Buffering Supercapacitor Mechanism based on Bidirectional DC/DC Converter for Mini All-Terrain Vehicle Application

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A B S T R A C T

Fundamentally, the Bidirectional DC/DC converter consists of Buck and Boost modes, which working alternately. Hence, it has two output directions: Buck mode for decreasing the voltage and Boost mode for increasing the voltage at certain levels. In this work, we applied a non-isolated topology of the Bidirectional DC/DC converter for electric vehicle, that is mini all-terrain vehicle (ATV). We set a Buck mode to charge the Supercapacitor when the battery current and the Supercapacitor voltage are lower than considered level. Whereas the Boost mode was used to discharge as well as buffer the mini ATV when the battery current and the Supercapacitor voltage are higher than considered level. The discussion of Buck mode has been presented in previous work, so in this work, we focus on the Boost mode analysis only. This mode is set to increase the Supercapacitor’s voltage. The Supercapacitor with 25 V/8 Farad was used as the secondary main power inside the 22.2 V/5000 mAh LiPo battery of the mini ATV motor. The mini ATV requires 36 V DC to work. Thus, it must be boosted first from 22.2 to 36 VDC using an external Boost converter. Moreover, it must be maintained at 36 V DC. Based on the requirement, we first design the bidirectional DC/DC converter involving the mathematical calculation and then simulate it into LTSpice®. The Printed-Circuit Board is then lay-outed and mounted. Later, we connected the designed system to mini ATV motor and tested the performance as well. According to the laboratory test, the Bidirectional DC/DC converter can increase (Boost) the voltage of the Supercapacitor from a certain level to 36 V DC. On the other hand, it can maintain 36 VDC. The central control in this system uses the STM32F4 Microcontroller, while the battery monitoring system employs the STMStudio.

1. Introduction

Battery Management System (BMS) is one of many ways or strategies to maintain battery in excellent performance and health conditions, which is widely implemented today, especially in the electrical vehicles, e.g., reported by [1]-[5]. Most of electric vehicles use DC source (rechargeable battery) as the main power. BMS contains several issues, e.g., 1) remaining run-time information; 2) battery-capacity monitoring; 3) charge control; and 4) charge-cycle counting [6]. BMS allows the battery of electric vehicles to have a longer life time, and it cannot be damaged easily because the battery indicator is managed well and always monitored. For this reason, some research uses a Supercapacitor as a secondary power besides the use of the primary battery; it has very fast in charging-discharging times. The Supercapacitor has a high density so it can be utilized to prevent the primary battery from the sudden voltages or currents in a short time due to energy fluctuation. Prior works related to battery/Supercapacitor for energy storage system have been presented by [7]-[10].

This work will focus on the battery-capacity monitoring issue on the BMS. There are various BMS types; one of them is the Bidirectional DC/DC converter, which is a circuit formed by Buck
and Boost converters. This type has been reported in [11]-[14]. In this work, Buck-Boost mode is chosen due to easy operation; we can control the voltage/current output by Pulse Width Modulation (PWM). Moreover, Buck-Boost mode has a low-cost implementation and it has a high-efficiency. Based on the switching technique, DC/DC converter is divided into two parts, i.e., non-isolated and isolated topologies [15]. Non-isolated serves many advantages compared to isolated-topology one, such as simple circuit structure, and it contains little electronic components. Hence, the circuit dimension/size can be reduced. Furthermore, the copper losses in the Transformers component and heat waste caused by the power MOSFET’s switching can be minimized.

In this work, a non-isolated topology is selected. The illustration of the converter power flow is illustrated in Figure 1(a) while Figure 1(b) shows the basic non-isolated topology. As we can see, the Bidirectional DC/DC converter have two ways (directions) of the current flow. If the $V_A$ node is the input voltage (Buck mode), then the “$V_B$” node acts as the output voltage, whereas if the “$V_B$” node is input voltage (Boost mode), then the “$V_A$” node acts as the input voltage.

- **Mode I:** In this mode, the DC/DC converter acts in buck mode when the high voltage ($V_{hi}$) is greater than the reference voltage $V_{ref}$. In this mode, the DC/DC converter controls the current to charge the Supercapacitor.
- **Mode II:** In this mode, the DC/DC converter acts in boost mode when $V_{hi}$ falls below the reference value. In this mode, the Supercapacitor discharges.
- **Mode III:** When Supercapacitor is fully charged, the DC/DC converter shuts down to avoid damaging the Supercapacitor.
- **Mode IV:** When the Supercapacitor is fully discharged, the conditioner shutdown until the supply produces sufficient current to resume charging of the Supercapacitor.

Mode I and Mode III are used to configure the Bidirectional DC/DC converter in a Buck mode (charging mechanism). This mode has been used in previous work to decrease the voltage of the external Boost converter module from $36 \ V_{DC}$ to $18 \ V_{DC}$ and charge the Supercapacitor [17]. Whereas to discharge and buffer the voltage and current for an electrical All-Terrain Vehicle (ATV) motor, we will use Mode II and Mode IV. The difference between our work to [7-10] is the use of Microcontroller as the primary control. The STM32F4 Microcontroller was used due to serve a user interface feature, i.e., STMStudio. Therefore, we do not need to design a graphical user interface (GUI) from scratch to display the charge-discharge Supercapacitor mechanism. We just employ this software to save effort in designing and implementing the Bidirectional DC/DC converter. As stated by T. Adiono, et al., [18] and A.T. Agung, et al., [19] that an open-source software enables us to cut the required time during the design and implement a specified system.

The discussion of this paper is divided into four sections, which are: (1) Introduction which presents the research background and purpose; (2) Material and Methods which discusses the Bidirectional DC/DC converter design and its simulation employing LTspice® software; (3) Results and Analysis which shows the experimental data of Supercapacitor discharging mechanism in the real test; the last one is (4) Conclusion and References.

2. Materials and Methods

2.1. Boost Converter: Overview

The Boost converter is one of the DC/DC Converter types functioned to increase certain voltage levels. Commonly, the Boost converter circuit has a topology, as illustrated in Figure 2 (a) and the working principle, as in Figure 2 (b). Based on Figure 2(a), we can see that Boost converter circuit contains several electronics components: a switch represented by $S$, a Diode represented by $D$, an Inductor represented by $L$, a Capacitor represented by $C$, a load represented by $R$, and $Vs$ as a source voltage or input voltage.

Similar to the Buck converter circuit, the Boost converter circuit also has two modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) with respect to the current flowing at the Inductor ($i_L$).

The difference between these modes lies in the value of the components inside and also the current passing through the Inductor. In CCM mode, the current flow through the inductor will never be zero. While in DCM mode, the current flow through the inductor will have a value when the current flow is zero. The relationship between the output and input voltage in the boost converter can be written as an Eq. (1),

$$V_{out} = \frac{V_S}{1-D}$$

(1)
Figure 2: (a) Boost converter circuit configuration and (b) Boost converter waveform, obtained from [1]

Where \( V_O \) is output voltage, \( V_S \) is source voltage (input voltage), and \( D \) is the used Duty cycle in the Bidirectional DC/DC converter. In a Boost converter mode, the CCM and DCM limits are expressed by Eq (2),

\[
L_b = \frac{(1-D)^2DR}{2f} \tag{2}
\]

Where \( f \) can be defined as \( F_{SW} \) and \( R \) is a dummy load. If \( L > L_b \), then Boost converter will be on CCM mode. The use of capacitor as filters in this mode must be set to have a minimum value. Accordingly, it does not have a large DC ripple voltage \( (V_r) \). To limit it, the Capacitor value used for Boost mode must be greater than Eq. (3),

\[
C_{min} = \frac{DV_O}{V_rRF} \tag{3}
\]

From Eq. (2) and Eq. (3) the Inductor and Capacitor values can be found, which is then applied in the circuit. Besides, we can also determine the operated frequency value in the circuit.

2.2. Bidirectional DC/DC Converter in Boost Mode: Design

We have a Supercapacitor designed by ourselves as the secondary power of the mini ATV motor rated in 25 VDC 8F. This Supercapacitor contains several commercially available Electrolytic Capacitor/Condensator (Elco) connected in series/parallel. We charged the Supercapacitor at least under 22 VDC to keep it healthy, precisely is 18 VDC. To buffer the DC motor of mini ATV, we need to increase the minimum voltage of Supercapacitor, that is 18 VDC to DC motor working voltage, that is 36 VDC.

Figure 3 shows the complete circuit of the Bidirectional DC/DC converter that has dual-mode in a single circuit: Boost and Buck.
Later, we calculate the values of inductor and capacitor needed for the circuit. The formula for the inductor is given by Eq. (4),

$$V_L = L \frac{di}{dt}$$

(4)

Where $L$ is the value of the inductor, $V_L$ is the voltage at the inductor, $dt$ is the switching period, $di$ is the ripple current. $D$ is the selected Duty cycle. According to the specification, our experiment used $F_{sw} = 10$ kHz and $50\%$ of Duty cycle, then, the calculation for the inductor would be,

$$36 - 18 = L \frac{1.2}{0.5 \times 10kHz} \Rightarrow L = 750 \mu H$$

To seek the Capacitor value, we used Eq. (5),

$$i_c = C \frac{dv}{dt}$$

(5)

where $C$ is the used Capacitor value, $i_c$ is the Capacitor current. By setting $F_{sw} = 10$ kHz and $D = 50\%$, then the calculation for the capacitor would be,

$$C = \frac{1.2A \times 0.5 \times 10kHz}{0.18V} = 333.33 \mu F$$

But in practical design, we used 2.5 mH and 100 µF of inductor and capacitor values, respectively.

The PWM output from the microcontroller will trigger the Gate of the MOSFETs. Our Bidirectional DC/DC converter circuit is needed a complementary PWM to work. To do this case, we configure the microcontroller in complementary PWM in which the STM32F4 microcontroller has a feature for it.

We used TLP250 for gate driver on the Power MOSFET that has a maximum operating frequency at 25 kHz. As stated in the system requirement, we only used 10 kHz as the PWM switching frequency. The gate driver configuration is depicted as Figure 4.

![Figure 4: The Gate driver schematic of Bidirectional DC/DC converter in Boost mode](image)

After the circuit has been constructed in LTSpice®, we convert it into a block as visualized in Figure 5, where X1 is our Bidirectional DC/DC converter, V1 is voltage input with 18 VDC, and R1 is a dummy load with 10 Ω. Based on the real measurement using digital Multimeter, the DC motor of the mini ATV has total resistance about 10 Ω. Therefore, we set it as a load to represent DC motor in our simulation. The simulation result is shown in Figure 6, we can see that the output voltage is 35.026818 VDC when the Duty cycle is set 50%. The average of output current flows in the circuit is 3.2329 A and 3.3171 A of RMS current. The output voltage will swing in the initial state from 0V to the maximum of 40 VDC until it reached the steady state of ~ 36 VDC, that is 35.026818 VDC while the output current will swing in the initial state from 0 A to the maximum of 4 A. In this Boost mode, the output voltage will buffer mini ATV. For data comparison, the Duty cycles in LTSpice® simulation are varied from 50% to 30%, 40% and 60% and we obtained 23.367980 VDC, 27.424739 VDC, and 38.787089 VDC, respectively.

3. Results and Analysis

After the simulation has been done perfectly, we tested the Supercapacitor performance whether it can increase the voltage from 18 to 36 VDC or not. As specified in system identification, the output voltage should stay at approximately 36 VDC even the input voltage from the Supercapacitor is decreasing. To meet the qualification, we set the experiment parameters as Table 2.

![Table 1. Simulation Parameters](image)

| No | Parameters | Value     |
|----|------------|-----------|
| 1  | V_in       | 18 VDC    |
| 2  | C_cap      | 100 µF    |
| 3  | C_cap_out  | 100 µF    |
| 4  | R_load     | 10 Ω      |
| 5  | L           | 2.5 mH    |
| 6  | F_sw        | 10 kHz    |
| 7  | Duty cycle  | 50% (0.5) |
| 8  | Supercapactor | 8 F    |
Figure 5: Bidirectional DC/DC converter circuit under the LTSpice® simulation, $18 \rightarrow 36 \text{V}_{\text{DC}}$ for discharger and buffer operation, then $36 \text{V}_{\text{DC}}$ (DC motor) $\rightarrow 18 \text{V}_{\text{DC}}$ (Supercapacitor) for charger operation. This simulation will focus on discharger/buffer operation from $18 \text{V}_{\text{DC}}$ (Supercapacitor) to $36 \text{V}_{\text{DC}}$ (DC motor).

Figure 6: Simulation result of the Bidirectional DC/DC converter on Boost mode with Duty cycle = 50%.

A Photograph of experimental setting to verify the circuit design and the printed-circuit board (PCB) of the designed bidirectional DC/DC converter are visualized in Figure 7(a) and Figure 7(b), respectively.

We set the voltage limit at the Supercapacitor to be $10 \text{V}_{\text{DC}}$ minimum and $18 \text{V}_{\text{DC}}$ maximum (fully-charged). Thus, when the DC/DC converter in a boost mode, it will be no longer in this mode if the Supercapacitor voltage reaches $10 \text{V}_{\text{DC}}$ from $18 \text{V}_{\text{DC}}$.

The test scenario is the same as previous work [17]. It is shown in Figure 8 (reproduced from [17] with permission). An external Boost converter module was used to increase a $22.2 \text{V}_{\text{DC}}/5000$ mAh LiPo battery (series configuration of two $11.1 \text{V}_{\text{DC}}$ LiPo batteries). Afterward, this voltage output is connected to the mini ATV that requires $36 \text{V}_{\text{DC}}$ of voltage to work.

Table 2. Experiment Parameters

| No | Parameters          | Value                           |
|----|---------------------|---------------------------------|
| 1  | $V_n$               | $18 \text{V}_{\text{DC}}$ (Supercapacitor voltage when it is fully charged) |
| 2  | $L$                 | $2.5 \text{mH}$                |
| 3  | $f_{\text{sw}}$     | $10 \text{kHz}$               |
| 4  | Supply at the Gate driver | single supply (11.1 V_{DC}) |
To monitor the Supercapacitor condition, we need a user interface. We employed the STMStudio to display the discharging voltage of the Supercapacitor. The experimental results are shown in Figure 9. The vertical axis represents Supercapacitor voltage while the horizontal axis represents Supercapacitor’s discharging time. The pink line represents the Supercapacitor voltage while the orange line represents the output voltage of the Bidirectional DC/DC Converter in a boost mode. To easily understand the mentioned lines when this paper is printed in a grayscale format, we marked it as in Figure 9.

From the window, it can be seen that the output voltage stays at a certain level even the voltage at the Supercapacitor is decreasing from 17.5 V\textsubscript{DC} down to 10 V\textsubscript{DC} as pointed out by the GUI. However, the displayed values on the STMStudio is not accurate enough. Therefore, it can be used only to ensure that the output voltage is almost stable (information based on the visual observation). Digital multimeter was used to measure a real value; we got a stable voltage, i.e., ~36 V\textsubscript{DC} when 50\% of the Duty Cycle is set. This voltage level can be reached by controlling the PWM (Duty cycle) properly.

Whereas to measure the Supercapacitors current accurately, we used the ACS712 current sensor reading in an Analog to Digital Converter (ADC). As a result, the current can be buffered to the mini ATV by the Supercapacitor varied from 0 to 6 A. In this experiment, our circuit can work well as expected: the input of the converter can be output, and vice versa, the output can be the input.

Afterward, the simulation results as presented in Section 2.3 are compared with the laboratory measurements. We adjust PWM variations according to the simulation settings, which are 30\%, 40\%, and 60\%, and we obtained 25.1 V\textsubscript{DC}, 29.2 V\textsubscript{DC}, and 36.5 V\textsubscript{DC}, respectively. Table 3 is a comparison between simulation and real experiment of the Bidirectional DC/DC converter in a Boost mode.
To make it easier to see the difference level, a graph is served as shown in Figure 10, it can be seen that there is a difference between using simulations and implementing hardware. This can occur due to several factors like tolerance factor of the used components that make it non-ideal.

Table 3: Comparison between voltage output from a simulation and implementation (real condition) on the Bidirectional DC/DC converter circuit with Boost mode

| No | Duty Cycle (%) | Output voltage in Simulation (V) | Output voltage in Implementation (V) |
|----|----------------|----------------------------------|-------------------------------------|
| 1  | 30%            | 23.367980 V_DC                  | 25.1 V_DC                           |
| 2  | 40%            | 27.424739 V_DC                  | 29.2 V_DC                           |
| 3  | 50%            | 35.026818 V_DC                  | 32.7 V_DC                           |
| 4  | 60%            | 38.787089 V_DC                  | 36.5 V_DC                           |

Figure 10: A Graph of simulation vs. measured output on the Bidirectional DC/DC converter circuit with Boost mode. Horizontal axis: Duty Cycle (%) and Vertical axis: Output voltage (V)

4. Conclusion

Supercapacitor plays an essential role in the BMS of modern electric vehicles. By using Supercapacitor as a supplementary battery, the need for high current from the main battery can be buffered and maintained at the considered level. Thus, the main battery will have a long time span. In this work, non-isolated bidirectional converter is chosen due to the use of fewer components than the isolated bidirectional converter. So, in terms of PCB size, it will be relatively smaller than the isolated Bidirectional DC/DC converter. The effect of the transformer's usage on isolated topology makes power losses due to overheating production. While for non-isolated, careful calculation needs to be done in determining the inductor as well as capacitor values. Thus, the circuit can operate properly, both for Boost or Buck modes. The use of the inductor on the non-isolated topology can reduce power losses.

In this work, we realize a BMS using a non-isolated bidirectional DC/DC converter controlled by the PWM. Our circuit is used as a current and voltage control system that operates in Buck and Boost. By changing the PWM Duty cycle in the Microcontroller STM32F4, we can manually adjust the output voltage of the bidirectional DC/DC converter.

Based on the simulation result through LTSpice®, the circuit can work well as expected; the output voltage is ~36 V_DC with 50% of Duty cycle. This voltage will be used to buffer/discharge the DC motor of mini ATV. According to the functional test, it can be seen that the supercapacitor can perform a discharging function. Hence, it can be used as a secondary power distributor to buffer voltage and current, which is then successfully implemented on the mini ATV. Discharging time of the Supercapacitor takes approximately 30 – 50 seconds, depending on the battery capacity with a current of up to 6A. This high current can be pulled from a 25 V_DC/8F Supercapacitor to the mini ATV. The detail of this paper including the improved Buck mode using Resistor-Capacitor-Diode (RCD) Snubber circuit and Hybrid mode (Buck & Boost).

In future work, we will more emphasized the effects of different construction features upon the systems functioning.

Conflict of Interest

The authors declare no conflict of interest.

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