Output Voltage Overshoot Reduction Techniques for Cascade Buck-Boost Converters

Seung-Woo Baek[1], Su-Jin Choi[2], Hag-Wone Kim[2], Kwan-Yuhl Cho[2], and Kyung-Ahn Kwon[1]
[1] Techcross, Korea
[2] Korea National University of Transportation, Korea

***Abstract*-- This study proposes a switching control strategy to reduce overshoot caused by load variations in a bidirectional Cascade buck-boost converter operating in boost mode. To achieve this, the cause of overshoot that occurs when the load decreases is analyzed, which is found to be due to the magnitude of the voltage applied to the inductor, which is the difference between the input and output voltages. The proposed switching control strategy ensures that only the output voltage is applied to the inductor. The proposed method reduces overshoot by about 55%, from 42V to 19V, and this has been verified through simulation.**

***Index Terms*—Dc-dc converter, Overshoot, feedforward, cascade buck-boost**

I. Introduction

A well-made power converter is an important component in many electronic systems as it plays a crucial role in providing the necessary electrical power in a safe and efficient manner. The converter should be designed to convert electrical power from one form to another while producing a stable output voltage or current, even when the input voltage or load varies. To achieve this, a well-made power converter needs to use high-quality components and robust control algorithms that can quickly adjust the converter's output to maintain a stable voltage or current. This not only ensures efficient power conversion but also improves the reliability and longevity of the converter. In addition to producing stable output voltage or current, a well-made power converter should generate minimal electromagnetic interference (EMI) or audible noise. Careful component selection and layout can help to minimize EMI while the control algorithms can be designed to minimize audible noise. A well-made power converter should also include robust protection features to prevent damage to the converter or the load in the event of a fault. Overvoltage and overcurrent protection and thermal shutdown are some of the protection features that a well-made power converter should have. Finally, a well-made power converter should be designed to operate reliably for a long time without requiring maintenance or repair. This requires the use of high-quality components, careful design and testing, and robust protection features for longevity and reliability.

Maintaining a stable voltage in a power converter is a complex process that requires careful attention to the design of the feedback control loop. The feedback loop is responsible for quickly responding to changes in the load or input voltage to maintain a stable output voltage. This feedback loop typically includes a sensor that measures the output voltage, an error amplifier that compares the output voltage to a reference voltage, and a control algorithm that adjusts the converter's duty cycle or switching frequency to maintain a stable output voltage.

To maintain a stable voltage, the feedback loop must be designed with a balance between fast response and stability. The gain and bandwidth of the feedback loop must be carefully selected to ensure stable operation and prevent oscillation or instability. Additional compensation may be required, such as a lead-lag or PID controller, to adjust the phase and gain of the feedback loop. Component selection is also critical to maintaining a stable voltage in a power converter. The components used in the feedback loop, such as the sensing elements, amplifiers, and control ICs, should be carefully selected to ensure that they are stable and reliable over the operating range of the converter. In addition to compensating the feedback loop, another technique to improve stability and transient response is to compensate the output current or duty cycle with feedforward[1-5]. This technique involves predicting changes in the output current or duty cycle and compensating for these changes before they occur. This can help to improve the stability and transient response of the converter and prevent oscillation or instability. Overall, designing a power converter that can maintain a stable voltage under a variety of load and input voltage conditions requires careful attention to the design of the feedback control loop, component selection, and the use of compensation techniques such as feedforward. By following these principles, it is possible to design a power converter that is reliable and stable over the long term.

Feedforward compensation is a technique used in power converter control to improve the converter's transient response by anticipating changes in the load or input voltage. It involves adding a signal to the control loop that adjusts the converter's duty cycle or switching frequency to compensate for changes before they affect the output voltage or current. This can reduce the settling time and overshoot of the output voltage or current, improving the converter's performance. To implement feedforward compensation, accurate knowledge of the system dynamics is essential, along with a well-modeled converter and load. The feedforward signal can be generated through a mathematical model of the system or through direct measurement of the load or input voltage. The feedforward

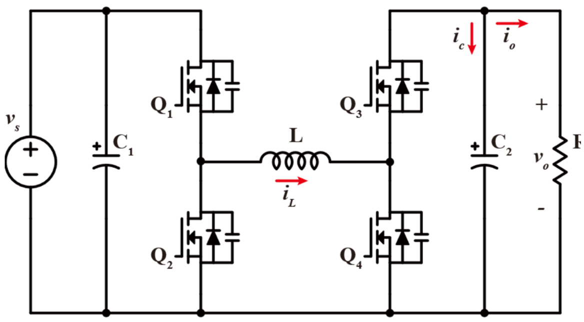

Fig. 1. Circuit diagram of the bidirectional cascade buck-boost converter

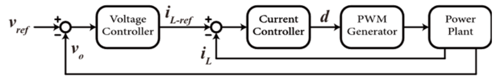

Fig. 2. Block diagram of a basic dual-loop controller

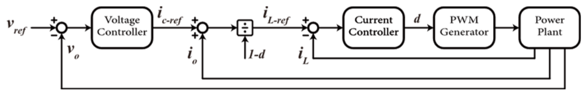

Fig. 3. Block diagram of a dual-loop controller with output current and duty feedforward compensation

signal is added to the control loop through a summing junction, where it is combined with the output of the error amplifier. The resulting signal is then used to adjust the converter's duty cycle or switching frequency, compensating for changes in the load or input voltage. However, implementing feedforward compensation requires careful tuning of the feedforward signal and may be used in combination with feedback compensation to achieve the best performance. Accurate modeling of the system dynamics and careful selection of components are also important for stable operation.

In summary, feedforward compensation is a powerful technique that can improve the stability and transient response of a power converter. By accurately anticipating changes in the load or input voltage, feedforward compensation can adjust the converter's output to maintain a stable voltage or current, reducing settling time and overshoot.

In some studies, compensating for the load current and duty cycle has been shown to maintain stable output voltage when the load varies. This achieves stable output voltage by rapidly changing the current flowing through the inductor when the load size changes. However, depending on the size of the inductor and output capacitor, and the voltage that can be applied to vary the inductor current, it may not be possible to completely eliminate the overshoot of output voltage.

This paper analyzes the limits of overshoot depending on the size of the inductor and output capacitor, and the voltage applied to the inductor, in a system that compensates for the output current and duty cycle with feedforward. It also provides techniques for reducing overshoot in a Cascade Buck-boost converter.

TABLE I
PARAMETERS OF THE CASCADE BUCK BOOST CONVERTER

	Value	Unit
Input voltage	200	V
Output voltage	300	V
Inductance	330	uH
Capacitance	300	uF
Switching Frequency	40	kHz

II. LIMITATION OF FEEDFORWARD CURRENT AND DUTY COMPENSATION

The bidirectional Cascade Buck-Boost converter is a type of DC-DC converter that can transfer power bidirectionally between two voltage domains, such as a battery and a load[6-8]. It is a two-stage converter that consists of a buck-boost converter followed by another buck-boost converter, with a common inductor and a capacitor.

In the first stage, the input voltage can be either positive or negative. The buck-boost converter reduces the input voltage to a lower voltage level and stores energy in the inductor and capacitor. In the second stage, the output voltage can also be either positive or negative. The second buck-boost converter increases the voltage to a higher level and transfers the stored energy to the output. The bidirectional Cascade Buck-Boost converter can operate in four-quadrant operation, allowing power to flow bidirectionally between the input and output domains.

The bidirectional cascade buck-boost converter has many applications, such as in electric vehicles, renewable energy systems, and battery charging. However, it requires careful design and control to ensure stable and efficient operation, and also requires bidirectional switches, such as MOSFETs or IGBTs, that can handle both positive and negative voltages and currents. Fig. 1 shows the circuit diagram of a cascade buck-boost converter. There are three switching techniques in this circuit. One operates in full buck mode, another in full boost mode, and the other operates in buck-boost mode. This paper analyzes the full boost mode. In full boost mode, Q1 is always on and Q2 is always off, and Q3 and Q4 are switched complementarily. Therefore, the full boost mode is the same as a conventional boost converter.

Fig. 2 and 3 show each control configuration. Fig. 2 represents a basic dual-loop controller, and Fig. 3 represents a controller that compensates for load current and duty cycle. The general circuit information is presented in Table 1.

Fig. 4 and 5 show the simulation results of load variations according to each controller configuration. The load size was changed from 20A to 10A. Fig. 4 shows that when a load variation occurs with a traditional dual-loop controller, an overshoot of about 40V occurs. This could

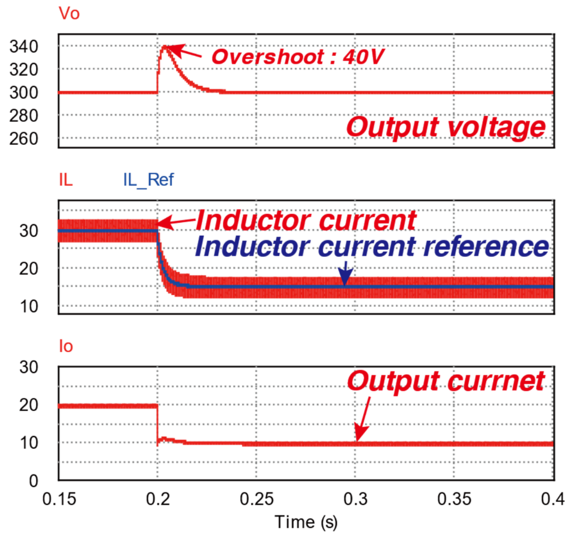

Fig. 4. Simulation waveform of basic dual loop controller when small load variation occurs

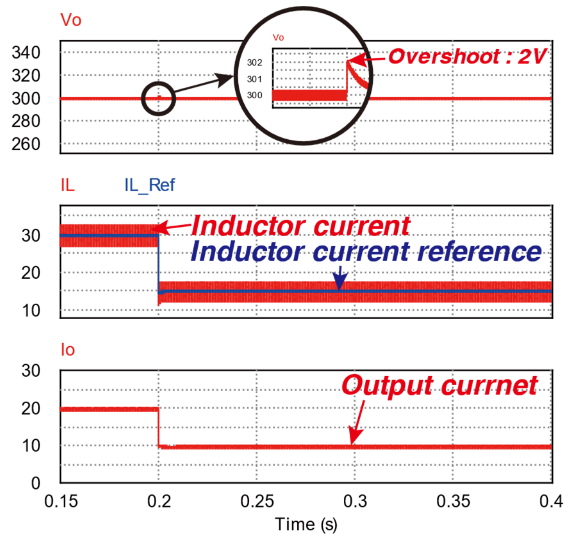

Fig. 5. Simulation waveform of dual-loop controller with output current and duty feedforward compensation when small load variation occurs

potentially damage the load and even destroy the switching device of the circuit. The simulation waveform of the controller with load current and duty feedforward compensation, which complements this issue, is presented in Fig. 5. Compared to Fig. 4, the overshoot has decreased to about 2V. Therefore, the method of feedforward compensation of load current and duty shows that it can quickly respond to load variations.

However, this controller still shows overshoot when the load current varies more significantly. Fig. 6 shows that even with load current and duty feedforward compensation, there is still significant overshoot when the load current varies from 80A to 5A. This is because it is not possible to quickly decrease the inductor current when the load size changes.

When the load current decreases rapidly, the duty command also decreases rapidly due to feedforward, and

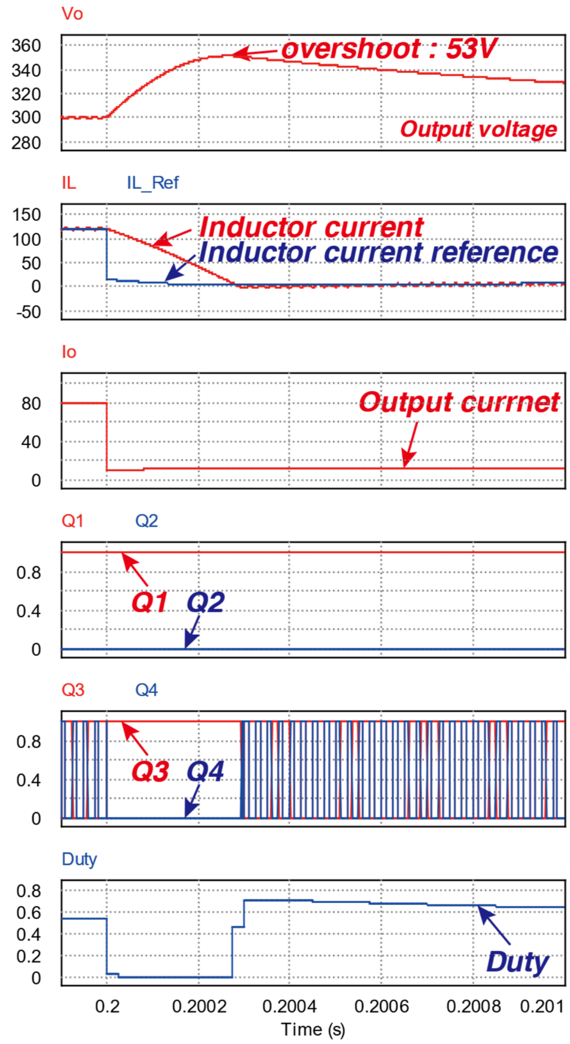

Fig. 6. Simulation waveform of dual-loop controller with output current and duty feedforward compensation when heavy load variation occurs

the voltage of the capacitor increases, causing the current command to decrease. As a result, the duty command becomes zero. This means that in order to maintain the desired voltage, the transfer of energy to the capacitor must be stopped, and the current in the inductor must be reduced. However, the energy stored in the inductor is discharged proportionally to the applied voltage. When the duty command is zero, Q_1 and Q_3 are always turned on, and Q_2 and Q_4 are turned off. This state continues until the current in the inductor approaches the current command.

III. Limitation of Feedforward Current and Duty Compensation

In this section, we discuss the maximum overshoot that occurs during load fluctuations. Fig. 7 shows the waveform of a converter operating under normal conditions, when a load fluctuation occurs at time t0. As the load current is being fed forward, the reference value of the inductor current immediately decreases, as shown by $i_{L\text{-}ref}$ in Fig. 7. However, since the actual inductor current cannot follow the command, the duty cycle

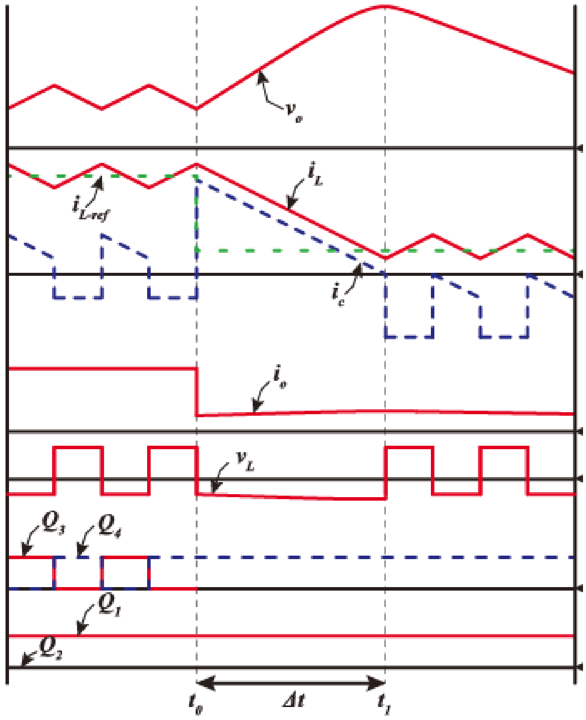

Fig. 7. The waveform without the proposed strategy applied to the compensated controller with output current and duty compensation.

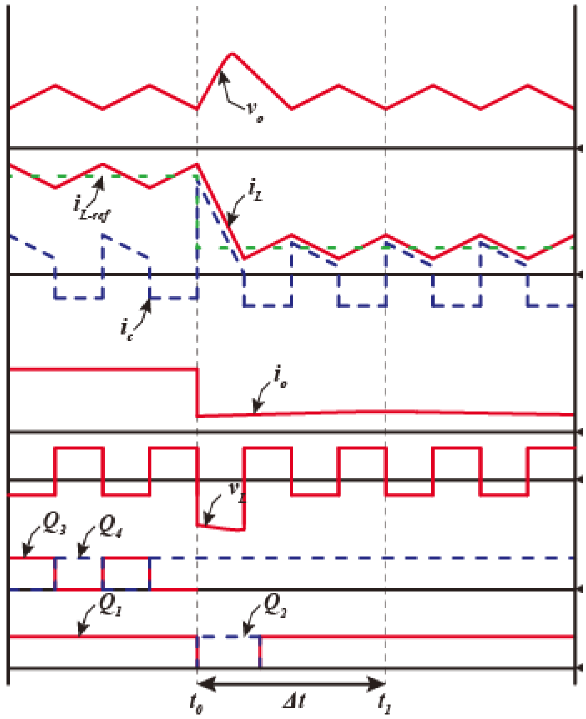

Fig. 8. The waveform of the proposed strategy applied to the compensated controller with output current and duty compensation.

decreases to zero and Q_4 and Q_1 remain continuously conducting from time t0 to t1. At this time, the decrease in inductor current is determined by the magnitude of the voltage applied to the inductor and can be expressed as follows:

$$v_L(t) = V_s - v_c(t) \tag{1}$$

Here, V_L is the inductor voltage, v_c is the capacitor voltage, and Vs is the input voltage. To determine the overshoot, we need to know the magnitude and time of the current going into the capacitor.

As shown in Fig. 7, the initial current in the capacitor at t0 can be calculated as follows:

$$i_c(t_0) = i_L(t_0) - i_o(t_0) \tag{2}$$

Here, i_c is capacitor current, i_L is inductor current, io is output current, and D is steady state duty cycle. After that, the capacitor current continuously decreases and becomes 0 at time t_1. The average current of the capacitor can be calculated as follows because the capacitor current decreases in a triangular shape.

$$I_c\Big|_{t_0}^{t_1} = \frac{i_c(t_0)}{2} \tag{3}$$

Where, I_c is average current of the capacitor from t_1 to t_2. In addition, the slope of the decreasing current between t_1 and t_2 can be expressed as follows:

$$\frac{di_c(t)}{dt} = \frac{di_L(t)}{dt} = \frac{v_L(t)}{L} \tag{4}$$

Here L is inductance. Therefore, the time t_1 when the capacitor current reaches 0 can be calculated as follows:

$$t_1 = t_0 - L\frac{i_c(t_0) - 0}{V_s - v_c(t)} \tag{5}$$

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Equations (3) and (5) allow us to determine the time and average current applied to the capacitor. Therefore, the additional energy stored in the capacitor can be expressed as follows:

$$Q_c\Big|_{t0}^{t1} = \frac{I_c \Delta t}{C} \tag{6}$$

Here, Q is the amount of charge accumulated in the capacitor during Δt, and Δt is as follows.

$$\Delta t = t_1 - t_0 \tag{7}$$

The initial charge of the capacitor can be expressed as follows.

$$Q_c(t_0) = C v_c(t_0) \tag{8}$$

Therefore, the accumulated charge on the capacitor at time t_1 can be calculated as follows:

$$Q_c(t_1) = Q_c(t_0) + \frac{I_c \Delta t}{C} \tag{9}$$

Using equation (7), we can calculate the voltage across the capacitor at t_1 as follows:

$$v_c(t_1) = \frac{Q_c(t_1)}{C} \tag{10}$$

In the waveform shown in Fig. 6, the load current changes from 80A to 20A at 0.2 seconds, the inductor current is 120A, and the current after the load change is 30A. In addition, the input voltage is 200V and the output voltage is 300V, so Δt is approximately 3ms according to equation (5). Furthermore, the amount of charge accumulated in the capacitor before the load change is 0.09C according to equation (8), and the amount of charge accumulated after the load change is about 0.0165C. Therefore, at time t_1, the voltage across the capacitor is

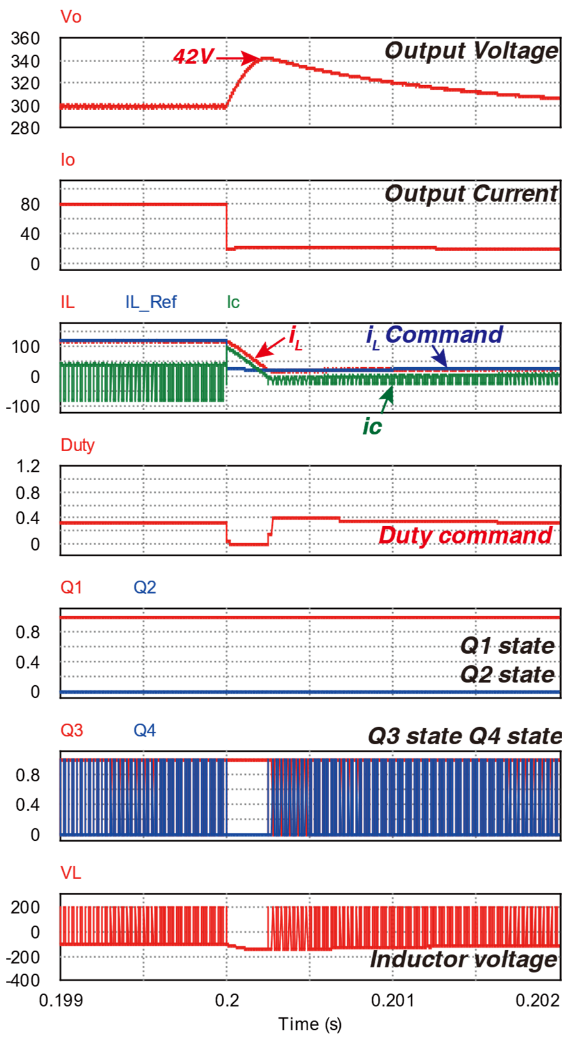

Fig. 9. The simulation result waveform without the proposed strategy applied to the compensated controller with output current and duty compensation.

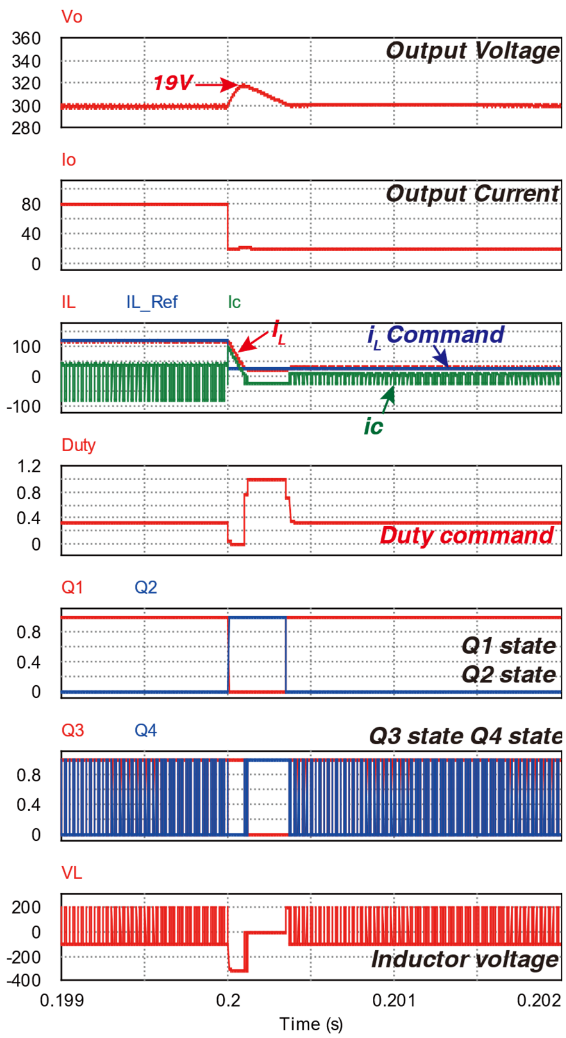

Fig. 10. The simulation result waveform with the proposed strategy applied to the compensated controller with output current and duty compensation.

approximately 355V according to the equation, which has a difference of about 13V from the overshoot shown in Fig. 6. This is due to the slight increase in voltage applied to the inductor caused by the overshoot.

IV. CONTROL STRATEGY TO REDUCE OVERSHOOT

As shown in section 3, even with compensation of load current and duty cycle, a large overshoot occurs when there is a sudden load change. This is because the inability to quickly decrease the inductor current has an effect on it. Decreasing the inductor current is determined by the voltage applied, as shown in equation (2). The previous control method always kept Q_1 and Q_3 conducting during a load change, and the voltage across the inductor was then represented by the difference between the output voltage and the input voltage. The input voltage then acts as an interfering factor in reducing the inductor current. Therefore, by turning off Q_1 and turning on Q_2, a greater reverse voltage can be applied to the inductor, which can more quickly decrease the current. Fig. 8 represents the waveform with the proposed strategy applied. This results in a more effective control strategy to reduce overshoot. Therefore, equation (1) is modified as follows.

$$v_L(t) = -v_c(t) \tag{11}$$

Through this, a greater reverse voltage can be applied to the inductor after a load change. Furthermore, equation (5) becomes as follows.

$$t_1 = t_0 - L\frac{i_c(t_0) - 0}{-v_c(t)} \tag{11}$$

This is because the negative voltage becomes much larger compared to equation (5), resulting in a much smaller value for t_1.

Fig. 9 and 10 show simulation results with and without the proposed control strategy. The input voltage is 200V and the output voltage is 300V. The load current decreases from 80A to 20A in 0.2 seconds.

Fig. 9 represents the case where the proposed strategy is not applied, and it shows a significant overshoot of about 42V with Q_1 and Q_3 always conducting after a load disturbance. The voltage drops to about -100V across the inductor after the load disturbance, given an input voltage of 200V and an output voltage of 300V. Additionally, the capacitor current decreases from 100A to 0A over a time interval that can be theoretically calculated using equations (5) and (7) to be 0.33ms, while the simulation result shows 0.3ms. This error is caused by an increase in the capacitor voltage due to overshoot, which leads to an increase in voltage across the inductor. As a result, the maximum overshoot was calculated to be 55V, but the simulation result shows 42V.

On the other hand, Fig. 10 represents the case where the proposed strategy is applied, and it controls Q_1 to turn off and Q_2 to turn on when an overshoot is detected after a load disturbance. As a result, the voltage across the inductor is -300V, which is the same as the output voltage after the load disturbance. Therefore, the inductor and capacitor currents decrease rapidly, and the time for this is theoretically calculated to be 0.11ms, which is 0.22ms shorter than the case where the proposed strategy is not applied. The overshoot is calculated to be 18.3V. The simulation result also shows a time of 0.11ms and an overshoot of about 19V, indicating that the overshoot is reduced and the error is also reduced compared to the case where the proposed strategy is not applied.

V. Conclusions

In this study, we proposed a control strategy to reduce the overshoot caused by load disturbances when using a bidirectional cascade buck-boost converter in boost mode. We analyzed the cause of the overshoot and mathematically analyzed its magnitude. As a result, we identified that the voltage across the inductor after load changes was the cause and proposed a solution by changing the switching logic to apply a greater reverse voltage. The proposed method was verified through simulations, and it achieved a reduction in overshoot of about 55%, from 42V in the conventional control method to 19V in the proposed method. The proposed method is expected to increase the stability of bidirectional cascade buck-boost converters when load changes occur.

Acknowledgment

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