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Inductor-Diode Boosting Technique of 3QBC Converters Family with Single-Active Switch

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***Abstract*—This work integrates two well-known inductor-diode boosting techniques (LDBT)—Switched Inductor (SL) cell and Voltage Lift (VL) cell—into a single stage to develop 3QBC converters family, a novel group of non-isolated step-up DC/DC converters. The new 3QBC converters family can function effectively with low-duty cycles, enabling an increase in the voltage gain. It also includes a Switched Capacitor (SC) cell at the output side, which effectively halves the voltage stress imposed on the active switch compared to the converter's output voltage and provides a double voltage gain. Another advantage of the 3QBC converter family is its high-power rating, simple structure, and controllability. In contrast to the classical converter, the 3QBC converter family demonstrates superior voltage gain and alleviates the voltage stress imposed on the active switch, resulting in enhanced levels of performance and efficiency.**

***Index Terms*—Inductor-diode boosting technique, Switched Inductor, Voltage lift, Switched capacitor.**

I. INTRODUCTION

Photovoltaics (PV) and turbines are renewable energy sources (RESs), gaining significant traction due to their capacity to produce clean and sustainable energy. As a result, there is a high demand for their use in various applications. Indeed, RESs are an effective solution for traditional power systems because of their reliability and widespread, making them risk-free [1], [2]. In addition, they can be produced locally, helping to alleviate dependence on fossil fuels [3]. Nevertheless, 18 – 40 V is a very low DC voltage that does not match some applications' requirements. The boost converter can solve this issue by boosting the low DC voltage (18 – 40 V) to high DC bus voltage (380 – 400 V) and then connecting to the AC grid.

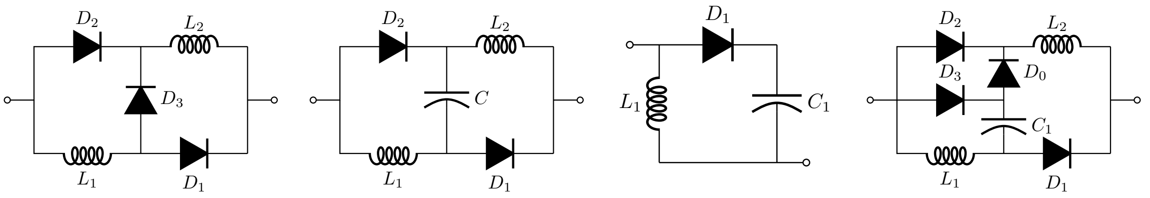
In literature [1], [4]–[9], many non-isolated or isolated topologies are employed in the RES for providing high voltage gain. Due to its simple structure and fewer components, the conventional boost converter (CBC) can be used to achieve high voltage conversion ratio. Therefore, the CBC must operate at an extremely high duty cycle to attain the desired voltage, leading to increased leakage resistance of the inductor and voltage stress on the semiconductor devices. However, the CBC performance degrades, resulting in a reduction in the converter's efficiency. In [10], another topology known as the quadratic boost converter (QBC) is introduced for attaining an enhanced conversion ratio. The QBC effectively integrates two boost converters in a cascade, all regulated by a singular active switch. The voltage stress of the QBC is the main drawback because it is extremely high, leading to a decrease in the performance of the QBC converter. Providing a step-up DC/DC converter with significant voltage enhancement while avoiding extremely high-duty cycles can be categorised into using more than one switch, coupled inductor or transformer, and boosting techniques such as SC, SL and VL. [1]. Using more than one switch can be one of the solutions to attain a high voltage gain. In contrast, the system is complicated, uncontrollable and costly because each active switch needs a gate driver. Using coupled inductor or transformer has been introduced in many topologies [11], [12]. Electromagnetic interference (EMI) issues and switching losses arise as a result of the leakage inductance associated with the coupled inductor or transformer, thereby resulting in significant extreme voltage stress experienced by the active switch. A high voltage gain in the DC/DC converter can be enhanced by integrating one or more boosting techniques in the literature [4], [10], [13]. SL, VL, Elementary-Lift Cell, Self-Lift SL cell and Double Self-Lift Cell are the basic structure of the LDBT as shown in Fig. 1.

A new family of the 3QBC converters named the $3QBC_{SL/VL}$ converters family is proposed in this paper. $3QBC_{SL/VL}$ converters family achieves a high voltage conversion ratio, allowing for use in renewable energy applications. In addition, the SC cell is incorporated after the active switch, doubling the output voltage and reducing the voltage stress. Other advantages of the SC cell are small size, including capacitors and diodes, high efficiency and low EMI because the SC cell does not comprise any inductive element.

$3QBC_{SL/VL}$ converters family are explained in detail in section II and their operational modes during steady-state conditions, specifically focusing on the continuous condition mode (CCM) in section III. Section IV presents the simulation and experimental result of $3QBC_{VL}$ converter. Ultimately, the conclusion is summarised in section V.

II. NEW FAMILY OF 3QBC CONVERTERS WITH HIGH GAIN

The SL cell is the most significant LDBT for attaining high voltage conversion ratio, as shown in Fig. 1 (a), comprising



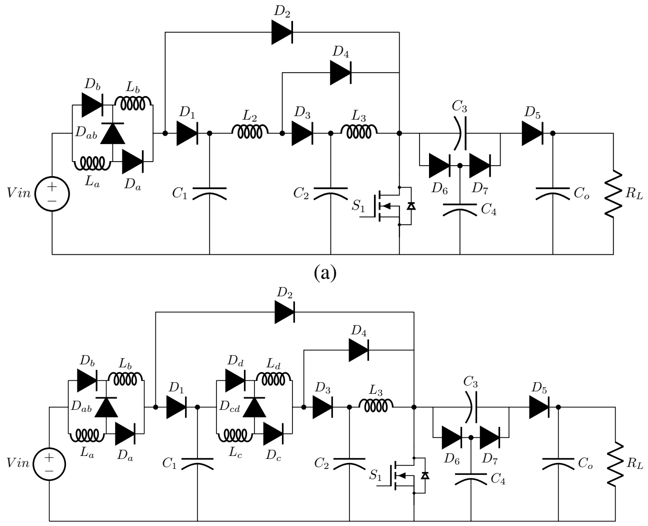
(a) (b) (c) (d)

Fig. 1. Inductor-Diode Boosting Technique (a) SL Cell. (b) VL Cell. (c) Elementary-Lift-Cell. (d) Self-Lift-SL-Cell

two inductors and three diodes. The SL cell concept operates in parallel charging and series discharging of the inductor. Another LDBT is the VL cell, broadly utilised in many DC/DC converters to enhance the level of the output voltage. The VL cell is a simple structure including two inductors, two diodes and a capacitor, as shown in Fig. 1 (b), operating by charging the capacitor to a certain voltage and then boosting the output to match the level of the charged capacitor. Moreover, the VL technique includes high efficiency, high power density, and a small current ripple.

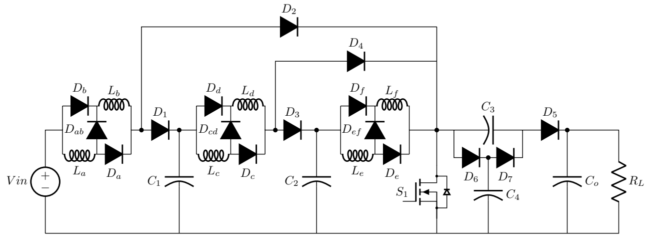
A. $3QBC_{SL}$, $3QBC_{2SL}$ and $3QBC_{3SL}$ Converter

The SL cell is a boosting technique integrated into the 3QBC converter by replacing the 1st inductor of the converter, as shown in Fig. 2 (a), which the voltage conversion ratio increases 7.5 times. Meanwhile, the advantage of the SC cell is that it decreases the power switch's voltage stress by half of the output voltage. Achieving high voltage gain ten times, the 1st and 2nd inductors of the converter should be replaced as shown in Fig. 2 (b). The result of replacing the 1st, 2nd and 3rd inductors of the converter, the conversion ratio reaches 13 times as shown Fig. 2 (c). As a result, the LDBT proves to be suitable for applications that require high voltage gain, such as those found in telecommunications or automotive technology.



(a)

(b)

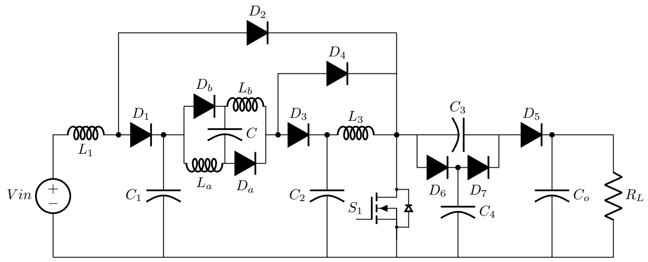


(c)

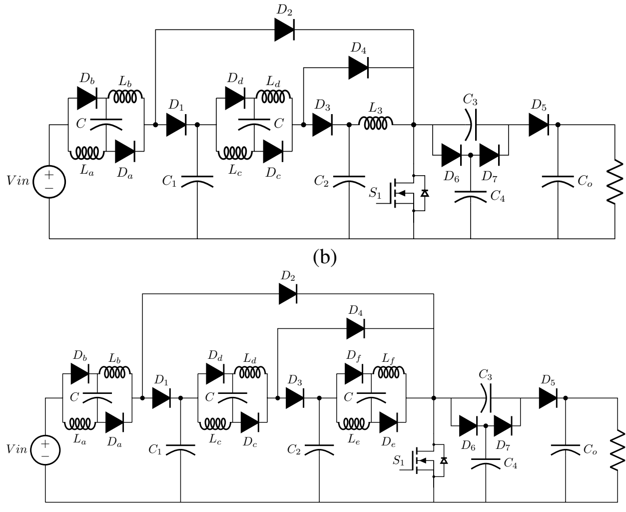
Fig. 2. NQBC Converter Family: (a) $3QBC_{SL}$. (b) $3QBC_{2SL}$. (c) $3QBC_{3SL}$.

B. $3QBC_{VL}$, $3QBC_{2VL}$ and $3QBC_{3VL}$ Converter

In this section, the VL technique is utilised in the 3QBC converter by replacing the 2st inductor of the converter as shown in Fig. 3 (a), which the voltage ratio increases 12 times. In addition, the SC cell is employed in the 3QBC converter to decrease the voltage stress imposed on the semiconductor switch to equal half of the converter's output voltage. In Fig. 3 (b), the VL technique is employed in the 3QBC by replacing the 1st and 2nd inductors, increasing the voltage gain at 23 times. Meanwhile, the result of replacing the 1st, 2nd and 3rd inductors of the converter led to an increase in the step-up ratio to 35 times. Consequently, it is deemed appropriate in applications requiring high-voltage gain, particularly those associated with on-grid AC systems. In general, achieving high voltage conversion can be done by increasing the stage number of Nth-QBC converter, which allows for integration of the LDBT technique by replacing the Lth inductors of the converter.



(a)



(b)

(c)

Fig. 3. NQBC Converter Family: (a) $3QBC_{2VL}$. (b) $3QBC_{3VL}$.

III. Operation Mode of $3QBC_{2SL}$ Converters Family

LDBT has a similar operation mode and this paper focuses on analysing only the $3QBC_{2SL}$ converter as illustrated in Fig. 2 (b). This converter has two SL cells, each consisting of two inductors and three diodes. At the output side of the converter, the SC cell is connected, which is another boosting technique. It is also called the Capacitor-Diode boosting technique (CDBT).

During one switching state, the analysis of the converter is simplified by assuming steady-state operation and making the following assumptions:

- All the converter components are ideal.
- All inductors current at continuous conduction mode (CCM) are linearly increased and decreased.
- All capacitors feature significant capacitance during the switching state and have constant voltage across them.

According to the Fig. 4, the $3QBC_{2SL}$ converter has two operation modes:

- **ON STATE** [$t_o - t_1$]: During the conduction of switch S, the diodes ($D_a, D_b, D_c, D_d, D_2, D_4$ and D_7) exhibit ON state, while the diodes (D_{ab}, D_{cd}, D_1, D_3 and D_6) remain in the OFF state, as shown in Fig. 4 (a). The 1st SL cell inductors (L_a and L_b) get concurrently charged in parallel by using the input voltage (V_{in}). In contrast, the 2nd SL cell inductors (L_c and L_d) get simultaneous charged in parallel through the capacitor (C_1). The 3rd inductor of the converter (L_3) get charged by the capacitor (C_2).

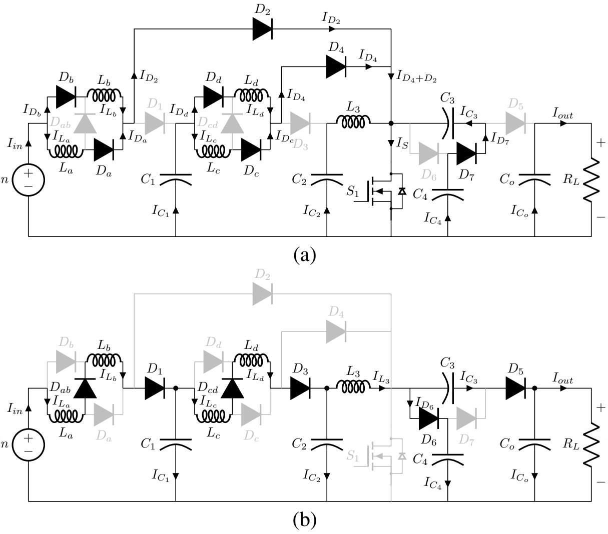
During the ON state, Kirchhoff's Voltage Law (KVL) is applied and it is possible to express the inductors voltage as:

$$\begin{cases} V_{L_a} = V_{L_b} = V_{in} \\ V_{L_c} = V_{L_d} = V_{C_1} \\ V_{L_3} = V_{C_2} \\ V_{C_3} = V_{C_4} \end{cases} \tag{1}$$

- **OFF STATE** [$t_1 - t_2$]: During the non-conducting state of switch S, the diodes (D_{ab}, D_{cd}, D_1, D_3 and D_6) exhibit ON state, while the diodes ($D_a, D_b, D_c, D_d, D_2, D_4$ and D_7) remain in the OFF state, as shown in Fig. 4 (b). The 1st SL cell stored energy in inductors (L_a and L_b) get discharged in series through the capacitor (C_1), whereas the 2nd SL cell stored energy in inductors (L_c and L_d) get discharged in series through the capacitor (C_2). The 3rd inductor of the converter stored energy (L_3) get discharged through the capacitor (C_3 and C_4), respectively.

During OFF state, the KVL is applied and the voltage across the inductor can be written as:

$$\begin{cases} V_{L_a} = V_{L_b} = \dfrac{V_{in} - V_{C_1}}{2} \\ V_{L_c} = V_{L_d} = \dfrac{V_{C_1} - V_{C_2}}{2} \\ V_{L_3} = V_{C_2} - V_{C_3} \\ V_o = V_{C_3} + V_{C_4} \end{cases} \tag{2}$$



(a)

(b)

Fig. 4. $3QBC_{2SL}$ Converter Operation Modes during: (a) ON State . (b) OFF State.

The equation representing the inductor volt-second balance is written as follows:

$$\int_0^{DT} v_L(t)\,dt + \int_{DT}^{(1-D)T} v_L(t)\,dt = 0 \tag{3}$$

According to (3) in CCM, the $3QBC_{2SL}$ converter voltage gain is written as:

$$M = \frac{V_o}{V_{in}} = \frac{2(D+1)^2}{(1-D)^3} \tag{4}$$

Depending on the stage number of the $nQBC_{nSL}$ converter where n is the stage number of the converter and SL cell, the general voltage gain of (4) can be expressed as:

$$M = \frac{V_o}{V_{in}} = \frac{2(D+1)^n}{(1-D)^n} \tag{5}$$

While using number of the VL technique in the $nQBC_{nVL}$, the general voltage gain of the $nQBC_{nVL}$ is written as:

$$M = \frac{V_o}{V_{in}} = \frac{2n}{(1-D)^n} \tag{6}$$

Accordingly to Table I, the $3QBC_{SL/VL}$ converters family voltage gain is compared with classical converters such as BC, BC_{SL}, BC_{VL}, QBC, QBC_{SL} and QBC_{VL} as shown in Fig. 5. It shows the highest voltage gain of the $3QBC_{SL/VL}$ converters family at all duty cycles. In addition, the $3QBC_{SL/VL}$ converters family voltage stress is half of the output voltage while the classical converters family voltage stress equals the output voltage as shown in Fig. 6.

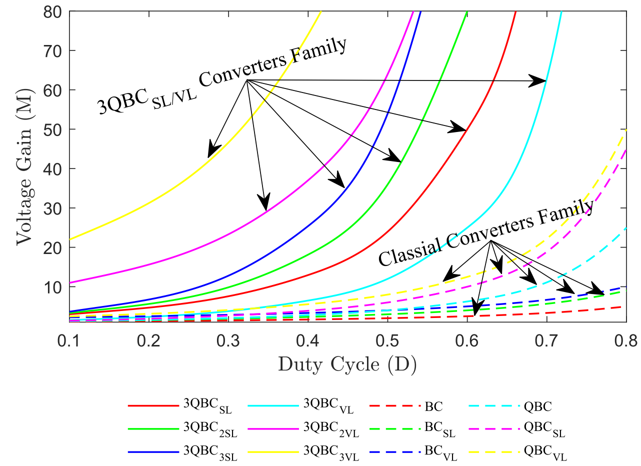


Fig. 5. Voltage Gain (M) vs Duty Cycle (D)

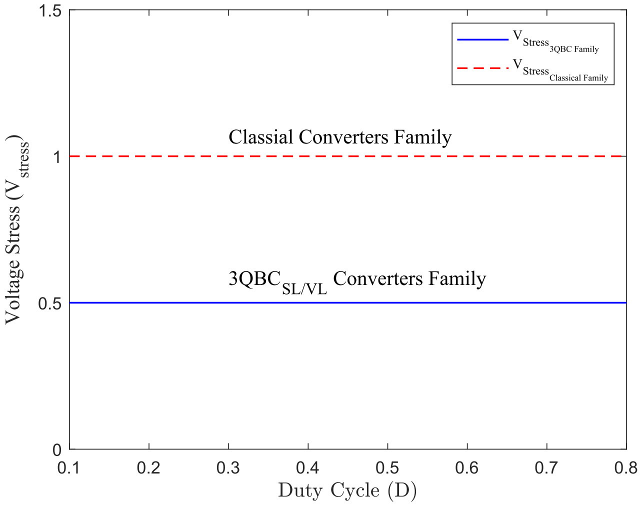


Fig. 6. Voltage Stress (V_{stress}) vs Duty Cycle (D)

TABLE I
VOLTAGE GAIN COMPARISON

Converter		Voltage Gain (M)	Voltage Stress
3QBC Converters Family	$3QBC_{SL}$	$M_{3QBC_{SL}} = \frac{2(D+1)}{(1-D)^3}$	$\frac{V_o}{2}$
	$3QBC_{2SL}$	$M_{3QBC_{2SL}} = \frac{2(D+1)^2}{(1-D)^3}$	
	$3QBC_{3SL}$	$M_{3QBC_{3SL}} = \frac{2(D+1)^3}{(1-D)^3}$	
	$3QBC_{VL}$	$M_{3QBC_{VL}} = \frac{4}{(1-D)^3}$	
	$3QBC_{2VL}$	$M_{3QBC_{2VL}} = \frac{8}{(1-D)^3}$	
	$3QBC_{3VL}$	$M_{3QBC_{3VL}} = \frac{12}{(1-D)^3}$	
Classical Converters Family	BC	$M_{BC} = \frac{1}{(1-D)}$	V_o
	BC_{SL}	$M_{BC_{SL}} = \frac{(D+1)}{(1-D)}$	
	BC_{VL}	$M_{BC_{VL}} = \frac{2}{(1-D)}$	
	QBC	$M_{QBC} = \frac{1}{(1-D)^2}$	
	QBC_{SL}	$M_{QBC_{SL}} = \frac{(D+1)}{(1-D)^2}$	
	QBC_{VL}	$M_{BC_{VL}} = \frac{2}{(1-D)^2}$	

IV. SIMULATION AND EXPERIMENTAL RESULTS

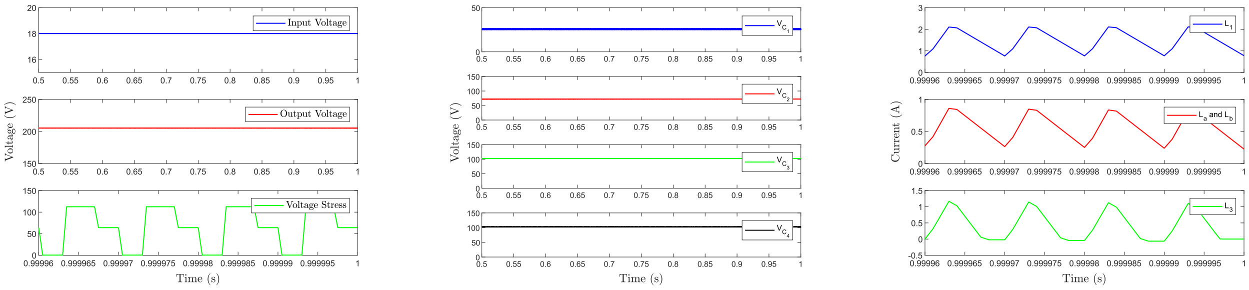
The simulation and experimental results are shown in this section for the converter as illustrated in Fig. 3 (a), comparing the simulation performance and the converter prototype performance in the lab. The $3QBC_{VL}$ operation mode is continuous conduction mode (CCM).

A. Simulation Results

The simulation result of $3QBC_{VL}$ is built using MATLAB/SIMULINK, investigating the operation and performance of the converter. Table II tabulates the component parameters and operation of the $3QBC_{VL}$ at CCM. A duty cycle of 30% and 100 kHz switching frequency is applied to generate a pulse width modulation (PWM) signal. For 18 V input voltage (V_{in}), the output voltage (V_{out}) of the $3QBC_{VL}$ is 207.7 V and the voltage stress on the MOSFET (V_{stress}) is 103.85 V as observed in Fig. 7 (a). While Fig. 7 (b) depicts the waveform of the voltage across the capacitors (V_{C_1}, V_{C_2}, V_{C_3} and V_{C_4}) and Fig. 7 (c) shows the waveform of the current passes

TABLE II
THE PARAMETER OF THE COMPONENTS.

Parameters		Value
Input Voltage V_{in}		18 V
Switching frequency f_s		100 kHz
Duty Cycle D		30%
Inductor	L_1	33 μH
	$L_a L_b$	100 μH
	L_3	150 μH
Capacitor	$C_1 C_2$	100 μF
	$C_3 C_4$	100 μF
	$C_o C$	100 μF



(a) (b) (c)

Fig. 7. Simulation results of (a) V_{in}, V_{out} and V_{stress}. (b) V_{C_1}, V_{C_2}, V_{C_3} and V_{C_4}. (c) I_{L_1}, I_{L_a}, I_{L_b} and I_{L_3}.

through the inductors (I_{L_1}, I_{L_a}, I_{L_b} and I_{L_3}). Observing the results in Fig. 7 (b), the value of the V_{C_1}, V_{C_2}, V_{C_3} and V_{C_4} are 24.32 V, 64 V, 103.85 V and 103.85 V, respectively, which is approximately agreed with V_o in (2).

B. Experimental Results

The $3QBC_{VL}$ converter prototype is designed and tested in the lab, the setup of the $3QBC_{VL}$ converter is shown in Fig. 8 and the component parameters are tabulated in Table II, leading to investigate the $3QBC_{VL}$ converter performance at CCM.

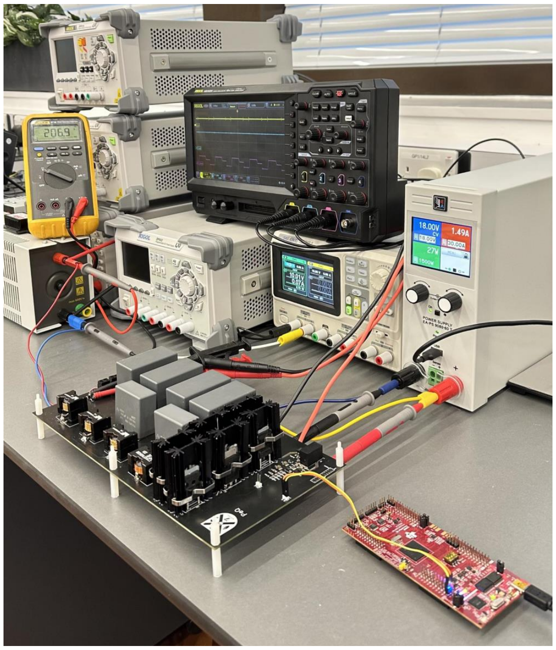


Fig. 8. The setup of the $3QBC_{VL}$ converter on the lab.

Applying the same simulation parameters to generate a PWM signal and 18 V as the input voltage in the experiment. However, the output voltage of the experimental is 206.9 V and the voltage stress on the SiC MOSFET is 100.4 V, as shown in Fig. 8.

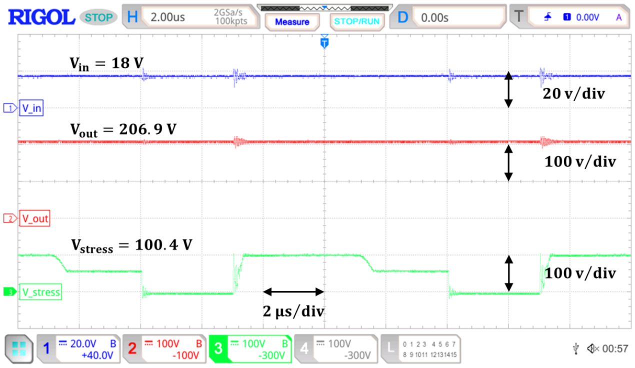


Fig. 9. Experimental results of: (a) V_{in}, V_{out} and V_{stress}.

According to the experimental results, the voltage across the capacitors (V_{C_1}, V_{C_2}, V_{C_3} and V_{C_4}) are shown in Fig. 10. The voltage value of the V_{C_1} and V_{C_2} are 24 V and 63 V, respectively. Meanwhile, the voltage value of the V_{C_3} and V_{C_4} are 103 V and 103 V, respectively, which is nearly the result obtained in (1).

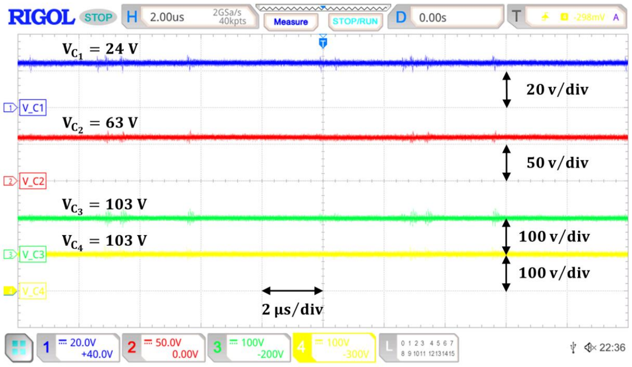


Fig. 10. The experimental result of the voltage across capacitors V_{C_1}, V_{C_2}, V_{C_3} and V_{C_4}.

The experimental result of the current passes through inductors (I_{L_1}, I_{L_a}, I_{L_b} and I_{L_3}) are shown Fig. 11. The current value of the I_{L_a} and I_{L_b} equals 0.75 A, which means both inductors of the VL are charging in parallel and discharging in the series. The current value of the I_{L_1} and I_{L_3} is 1.49 A and 0.5 A, respectively.

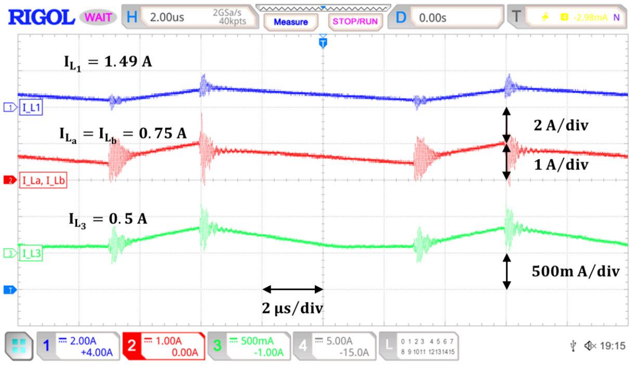


Fig. 11. The experimental result of the current pass through inductors I_{L_1}, I_{L_a}, I_{L_b} and I_{L_3}.

According to (6) for Fig. 3 (a), the output voltage of the theoretical result compared with the output voltage of the simulation and experimental result as shown in Fig. 12. Applying the (6) at duty cycle 0.3, the output voltage of the theoretical is 210 V, whereas the output voltage of the simulation and experimental are 207.7 V and 206.9 V, respectively. The output voltage difference between theoretical and simulation are 2.3 V, while the output voltage difference between theoretical and experimental are 3.1 V. Hence, it can be negligible as shown in Fig. 12.

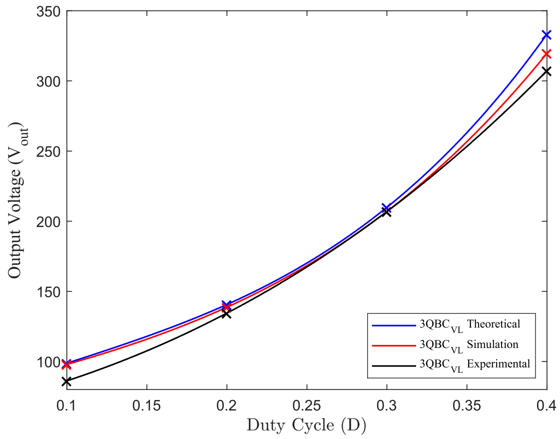


Fig. 12. Output voltage V_{out} of the theoretical, simulation and experimental results.

V. CONCLUSION

In this paper, a unique topology is presented to enhance the performance of a recently introduced family of non-isolated step-up DC/DC converters. This improvement is achieved by integrating an LDBT on the $3QBC_{SL/VL}$ converter family with a single switch, allowing for the realisation of a high voltage conversion ratio without requiring excessively high-duty cycle operation. It is particularly advantageous for automotive, telecom and AC grid system applications. Employing the SC cell at the output side of the $3QBC_{SL/VL}$ converter can double the voltage gain and reduce the voltage stress on the power switch, leading to the use of a low voltage rating of the MOSFET and a low $R_{DS_{ON}}$ MOSFET. Meanwhile, the Schottky diodes can alleviate the reverse recovery current problem by providing low switching and conduction losses.

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