A Multi-phase Series Capacitor Trans-inductor Voltage Regulator with High Switching Frequency and Fast Dynamic Response

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***Abstract*—In this paper, a novel multi-phase series capacitor trans-inductor voltage regulator (TLVR) with high frequency and fast dynamic response is proposed. The proposed voltage regulator combines the advantages of series capacitor buck converter and TLVR. The switching frequency can be improved a lot due to the reduced switching losses and doubled duty cycle. Moreover, the transient performance is enhanced with trans-inductor structure. The equivalent transient inductance is reduced remarkably without affecting steady-state performance. The proposed concept is validated by simulation and experiment. A significant dynamic performance improvement can be observed through the simulation results comparison.**

***Index Terms*—dynamic response, load transient, series capacitor buck, trans-inductor voltage regulator.**

I. Introduction

With the evolvement of high-performance computation and VLSI technology, a single microprocessor can consume hundreds of amperes with ultra-low voltage (sub 1V). Ultra-fast load transit (over 1000A/μs) is inevitable during the operation of chips, which brings tough challenges to the power supply design [1]. Therefore, a high efficiency, high power density, fast dynamic response high-speed power supply with advanced topology and control method is preferred for the voltage regulation modules (VRM).

Multi-phase buck converter is the most popular point-of-load (PoL) converter with simple structure, low cost, and extensibility. Thus, it is widely used in industry. To reduce the size of passive components and improve the dynamic response, a higher switching frequency is preferred. However, the switching frequency is usually limited by the switching losses. Moreover, the on-time of high-side switch is extremely short in high frequency, high step-down ratio applications. The control precision cannot be ensured. Series capacitor buck converter has superior performance and overcomes the challenges of conventional buck converters [2]. Compared with the conventional buck converter, the duty cycle of its high-side switch is doubled and the voltage stress of the switch is halved. Therefore, the switching losses can be reduced and the control precision can be improved. The only cost is one additional dc blocking capacitor. Hence, the series capacitor buck converter is superior in high frequency, high current, and high step-down ratio applications. A higher switching frequency facilitates higher bandwidth and faster response speed.

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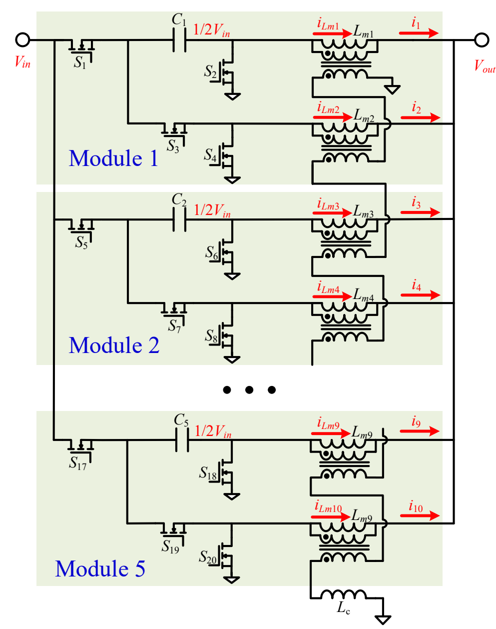

Fig. 1. The proposed multi-phase series capacitor trans-inductor voltage regulator.

To improve dynamic performance, research on advanced control strategies and topologies is conducted. On the control side, constant on-time (CoT) control [3], [4] is a popular method with fast transient response speed and high light-load efficiency. Many other advanced control methods [5], [6] with optimal transient response are proposed to enhance the transient performance. However, the theoretical transient speed is constrained by topology. In [7], [8], multi-phase buck converters with coupled inductors are proposed to unblock the theoretical barrier of the conventional buck converter. The equivalent transient inductance (L_{tr}) can be reduced without affecting steady-state inductance (L_{ss}) [9]. However, the magnetic core design is complicated, especially when more

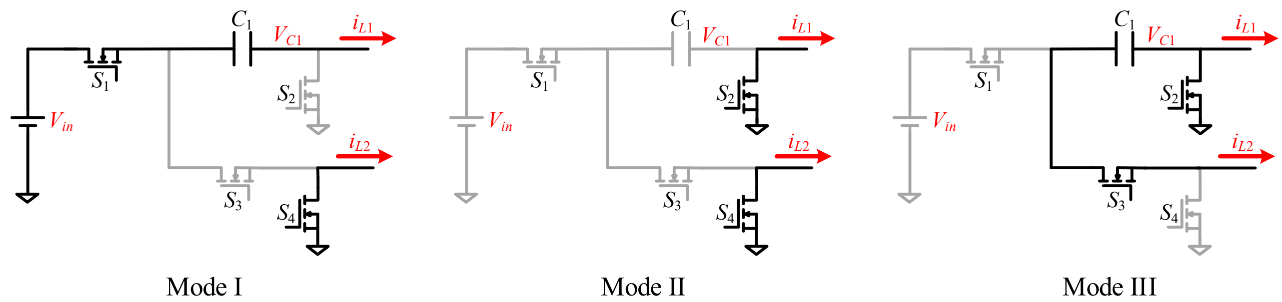

Fig. 2. The equivalent circuit of the series capacitor structure in different modes

than two phases are coupled. To improve industrial manufacturability and extensibility, trans-inductor voltage regulator (TLVR) is derived based on the multi-phase buck converter with coupled inductors [10], [11], [12]. Due to the identical mathematical model [13], TLVR can achieve similar dynamic performance. TLVR was quickly embraced by the industry and expected as the next generation VRM.

In this paper, a multi-phase series capacitor TLVR is proposed. The proposed converter is depicted in Fig. 1. The proposed converter facilitates higher switching frequency, less switching loss, less conduction loss, and faster transient performance. The detailed operation principles are analyzed. The performances are compared quantitatively between the conventional multi-phase buck converter and the proposed series capacitor TLVR.

This paper is organized as follows: Section II introduces the topology and basic operation principles of the proposed topology. Simulation results are exhibited in Section III. Section IV demonstrates experimental results. Finally, this paper is concluded in Section V.

II. Topology and Basic Operation Principles

A. Topology description

Fig. 1 plots the schematic of the proposed multi-phase series capacitor TLVR. In this paper, a ten-phase topology is used as an example for analysis. As shown in Fig. 1, there are five paralleled series capacitor buck modules. Each module comprises two buck cells and one dc blocking capacitor. The first module is taken as an example to analyze. The driving signals for S_1 and S_2 (S_3 and S_4) are complimentary with certain deadband. They are driven in an interleaving manner with regulated duty cycle and 180° phase shift. The duty cycle of each cell's high-side MOSFET is defined as D. The series capacitors block the dc voltage and function as the input source of bottom cells. Ten phases are interleaved to reduce the current ripples. Compared with conventional multi-phase buck converters, transformers with low leakage inductances are adopted to replace discrete output inductors. The transformer turns ratio is set to be 1:1 in this paper. Each phase connects to a secondary winding of a transformer. All primary windings are connected in a series loop with a compensation inductor L_c. The magnetizing inductor of the transformer carries the dc current.

B. Steady state analysis

At steady state, there are three different modes in one cycle as shown in Fig.2. In Mode I, S_1 and S_4 are turned on. C_1 is charged through the first phase. The voltage stress of S_2 is $V_{in} - V_{c1}$. The voltage across S_3 is V_{in}. In Mode II, S_2 and S_4 are turned on. There is no current through C_1. The voltage stress of S_1 is $V_{in} - V_{c1}$. The voltage stress of S_3 is V_{c1}. In Mode III, S_21 and S_3 are turned on. C_1 is discharged through the second phase. The voltage stress of S_1 is $V_{in} - V_{c1}$. The voltage stress of S_4 is V_{c1}. At steady state, the voltages across dc blocking capacitors are half of the input voltage. Therefore, each module is equivalent to two interleaved buck converters with half input voltage. Compared with a conventional buck converter, the duty cycle D is doubled, which can be expressed as,

$$D = 2V_o/V_{in} \tag{1}$$

The critical steady-state waveforms of the proposed converter are plotted in Fig. 3. At steady-state, only the voltage stress of S_3 in module 1 is V_{in}. The voltage stresses of the other three MOSFETs in the first module is $V_{in}/2$. The switching loss can be calculated as,

$$P_{SW} = \frac{1}{2}C_{oss}v_{ds}^2 \tag{2}$$

Therefore, the switching loss can be greatly reduced due to the half drain-to-source voltage, which facilitates a higher switching frequency. The inductor current ripple can also be decreased due to the reduced voltage conversion ratio. It should be noted that the inductor currents of two phases in one module can be automatically balanced. These factors are beneficial to high frequency, high current, and high voltage conversion ratio applications.

At steady state, the voltage across the compensation inductor L_c is equal to $nV_{in}/2 - NV_{out}$, where n is the phase number with turned-on high-side MOSFET and N is the total phase number. n can be two adjacent integers determined by the phase number N and duty cycle D. Therefore, there is an Nf_s current ripple in L_c as shown in Fig. 3. The current ripple of i_{L_c} through primary-side windings can be reflected in the secondary-side windings and the output currents. Therefore, compared with conventional buck converter, there is a high-frequency current component in the output current of each phase.

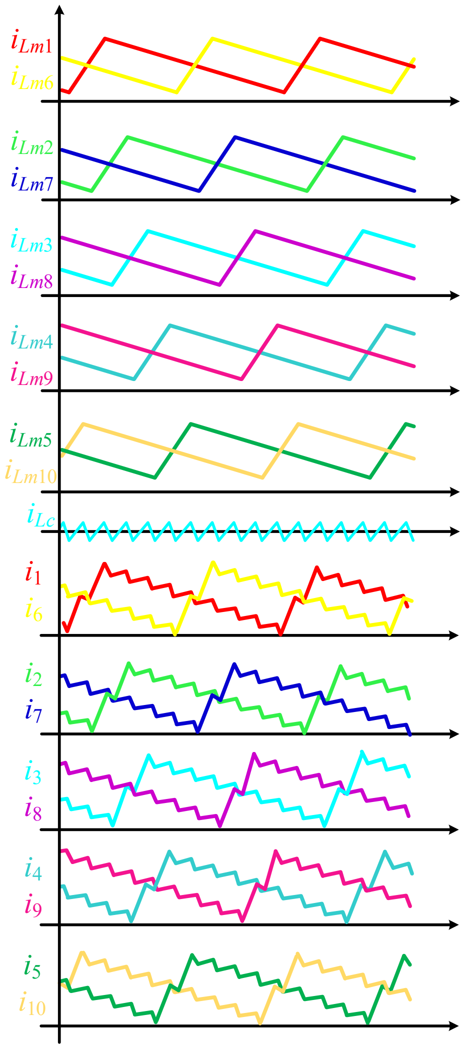

Fig. 3. The steady-state waveforms of the proposed converter.

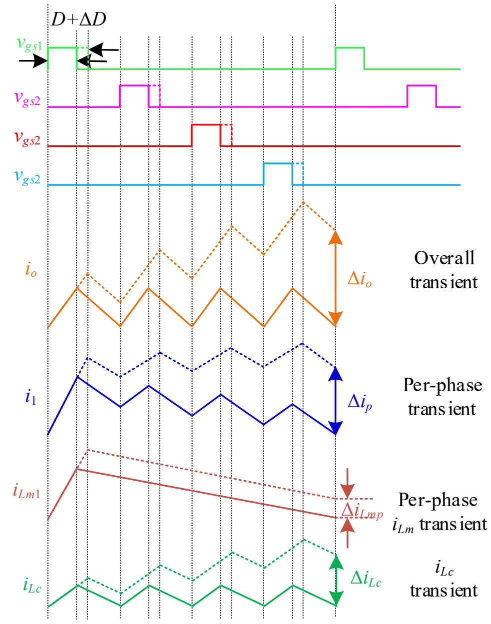

Fig. 4. Overall transient response and per-phase transient response

C. Transient state analysis

During the load transient, a sudden load current fluctuation results in the duty cycle adjustments of the converter. Accordingly, a sudden current change can be observed in i_{L_c}. Then, the changing current of i_{L_c} can be reflected in all phases of the converter. Therefore, a fast transient can be achieved. For the proposed series capacitor TLVR, a higher switching frequency also facilitates a fast dynamic response.

TLVR is popular due to its nonlinear inductance property. It can achieve large steady-state inductance, which induces small phase current ripple. Nevertheless, the transient inductance is much smaller compared with the steady-state inductance. The transient inductance reveals the transient performance of the converter.

The transient inductance can be divided into overall transient inductance (L_{otr}) and per-phase transient inductance (L_{ptr}) as shown in Fig. 4 [13]. L_{otr} means the equivalent discrete inductance with the same overall transient response. L_{ptr} means the equivalent inductance with the per-phase transient response. They are defined as follows,

$$\Delta i_o = \frac{V_{in}}{L_{otr}} \Delta DT \tag{3}$$

$$\Delta i_p = \frac{V_{in}}{L_{ptr}} \Delta DT \tag{4}$$

where V_{in} is the input voltage of each phase. For an N phase interleaving TLVR converter, if the leakage inductance is ignored and the turns ratio is 1:1, the following relationship can be derived.

We define an index k that is related to the phase number N and duty cycle D,

$$\frac{k}{N} \leq D < \frac{k+1}{N} \tag{5}$$

During $\frac{k}{N}T < t < DT$, there are $k+1$ coupled inductors which have V_{in}-V_{out} across them. $N-k-1$ coupled inductor have $-V_{out}$ across them. Therefore, the voltage across the compensated inductor can be derived as $(k+1)V_{in} - NV_o$. i_{Lc} ramps up.

During $DT < t < \frac{k+1}{N}T$, there are k coupled inductors which have V_{in}-V_{out} across them. $N-k$ coupled inductor have $-V_{out}$ across them. Therefore, the voltage across the compensated inductor can be derived as $kV_{in} - NV_o$. i_{Lc} ramps down.

Therefore, when the duty cycle of all phases is increased ΔD, the variation of i_{Lc} during one period can be derived as shown in Fig. 4.

$$\Delta i_{Lc} = \frac{(k+1)V_{in}}{L_c} N \Delta DT \tag{6}$$

The variation of perphase i_{Lm} can be derived as,

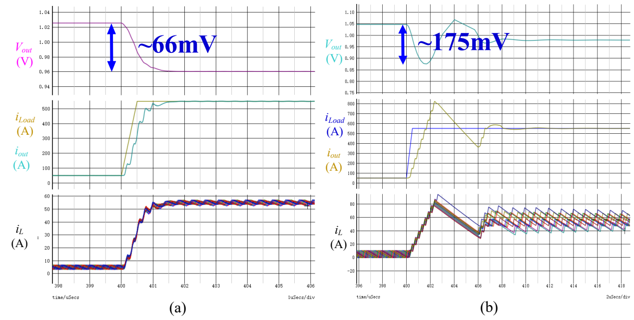

Fig. 5. Simulation results of the load transient from 50A to 550A at a rate of 1000A/μs. (a) Proposed series capacitor TLVR (b) Conventional multi-phase buck converter.

$$\Delta i_{Lmp} = \frac{V_{in}}{L_m} \Delta DT \quad (7)$$

Therefore, the variation of per-phase inductor current can be calculated by (6) and (7),

$$\Delta i_p = \Delta i_{Lc} + \Delta i_{Lmp} = [\frac{N(k+1)V_{in}}{L_c} + \frac{V_{in}}{L_m}]\Delta DT \quad (8)$$

The overall current variation is the summation of all phase currents,

$$\Delta i_o = N(\Delta i_{Lc} + \Delta i_{Lmp}) = [\frac{N(k+1)V_{in}}{L_c} + \frac{V_{in}}{L_m}]N\Delta DT \quad (9)$$

Therefore, L_{otr} and L_{ptr} of an N phase series capacitor TLVR can be calculated by combining (3) and (9), (4) and (8) separately,

$$L_{otr} = \frac{L_m L_c}{L_m N^2(k+1) + N L_c} \quad (10)$$

$$L_{ptr} = \frac{L_m L_c}{L_m N(k+1) + L_c} \quad (11)$$

The equivalent per-phase transient inductance of conventional N phase buck converter is L and the overall transient inductance is L/N. Therefore, the transient inductance of TLVR is much smaller than the conventional multiphase buck converter, which facilitates faster dynamic response.

III. Simulation Results

To validate the superiority of the proposed converter, SIMPLIS simulations of both the proposed converter and conventional multi-phase buck converter are conducted to compare the performance. The parameters and control method are listed in Table I. fs of the conventional multi-phase buck converter is set to be 800kHz. While f_s of the proposed converter can be set higher to 1.2MHz. Constant on-time control is adopted too. ON time of high-side MOSFET of each phase is constant. During the transient, the OFF-time is adjusted to regulate the output currents. Both inductor current ramp compensation and external ramp compensation are adopted in

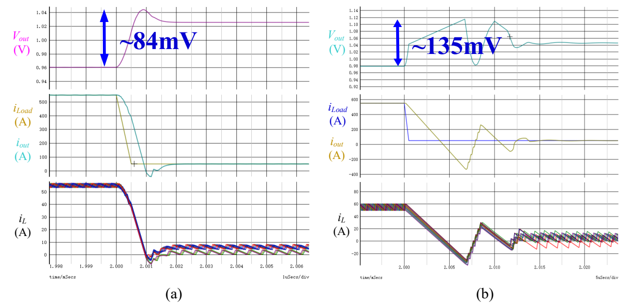

Fig. 6. Simulation results of the load transient from 550A to 50A at a rate of 1000A/μs. (a) Proposed series capacitor TLVR (b) Conventional multi-phase buck converter.

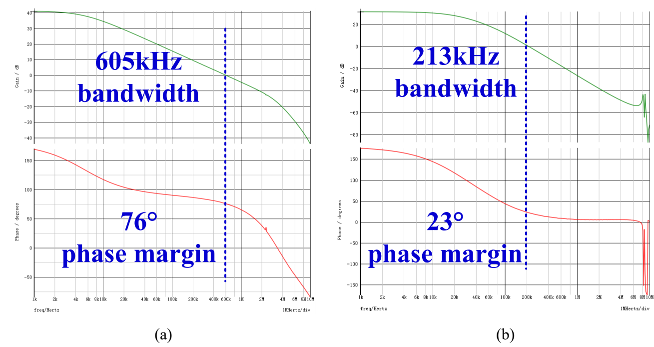

Fig. 7. The loop response of (a) proposed series capacitor TLVR and (b) conventional multi-phase buck converter.

the controller to improve system stability. To reduce the output capacitance, adaptive voltage positioning (AVP) is adopted. The reference output voltage varies inversely with the output current. The transient performance can be improved with AVP technique. The output voltage overshoot and undershoot can be effectively suppressed.

TABLE I
Comparison of Parameters and Control

Item	Proposed	Conventional
Coupled inductor L_m	$100nH$	$100nH$
Compensation inductor L_c	$80nH$	N/A
Output capacitance	2mF	2mF
Switching frequency	1.2MHz	800kHz
Input voltage	12V	12V
Output voltage	1V	1V
Phase number	10	10
Load slew rate	1000A/μs	1000A/μs
Control method	COT	COT

The comparative simulation results are visualized in Figs. 5-7. Fig. 5 exhibits the simulation results which load current steps up from 50A to 550A at a rate of 1000A/μs. There is only about a 66mV output voltage droop in the proposed converter. The output inductor currents respond fast without overshooting. Nevertheless, 175mV output voltage undershoot is induced in the conventional multi-phase buck converter. Smaller equivalent transient inductance facilitates higher out-

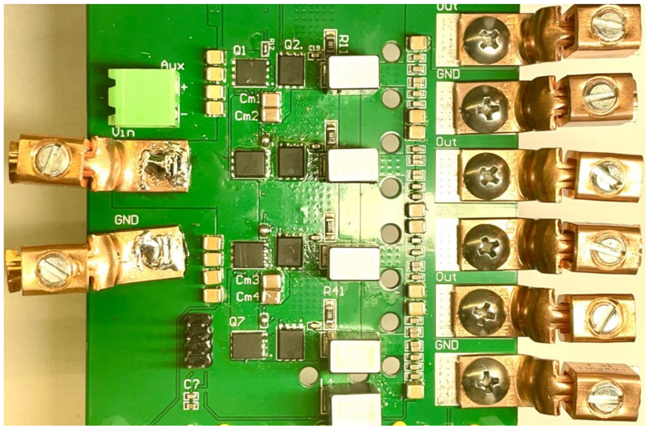

Fig. 8. Picture of the design series capacitor TLVR

put current slew rate. The simulation results with load current step down from 550A to 50A at a rate of 1000A/μs are illustrated in Fig. 6. There is a lower voltage overshoot in the proposed converter. The inductor currents droop at a faster speed to follow the load current. A longer time is required to return to the steady state for the conventional solution. Simulation results reveal that the proposed converter has smaller transient inductance. The output current can track the load current rapidly.

Fig. 7 exhibits the simulated loop response of the proposed series capacitor TLVR and conventional multi-phase buck converter. Compared with conventional buck converter, the proposed series capacitor TLVR can achieve almost tripled bandwidth. The higher phase margin of the proposed converter proves better stability. The converter output impedance with closed-loop control can be expressed as,

$$\frac{\widehat{v}(s)}{-\widehat{i}_{load}(s)} = \frac{Z_{out}(s)}{1+T(s)} \tag{12}$$

where $Z_{out}(s)$ is the open-loop output impedance, $T(s)$ is the loop gain. Hence, the feedback loop reduces the converter output impedance by a factor of $1/(1+T(s))$. The influence of load current variation on the output voltage is reduced. The loop gain of the proposed converter has wider bandwidth and larger amplitude. Therefore, the reduction can be substantial.

IV. Experimental Results

To verify the effectiveness of the proposed converter, a two-module four-phase series capacitor trans-inductor voltage regulator prototype is built. The photograph of the power stage is given in Fig.8. The key parameters are summarized in Table II. Due to discrete MOSFETs and drivers are being adopted in the prototype, 400kHz switching frequency is utilized to verify the concept. Integrated devices can be applied to further improve the switching frequency. Holes are reserved for coupled inductor currents measurement.

Fig. 9 shows the steady-state phase inductor current waveforms. Since Rogowski coils are utilized to measure the currents, only the ac components can be monitored. Two phases in one module are interleaved with 180° phase shift. Two modules are also interleaved with 90° phase shift. As shown in the current waveforms, four phases are coupled indirectly through the tran-inductor structure. The red curve in Fig. 9 shows the total output current, which is the summation of four-phase inductor currents. The frequency of the total output inductor current is four times higher than the switching frequency.

The gate driving signal v_{gs1} and compensated inductor

TABLE II
Design Parameters of the Prototype

Components	Values
L_m	$120nH$
L_c	$100nH$
Output capacitance	1.2mF
Switching frequency	400kHz
Input voltage	12V
Output voltage	1V
Phase number	4
High-side MOSFETs	SM4364
Low-side MOSFETs	SM4373
Gate driver	NCP81062

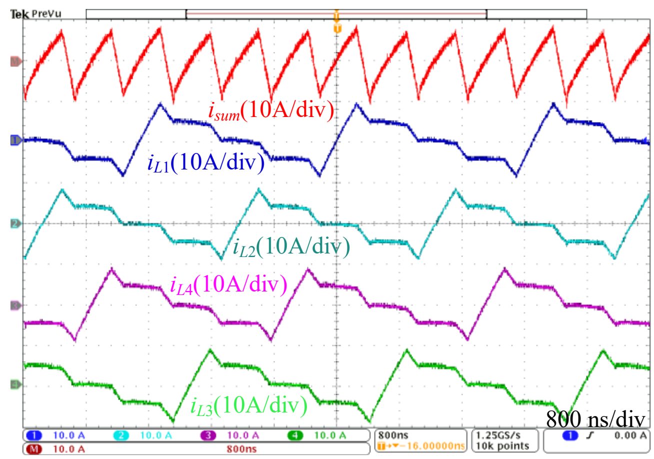

Fig. 9. Experimental steady-state waveforms of four-phase currents.

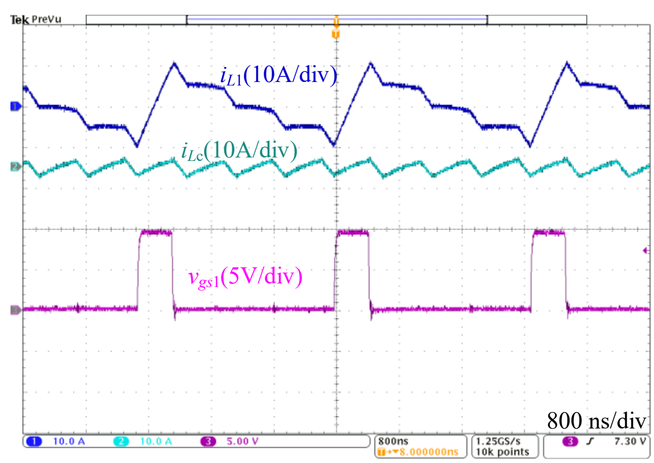

Fig. 10. Experimental steady-state waveforms of i_{L1}, i_{Lc}, and v_{gs1}.

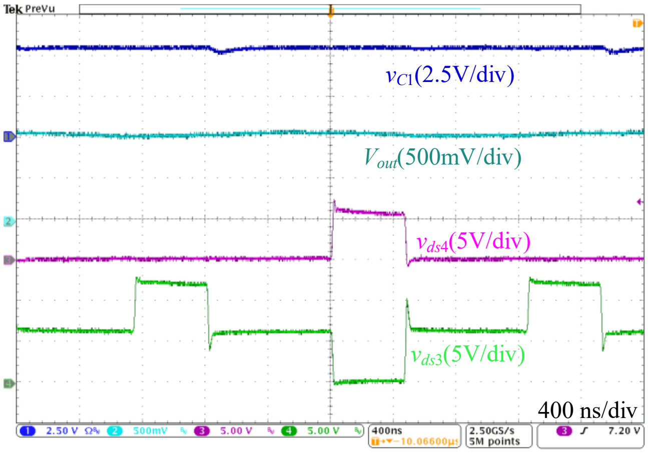

Fig. 11. Experimental steady-state waveforms of V_{C1}, V_{out}, v_{ds4}, and v_{ds3}.

current i_{Lc} are exhibited in Fig. 10. The duty cycle of the high-side driving signal is about $1/6$, which is doubled compared with the conventional 12V-to-1V buck converter. Meanwhile, the switch utilization ratio can be improved. The frequency of i_{Lc} is $4f_s$.

Several critical voltage waveforms are shown in Fig. 11. The output voltage is regulated well in 1V. The voltage of the dc blocking capacitor V_{C1} is about 6V, which is half of the input voltage. v_{ds3} is a three-level voltage in one cycle. At steady state, excepting the voltage stress of S_3 is V_{in}, the voltage stress of other switches in the first module is $V_{in}/2$. The experimental results agree well with the theoretical analysis. The efficiency at 40A load current is measured as 81.6%. It can be further improved in the future work.

V. Conclusion

This paper proposes a novel series capacitor TLVR. The proposed converter combines the benefits of series capacitor buck converter and TLVR. The switching losses and equivalent voltage conversion ratio can be reduced. A higher frequency can be implemented. Trans-inductor significantly reduces the equivalent transient inductance and dramatically improves the dynamic response. The operation principles at steady state and transient state are analyzed in detail. The simulation is conducted to verify the proposed concept. Fast dynamic response results reflect the excellent performance of the proposed converter. Some steady-state experimental results are provided to verify the effectiveness of the proposed converter.

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