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The Control of Isolated Full-Bridge Bidirectional DC-DC Converter for Battery Power Management

Hasan Üzmuş[1,*], Naci Genç[2,3]

[1]Faculty of Engineering, Electrical and Electronics Engineering Department, Van Yuzuncu Yil University, Van, Turkey; hasanuzmus@yyu.edu.tr
[2]Faculty of Engineering, Electrical and Electronics Engineering Department, Yalova University, Yalova, Turkey; naci.genc@yalova.edu.tr
[3] Electrical Engineering Department, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan;
*Correspondence: hasanuzmus@yyu.edu.tr;

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Abstract

The advancement of direct current (DC) technologies enables electrochemical energy storage for DC electrical power with batteries to be deployed for locations devoid of grids and mobile devices. Battery-based energy storage systems are essential for applications such as electric vehicles and mobile devices. DC-DC converters with two-directions power flow are required for Battery-based energy storage systems for both charging and discharging. Bidirectional DC-DC converters are used for power flowing in two directions. Isolation between battery and system can be realized by bidirectional DC-DC converter. In this study, an isolated full-bridge bidirectional DC-DC converter is proposed for charging- discharging of batteries. The transformer used for isolation is operated with high frequency for compactness. The proposed DC-DC converter is controlled with PI for both high and low sides. The control parameters of PI are tuned via Ziegler -Nichols method. The proposed DC-DC converter design with 0.6-3 kW power range with approximately 90% efficiency. MATLAB/Simulink is used for designing and simulations.

Keywords: Isolated bidirectional DC-DC converter; full-bridge; battery charging/discharging.

1. Introduction

Developments in DC electrical power technologies have made energy storage by electrochemical processes in batteries feasible [1]. The Batteries are produced in two different forms: disposable and rechargeable, with varying power levels. Many studies are being conducted to ensure these batteries are long-lasting, safe, and have high capacity. Rechargeable batteries can be produced in various forms, including lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), and lithium-ion (Li-ion), with dry, wet, and gel contents [2]. The storaged energy in DC the form by batteries is utilized for locations without a grid, electrical vehicles and portable electrical devices. Recharging is essential for sustainability of the system used batteries. The power converter circuits are necessary in this system for power flow by charging and discharging. Generally, DC-DC buck converters are used for charging, and DC-DC boost are utilized for discharging. Instead of two different DC-DC converters, a DC-DC converter has two-directions power flow is more attractive. The converters with two-directions power flow are named bidirectional [3]. A bidirectional DC-DC converter is required for achieving power flow in two directions as charging and discharging [4]. There are two types classification for bidirectional DC-DC converters as isolated and non-isolated [5]. The non-isolated bidirectional DC-DC converters are cheaper with easy control; however, they lack of galvanic isolation that is undesirable for many power applications [6]. The isolated bidirectional DC-DC converter basically consists of DC-AC, AC-AC with a transformer and AC-DC power converters. The galvanic isolation can be achieved by transformer used for AC-AC power transformation. For charging; high side DC voltage invert in AC by DC-AC converter, inverted AC voltage decreased and flow the low side via transformer with isolation, decreased AC voltage convert DC by AC-DC converted for batteries. For discharging; the power flow is exact opposite direction [7].

In this study, an isolated full-bridge bidirectional DC-DC converter was proposed. The proposed converter is utilized for two-directions power flow with galvanic isolation. Moreover, the proposed converter was simulated and analyzed for different loads and SOC situations with two independent PI controller for boost (discharging) and buck (charging) modes. A unified control strategy based on PI controllers is employed for both modes, with the control gains determined using the Ziegler–Nichols method. The proposed converter is analyzed and simulated in MATLAB/Simulink for battery charging and discharging modes.

2. Materials and Methods

The proposed DC-DC converter with charging (buck) and discharging (boost) modes is described in this section. In this study, the proposed DC-DC converter given in Figure 1 is designed for 0.6-3 kW with high voltage side (boost mode) in the of 200-400 V and low voltage side (buck mode) in the range of 24-48 V [8].

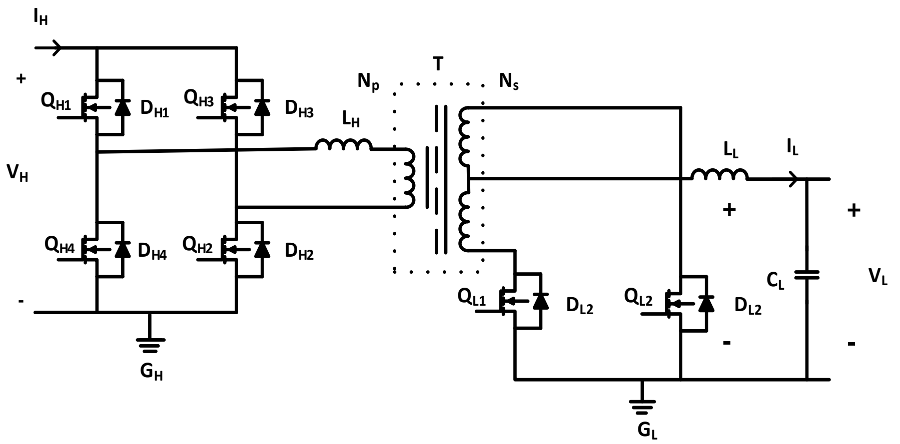


Figure 1. The proposed DC-DC converter.

The ideal relationship between input and output voltages is given in Equation 1. The primary winding is (Np), the secondary winding is (Ns), and d is the duty cycle.

$$\frac{V_L}{V_H} = 2d\frac{N_s}{N_p} \quad (1)$$

The proposed DC-DC converter for buck (charging) mode is predicted in Figure 2, the primary winding (Np) is driven by a square wave forming an alternating current (AC) on the primary side to transform to the secondary winding (Ns). The square waveform is rectified by D_{L1} and D_{L2} diodes and filtered by L_L inductor and C_L capacitor, and then delivered to battery for charging when Q_{L1} and Q_{L2} switches are off.

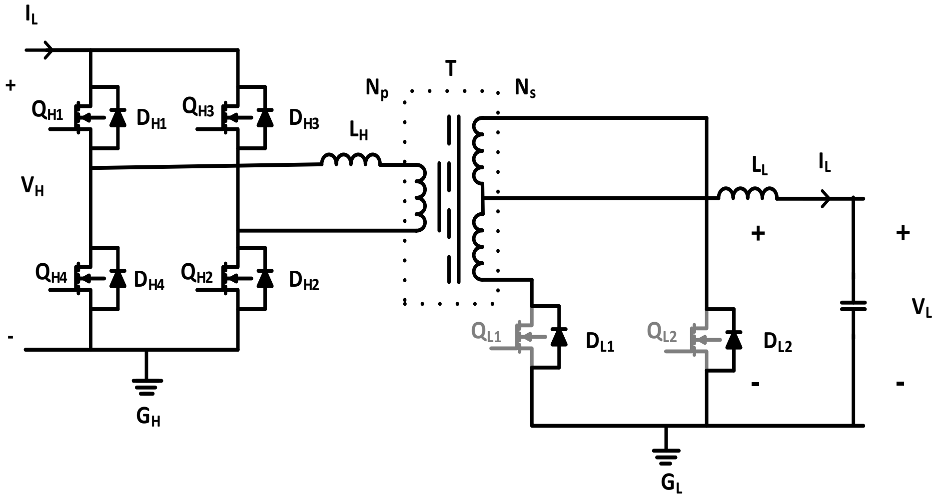


Figure 2. The proposed DC-DC converter for buck (charging) mode.

For charging the battery from the high voltage side, the circuit operates as a buck converter. The gating of Q_{H1}–Q_{H2} and Q_{H3}–Q_{H4} with a 180° phase difference and duty cycle up to 50% enables energy transfer from the high voltage side to the low voltage side with isolation.

The proposed DC-DC converter for boost (discharging) mode is shown in Figure 3, the Np is driven by a square wave forming on the secondary side to transform to Ns. The square waveform is rectified by D_{H1}, D_{H2}, D_{H3} and D_{H4} diodes, filtered by L_H inductor and then delivered to the high voltage side when Q_{H1}, Q_{H2}, Q_{H3} and Q_{H4} switches are off.

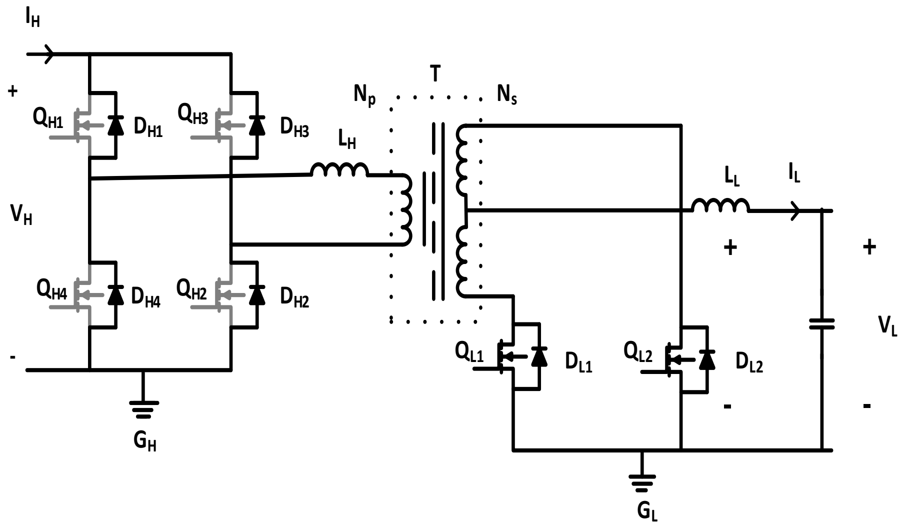


Figure 3. The proposed DC-DC converter for boost (discharging) mode.

For discharging the battery to a higher DC level, the switching pairs Q_{L1}–Q_{L2} are driven with a 180° phase difference with a duty cycle greater than 50%. Energy is transferred from the battery (low voltage side) to the high voltage side, providing regulated higher voltage on the DC link or supplying a load.

High-frequency transformers are used to achieve compact size and reduced weight. Transformer design considers parasitic effects, filter components (L_L inductor and C_L capacitor), and overall performance including transient response and stability. The usage of high-frequency transformers also improves isolation and allows for flexible voltage scaling between the high and low voltage sides.

Two different PI controllers are used for two-directions power flow (charging and discharging). PWM generates the reference control signals, which are then processed by the PI controllers to produce the drive signals for the switching devices. The parameters of proposed DC-DC converter are given in Table 1.

Table 1. The parameters of proposed DC-DC converter.

Parameters	Values
Tr Power (P_T)	3 kW
High Side Voltage (V_H)	380-400 V
Frequency (f)	50 kHz
Low Side Voltage (V_L)	43-48 V
Target Efficiency (η)	%90
Regulation	%0.5

3. Results and Discussion

The isolated full-bridge bidirectional DC-DC converter r can be operated both as a boost and a buck converter with isolation. In both cases, to obtain the desired output values, the system output voltage was compared with the reference voltage. The signal processed in the PI controller and obtained was converted into the control signal using the PWM. When the proposed converter is operated for boost mode, the proportional (P) controller coefficient (Kp) and the integral (Ki) controller coefficient Ki of the PI controller were adjusted using the Ziegler-Nichols method. The coefficients of PI controller for the boost mode given in Table2.

Table 2. Kp and Ki coefficients for boost mode. The parameters of proposed DC-DC converter

Coefficients	Values
Proportional (K)	0.001
Integral (Ki)	0.9

Q_{H1}, Q_{H2}, Q_{H3} and Q_{H4} switches are off and Q_{L1} and Q_{L2} switches are on, when the proposed DC-DC converter is operated for boost mode (Figure 4). Q_{L1} and Q_{L2} switches are triggered with a 180° phase differences.

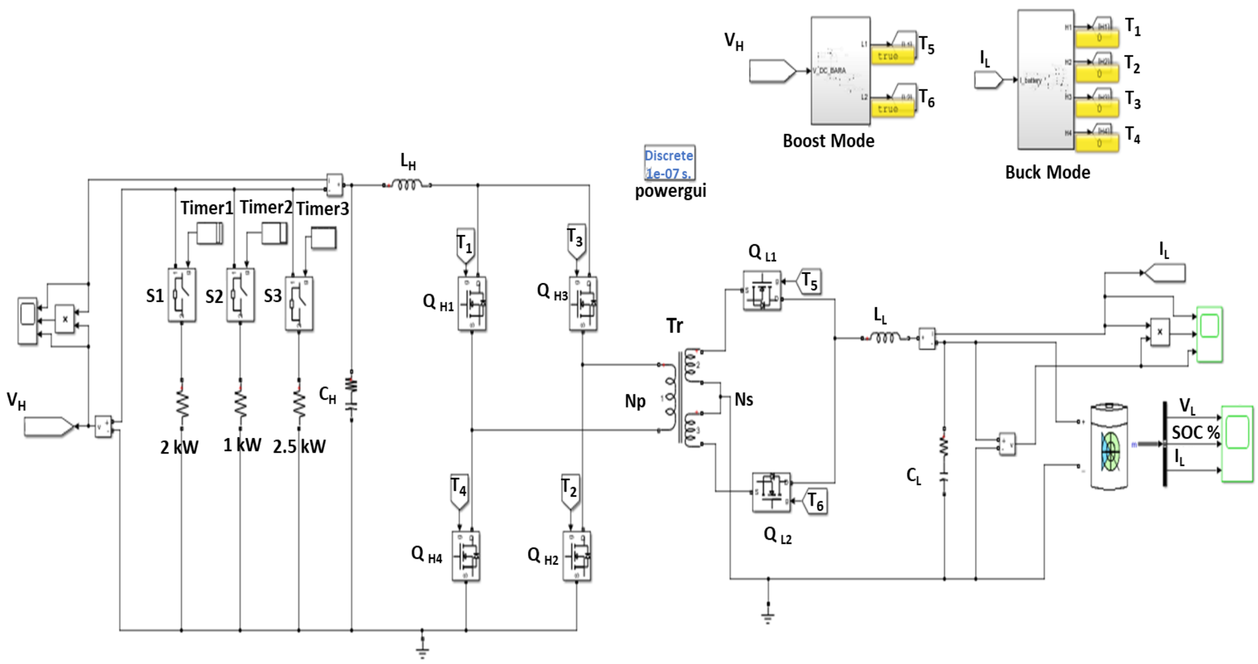


Figure 4. The simulation of proposed DC-DC converter for boost (discharging) mode.

The proposed DC-DC converter is operated in boost mode for different loads (2 kW, 1kW and 2.5 kW). The percentage state of charge (SOC) of the battery group can be determined from the battery status. In these simulations, the SOC was set to 80%. The simulation results for high and low sides under different loads are given in Figure 5.

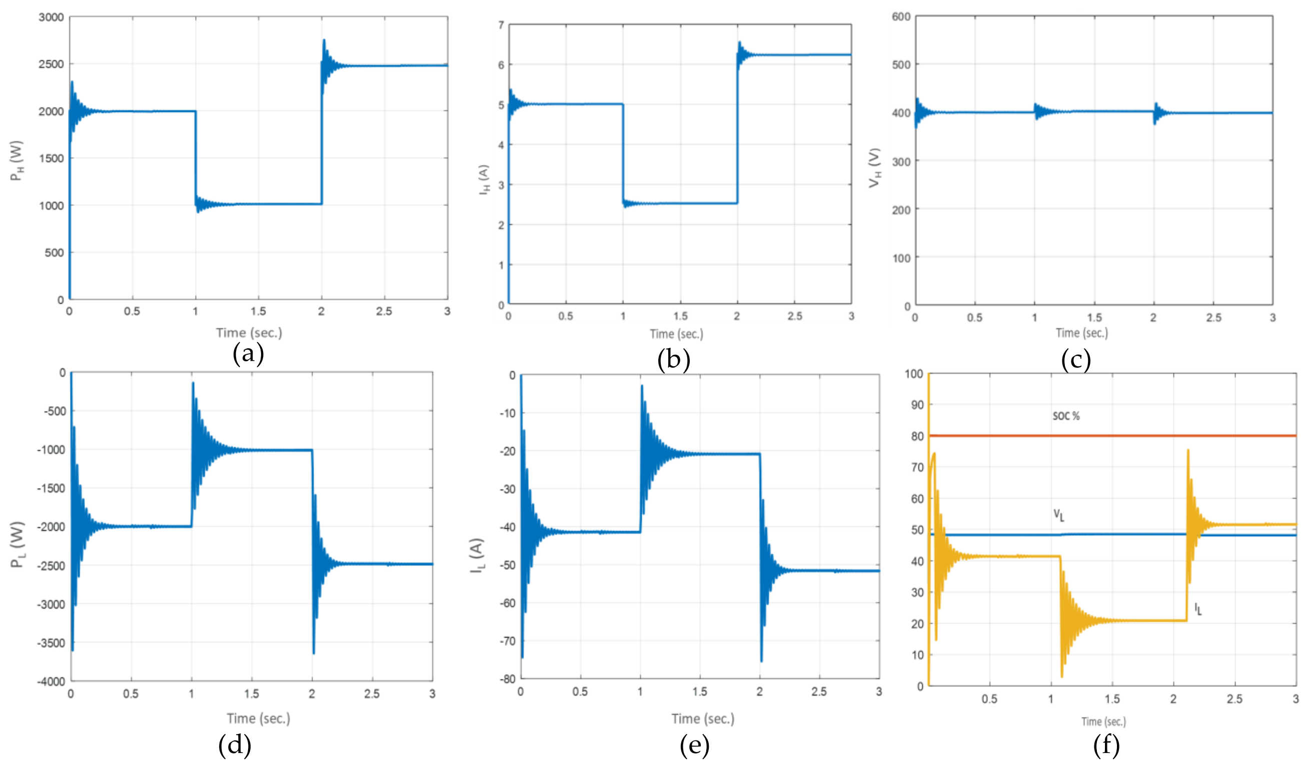


Figure 5. (a) P_H, (b) I_H, (c) V_H, (d) P_L, (e) I_L, and (f) the status of the battery for boost mode

Q_{L1} and Q_{L2} switches are off and Q_{H1}, Q_{H2}, Q_{H3} and Q_{H4} switches are on, when the proposed DC-DC converter is operated for boost mode (Figure 6). Q_{H1}–Q_{H2} and Q_{H3}–Q_{H4} switches are triggered with a 180° phase differences. The coefficients of PI controller for the buck mode given in Table3.

Table 3. Kp and Ki coefficients for buck mode. The parameters of proposed DC-DC converter.

Coefficients	Values
Proportional (Kp)	0.0085
Integral (Ki)	0.1

The path followed by the energy storage system in the battery for the proposed converter is shown in Figure 6, based on a constant reference current of 20 A; in other words, current control is implemented. Since the voltage of the battery pack constantly changes according to the charge state, controlling it becomes quite difficult. To overcome this, it was proposed to charge the battery pack at a constant current value, and the studies were carried out accordingly.

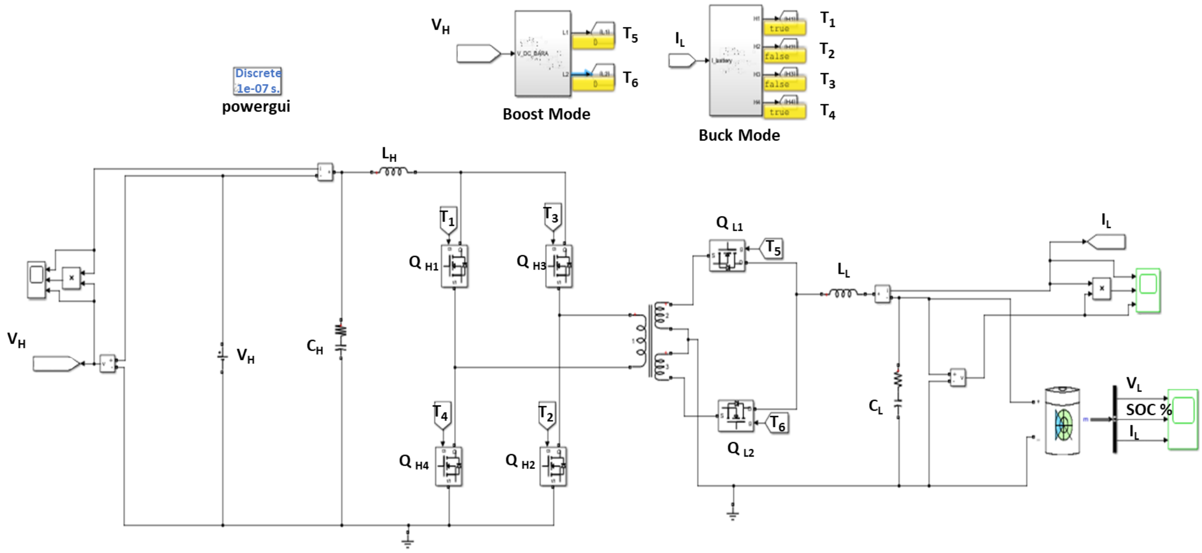
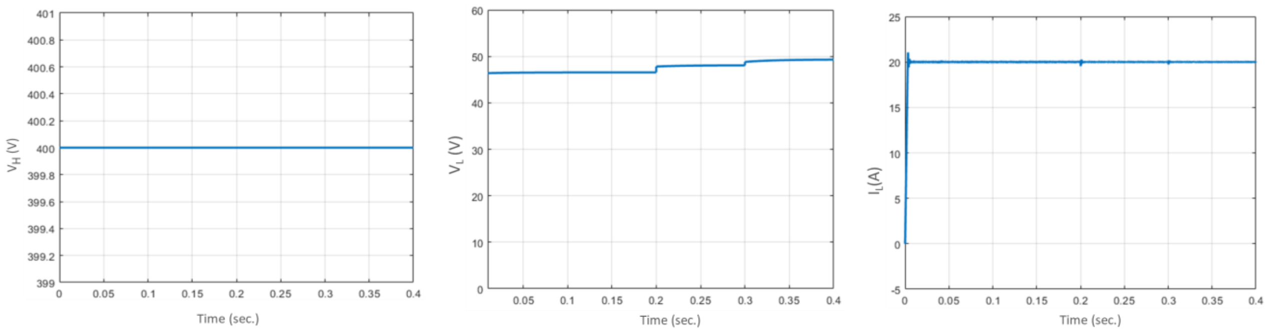
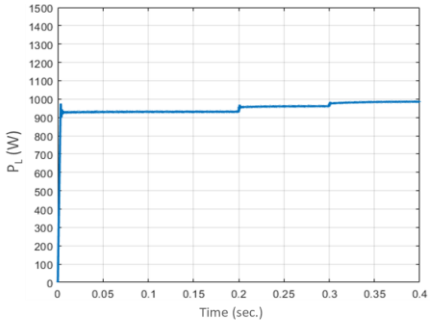


Figure 6. The simulation of proposed DC-DC converter for buck (charging) mode.

The simulations of the proposed converter shown in Figure 4 were performed for SOC values with different percentages (30%, 50%, and 80%). The simulation results for high and low sides under different loads are given in Figure 7.



(a) (b) (c)



(d)

Figure 6. (a) V_H, (b) V_L, (c) I_L and P_L for buck mode.

4. Conclusions

The proposed DC-DC converter was used in simulation studies for bidirectional power flow with PI controllers. In the boost mode, voltage control was performed, while in the buck mode, current control was performed. The proposed DC-DC converter was operated in boost (discharge) mode for 2 kW, 1kW and 2.5 kW loads. When examining the simulation results for 2 kW, 1kW and 2.5 kW loads in the boost mode, it can be seen that the desired values are obtained thanks to the PI controller (Figure 5). The proposed DC-DC converter must be operated in buck (charging) mode with PI control for charging battery with 30%, 50%, and 80% SOC values. The proposed DC-DC converter was operated for 0.6-3 kW power range with approximately 90% efficiency.

The proposed DC-DC converter can be used for charging and discharging electric devices. Instead of two separate circuits, a single circuit was used. Its high-frequency switching reduces the size of the transformer. A smaller, more compact, more usable, and safer converter has been obtained.

Future studies are envisaged regarding the integration of the proposed circuits into renewable energy systems.

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