LEGO-PoL: A 93.1% 54V-1.5V 300A Merged-Two-Stage Hybrid Converter with a Linear Extendable Group Operated Point-of-Load (LEGO-PoL) Architecture

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***Abstract*—This paper presents a merged-two-stage *Linear Extendable Group Operated* Point-of-Load (LEGO-PoL) architecture targeting applications with high voltage conversion ratio and very high output current (a few hundreds Amps). In the merged-two-stage LEGO-PoL architecture, many switched capacitor units are connected in series to split the input voltage into multiple voltage domains, and many buck units are connected in parallel to split the output current into multiple current paths. One submodule of the LEGO-PoL architecture merges the operation of a switched capacitor unit and a multi-phase buck unit to create mutual advantages. The buck units are used as current sources to soft-charge and soft-switch the switched capacitor units, and the switched capacitor units are utilized to ensure current sharing among a large number of buck units. The LEGO-PoL architecture can be *linearly-extended* to cover wide input voltage range and output current range. The modular units are *group-operated* to ensure voltage balancing and current sharing automatically. A 450W, 54V-1.5V, 300A LEGO-PoL architecture with a peak efficiency of 93.1% has been built and tested to verify the effectiveness of the proposed approach.**

***Index Terms*—DC-DC power conversion, hybrid switched capacitor circuit, linear extendable group operated (LEGO) architecture, point of load (PoL) converter**

I. INTRODUCTION

Power delivery architecture with high efficiency, high power density, and high bandwidth are needed to support future high performance computing system (CPUs, GPUs, and TPUs) [1]–[12]. One emerging trend in data center power delivery is to feed the servers with high voltage (48V-54V) from the open compute racks. Delivering power at high voltages reduces the conduction loss, improves the UPS deployment, flexibility, and can leverage the existing semiconductor devices and circuit topologies of the 48V telecom power ecosystems. High performance microprocessors comprise billions of transistors, switch at a few GHz, and each consumes hundreds of ampere of current at very low voltage (i.e., <0.8V). High efficiency, high power density and high bandwidth power electronics are needed to support the energy saving functions (e.g., voltage scaling) of high performance CPUs and GPUs. Delivering hundreds of watts of power with stability and fast control while maintaining high efficiency is a major obstacle to reducing the energy consumption in future data centers.

The challenges of designing high voltage conversion ratio and high output current point-of-load (PoL) converters include high input voltage (48V to 54V), high output current (a few hundred amps) and high bandwidth (up to a few MHz). One popular approach is to use a transformer based dc-dc converter as the first stage to step the voltage down to 12V as an intermediate stage, and use a multi-phase buck converter as the second stage [1]–[4] to interface with the CPU. This approach can achieve high heavy load efficiency but has poor light load efficiency and low power density. Single-stage transformer based-designs [5]–[8] can achieve high voltage conversion ratio with high transformer turns-ratio. However, it is challenging for a single-stage transformer based design to achieve high control bandwidth due to the sophisticated circuit structure. Another approach is to connect many single-stage converters with input in series and output in parallel. This approach needs many magnetic components, and requires additional control schemes and design constraints to obtain the balanced output current sharing operation. Two-stage hybrid-switched-capacitor-based designs are becoming increasingly popular due to the transformer-free implementation and high modularity [9]–[12]. For example, the recently proposed switched tank converter (STC) [9] can achieve unique advantages in uniform device voltage stress and current stress, and can obtain soft charging [13], [14] and soft switching operation for high efficiency and high power density. However, typical two-stage switched-capacitor converters require one or more resonant inductors to achieve soft-charging and soft-switching operation [15]. The operation of the switched-capacitor stage and the buck stage are completely decoupled, limiting the system efficiency and power density. Furthermore, typical two-stage approaches cannot guarantee voltage-balancing and load-sharing when they are connected in series/parallel to cover much higher input voltage and output current range.

This paper introduces the principles of a *Linear Extendable Group Operated* point-of-load (LEGO-PoL) architecture to achieve high voltage conversion ratio and deliver very high output current. The LEGO-PoL architecture can automatically distribute the voltage stress and current stress, and achieve soft charging and soft switching without additional resonant inductors. As a design example, this paper presents a merged-two-stage LEGO-PoL converter targeting the 54V-1.5V/300A

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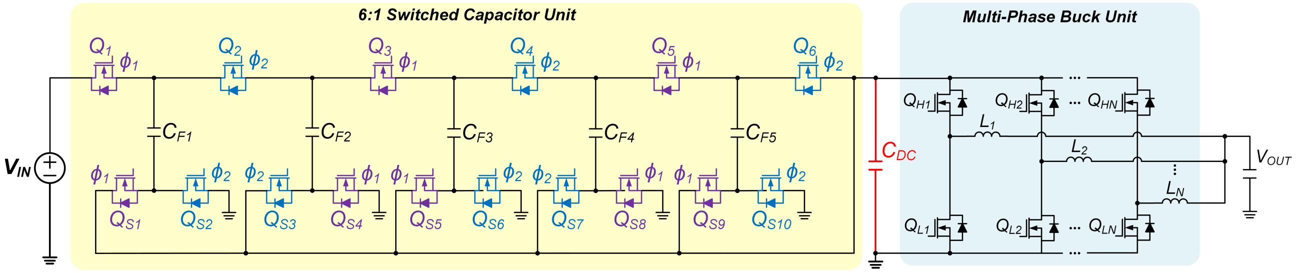


Fig. 1. Schematic of a traditional two-stage PoL converter including a 6:1 switched capacitor converter and a 6:1 multi-phase buck converter. There is a large decoupling capacitor between the two voltage conversion stages serving as an intermediate bus. The operation of the two stages are separated.

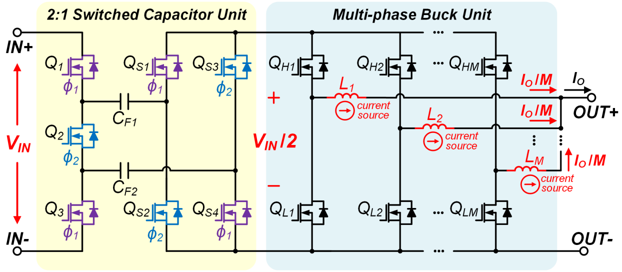


Fig. 2. One submodule of the merged-two-stage LEGO-PoL architecture including a 2:1 switched capacitor (SC) unit and a multi-phase buck unit. Multiple SC units can be stacked in series, and multiple multi-phase buck units can be connected in parallel. There is no large decoupling capacitor between the two stages. The capacitors of the SC units are used as the input capacitors for the buck units; the inductors of the multi-phase buck units are used as the soft-charging inductors for the SC units.

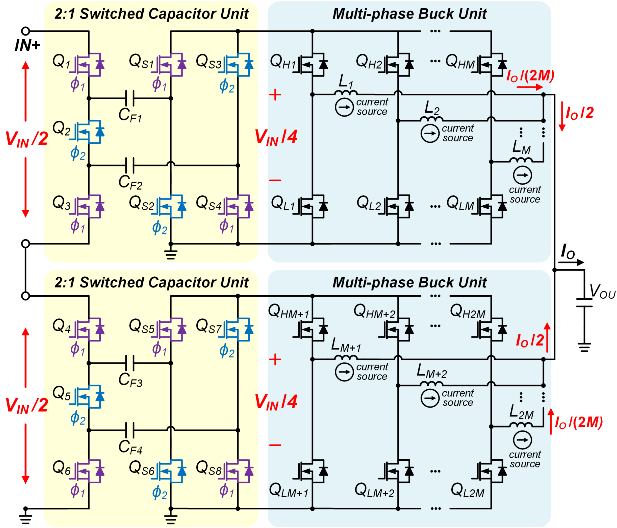


Fig. 3. Two submodules of the merged-two-stage LEGO-PoL architecture. It comprises two 2:1 SC units and two multi-phase buck units. The inputs of the multi-phase buck units are separated and the outputs of the multi-phase buck units are combined.

application. The LEGO-PoL architecture can separately address the high voltage stress, high current stress, and the high bandwidth requirements, and achieve voltage balancing, current sharing, soft-charging, and soft-switching. The LEGO-PoL architecture eliminates the resonant inductors and the decoupling capacitors in a two-stage hybrid-switched-capacitor design, and merges the operation of the switched-capacitor stage and the buck stage to create mutual advantages.

II. LEGO-POL ARCHITECTURE

A. *One Submodule of the LEGO-PoL Architecture*

Fig. 1 shows the schematic of a traditional two-stage PoL converter which is composed of a 6:1 switched capacitor converter and a multi-phase buck converter. The 6:1 switched capacitor converter can convert the 54V bus voltage down to 9V as needed by the PoL converter as an unregulated dc transformer (DCX). The multi-phase buck converter produces a low voltage output (e.g., 1.5V). With mature topology and advanced control, the multi-phase buck converter can achieve high bandwidth to meet the strict transient requirements of CPUs and GPUs. There is a large dc-link capacitor (C_{DC}) connected between the the 6:1 switched capacitor converter and the multi-phase buck converter decoupling the operation of the two stages.

As shown in Fig. 2, one submodule of the proposed merged-two-stage LEGO-PoL architecture comprises two building blocks: a 2:1 switched capacitor (SC) unit for series input, and a multi-phase buck unit for parallel output. The 2:1 SC unit operates with complementary 50% duty cycles (ϕ_1 and ϕ_2) to obtain an unregulated bus voltage, i.e., half of its input voltage. The multi-phase buck unit operates with interleaved duty cycles to reduce the input/output ripple current while providing high bandwidth. There is no decoupling capacitor between the SC unit and multi-phase buck unit and there is no resonant inductor in the SC unit. The capacitors of the SC units are used as the decoupling capacitors for the buck units; the inductors of the multi-phase buck units are used as the soft-charging inductors for the SC units.

B. *N-submodules of the LEGO-PoL Architecture*

The LEGO-PoL architecture can be *Linear Extended* and *Group Operated* to cover a wide input/output range. The topology shown in Fig. 3 stacks two 2:1 SC units in series and connects two multi-phase buck units in parallel. The input voltage of each 2:1 SC unit is one half of the input voltage ($V_{IN}/2$). The virtual intermediate bus voltage (without a decoupling capacitor) is one quarter of the input voltage ($V_{IN}/4$). The output current of each multi-phase buck unit is

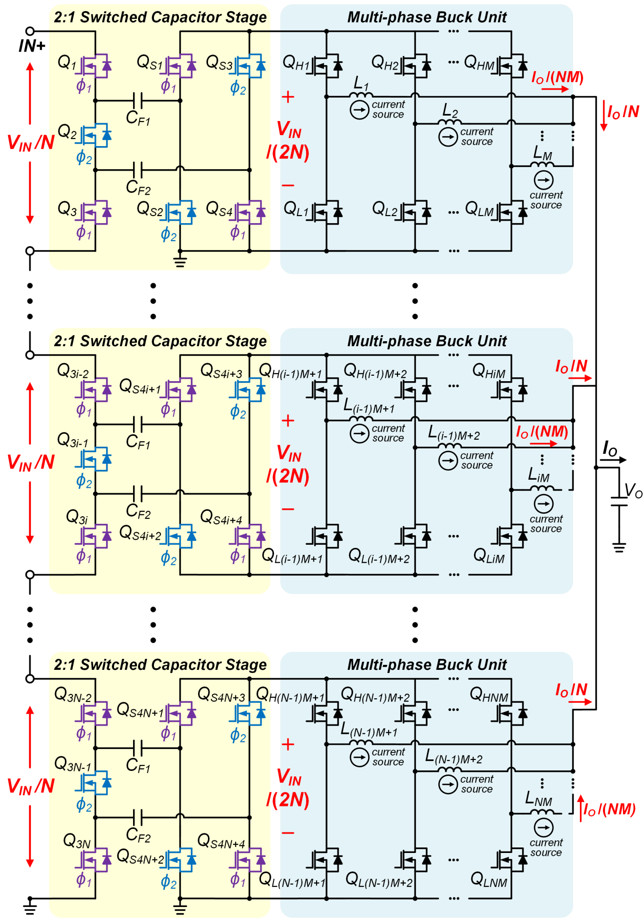
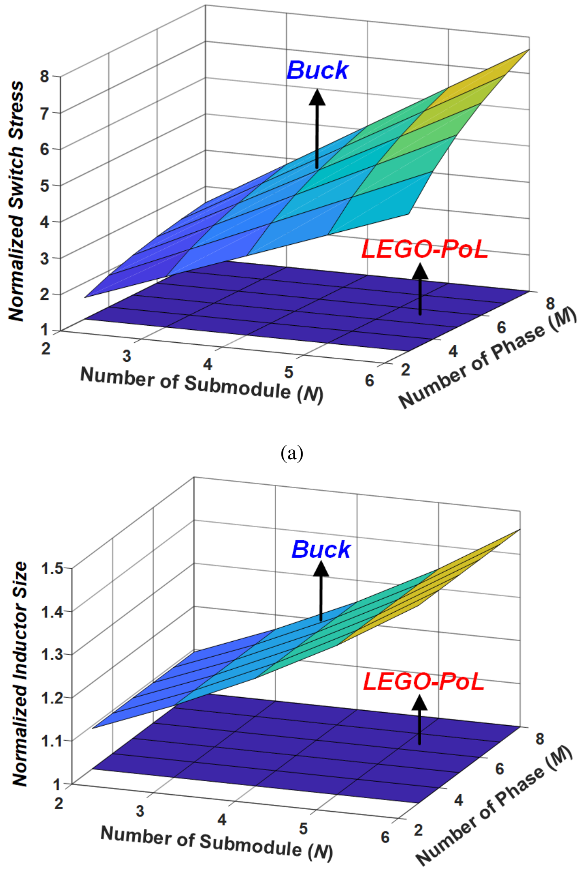


Fig. 4. N-submodules of the merged-two-stage LEGO-PoL architecture, comprising N 2:1 SC units and N multi-phase buck units. The LEGO-PoL architecture can be linearly extended for different applications.



(a)

(b)

Fig. 5. Comparison between a traditional buck converter and the LEGO-PoL architecture. (a) Normalized switch stress. (b) Normalized inductor size with the same semiconductor die area.

naturally one half of the output current because of the series connection of the SC units. This two-submodules merged-two-stage LEGO-PoL design extends the voltage conversion ratio of a traditional multi-phase buck converter by four times. Since many SC units are connected in series, the current sharing of the many multi-phase buck units is guaranteed. Similarly, since many multi-phase buck units are connected in parallel, the voltage balancing of the SC units is guaranteed. The input voltage is evenly divided among the SC units, and the output current is evenly shared by the multi-phase buck units. Therefore, the submodule of the LEGO-PoL architecture can decouple the input voltage stress and output current stress, and reduce the switch stress of the semiconductor devices compared to other traditional high voltage conversion ratio PoL solutions.

The number of submodules can be linearly extended to cover much wider input voltage range and much higher output current without additional control complexity - the SC units are group operated with synchronized 50% duty ratio, and the multi-phase buck units can be controlled by off-the-shelf PoL controllers. Fig. 4 shows a LEGO-PoL architecture with N-submodules. N series connected 2:1 SC units split the input voltage into N voltage domains, and N parallel connected multi-phase buck units split the output current into N current paths. By equally distributing high input voltage stress and high output current stress into each modules, the proposed LEGO-PoL architecture has the following advantages:

- **Reduced switch stress of semiconductor devices.** The LEGO-PoL architecture can reduce the semiconductor device switch stress by decoupling the voltage stress and the current stress. In a traditional non-isolated topology, one or many of the switches need to block high voltage and carry high current, result in very high switch stress of the devices. In the LEGO-PoL architecture, the switches in the SC units only need to block high voltage, and the switches in the multi-phase buck units only need to carry high current. The voltage stress and current stress are naturally decoupled, and the switch stress measured by multiplying the voltage and current are minimized. Moreover, the switches in the SC units operate with 50% duty ratio and square wave current, maximizing the utilization of switch ratings. The reduced switch stress can enable the LEGO-PoL architecture to use semiconductor devices with smaller size and higher performance compared to a traditional buck converter [5].

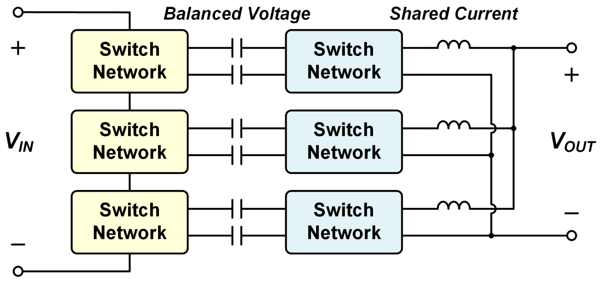


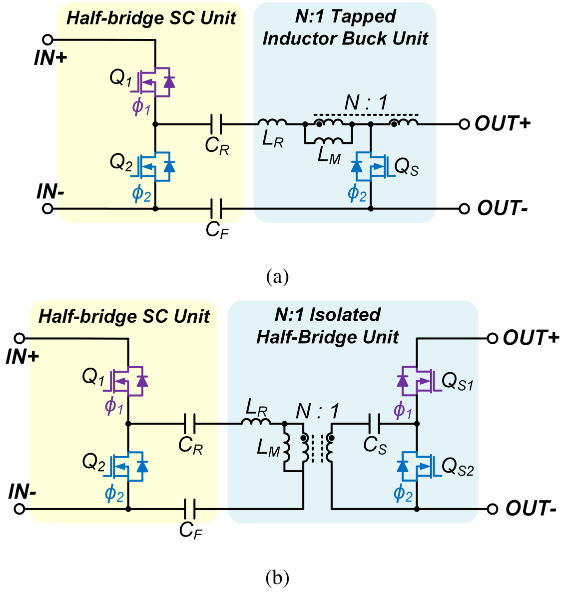
Fig. 6. Generalized block diagram of the LEGO-PoL architecture with two types of switch networks, an array of capacitors (balanced voltage sources), and an array of magnetics (shared current sources).

Fundamentally, the switch stress of the LEGO-PoL architecture is equivalent to that of a transformer-isolated topology. The LEGO-PoL architecture relies on the capacitors of the SC units to realize capacitive isolation. Fig. 5 compares the switch stress of the LEGO-PoL architecture against that of a traditional buck converter. The switch stress of a LEGO-PoL design with three stacked submodules and four phases in the multi-phase buck is one third of the switch stress of a comparable buck converter.

- **Reduced inductor size.** If the semiconductor die area is kept the same, the LEGO-PoL architecture can reduce the inductor size in the multiphase-buck converter. In a LEGO-PoL converter with N series-stacked submodules, the effective voltage conversion ratio of the multi-phase buck converter is N times lower than that of a traditional buck converter that needs to block the full input voltage.
- **Decoupled operation frequency.** To achieve a control bandwidth of 1 MHz or higher, the switching frequency of the multi-phase buck converter (or transformer-based PoL converter) needs to be high (usually around 5 MHz with multi-phase interleaving). It is a challenge to operate high voltage rating switches at this frequency with high efficiency. Decoupling SC units and multi-phase buck units allows the SC units to operate at a frequency that is much lower than that of the multi-phase buck converter (e.g. around 200 kHz), enabling high system efficiency without sacrificing the system dynamic performance. Benefiting from the non-resonant square-wave soft-charging operation, the switching frequency of the SC units and the buck units can be jointly optimized and dynamically modulated to balance the efficiency and bandwidth tradeoffs.

C. Extended Embodiments of the LEGO-PoL Architecture

As illustrated in Fig. 6, a LEGO-PoL architecture comprises two types of switch networks, an array of capacitors and an array of inductors. The key principles of the LEGO-PoL architecture is to use the capacitors to create multiple voltage domains, and use the inductors to share the output current. The capacitors also function as capacitive isolation barriers to connect the two types of switch networks together. It is known that capacitive-isolated topologies, if designed appropriately, can achieve much higher efficiency and power density than magnetic isolated topologies. The SC unit and the multi-phase buck unit as described in Fig. 4 are example implementations. The SC units and multi-phase buck units can be substituted with a variety of other topologies with capacitive isolation. Fig. 7 shows a few extended design options for the LEGO-PoL architecture. Fig. 7(a) shows a LEGO design with half-bridge switched capacitor unit and an N:1 tapped buck unit. This implementation enables all switches to achieve soft switching operation with resonant operation between capacitor (C_R) and inductors (L_R and L_M). It can also obtain very high voltage conversion ratio with N:1 tapped buck configuration. Fig. 7(b) is a LEGO-PoL design with an isolated half-bridge rectifier. This implementation offers galvanic isolation as well as additional voltage conversion ratio and soft switching operation. The capacitors in these designs enable the LEGO architecture to achieve the automatic current sharing. All implementations can be connected with input in parallel and output in series as step up converters.



(a)

(b)

Fig. 7. Other embodiments of the LEGO-PoL architecture. (a) Half-bridge switched capacitor unit and N:1 tapped buck unit. (b) Half-bridge switched capacitor unit and N:1 isolated half-bridge unit.

III. DESIGN EXAMPLE OF THE MERGED-TWO-STAGE LEGO-POL ARCHITECTURE

Fig. 8 shows an example 54V-1.5V/300A design with three series-stacked 2:1 switched capacitor (SC) units and three parallel connected multi-phase buck units. Compared to Fig. 4, the SC units in Fig. 8 are simplified. The series connected switches in SC units, such as Q_3 and Q_{3i-2} in Fig. 4, can be merged as one switch. Since the 2:1 SC unit in the bottom side should be tied to its output side, one capacitor (C_{F6}), one switch (Q_7), and two synchronous rectifier switches (Q_{S11} and Q_{S12}) can be eliminated. In this design example, the three SC units convert 54V to 9V, and the three multi-phase buck units share 300A. There is no decoupling capacitor between the SC units and the multi-phase buck units.

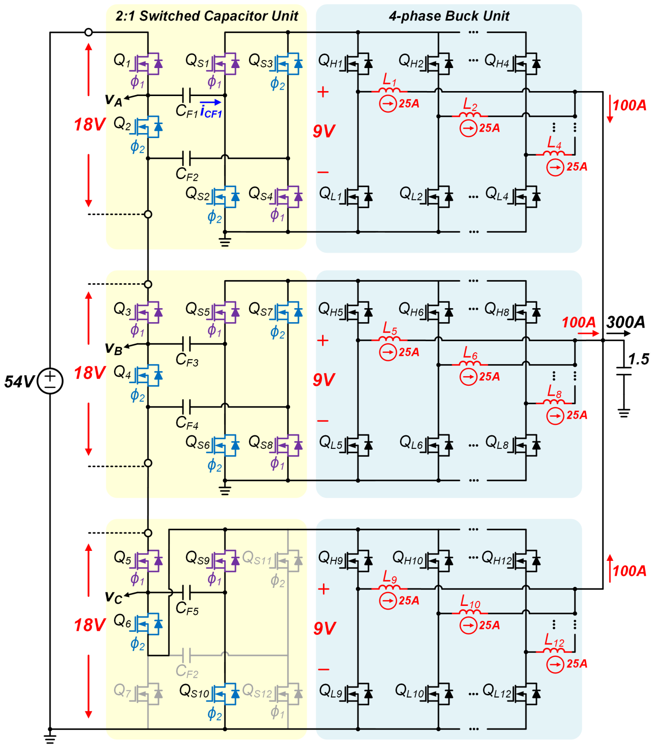


Fig. 8. A 54V-1.5V LEGO-PoL design with three stacked submodules. The virtual intermediate bus voltage is 9V. The duty ratio of the buck converter is 1/6. Three switches and one capacitor in the bottom submodule can be removed from the topology to enable better system performance.

A. Operational Principles

Several assumptions are made to perform topology analysis: 1) the capacitors in SC units (C_{F1}-C_{F5}) are large enough to be considered as constant voltage sources, 2) the output inductors (L_1-L_{12}) are large enough to be considered as constant current sources, 3) all parasitic components except for those specified in Fig. 8 are ignored, 4) the switching frequency of SC units is two times of that of 4-phase buck units (for illustration purpose), 5) the SC units and 4-phase buck units in three submodules are controlled with the same gate signals.

One switching period of the SC unit is divided into two phases, and each phase includes four buck operation modes. Buck inductor currents can only flow to each SC unit when high-side buck switches (Q_H) are turned on. By coordinating the switching sequences of the SC units and the multi-phase buck units, the LEGO-PoL converter can achieve zero current switching (ZCS) operation. The key principle is to change the state of the SC units during the free-wheeling state of the buck units, as illustrated in Fig. 9. The current going through the SC units is pulsed square wave current of the buck units, instead of the sinusoidal resonant current as needed in many resonant switched-capacitor topologies. The square wave current operation reduces the RMS current in the switches and reduces the loss. The capacitors in SC units can convert 54V input voltage to 9V virtual intermediate bus voltage (without intermediate capacitors) with 6 series stacked voltage domains (through 5 capacitors in Fig. 9).

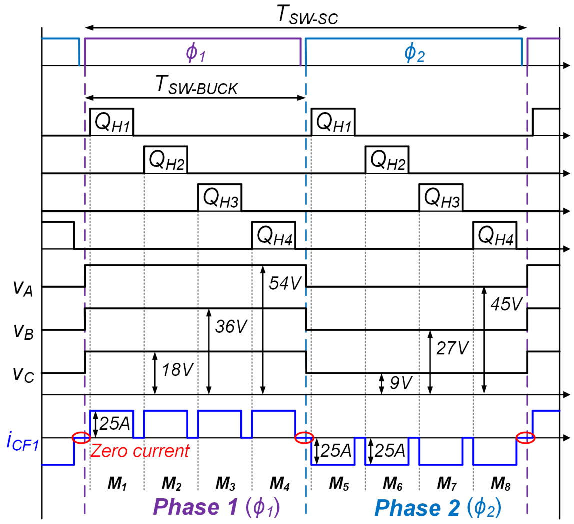


Fig. 9. Operational waveforms of 54V-1.5V/300A LEGO-PoL converter.

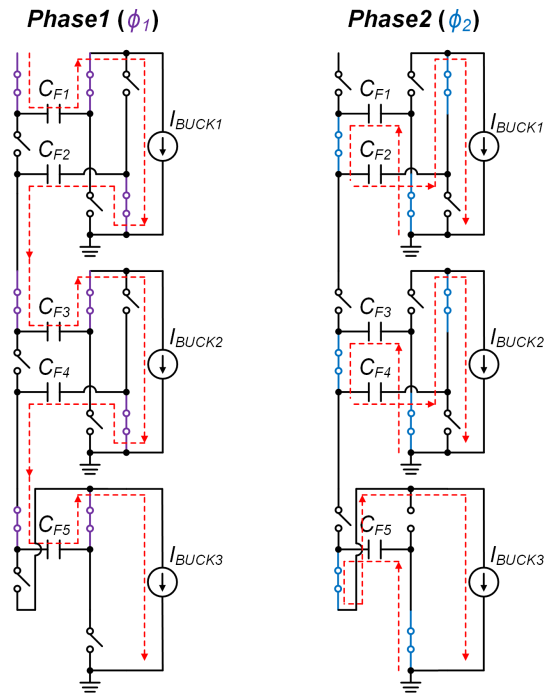


Fig. 10. Principles of soft charging operation. The capacitors are always charged/discharged by a current source, eliminating the charge transfer loss.

B. Voltage and Current Stresses of Semiconductor Devices

The LEGO-PoL architecture decouples the voltage stress and current stress with SC units, multi-phase buck units, and merged-two-stage operation. Unlike the traditional hybrid-switched capacitor topologies, since the proposed LEGO-PoL architecture uses only capacitors in the SC unit, voltage stress of all switches can be clamped by the capacitors. Only one phase current of the buck converter goes through the SC unit so the current stress of all semiconductor devices is equal to the one phase current of the buck converter.

TABLE I

KEY PARAMETERS OF THE 54V-1.5V/300A LEGO-POL CONVERTER

Q_1 & Q_6	BSZ013N2LS (25V, 1.3mΩ)
Q_2 - Q_5	BSZ019N03LS (30V, 1.9mΩ)
Q_{S1} - Q_{S10}	BSZ013N2LS (25V, 1.3mΩ)
Gate driver	UCC27212
C_{F1} - C_{F4}	10μF$\times$13 , 63V, X7R, Murata
C_{F5}	10μF$\times$13, 25V, X7S, Murata
Q_H& Q_L	SiC632 (DrMOS, 24V, 50A)
L_1 - L_{12}	1.0μH (XAL 1030-102ME)
Digital Controller	TMS320F28069

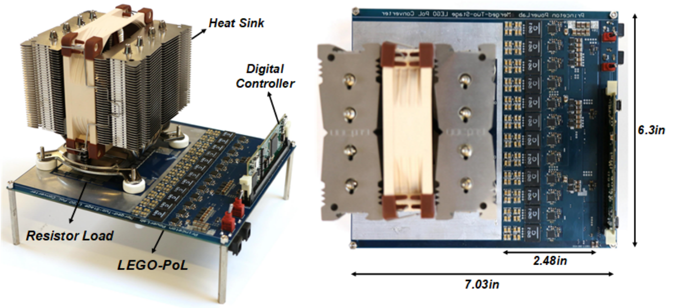


Fig. 11. Picture of the 54V-1.5V/300A LEGO PoL prototype with three series-input parallel-output submodules and four-phase interleaved buck units.

C. Soft Charging and Current Sharing

By eliminating the decoupling capacitor between the SC units and the multi-phase buck units, the capacitors in SC units are always soft-charged/discharged by the inductor of the multi-phase buck units, as illustrated in Fig. 10. No additional inductors are needed. The charge transfer loss in SC units is eliminated, allowing smaller capacitor size, lower switching frequency and lower switching loss. As shown in Fig. 10, the current sources in different submodules are effectively connected in series during Phase1 (ϕ_1). They are automatically rebalanced by the charge balancing requirement of the capacitors between the two phases. Current sharing among parallel-connected multi-phase buck converters is automatically achieved. The current sharing is robust against impedance and parasitics variations of semiconductor devices and passive components across a wide operation range.

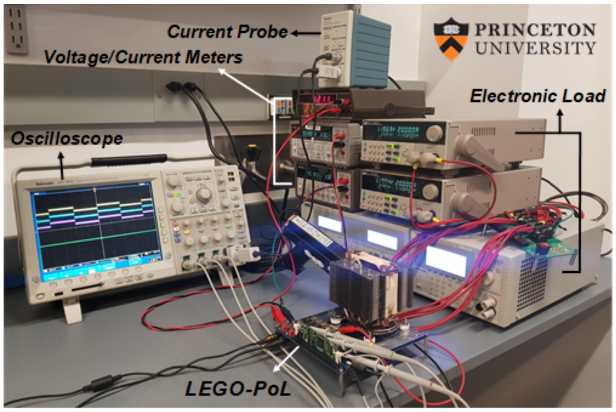
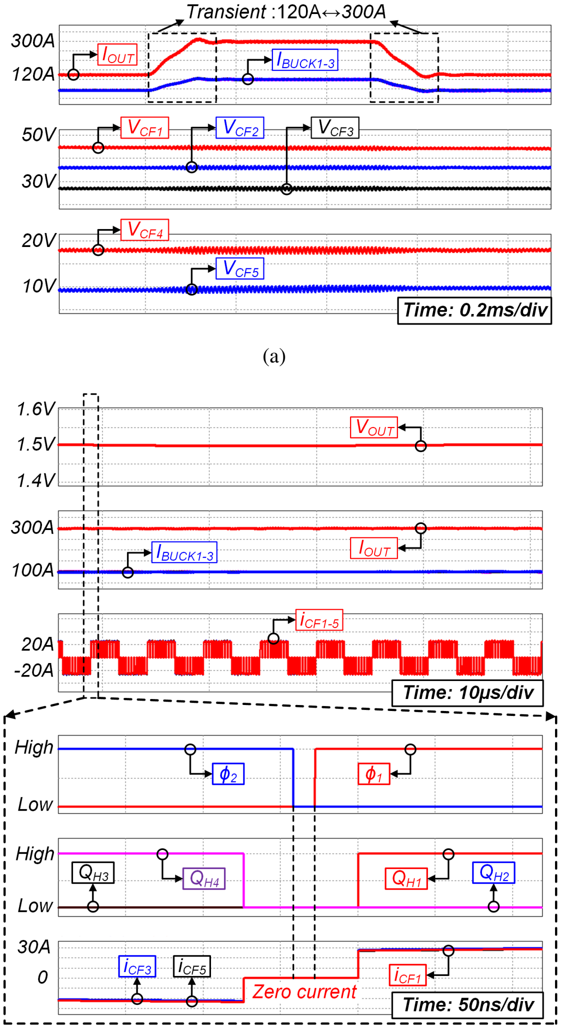


Fig. 12. Picture of the experimental platform including the 54V/1.5V 300A prototype, a few voltage/current meters and a few electronic loads.



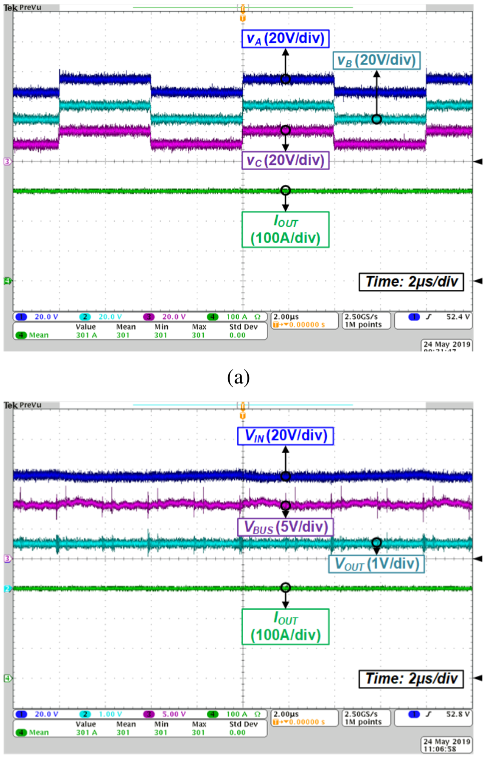
(a)

(b)

Fig. 13. Simulation results of the 54V-1.5V LEGO PoL converter. (a) Load step transient (I_{OUT}=120A↔300A). (b) 300A output condition. Current balancing is achieved throughout the transient process and normal operation.

IV. EXPERIMENTAL RESULTS

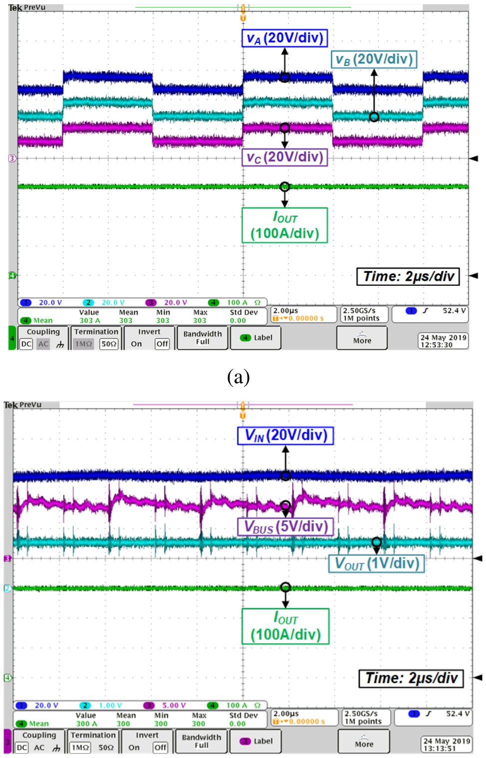
To verify the effectiveness of the LEGO-PoL architecture, a prototype system with 54V input and 1.5V/300A output is built and tested. Three 2:1 SC units were stacked in series on the input side (54V), and three 4-phase buck units were connected in parallel on the output side (1.5V/300A). Table I listed the key parameters of the components. Fig. 11 shows a picture of the prototype. The power density of the prototype is 152 W/in^3. As shown in Fig. 11, surface mount resistors (WSHP2818R0330FEA, Vishay) were used as a resistor load with a heat sink (NH-D9L, Noctua). Fig. 12 shows a picture of the experimental platform of the prototype. The load consists



(a)

(b)

Fig. 14. Measured waveforms of a 54V-1.5V/300A PoL converter with large decoupling capacitors between the SC units and the multi-phase buck units. (a) Switch node voltages and output current. (b) Input and output voltages.



(a)

(b)

Fig. 15. Measured waveforms of a 54V-1.5V/300A LEGO-PoL converter without decoupling capacitors and with merged-two-stage operation. (a) Switch node voltages and output current. (b) Input and output voltages.

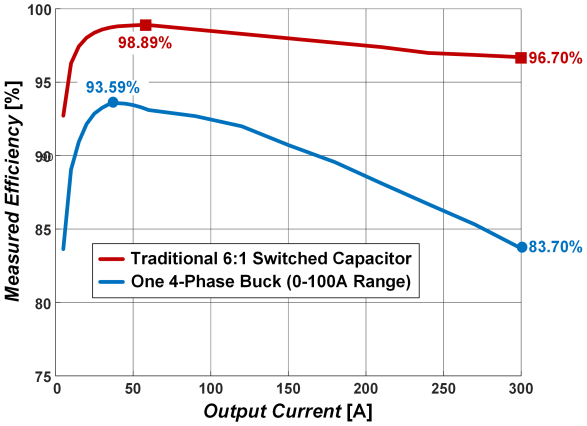


Fig. 16. Measured efficiency of a 6:1 switched capacitor converter (54V-9V/50A) and 4-phase buck converter (9V-1.5V/100A).

of chip-resist0.ors load and an electric load. To measure 300A output current, a Tektronix current probe (TCPA400) was used.

Fig. 13 shows the simulated waveforms of the 54V-1.5V/300A LEGO PoL converter. In Fig. 13(a), due to the automatic voltage balancing and current sharing mechanisms, all capacitors voltages ($V_{CF1} - V_{CF5}$) are well balanced and the output current is evenly shared by the three buck units ($I_{BUCK1-3}$) in both steady state and load step transient (between 120A and 300A). As shown in Fig. 13(b), the current of all capacitors (i_{CF1-5}) are also balanced. Moreover, all switches in the SC units achieve ZCS operation. The SC units are switching at 125 kHz, and the buck units are switching at 500 kHz.

Fig. 14 shows the measured waveforms of a traditional two-stage PoL converter with large decoupling capacitors (22 μF×45, 16V, X7R, Murata). Fig. 15 shows the measured waveforms of the merged two-stage LEGO-PoL converter. As shown in Fig. 15(a), three series-connected 2:1 SC units split 54V input into 6 voltage domains (Fig. 14(a)). The intermediate bus voltage (V_{BUS}) of the LEGO-PoL converter has a larger ripple voltage compared to the traditional converter. This is because V_{BUS} of the LEGO-PoL converter follows the ripple voltage of the capacitors in SC units. The LEGO-PoL converter well regulates the output voltage under the 300A load condition, as depicted in Fig. 15(b).

Fig. 16 shows the measured efficiency of a traditional 6:1 switched capacitor converter (98.89% peak efficiency) and a 4-phase buck converter (93.59% peak efficiency). Fig. 17 shows the measured efficiency of a merged-two-stage LEGO-PoL converter and traditional two-stage PoL converter. The 54V/1.5V 300A LEGO-PoL converter achieves a peak efficiency of 93.1% at 50A. Soft-charging operation and zero current switching operation in the SC units improved the efficiency by 0.4% at 50A and 2.7% at 300A and significantly reduced the capacitor size (about 3 times reduction

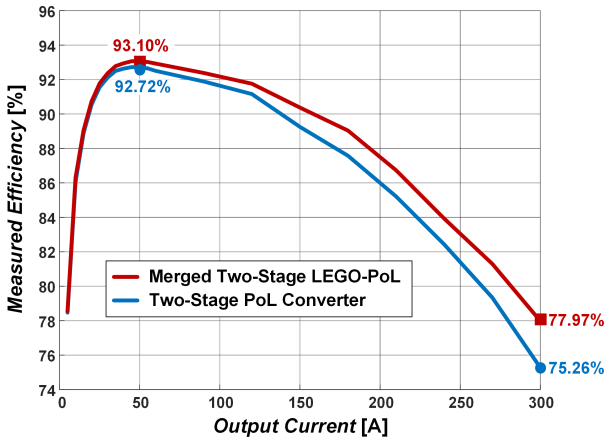


Fig. 17. Measured efficiency of a 54V-1.5V/300A LEGO-PoL converter.

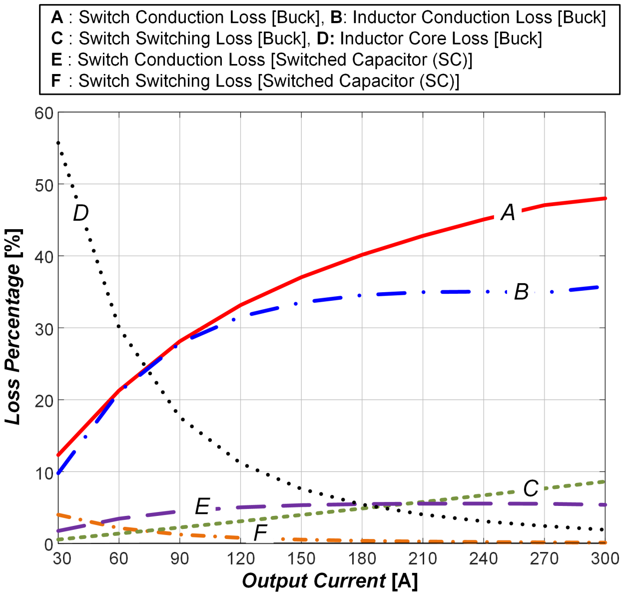


Fig. 18. Loss analysis of a 54V-1.5V/300A LEGO-PoL converter.

from 450 μF to 130 μF). Fig. 18 shows the estimated loss breakdown of the 54V-1.5V/300A LEGO-PoL converter as a function of the output power. The loss of SC units only contributes a little portion (under 10%) of total loss of the LEGO-PoL converter in a wide load range due to the soft charging operation, ZCS operation, and low current stress.

V. CONCLUSIONS

This paper presents a LEGO-PoL architecture with merged-two-stage operation for non-isolated high-conversion-ratio very-high-output-current dc-dc converters. By merging the operation of the switched capacitor units and the multi-phase buck units, a LEGO-PoL architecture can achieve soft charging, ZCS operation, and sqaure wave current without resonant inductors. The operation range of the system can be freely modified by linearly extending the number of the hybrid-switched-capacitor submodules with automatic voltage balancing and current sharing. A 54V-1.5V/300A prototype has been built and tested to verify the effectiveness of the proposed architecture. The peak efficiency of the 54V-1.5V LEGO-PoL converter is 93.1%.

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