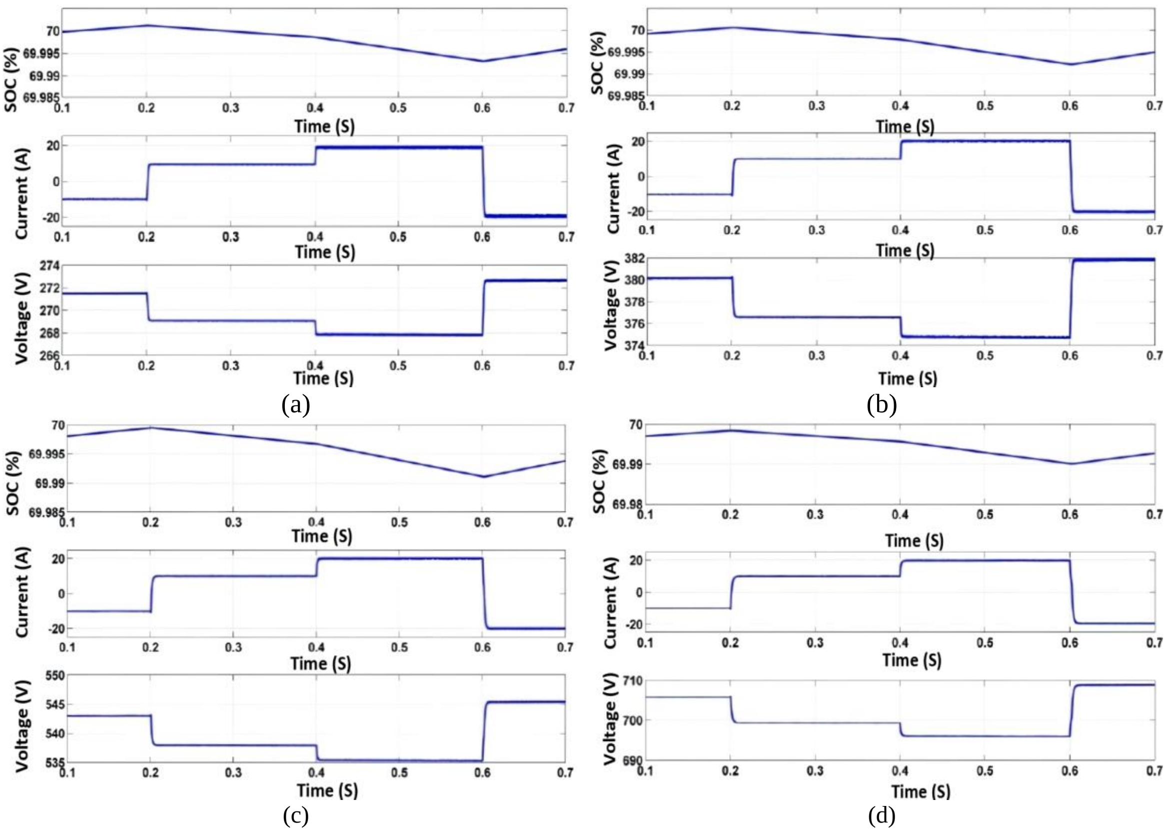

Figure 9. Battery states of charge with modified buck-boost converter for (a) 250 V, (b) 350 V, (c) 500 V, and (d) 650 V

5. RESULTANT FUNCTIONAL VOLTAGE OF THE CONVERTERS

We summarize the converters used to know which voltage is functional for the energy storage system. Table 1 shows, the buck-boost converter with negative output voltage only can operate regardless of the value of the nominal battery voltage. Besides, all the converters are capable of bidirectional power flow.

Table 1. Summary of converters usable in an energy storage system

Converters	$V_{bat} > V_{in}$	$V_{bat} = V_{in}$	$V_{bat} < V_{in}$	Bidirectional
Boost-buck	Capable	Capable	Incapable	Capable
Buck-boost	Incapable	Incapable	Capable	Capable
Buck-boost ($-V_{out}$)	Capable	Capable	Capable	Capable

6. CONCLUSION

The study of the different types of existing converters and batteries are carried out to choose the most suitable in term of performance for the smart grid application system. We analyzed the different operating ranges of boost-buck, buck-boost, and buck-boost with negative output voltage using MATLAB simulation. Then we studied the DC-DC converters capable of feeding the energy storage system. Each converter's control strategy is determined and chosen for the best topology. These converters help the batteries store a desired amount of energy and then return it to a grid at the desired speed. It is beneficial to store power from solar panels or wind turbines without wastage. The adaptability of a switched-mode power converter is appropriate for charging or discharging a battery. Also, the simplicity of the control techniques of converters gives significant efficiency. It seems efficient to use a bidirectional converter for the smart grid application to charge or discharge the battery without any constraints. Buck-boost converter with negative output voltage can operate regardless of the value of the nominal battery voltage. For the future scope of this research, boost-buck, buck-boost, and buck-boost ($-V_{out}$) converters could be implemented in the smart grid application to charge and discharge the vehicle's storage (battery) system as it is capable of bidirectional power flow to supply or absorb the power from the electrical network. To achieve a power network devoid of disturbances, it is possible to create filters that are specifically designed to offset the reactive power and harmonic currents produced by the power electronics converter.

ACKNOWLEDGEMENTS

The financial support for this research was provided by the Department of Engineering at Université du Québec en Abitibi Témiscamingue (UQAT).

REFERENCE

[1] H. Ramirez-Murillo, C. Restrepo, J. Calvente, A. Romero, and R. Giral, "Energy Management DC System Based on Current-Controlled Buck-Boost Modules," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2644–2653, Sep. 2014, doi: 10.1109/TSG.2014.2330198.

[2] J. W. Zapata, S. Kouro, G. Carrasco, H. Renaudineau, and T. A. Meynard, "Analysis of Partial Power DC–DC Converters for Two-Stage Photovoltaic Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 1, pp. 591–603, Mar. 2019, doi: 10.1109/JESTPE.2018.2842638.

[3] C. M. A. da Luz, E. R. Ribeiro, and F. L. Tofoli, "Analysis of the PV-to-PV architecture with a bidirectional Buck-Boost converter under shading conditions," *Solar Energy*, vol. 232, pp. 102–119, Jan. 2022, doi: 10.1016/j.solener.2021.12.028.

[4] T. Chen *et al.*, "An optimized bidirectional buck–boost converter for DC bus voltage stabilization in new generation poloidal field power supply," *Energy Reports*, vol. 8, pp. 188–200, May 2022, doi: 10.1016/j.egyr.2021.11.016.

[5] P. K. Gayen, P. R. Chowdhury, and P. K. Dhara, "An improved dynamic performance of bidirectional SEPIC-Zeta converter based battery energy storage system using adaptive sliding mode control technique," *Electric Power Systems Research*, vol. 160, pp. 348–361, Jul. 2018, doi: 10.1016/j.epsr.2018.03.016.

[6] M. J. Rahman, T. Tafticht, and M. L. Doumbia, "Power Stability and Frequency Control Techniques of DG for a High Penetration Wind-Based Energy Storage System Using Integral–Derivative Controller," *IEEE Canadian Journal of Electrical and Computer Engineering*, vol. 45, no. 3, pp. 232–241, 2022, doi: 10.1109/ICJECE.2021.3103524.

[7] M. J. Rahman, T. Tafticht, M. L. Doumbia, and N. M.-A. Mutombo, "Dynamic Stability of Wind Power Flow and Network Frequency for a High Penetration Wind-Based Energy Storage System Using Fuzzy Logic Controller," *Energies*, vol. 14, no. 14, p. 4111, Jul. 2021, doi: 10.3390/en14144111.

[8] N. A. Kumar, R. Dhanalakshmi, and C. Gayithri, "Investigations on bidirectional resonant converters for renewable energy sources and energy storage systems," in *2016 International Conference on Advanced Communication Control and Computing Technologies (ICACCCT)*, IEEE, May 2016, pp. 396–401. doi: 10.1109/ICACCCT.2016.7831669.

[9] M. J. Rahman, T. Tafticht, and M. L. Doumbia, "Frequency Control for a High Penetration Wind-Based Energy Storage System in the Power Network," in *2020 IEEE Electric Power and Energy Conference (EPEC)*, IEEE, Nov. 2020, pp. 1–6. doi: 10.1109/EPEC48502.2020.9320083.

[10] S. Hamasaki, R. Mukai, and M. Tsuji, “Control of power leveling unit with super capacitor using bidirectional buck/boost DC/DC converter,” in *2012 International Conference on Renewable Energy Research and Applications (ICRERA)*, IEEE, Nov. 2012, pp. 1–6. doi: 10.1109/ICRERA.2012.6477316.
[11] R. Smolenski, *Conducted Electromagnetic Interference (EMI) in Smart Grids*. in Power Systems. London: Springer London, 2012. doi: 10.1007/978-1-4471-2960-8.
[12] H. R., H. Daneshpajooh, A. Safaee, P. Jain, and A. Bakhshai, “Bidirectional DC - DC Converters for Energy Storage Systems,” in *Energy Storage in the Emerging Era of Smart Grids*, InTech, 2011. doi: 10.5772/23494.
[13] N. Hassanpour, A. Chub, A. Blinov, and D. Vinnikov, “Comparison of Full Power and Partial Power Buck-Boost DC-DC Converters for Residential Battery Energy Storage Applications,” in *2022 IEEE 16th International Conference on Compatibility, Power Electronics, and Power Engineering (CPE-POWERENG)*, IEEE, Jun. 2022, pp. 1–6. doi: 10.1109/CPE-POWERENG54966.2022.9880862.
[14] M. Kaouane, A. Boukhelifa, and A. Cheriti, “Regulated output voltage double switch Buck-Boost converter for photovoltaic energy application,” *International Journal of Hydrogen Energy*, vol. 41, no. 45, pp. 20847–20857, Dec. 2016, doi: 10.1016/j.ijhydene.2016.06.140.
[15] R. W. A. A. De Doncker, D. M. Divan, and M. H. Kheraluwala, “A three-phase soft-switched high-power-density DC/DC converter for high-power applications,” *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 63–73, 1991, doi: 10.1109/28.67533.
[16] A. M. Soomro, S. F. Khahro, S. Talpur, L. Xiaozhong, and F. Manzoor, “Input-Current and Load Voltage Sharing in Input-Parallel Output-Series Connected Boost Half Bridge DC-DC Converter Using Stable Control Scheme,” *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol. 12, no. 5, May 2014, doi: 10.11591/telkomnika.v12i5.4188.
[17] K. Shi, T. Bui, and J. Marco, “Optimal control of bidirectional active clamp forward converter with synchronous rectifier based cell-to-external-storage active balancing system,” *Journal of Energy Storage*, vol. 41, p. 102851, Sep. 2021, doi: 10.1016/j.est.2021.102851.
[18] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, “Family of multiport bidirectional DC–DC converters,” *IEE Proceedings - Electric Power Applications*, vol. 153, no. 3, p. 451, 2006, doi: 10.1049/ip-epa:20050362.
[19] M. Parchomiuk, R. Strzelecki, K. Zymmer, and A. Domino, “Modular power converter topologies for energy storage and electric power distribution systems,” in *2017 Progress in Applied Electrical Engineering (PAEE)*, IEEE, Jun. 2017, pp. 1–6. doi: 10.1109/PAEE.2017.8009022.
[20] J. R. R. Zientarski, M. L. da S. Martins, J. R. Pinheiro, and H. L. Hey, “Series-Connected Partial-Power Converters Applied to PV Systems: A Design Approach Based on Step-Up/Down Voltage Regulation Range,” *IEEE Transactions on Power Electronics*, vol. 33, no. 9, pp. 7622–7633, Sep. 2018, doi: 10.1109/TPEL.2017.2765928.
[21] M. C. Mira, Z. Zhang, K. L. Jorgensen, and M. A. E. Andersen, “Fractional Charging Converter With High Efficiency and Low Cost for Electrochemical Energy Storage Devices,” *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7461–7470, Nov. 2019, doi: 10.1109/TIA.2019.2921295.
[22] M. C. Mira, Z. Zhang, and A. E. M. Andersen, “Analysis and Comparison of DC/DC Topologies in Partial Power Processing Configuration for Energy Storage Systems,” in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, IEEE, May 2018, pp. 1351–1357. doi: 10.23919/IPEC.2018.8507937.
[23] Y. Yang, X. He, R. Shao, S. Xu, and L. Chang, “Multi-Input Single-Phase Grid-Connected Inverter for Hybrid PV/Wind Power System,” *International Journal of Renewable and Sustainable Energy*, vol. 3, no. 2, p. 35, 2014, doi: 10.11648/j.ijrse.20140302.11.
[24] T. Tafticht, M. Tchakala, and M. J. Rahman, “GMPPT approach for photovoltaic systems under partial shading conditions using a genetic algorithm,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 2, p. 1238, Jun. 2022, doi: 10.11591/ijpeds.v13.i2.pp1238-1245.
[25] G. Canciello, A. Russo, B. Guida, and A. Cavallo, “Supervisory Control for Energy Storage System Onboard Aircraft,” in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, IEEE, Jun. 2018, pp. 1–6. doi: 10.1109/EEEIC.2018.8494347.
[26] M. F. Khan, A. Pervez, U. M. Modibbo, J. Chauhan, and I. Ali, “Flexible Fuzzy Goal Programming Approach in Optimal Mix of Power Generation for Socio-Economic Sustainability: A Case Study,” *Sustainability*, vol. 13, no. 15, p. 8256, Jul. 2021, doi: 10.3390/su13158256.
[27] V. M. Iyer, S. Gulur, S. Bhattacharya, and R. Ramabhadran, “A Partial Power Converter Interface for Battery Energy Storage Integration with a DC Microgrid,” in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, IEEE, Sep. 2019, pp. 5783–5790. doi: 10.1109/ECCE.2019.8912590.
[28] K. E. L. Marcillo *et al.*, “Interval Robust Controller to Minimize Oscillations Effects Caused by Constant Power Load in a DC Multi-Converter Buck-Buck System,” *IEEE Access*, vol. 7, pp. 26324–26342, 2019, doi: 10.1109/ACCESS.2019.2901441.
[29] Y. Yao, F. Fassinou, and T. Hu, “Stability and Robust Regulation of Battery-Driven Boost Converter With Simple Feedback,” *IEEE Transactions on Power Electronics*, vol. 26, no. 9, pp. 2614–2626, Sep. 2011, doi: 10.1109/TPEL.2011.2112781.

BIOGRAPHIES OF AUTHORS

Md Jahidur Rahman received the B.Sc. degree in electrical and electronic engineering from Stamford University Bangladesh, Bangladesh in 2013, and the M.Sc. degree in electrical engineering from École de technologie supérieure, Université du Québec, Canada in 2017. He is currently pursuing the Ph.D. degree in the Department of Engineering at Université du Québec en Abitibi-Témiscamingue, Canada. His current research interests include distributed generation, smart grid, control, and renewable energy technologies. He can be contacted at email: mdjahidur.rahman@uqat.ca.

Tahar Tafticht received the MSc degree in electrical engineering from the University of Sciences and Technology Houari Boumedienne, Algiers, Algeria, and the Ph.D. degree in electrical engineering from the Université du Québec à Trois-Rivières, Canada, in 2006. Currently, he is a Professor at the Université du Québec en Abitibi-Témiscamingue (UQAT). His research interests include power electronics, photovoltaic and wind energy conversion systems, integration of renewable energy system, and distributed generation systems. He can be contacted at email: tahar.tafticht@uqat.ca.

Mamadou Lamine Doumbia received the M.Sc. degree in Electrical Engineering from Moscow Power Engineering Institute (Technical University), Russia, in 1989; the M.Sc. in Industrial Electronics from the Université du Quebec à Trois-Rivières (UQTR), Canada, in 1994; and the Ph.D. degree in Electrical Engineering from the Ecole Polytechnique de Montréal, Canada, in 2000. From 2000 to 2002, he was a lecturer at the Ecole Polytechnique de Montréal and the CEGEP Saint-Laurent, Montreal. He worked as Senior Research Engineer (2002-2003) at the CANMET Energy Technology Centre (Natural Resources Canada), post-doctoral researcher (2003-2005) at Hydrogen Research Institute (HRI). Since 2005 he is Professor at the Department of Electrical and Computer Engineering, Université du Québec à Trois-Rivières. His research interests include renewable energy systems, distributed energy resources, electric drives, power electronics, and power quality. He has published more than 80 papers in international journals and conferences and has been serving as an editorial board member. M. L. Doumbia is a member of the Hydrogen Research Institute, member of IEEE Power Electronics Society, IEEE Communications Society, and responsible for the educational activities of the IEEE Saint Maurice Section. He is a Professional Engineer and member of the Ordre des Ingénieurs du Québec (OIQ). He can be contacted at email: mamadou.doumbia@uqtr.ca.