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A new family of bidirectional DC-DC power converters with very low input and output ripples

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ABSTRACT

Bidirectional DC-DC converters with very low ripple contents in the input and output sides are desirable in many applications. This paper proposes a new family of bidirectional DC-DC converters with very low input and output ripples that is derived from the conventional Cuk DC-DC converter. At first, a new family of single-phase DC-DC converter is derived. Then, extension of this family into the multiphase ones is presented. Output voltage expressions of the proposed DC-DC converters are presented. It is found that the derived DC-DC converters have lower conduction losses than the conventional DC-DC converters. Expressions of input and output ripples of the proposed DC-DC converters are then also presented. Finally, some experimental results are included to show the basic performance of the proposed converters. Thus, the outcome of the proposed DC-DC converter can be achieved by using the duty ratio is half and the multiphase technique is upper-middle inductors. It given that the current and voltage ripples of proposed DC-DC converter is very low and almost zero.

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1. INTRODUCTION

A DC-DC power converter is commonly used in dc switched-mode power supply, renewable power generation system, battery charger/discharger and DC voltage regulator. In power plants, especially energy comes from photovoltaic (PV) which can supply energy to the grid or electrical load, but the problem is the difference in power voltage levels where the PV output voltage is very low when compared to the voltage on the DC network which is generally high, therefore it is necessary DC-DC converter. In most of applications, very low input and output ripples are desirable. Moreover, the efficiency must be as high as possible.

In order to achieve the above requirements, various DC-DC power converter topologies were developed and applied in practices [1]-[3]. At present, the most commonly used DC-DC power converter is the one as shown in Figure 1. This converter is also a basic cell of a voltage-source inverter or more complicated DC-DC power converters. It should be noted that the converter in Figure 1 is a bidirectional converter and, therefore, it can be used also as a buck DC-DC power converter [4]-[6].

The basic DC-DC power converters can be cascaded to achieve very high voltage ratio[7], [8]. As the power is converted several times, however, the efficiency can be very low. The cascaded DC-DC power converters can also be simplified so that the number of active switching devices can be reduced [9]-[11]. The voltage ratio can also be extended by using coupled inductor [12]-[17]. The drawback of this method is leakage and resonant issues.

By using soft switching techniques and by eliminating the galvanic isolation, efficiency can be increased signficantly [18]-[26]. Various methods to minimize the input and output ripples were also proposed [27]-[29]. Switching ripples can be minimized or eliminated by using multiphase or interleaved technique [30]-[41].

In 1977, Prof. Slobodan Cuk from the California Institute of Technology has proposed a DC-DC converter that can be considered as an optimum DC-DC converter [42]. This converter has continuous current of the input and output sides and also produced very low ripple of the current and voltage. A very low input current ripple is desirable in most of the applications such as photovoltaic and fuel cell power generation systems. In recent papers, the authors have proposed the modified Cuk DC-DC converter [43], [44]. This modified Cuk DC-DC converter can be step-down as a DC-DC buck converter or also can be step-up as a DC-DC boost converter. As it is derived from the Cuk DC-DC power converters, the modified Cuk DC-DC converter has also very low ripples content either in input and output sides. Many applications desirable the converters that has highly efficient and very low of ripples contets. However, many of the converters are having dicontinous input and output currents which also increasing ripple content. The modified Cuk DC-DC converter that has continuous currents of the input and output sides can be able to solve this problem.

This paper presents a new family of bidirectional DC-DC power converters with very low input and output ripples. The proposed family of DC-DC power converters are derived from the conventional Cuk converter. In addition to achieve very low rippls of the input and output sides, it is shown here that the proposed power converters have lower conduction losses. After a discussion on single-phase DC-DC power converters, the concept is extended to multiphase DC-DC power converters. The experimental results also showed to verify of the proposed topology.

This paper is organized as follows. Section 2 presents the proposed topology and output voltage analysis. Section 3 gives the comparison of the ripple analysis for single-phase and multiphase proposed converter and section 4 shows experimental results obtained of the hardware. Finally, section 5 gives the conclusions.

2. NEW FAMILY OF DC-DC POWER CONVERTERS

2.1. Single-phase modified Cuk converter (SMCC)

Dahono *et al*. [43], Dahono and Dahono [44], have shown that the conventional Cuk converter can be modified into the one shown in Figure 2. As it is derived from convensional topology of the Cuk DC-DC converter, this converter has very low ripple contents in the input and output sides. Moreover, this topology of the SMCC has lower conduction losses than several topologies of conventional converter.

Under continuous conduction mode for Figure 2, it can be shown the average output voltage $\bar{v}_L$ is:

$$\bar{v}_L = E_d \frac{1}{1-k} - \frac{V_S\alpha + V_D(1-k)}{1-k} - \frac{R_d\left(1-2k+2k^2\right) + R_S\alpha + R_D(1-k)}{(1-k)^2} I_L \qquad (1)$$

Where k is the duty ratio of transistor S_2, V_S is the constant component of voltage drop of transistor, V_D is the constant component of voltage drop of body diode D, R_d is the internal resistance of inductors, R_d is the internal resistance of diode, R_S is the internal resistance of transistor, and I_L is the average load output current. On the other hand, it can be shown that average output voltage of conventional boost converter as shown in Figure 1 can be obtained as:

$$\bar{v}_L = E_d \frac{1}{1-k} - \frac{V_S + V_D(1-k)}{1-k} - \frac{R_d + R_S\alpha + R_D}{(1-k)^2} I_L \qquad (2)$$

Comparison between (1) and (2) shows that the voltage drop due to the inductor resistances is lower in the SMCC than the one in conventional boost converter. As the voltage drop in the inductor resistances represent the conduction losses, the proposed SMCC has lower conduction losses than the conventional boost converter. The operating voltage and current of the SMCC are the same as the conventional boost converter and, therefore, the switching losses are the same. Thus, the total losses of the proposed DC-DC power converter are lower than the conventional boost converter. Moreover, as the output current of SMCC is continuous, the output current ripple is lower than conventional boost converter.

It should be noted that the SMCC in Figure 2 can be operated also as a step-down DC-DC power converter. As a step-down, the load and DC source are interchanged. Different to conventional buck DC-DC power converter, the proposed converter has continuous input and output currents with low ripple content. Moreover, the conduction losses of the proposed converter are lower than the ones in conventional buck converter.

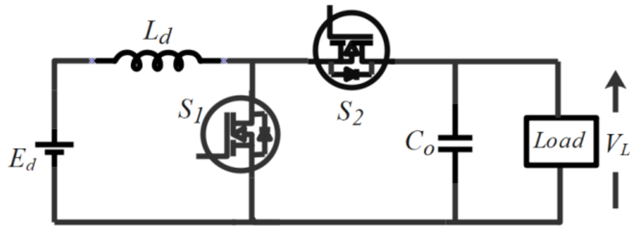


Figure 1. Conventional bidirectional boost power converter

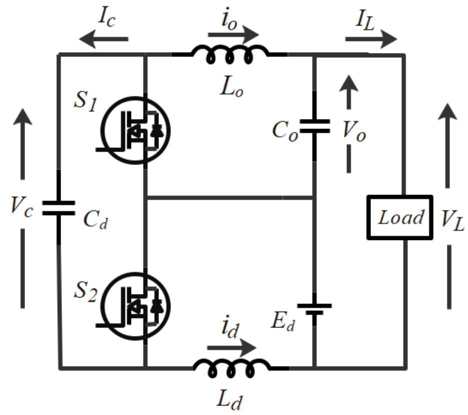


Figure 2. First bidirectional modified Cuk DC-DC power converter

In this paper, the SMCC in Figure 2 is further modified to achieve certain features. Possible modification comes from the position of two inductors in Figure 2. The position of these two inductors can be modified into the ones as shown in Figure 3(a) and Figure 3(b) without changing the operating principle. In this modification, the proposed converter has an inductor in the center line of L_m. By relocating these two inductors, the average output voltage will become as shown in (3).

$$\bar{v}_L = E_d \frac{1}{1-k} - \frac{V_S k + V_D(1-k)}{1-k} - \frac{R_d(2-2k+k^2)+R_S k + R_D}{(1-k)^2} I_L \quad (3)$$

for Figure 3(a), and

$$\bar{v}_L = E_d \frac{1}{1-k} - \frac{V_S \alpha + V_D(1-k)}{1-k} - \frac{R_d(1+k^2)+R_S k + R_D}{(1-k)^2} I_L \quad (4)$$

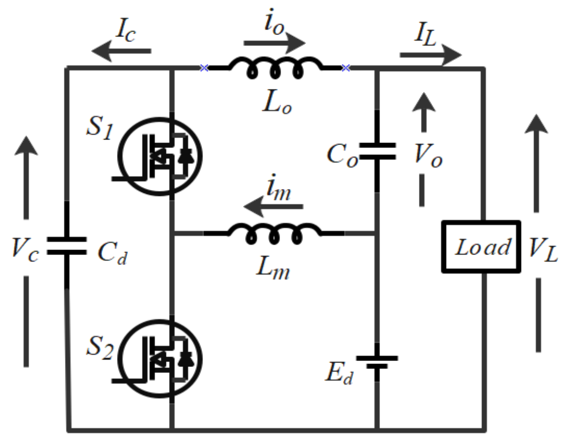
for Figure 3(b).

Comparison among (1), (3), and (4) shows that the SMCC in Figure 2 has the lowest voltage drop and the one in Figure 3(b) has the largest voltage drop. Thus, the conduction losses of the SMCC in Figure 3(b) will be the largest and the ones in Figure 2 will be the lowest. Switching losses of all converters are just the same.

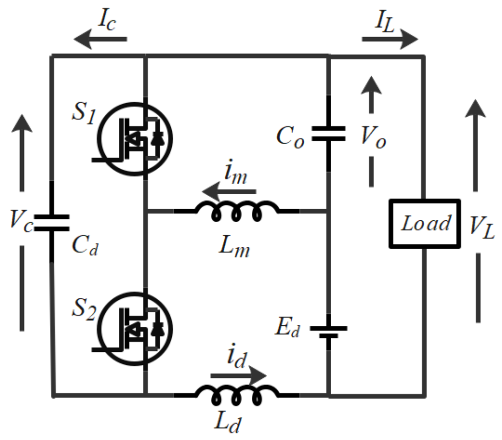
2.2. Multiphase modified Cuk converter (MMCC)

In addition to increase the current rating, multiphasing or interleaving is commonly used in power electronics to increase the capacity while minimize the switching ripples. In this case, the new MMCC that are derived from Figure 2, Figure 3(a), and Figure 3(b) are proposed. New two-phase topology of MMCC will be used as examples.

Figure 4(a) shows the MMCC that is derived from Figure 2. It can be seen that in this case, the number of switching devices, inductors, and transfer capacitor C_d are doubled. By using multiphase technique, the input and output ripples will be much lower than the single-phase case. However, transfer capacitors with large ripple current rating are still required.



(a)



(b)

Figure 3. New modified Cuk DC-DC power converters: (a) second modifications and (b) third modifications

Figure 4(b) and Figure 4(c) show the two-phase version of MMCC is derived in Figure 3(a) and Figure 3(b), respectively. In this modification, just the number of switching devices are doubled. The number of inductors is increased into $N+1$ where N is the number of phase. In terms of component count, the multiphase modified Cuk converter or MMCC in Figure 4(b) and Figure 4(c) is lower than the one in Figure 4(a). It also shown that the ripple current rating of transfer capacitor is reduced.

The average output voltages of MMCC in Figure 4(a), Figure 4(b), and Figure 4(c) are:

$$V_L = E_d \frac{1}{1-k} - \frac{V_S k - V_D(1-k)}{1-k} - \frac{NR_d\left(1-2k+2k^2\right)+R_S k+R_D(1-k)}{N(1-k)^2} I_L \tag{5}$$

for Figure 4(a),

$$V_L = E_d \frac{1}{1-k} - \frac{V_S k + V_D(1-k)}{1-k} - \frac{R_m+R_o N(1-k)^2+R_S k+R_D(1-k)}{N(1-k)^2} I_L \tag{6}$$

for Figure 4(b), and

$$V_L = E_d \frac{1}{1-k} - \frac{V_S k + V_D(1-k)}{1-k} - \frac{NR_m k^2+R_d+R_S k+R_D(1-k)}{N(1-k)^2} I_L \tag{7}$$

for Figure 4(c).

In the analysis (5), (6), and (7), the losses from devices of inductors and transistors also significantly can be reduced by adding the number of phase. The proposed converter in Figure 4(b) is more promising because the current that across inductor L_o is smaller than the current that accros the inductor L_d of MMCC in Figure 4(c). The detailed comparison among (5), (6), and (7) is shown in Table 1. It can be seen that the MMCC of Figure 4(c) has the largest inductor voltage drop. The MMCC in Figure 4(a) needs the highest component count compared to the ones in Figure 4(b) and Figure 4(c). Thus, the MMCC in Figure 4(c) will have the highest conduction losses.

Table 1. Multiphase modified Cuk converter performance comparison

	Figure 4(a)	Figure 4(b)	Figure 4(c)
Voltage drops due inductor resistance	$\frac{R_d(1-2k+2k^2)}{(1-k)^2} I_L$	$\frac{R_m + R_o N(1-k)^2}{N(1-k)^2} I_L$	$\frac{NR_m k^2 + R_d}{N(1-k)^2} I_L$
Transistor and diode	$2NS$ and $2ND$	$2NS$ and $2ND$	$2NS$ and $2ND$
Inductor	NL_o and NL_d	L_o and NL_m	L_d and NL_m
Capacitor	NC_d and C_o	C_d and C_o	C_d and C_o

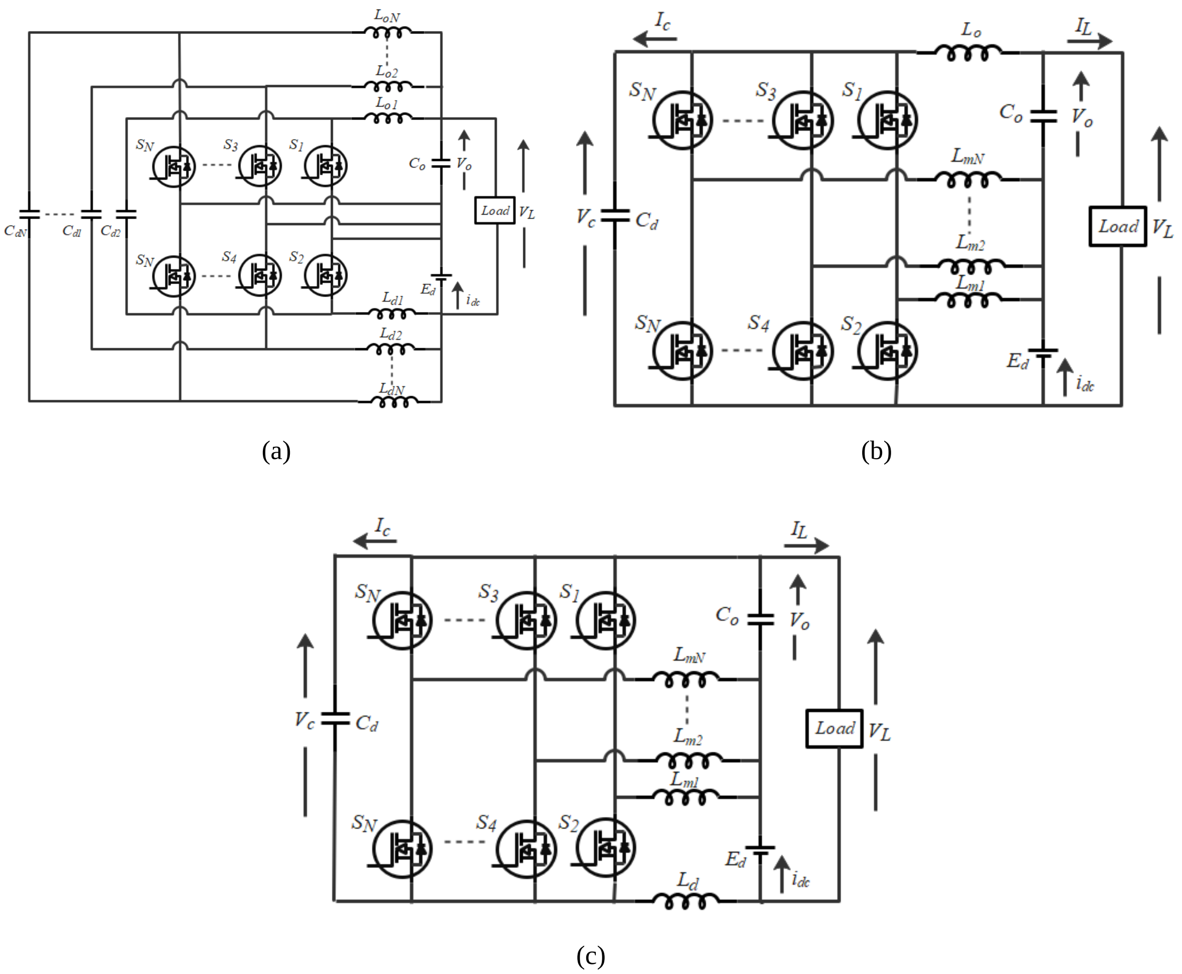


Figure 4. MMCC for: (a) upper-lower, (b) upper-middle, and (c) middle-lower

Figure 5 shows the average output voltage of MMCC in Figure 4 as a function of load current for several values of duty ratio. In this case, it is assumed that the switching devices are ideal with no voltage drops. In this calculation, it is assumed that the DC input voltage is 24 volts. All components of the inductor are assumed as identical inductors with resistance of 0.3 Ohm. It can be seen that the load voltage V_L differences among the converters are smaller when the duty ratio is small. At small duty cycle, the average load voltage V_L of MMCC in Figure 4(a) and Figure 4(b) are almost the same.

Figure 6 shows comparison between the average load voltages V_L of two-phase and four-phase MMCCs. It can be seen that the differences are reduced when the converter phase number is increased. Thus, the disadvantages of higher voltage drop in the converters of Figure 4(b) and Figure 4(c) are reduced when the duty ratio is small and phase number is higher.

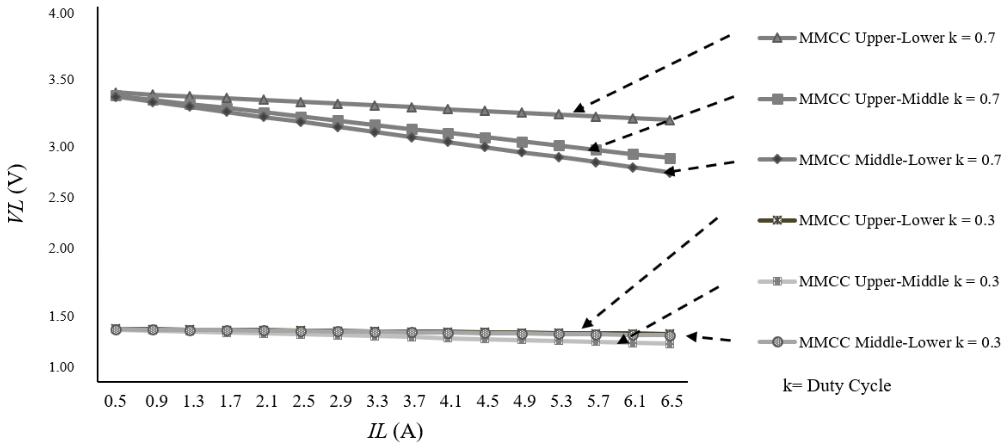


Figure 5. Output voltage comparison of two-phase modified Cuk converters

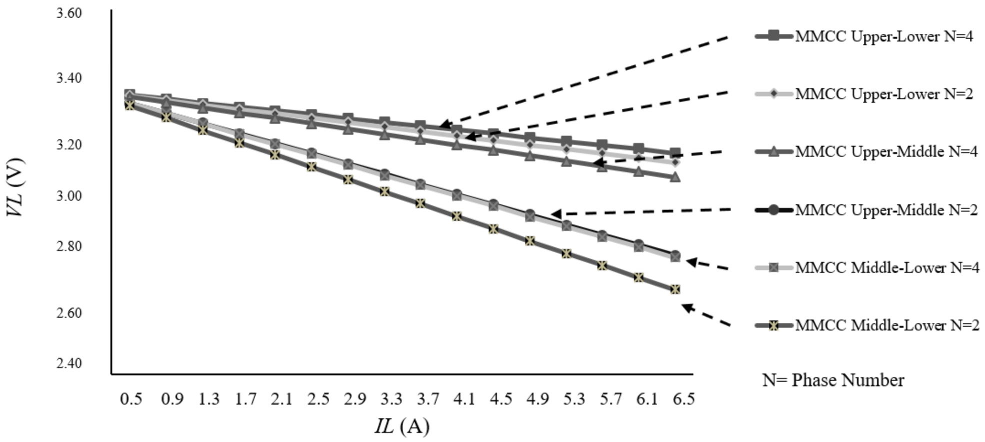


Figure 6. Output voltage comparison of two-phase and four-phase modified Cuk converters

3. RIPPLE ANALYSIS

3.1. Single-phase modified Cuk converters

In this analysis, it is assumed that all conmponents of the switching device are ideal components. The inductor resistances are also neglected. The source of input voltage is a constant and without ripple. Similarly, the load current is a constant current without ripple.

The detailed derivation of ripple currents for SMCC in Figure 2 has been given in [45]. By using the same method, we can derive the detailed ripple expressions for SMCC in Figure 3(a) and Figure 3(b). The summary is given in Table 2. Based on this table, the three modified Cuk converters have the same transfer capacitor current ripples. For SMCC in Figure 2, the two inductors have the same current ripples. These two current ripples represent the ripple of the source current and the output filter capacitor current, respectively. For SMCC in Figure 3(a), the middle inductor has current ripple that is equal to the ripple of inductor current in Figure 2. The upper or second inductor has much smaller inductor current ripple. As the ripple is much smaller, the required inductance can be much smaller than the middle inductor. Similarly, for SMCC in Figure 3(b), the middle inductor has the same current ripple as the other converters. The current ripple in the lower inductor is much smaller than the current ripple in the middle inductor and, therefore, the required inductance will be much smaller. In conclusion, the required total inductance of converter in Figure 3(a) and Figure 3(b) can be smaller than the one in Figure 2. Thus, the average voltage drop disadvantages of converters in Figure 3(a) and Figure 3(b) can be compensated.

Table 2. Single-phase ripple comparison

	Figure 2	Figure 3(a)	Figure 3(b)
$\tilde{I}_o$	$\frac{E_d}{L_o f_s}\frac{k(1-k)}{2\sqrt{3}}$	$\frac{I_L k(1-k)(1-k+k^2)^{1/2}}{C_d L_o f_s^2 6\sqrt{10}}$	
$\tilde{I}_d$	$\frac{E_d}{L_d f_s}\frac{k(1-k)}{2\sqrt{3}}$		$\frac{I_L \alpha(1-k)(1-k+k^2)^{1/2}}{C_d L_d f_s^2 6\sqrt{10}}$
$\tilde{I}_m$		$\frac{E_d}{L_m f_s}\frac{k(1-k)}{2\sqrt{3}}$	$\frac{E_d}{L_m f_s}\frac{k(1-k)}{2\sqrt{3}}$
$\tilde{I}_C$		$I_L\sqrt{\frac{k}{1-k}}$	

3.2. Ripple analysis of two-phase modified Cuk converters

By using a similar method that was used in [30], detailed expressions of current ripples of multiphase converters can be obtained. Table 3 shows the summary for two-phase topology of MMCC. The detailed derivation can be extended to phase number more than two.

Table 3 shows that the MMCC in Figure 4(b) and Figure 4(c) have smaller transfer capacitor current ripple than the one in Figure 4(a). The transfer capacitor current ripples C_d of MMCC in Figure 4(b) and Figure 4(c) will be zero when the duty ratio is half. Similarly, the current ripples of upper and lower inductors for MMCC in Figure 4(b) and Figure 4(c) are much smaller than MMCC in Figure 4(a). In duty ratio is half, these current ripples will also be zero.

Table 3. Multiphase ripple comparison

	Figure 4(a)	Figure 4(b) and Figure 4(c)
$\tilde{I}_{dc}$	For $0 < k < 0.5$: $\tilde{I}_{dc} = \frac{E_d k(1-2k)}{L_d f_s (1-k)}$ For $0.5 < k < 1.0$: $\tilde{I}_{dc} = \frac{E_d(2k-1)}{L_d f_s \sqrt{3}}$	For $0 < k < 0.5$: $\tilde{I}_{dc} = \frac{E_d k(1-2k)}{L_m f_s 2(1-k)}$ For $0.5 < k < 1.0$: $\tilde{I}_{dc} = \frac{E_d(2k-1)}{L_m f_s 2\sqrt{3}}$
$\tilde{I}_C$	$\tilde{I}_C = \frac{I_L}{2}\sqrt{\frac{k}{1-k}}$	For $0 < k < 0.5$: $\tilde{I}_C = \frac{I_L}{2}\frac{\sqrt{k(1-2k)}}{1-k}$ For $0.5 < k < 1.0$: $\tilde{I}_C = \frac{I_L}{2}\sqrt{\frac{-3+8k-4k^2}{1-k}}$

4. EXPERIMENTAL RESULTS

The small prototype hardware of SMCC as shown in Figure 2, Figure 3(a) and Figure 3(b) was constructed. The switching devices were constructed by using power MOSFET (IRF260N). In this experiment, film capacitors were used for all capacitors that are required. The two inductors were constructed by using a ferrite core.

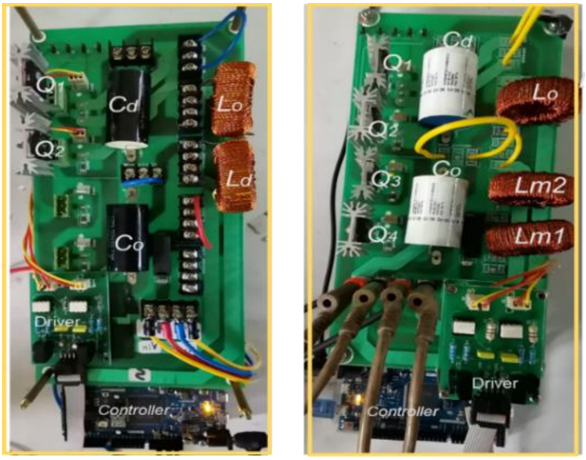
The experiment also was constructed into the new MMCC. Based on recomendation, the MMCC as the in Figure 4(a) with the upper and middle inductors that has lowest current and voltage ripples implemented into this multiphase experiment. The PWM signals for the converter was generated by Arduino microcontroller. The experimental data is shown in Table 4. The experimental hardware for SMCC is shown in Figure 7(a) and two-phase MMCC is shown in Figure 7(b). Switching frequency of the proposed converter was operated at 25 kHz.

Figure 8 shows comparison of average output voltages for SMCC's in Figure 2, Figure 3(a), and Figure 3(b), for several values of the duty ratio. In this experiment, the load resistance was constant. It can be seen that the average output voltage V_L of SMCC in Figure 2 is the highest especially when the duty ratio is high. The differences are getting smaller when the duty cycle is reduced. These results confirm the previous analysis.

Figure 9 shows the output voltage as the function of duty cycle for the two-phase topology of MMCC in Figure 4(a). Measurements were conducted under constant load current. Accurate output voltage expression that has been derived can be appreciated from this figure.

Table 4. Experimental data

Parameter	Value
Input voltage (Ed)	24 vdc
Inductor ($Ld = Lo$)	1 mH
Capacitor ($Cd = Co$)	12 uF
Switching frequency (fs)	25 kHz
Inductor resistance (Rd)	0.3 ohm
Switches resistance (RQ)	0.042 ohm



(a) (b)

Figure 7. The experimental hardware for modified Cuk DC-DC converters: (a) single-phase and (b) two-phase hardware of the SMCC

Figure 10 shows the source current ripple when duty ratio is changed for the two-phase topology of MMCC in Figure 4(a). The load resistance in this experiment was constant. It can be seen that the current ripple of the source will be zero when value of the duty ratio is half. Once again, accuracy of the derived expression can be appreciated from this figure

Figure 11 shows the middle inductor currents and load for the two-phase topology of MMCC in Figure 4(a) at the duty ratio is half. It can be seen that the inductor currents are almost the same magnitude but have opposite in phase. The load voltage is almost free of ripple.

Figure 12 shows the two-phase topology of MMCC in Figure 4(a) that is measures the ripple contents. The voltage and current ripple waveforms are measured by using the digital oscilloscope that having a capability of measuring the ac component only. It shows the ripple waveforms of source current, upper inductor current, and output capacitor voltage of the proposed converter when the duty ratio is half. It shown that all ripple waveforms are almost zero.

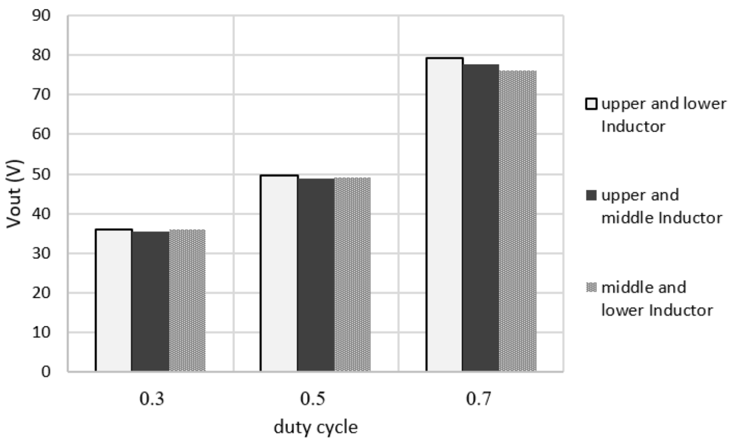


Figure 8. Output voltages of single-phase modified Cuk DC-DC power converters

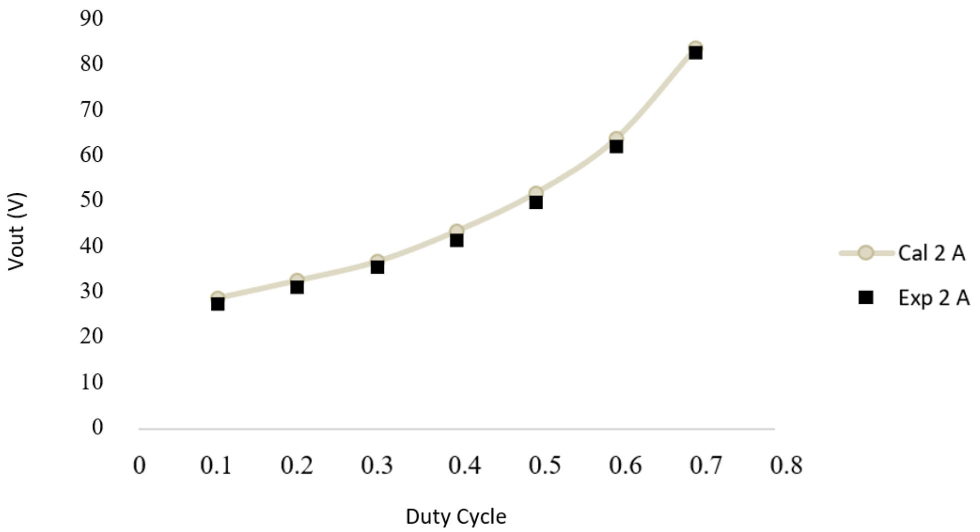


Figure 9. Output voltage for two-phase modified Cuk converter

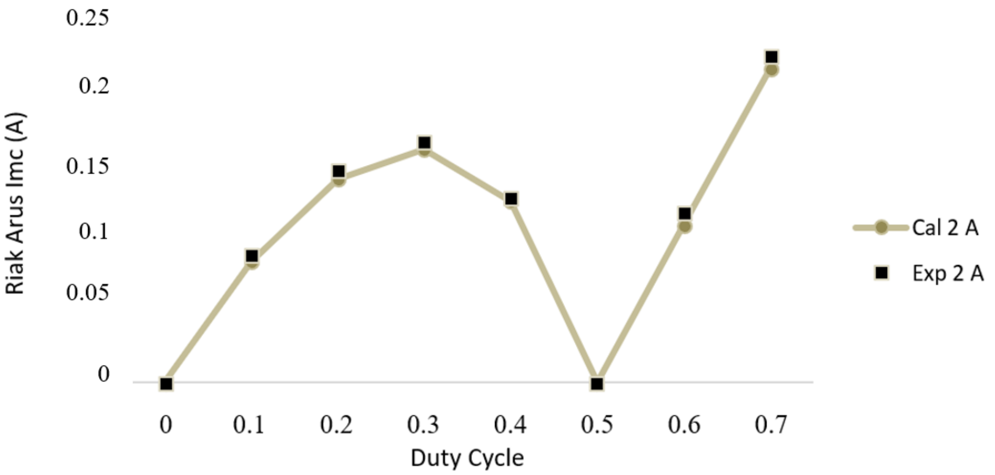


Figure 10. Source current ripple for two-phase modified Cuk converter

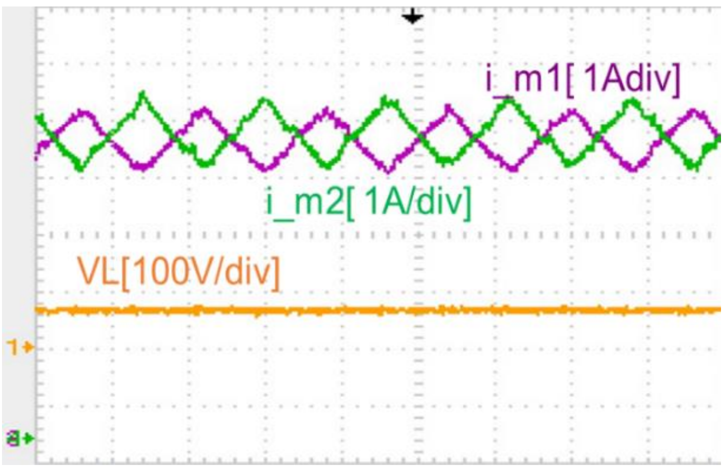


Figure 11. Middle inductor currents and load voltage for two-phase modified Cuk converter

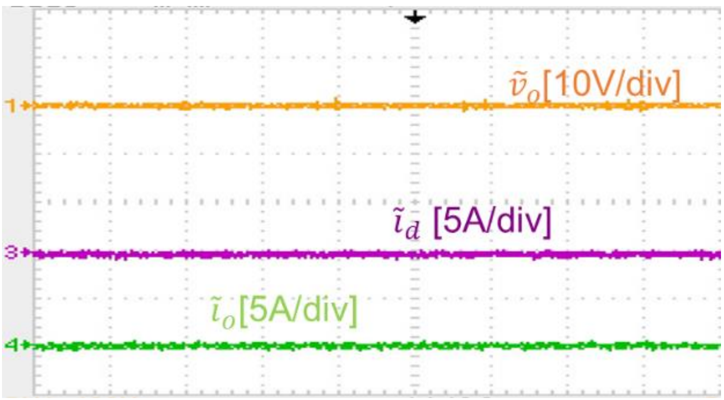


Figure 12. Ripple waveforms of source current, upper inductor current, and output capacitor voltage for two-phase modified Cuk converter

5. CONCLUSION

A new family of bidirectional DC-DC power converters based on modified Cuk power converter has been proposed. Output voltage expressions of the proposed power converters are derived. The ripple expressions that are useful in passive component selection are presented. Results of the experiment are given to show the basic proposed converter performance and to verify the employed analysis method. The proposed DC-DC power converters can be used as bacic cells of more complex various power converters. How to control the proposed converters is left for future investigation.

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