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Simplified cascade multiphase DC-DC buck power converter for low voltage large current applications: part I --- steady-state analysis

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ABSTRACT

This paper presents a new simplified cascade multiphase DC-DC buck power converter suitable for low voltage and large current applications. Cascade connection enables very low voltage ratio without using very small duty cycles nor transformers. Large current with very low ripple content is achieved by using the multiphase technique. The proposed converter needs smaller number of components compared to conventional cascade multiphase DC-DC buck power converters. This paper also presents useful analysis of the proposed DC-DC buck power converter with a method to optimize the phase and cascade number. Simulation and experimental results are included to verify the basic performance of the proposed DC-DC buck power converter.

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1. INTRODUCTION

A step-down DC-DC power converter is commonly used in DC power supplies, DC voltage regulators, DC welders, and cathodic protection systems. In some applications, the required output voltage is very low at very large output current. Moreover, the allowed output current ripple should be very low to not damage the internal components. In general, a step-down DC-DC power converter can be classified as isolated and non-isolated DC-DC power converter [1]. As efficiency is very important, the non-isolated one is the most commonly used. Several DC-DC power converters with very low voltage ratios have been proposed in the literature [2]-[10]. The most common method to achieve a very low voltage ratio is by cascading several conventional DC-DC buck power converters. However, the number of components is increased when the cascaded converters are increased. Different methods to simplify cascade DC-DC buck power converters have been proposed in the literature [11], [12].

To achieve large output current rating with reduced ripple content, the multiphase technique is commonly used [13]-[21]. If several multiphase DC-DC buck power converters are connected in cascade then, both very low voltage ratio and very small ripple content can be achieved. In this case, however, the required active and passive components number will be very high. This paper presents a new simplified cascade multiphase DC-DC buck power converter for very low output voltage and large output current applications. Very low voltage ratio is obtained by cascading several DC-DC buck power converters. In order to reduce the required components, the simplified version of cascade single-phase DC-DC buck power converter is used. In order to increase the current capability and to reduce the ripple content, several simplified cascade single-phase are connected in parallel and operated as a cascade multiphase DC-DC buck power converter. In order to reduce further the required number of components, the resulting cascade multiphase DC-DC buck power converter is then simplified. Output voltage analysis of the proposed converter is analyzed by considering voltage drops across active and passive components. The obtained output voltage expressions are useful to determine the conduction losses and, therefore, the efficiency. Based on the conduction losses, the required phase number and cascaded number of the proposed DC-DC buck power converter can be determined. Several calculated and experimental results are included to show the basic performance of the proposed DC-DC buck power converter.

This paper is arranged into five sections. In section 2, the proposed DC-DC buck power converter topologies are derived and explained in detail. Section 3 theoretically analyzes the converter where the output voltage, together with the power loss calculation, are discussed. The optimization of the phase number and the cascade number is also presented in this section. The proposed converter chosen design and the experimental results are presented in section 4 to prove the analysis in section 3. Finally, the conclusion is drawn in the last section.

2. PROPOSED DC-DC BUCK POWER CONVERTER

This section discusses the derivation of the proposed DC-DC buck power converter. The discussion is started by discussing the conventional DC-DC buck power converter and cascade DC-DC buck power converter. The discussion is then followed by simplified cascade multiphase DC-DC buck power converter towards the proposed DC-DC buck power converter. Here, the discussion neglects the effects of voltage drops across the active and passive components.

2.1. Conventional DC-DC buck power converters

Figure 1 (a) shows a conventional single-phase DC-DC buck power converter. Though a MOSFET has been used as the active switching device, in practice we can use other active switching devices depending on the application. Under continuous conduction mode, the voltage ratio is (1),

$$\frac{V_o}{E_d} = \alpha \quad (1)$$

with

$$\alpha = \frac{T_{ON}}{T_S} \quad (2)$$

where V_o is the output voltage, E_d is the input voltage, and α is the duty cycle, T_{ON} is the ON-period of the switch and T_S is the switching period of the transistor, respectively. The duty cycle α can be varied from zero to unity and, therefore, the output voltage can be varied from zero to E_d. In practice, however, the duty cycle cannot be made too low due to the minimum turn-off time of the switching device. Thus, the minimum voltage ratio is limited.

In order to increase the output current rating and to decrease the ripple content, several single-phase DC-DC buck power converters can be connected in parallel and operated as a multiphase DC-DC buck power converter, as shown in Figure 1 (b). If the phase number is N, both current rating and ripple frequency will increase N times compared to single-phase DC-DC buck power converter.

2.2. Cascade DC-DC buck power converters

In order to improve the voltage-ratio capability, several DC-DC buck power converters can be connected in cascade as shown in Figure 2 (a), in which the grey-colored shows the cascade configuration. If all transistors are operated at the same duty cycle, the voltage ratio is (3),

$$\frac{V_o}{E_d} = \alpha^M \quad (3)$$

where M is the number of cascaded converters. For the same duty cycle, the obtained voltage ratio will be smaller compared to a single-stage DC-DC buck power converter. The method in Figure 2 (a) can be extended into the multiphase one and the result is shown in Figure 2 (b). This topology is named conventional cascade multiphase (CCM) DC-DC buck power converters. The CCM DC-DC buck power converters have the same average output voltage as (3), with each switch is activated by similar carrier signals on phase difference of *2π/N*, where *N* is the number of phases. Nevertheless, the phase numbers of each stage do not have to be the same. Moreover, the duty cycle of each stage does not have to be the same. Both cascade number and phase number can be optimized to achieve a certain criterion.

2.3. Simplified cascade multiphase (SCM) DC-DC buck power converters

In order to reduce the required active switching devices, a simplified version of cascade single-phase DC-DC buck power converter shown in Figure 3 (a) was proposed [11]. This converter can also be configured into the multiphase one, as shown in Figure 3 (b). The obtained output voltage expression is still the same as given by (3). This converter can produce a very low voltage ratio with very low ripple content.

Even though the component number of active switching devices in Figure 3 (b) is lower than the one in Figure 2 (b), the requirement of electrolytic capacitors is higher. It has been shown in the literature [22]-[25] that electrolytic capacitors are the most unreliable component in power electronic system and, therefore, the used of electrolytic capacitors must be minimized.

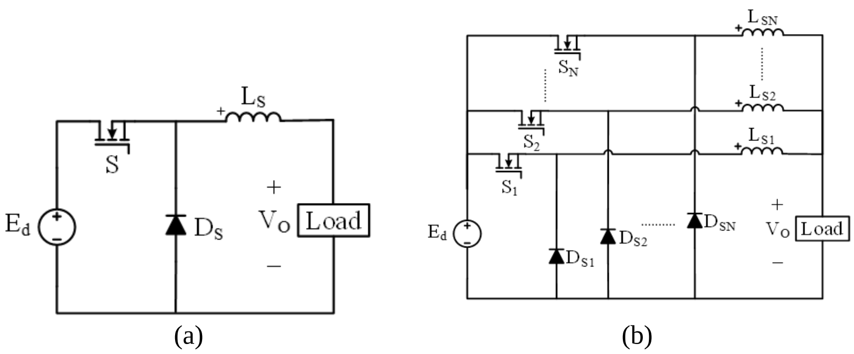

Figure 1. (a) conventional single-phase DC-DC buck power converter, (b) conventional multiphase DC-DC buck power converter

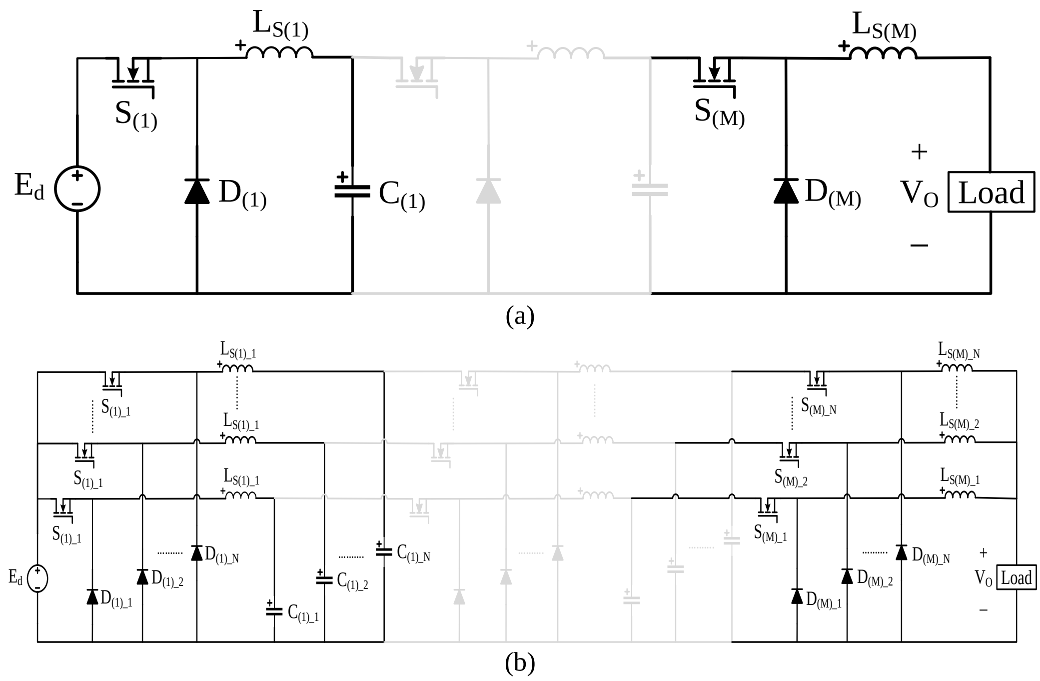

Figure 2. (a) conventional cascade single-phase DC-DC buck power converter, (b) conventional cascade multiphase (CCM) DC-DC buck power converter

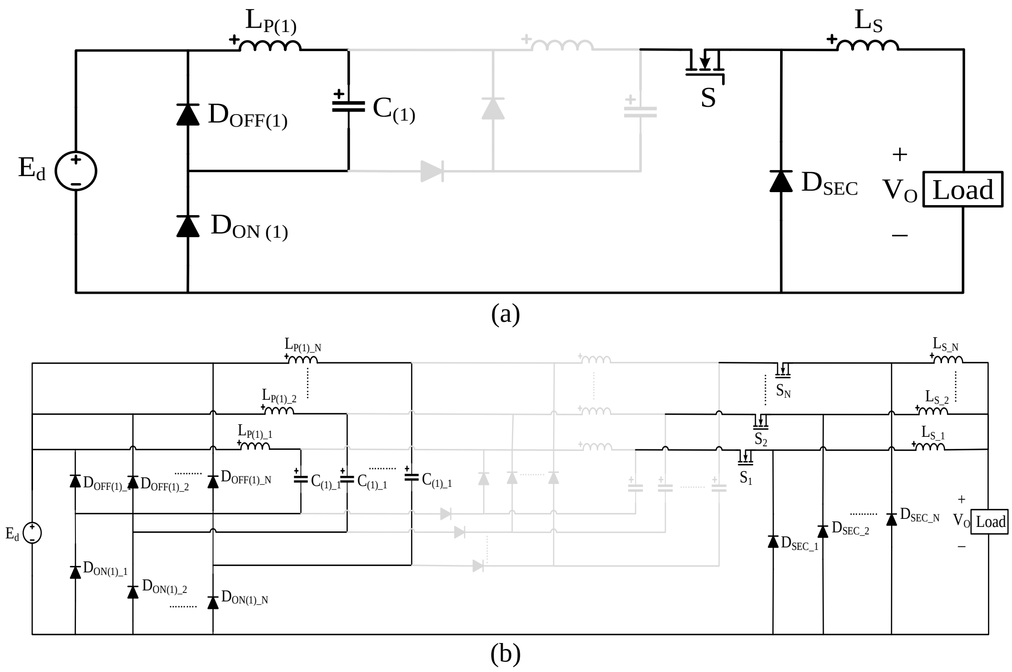

Figure 3. (a) simplified cascade single-phase DC-DC buck power converter, (b) simplified cascade multiphase (SCM) DC-DC buck power converter

2.4. New simplified cascade multiphase (NSCM) DC-DC buck power converters

Since the duty cycle of switches per phase is equal, all average voltages of capacitors on Figure 3(b) will be equal. When the voltages are identic, all capacitors that are installed in parallel can be replaced with only a single capacitor. Consequently, all diodes D_{ON}, diodes D_{OFF} and inductors L_P can also be replaced with only a single component each. This simplified scheme is named as a new simplified cascade multiphase (NSCM) DC-DC buck power converter, which is shown in Figure 4. The voltage ratio of the new scheme is shown by (4),

$$\frac{V_o}{E_d} = N^{M-1}\alpha^M \tag{4}$$

where N is the number of phases. In this case, the maximum duty cycle is limited to *1/N*.

NSCM DC-DC buck power converters have switching mechanisms as follows:

1) When switch S_1 is *ON* (other switches are *OFF*), all diodes D_{ON} and secondary diodes (excluding D_{SEC1}) will be forward biased, meanwhile the remaining diodes will be reverse biased. Current will flow in two directions: from DC source E_d to inductor L_P and from diode D_{ON} to capacitor C. Then, both currents sum up and charge inductor L_{S1}, before reaching the load. Other secondary inductors will discharge their currents to the load.
2) When switch S_1 is *OFF* (other switches are also *OFF*), all diodes D_{OFF} and secondary diodes will be forward biased. Diodes D_{ON} will be reverse biased. The load will only receive discharged currents from the secondary inductors. Both mechanisms will be repeated for other switches.

A comparison of components among conventional cascade multiphase DC-DC buck power converters/CCM (Figure 2 (b)), simplified cascade multiphase DC-DC buck power converters/SCM (Figure 3(b)), and the proposed cascade multiphase DC-DC buck power converters/NSCM (Figure 4) is represented in Table 1. The proposed converter has the least number of components compared to two other cascade multiphase topologies. It should be noted that this converter is the dual of the converter that has been proposed in [26].

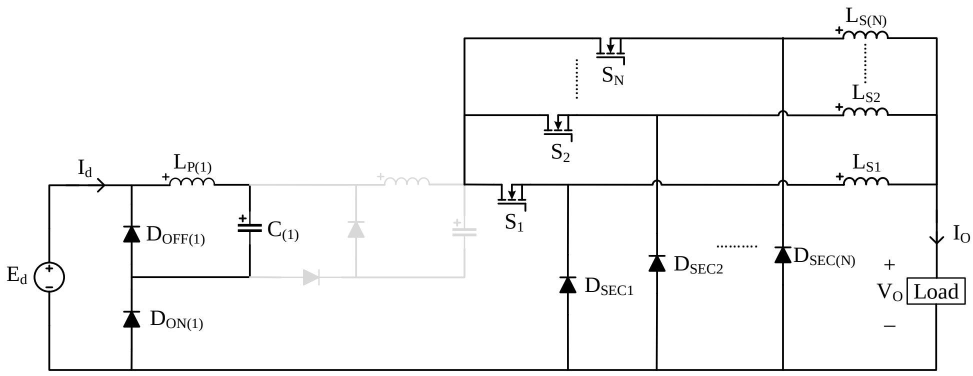

Figure 4. New simplified cascade multiphase (NSCM) DC-DC buck power converter

Table 1. Comparison of number of components in each cascade multiphase converter (2-cascade *N*-phase)

Converter Name	No. of Components			
	Inductors	Capacitors	Diodes	Switches
CCM	2*N*	*N*	2*N*	2*N*
SCM	2*N*	*N*	3*N*	*N*
NSCM	*N*+1	1	*N*+2	*N*

3. CONVERTER ANALYSIS

This section discusses the output voltage analysis of the cascade multiphase DC-DC buck power converters topologies, which are conventional cascade multiphase (CCM), simplified cascade multiphase (SCM), and the new simplified cascade multiphase (NSCM) DC-DC buck power converters. The discussion is then followed by deriving the conduction losses of NSCM DC-DC buck power converters. This section ends after the optimization of the number of cascades and the number of phases desired for the NSCM DC-DC buck power converter, based on conduction losses.

3.1. Output voltage analysis

All output voltage equations in section 2 have been derived by neglecting voltage drops across the diodes, inductors, and switching devices. In fact, the voltage drops across switching devices, diodes, and inductors will reduce the maximum output voltage that can be obtained.

In the derivation of average output voltage, it is assumed that the voltage drop across the transistor during conduction can be represented as (5)

$$v_Q = V_Q + R_Q i_Q \qquad (5)$$

and the voltage drop across the diode during conduction as (6)

$$v_D = V_D + R_D i_D \qquad (6)$$

where V_Q is the on-state drop voltage of the active switch, R_Q is the on-state drain-to-source resistance, i_Q is the current flowing in the switch, V_D is diode forward voltage, R_D is the diode internal resistance and i_D is the current flowing in the diode. The resistances of inductors are assumed the same as R_L. Note that all capacitors are assumed ideal with no parasitic components.

By using the state-space averaging method, the average output voltage under continuous conduction mode can be determined. The results are shown in Table 2, where it is assumed that the number of stages is equal to two. This concept can be extended easily for cascaded number more than two.

Output voltage expressions in Table 2 are then plotted in Figure 5. It is assumed that the active switching devices are MOSFETS (model FCH023N65S3). According to the datasheet, the resistance of FCH023N65S3 is 18 mΩ. All diodes are model MUR1560G with a constant voltage drop of 0.6 V and a resistance of 18.4 mΩ. Inductor resistances are assumed equal to 30 mΩ. It is assumed that the DC input voltage is constant at 312 V.

Figure 5 shows the output voltage as a function of output current. As the load increases, NSCM converter has higher steepness compared to SCM and CCM, indicating that NSCM produces high conduction losses. This steepness decreases as the number of phase decrease. The average output voltage of NSCM decreases faster than the others because it was assumed that all inductors are the same. In practice, the current rating of the primary inductor (L_P) of NSCM must be lower and, therefore, has the smallest resistance.

Based on the same voltage ratio, Figure 6 shows that NSCM has smaller duty cycle compared to two other figures. As the number of phases increases, the maximum duty cycle decreases. Fortunately, a small duty cycle is enough to achieve the desired low output voltage. This small duty cycle can be increased by adjusting the switching technique, which is left for future investigation.

Table 2. Output voltage expressions of CCM, SCM, and NSCM

Converter Name	Output Voltage Expression
CCM	$V_o=\alpha^2E_d-\left(1-\alpha^2\right)V_D-(\alpha^2+\alpha)V_Q-I_o\dfrac{\left[\left(\alpha^2+1\right)R_L+\left(\alpha^3+\alpha\right)R_Q+\left(1-\alpha+\alpha^2-\alpha^3\right)R_D\right]}{N}$
SCM	$V_o=\alpha^2E_d-\left(1+\alpha-2\alpha^2\right)V_D-\alpha V_Q-I_o\dfrac{\left[\left(\alpha^2+1\right)R_L+\alpha R_Q+\left(1-\alpha^2\right)R_D\right]}{N}$
NSCM	$V_o=N\alpha^2E_d-\left(1+\alpha-2N\alpha^2\right)V_D-\alpha V_Q-I_o\dfrac{\left[\left(N\alpha^2+1\right)R_L+\alpha R_Q+\left(1+N\alpha^2-2N^2\alpha^3\right)R_D\right]}{N}$

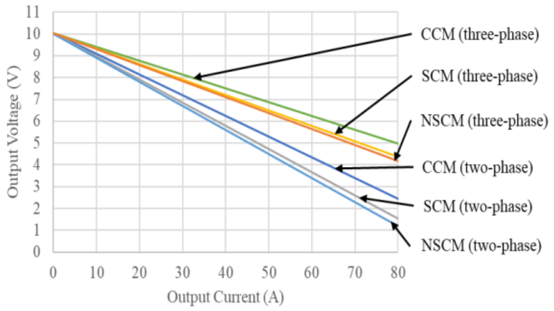

Figure 5. Output voltage as a function of output current

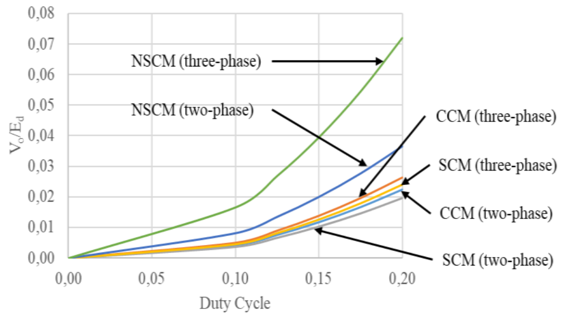

Figure 6. Voltage ratio as a function of duty cycle

3.2. Converter power loss analysis
3.2.1. Conduction losses

The output power of a DC-DC buck power converter is mentioned in (7)

$$P_o=V_oI_o \tag{7}$$

where P_o is the output power, V_o is the average output voltage, and I_o is the average output current of the converter.

By using the output voltage expression in Table 2 and (7), the output power of the new simplified cascade multiphase (NSCM) DC-DC buck power converter, as shown in Figure 6, is (8)

$$P_o=N\alpha^2E_dI_o-\left(1+\alpha-2N\alpha^2\right)V_DI_o-\alpha V_SI_o-I_o{}^2\frac{\left[\left(N\alpha^2+1\right)R_L+\alpha R_S+\left(1+N\alpha^2-2N^2\alpha^3\right)R_D\right]}{N} \tag{8}$$

The input current (I_d) of the DC-DC power converter is written in (9)

$$I_d = N\alpha^2 I_o \tag{9}$$

By substituting (9) into (8), the (10) is obtained

$$\begin{aligned} P_o &= E_d \bar{i}_d - \left(1+\alpha-2N\alpha^2\right)V_D I_o - \alpha V_S I_o \\ &\quad - I_o^{\,2}\frac{\left[\left(N\alpha^2+1\right)R_L+\alpha R_S+\left(1+N\alpha^2-2N^2\alpha^3\right)R_D\right]}{N} \end{aligned} \tag{10}$$

The power loss (P_{loss}) of the converter is the difference between the input and output power, which is shown in (11)

$$P_{loss} = P_i - P_o \tag{11}$$

Meanwhile, the converter input power (P_i) is mentioned in (12)

$$P_i = E_d I_d \tag{12}$$

By using (10)-(12), the (13) is obtained

$$\begin{aligned} P_{loss} &= \left(1+\alpha-2N\alpha^2\right)V_D I_o + \alpha V_S I_o \\ &\quad + I_o^{\,2}\frac{\left[\left(N\alpha^2+1\right)R_L+\alpha R_S+\left(1+N\alpha^2-2N^2\alpha^3\right)R_D\right]}{N} \end{aligned} \tag{13}$$

The (13) shows that voltage drops across the inductors, diodes, and power switches cause the conduction losses to occur. Figure 7 plots the comparison of conduction losses between CCM, SCM, and the NSCM. NSCM has higher conduction losses compared to two other cascade multiphase topology, due to larger number of used diodes. In practice, the resistance of the primary inductors (L_P) of the proposed converter is lower than the others because the current rating is higher and the required inductance is smaller. Thus, the total conduction losses will be just the same as the others, or even lower.

3.2.2. Switching losses

Switching losses of the converter depend on some parameters, which are: input voltage (E_d), switching frequency (f_s), current flow on the switch (I_{sw}), and the internal switch characteristics (rise time/t_r and turn-off crossover time/t_{cf}).

Based on the literature review [27], [28], the switching losses equation for CCM, SCM and NSCM is shown in (14). In this expression, K_1 is the sum of t_r and t_{cf}, while K_2 is the sum of current-linear dependent rise time and current-linear dependent turn-off crossover time.

$$P_{sw} = \frac{1}{2}E_d f_s (K_1 I_{sw} + K_2 I_{sw}^2) \tag{14}$$

The (14) shows that all DC-DC buck power converters have the same switching losses.

3.3. Converter optimization

Comparison between the number of phases and cascades is done to find the optimum topology of the proposed converter. Table 3 shows the variants to be optimized. The optimization is done based on the requirements of the converter as in Table 4, with the specification of the components in Table 5.

The graph in Figure 8 shows the comparison of conduction losses in each variation of cascades and phases under full load and half load conditions. As the number of cascades increases, the losses also increase. Meanwhile, when the number of phases increases, the losses decrease. Amongst the variants, the 2-cascade 4-phase topology has the lowest conduction losses. This topology will then be experimented further.

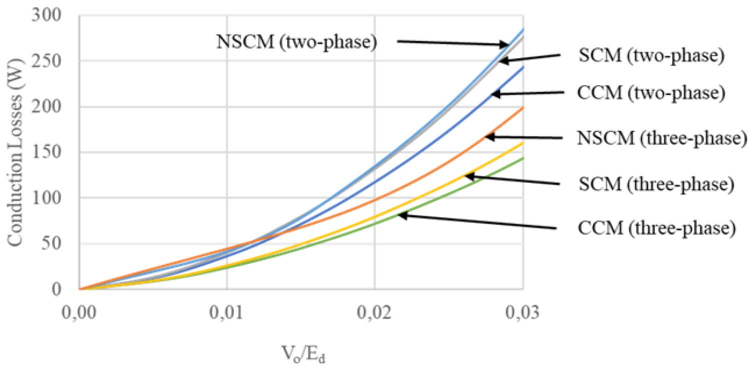

Figure 7. Conduction losses

Table 3. Six variations to find the optimum topology

No.	No. of Cascades	No. of Phases
1.		2
2.	2	3
3.		4
4.		2
5.	3	3
6.		4

Table 4. Converter specifications

No.	Converter' Specification	Value
1.	Input Voltage	(311.127 ± 10%) V
2.	Output Voltage	10 V
3.	Output Current	50 A
4.	Output Power	500 W

Table 5. Converter components

Components	Value
Inductors	L = 1 mH; R_L = 30 mΩ
Switches	R_S= 18 mΩ
Diodes	V_D = 0.85 V; R_D = 1.84 mΩ
Capacitor	470 µF; 400 V_{DC}
Switching Frequency	10 kHz

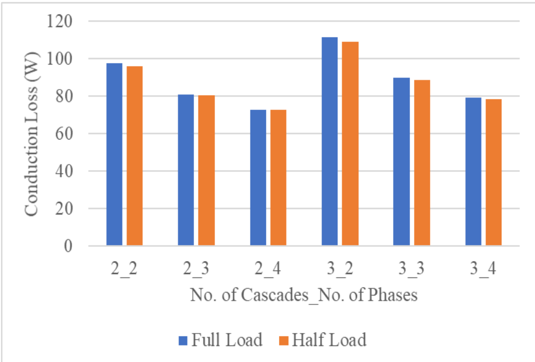

Figure 8. Conduction losses of the six analyzed variants

4. EXPERIMENTAL RESULTS

The chosen schematic design from section 3 can be seen in Figure 9. This schematic is then experimented, with the setup as shown in Figure 10. The primary inductor (L_P) has an inductance of 2.6 mH with an internal resistance of 0.9 Ω, while the secondary inductor on each phase (L_{S1}, L_{S2}, L_{S3}, and L_{S4}) is 1.03 mH with an internal resistance of 0.5 Ω. MOSFETs (FCH023N65S3) with an internal resistance of 18 mΩ are used as active switches. To drive the MOSFETs, four drivers model TLP350 are used. Ultrafast diodes MUR1560G are used in the topology, which has 0.6 V as the drop voltage with an internal resistance of 18.4 mΩ. The switching frequency of 10 kHz is used in all the experiments. The input voltage was downscaled to 100 V, with fixed aluminum resistors as the load resistance. No attempts have been done to select better inductors to improve converter performance.

Figure 11 shows the voltage ratio of the proposed converter, in which the measured results are very close to the calculations. Figure 12 shows the output voltage as a function of output current, which is obtained from changing the load resistance on fixed duty cycle of 0.125. Measured results are also close to the calculation results. Figure 13 shows the conduction losses of the converter as the function of the converter voltage ratio. Overall, these figures have shown that the calculation obtained from the formulas in Section 3 have been proven right. The measured results have small differences with the calculation ones due to inaccuracy of measuring inductors' resistance. Figure 14 shows output current waveform with the ripple waveform. These figures prove the converter claim for large output current with low output ripple.

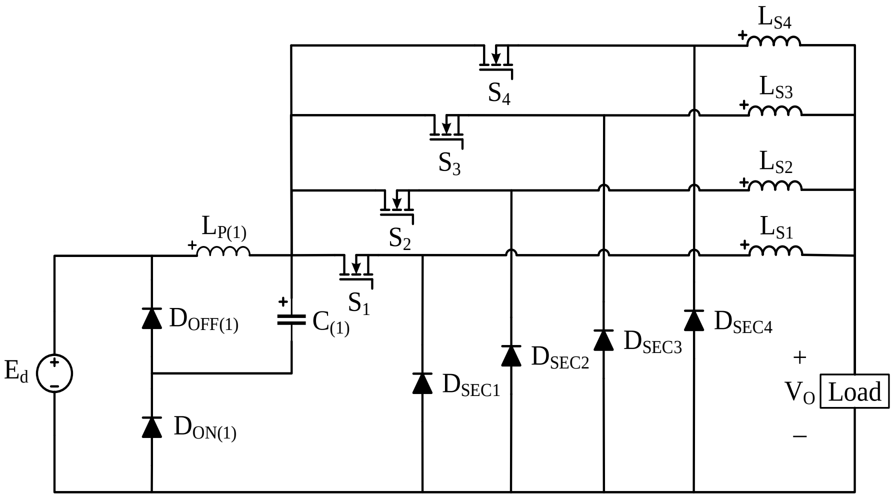

Figure 9. Two-cascade four-phase schematic design

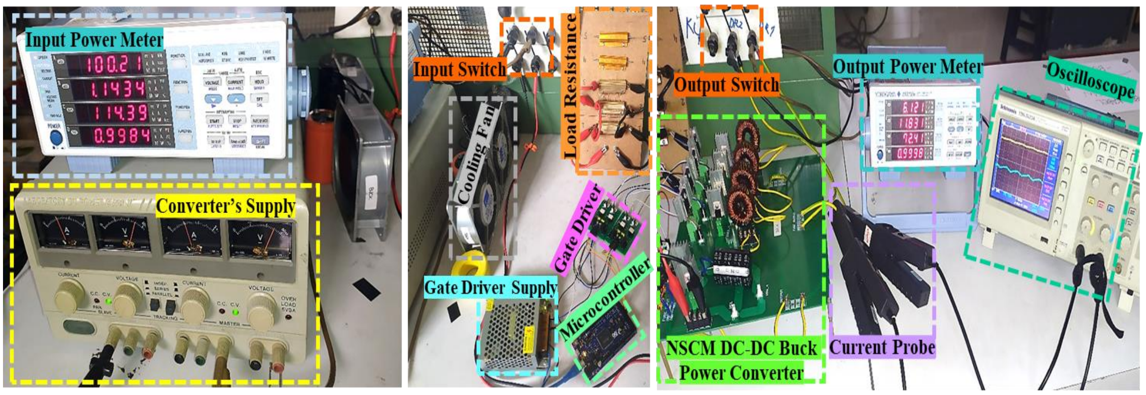

Figure 10. Experimental setup

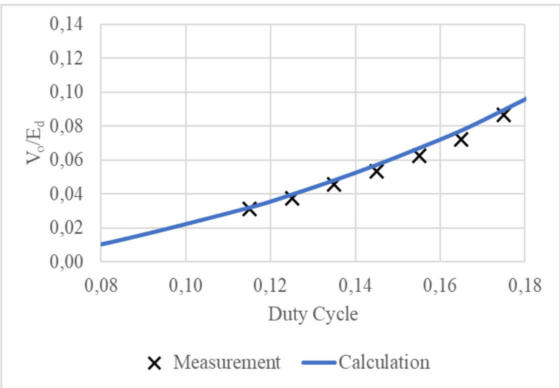

Figure 11. Voltage reduction ratio as a function of duty cycle

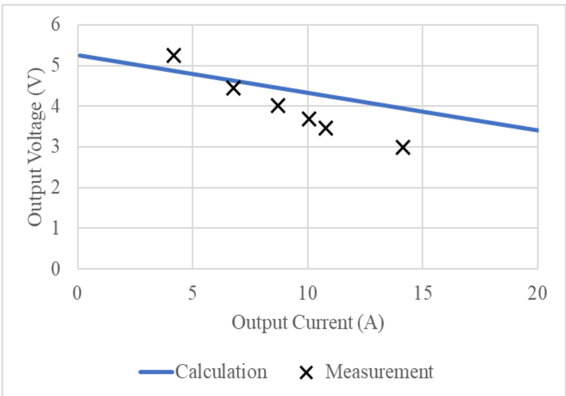

Figure 12. Output voltage as a function of output current

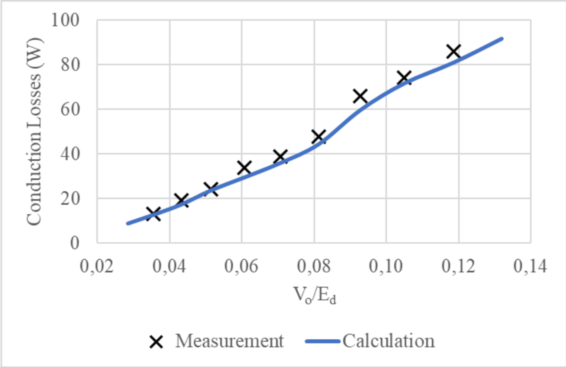

Figure 13. Conduction losses as a function of voltage ratio

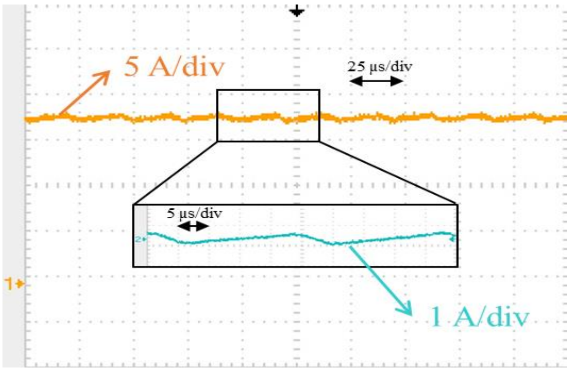

Figure 14. Output current waveform (orange-colored) with the enlarged output ripple waveform (blue-colored)

5. CONCLUSION

A new simplified cascade multiphase DC-DC buck power converter for low voltage large current applications has been proposed in this paper. The proposed converter has very high voltage reduction ratio with smaller number of components. Output voltage analysis, useful to estimate the conduction losses, is also presented. Even though conduction losses of the proposed converter are higher than the conventional cascade multiphase DC-DC buck power converter, the switching losses is lower. Optimum number of cascades and number of phases is presented in this paper. Experimental results showing the basic performance have been included. Selection of the optimal components for the proposed converters is under investigation.

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