Multiphase Control for Robust and Complete Soft-charging Operation of Dual Inductor Hybrid Converter

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***Abstract*—This paper presents a new Multiphase Dual Inductor Hybrid (MP-DIH) Converter for application in data center and telecommunication systems. The converter is based on addition of two output filter inductors to a Dickson switched-capacitor converter. The inductors are operated in multiple phases that are non-overlapped and evenly distributed over one switching cycle, completely soft-charging all flying capacitors even in the presence of practical capacitor mismatches and voltage ripples. In this converter operation, each branch of the switched-capacitor network is activated individually in one charging phase, and two interleaved inductors are employed to softly charge and discharge the capacitors to achieve high efficiency without any complex capacitor sizing or split phase operation. To verify the topology and its soft-charging advantages, a 48V-to-1.8V 20W experimental converter prototype is constructed. The converter achieves 92.4% peak efficiency for 40V-to-1.8V conversion and 92.1% peak efficiency for 48V-to-1.8V conversion at 4A load, and with 20% capacitance variations.**

***Keywords*—Hybrid converter, multiphase operation, complete soft-charging, switched capacitor network.**

I. Introduction

In data centers and telecommunication system, the power delivery system is desired to be capable of supplying core voltages ranging from ∼0.6-V to 1.8-V from a dc supply voltage as high as 400-V. Multistage solutions for this extreme conversion suffer from efficiency degradation in every stage. Making the problem worse, the last conversion stage is required to support load currents that are increasing exponentially for ever-demanding computations in today's high-performance digital systems. Therefore, it is desirable to have point-of-load (PoL) converters that can support both larger load currents and larger conversion ratios to reduce board-level distributions, i.e. by lowering currents at higher input bus voltage. In this trend, 48-V PoL converters are replacing conventional 12-V solutions[1]. For isolated point-of-load solutions, the resonant ICN converter presented in [2] achieved ∼90% efficiency while delivering 90W output power, while the 48/1V quasi-parallel converter proposed in [3] achieved 93.4% peak efficiency with multiple coupled magnetics. Although they all have the capability of handling high power loads, their design complexity and relatively large magnetic components along with the bill of material (BOM) cost are the trade-off. On the other hand, hybrid converter topologies employing a combination of switched-capacitor (SC) and switched inductor network are good candidates for the PoL applications given their superior power density and efficiency. A capacitor charge balance method is proposed in the flying capacitor multilevel (FCML) converter reported in [4] that achieves an efficiency of 91% at 48-to-2V regulated output. A hybrid Dickson SC converter combining a Dickson SC with a traditional Buck converter is another interesting approach [5]. A series capacitor buck converter [6], [7], [8], following a Double Step-Down Two-Phase Buck Converter of the same type [9], achieved a peak efficiency of 87.7% for 12V-to-1.2V conversion at a 4A load. Inheriting the advantages of different topologies from these previous works, a Dual Inductor Hybrid (DIH) converter has recently been demonstrated [10]. This DIH converter can achieve a large conversion ratio of 48V-to-1.8V, while reaching a breakthrough efficiency of 95%. Even though this converter can naturally balance all the flying capacitor voltages without any additional control effort, its operation is subjected to hard-charging because of charge re-distribution forced by capacitor

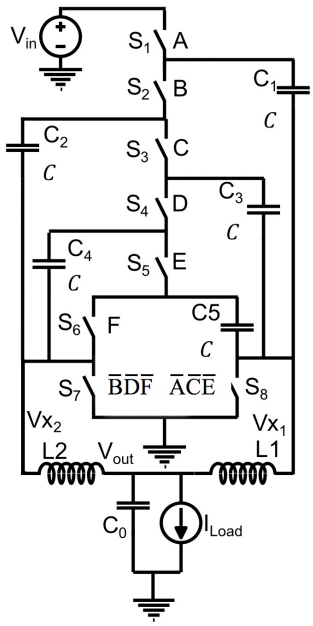


Fig. 1. 6-to-1 Multi-Phase Dual Inductor Hybrid Converter

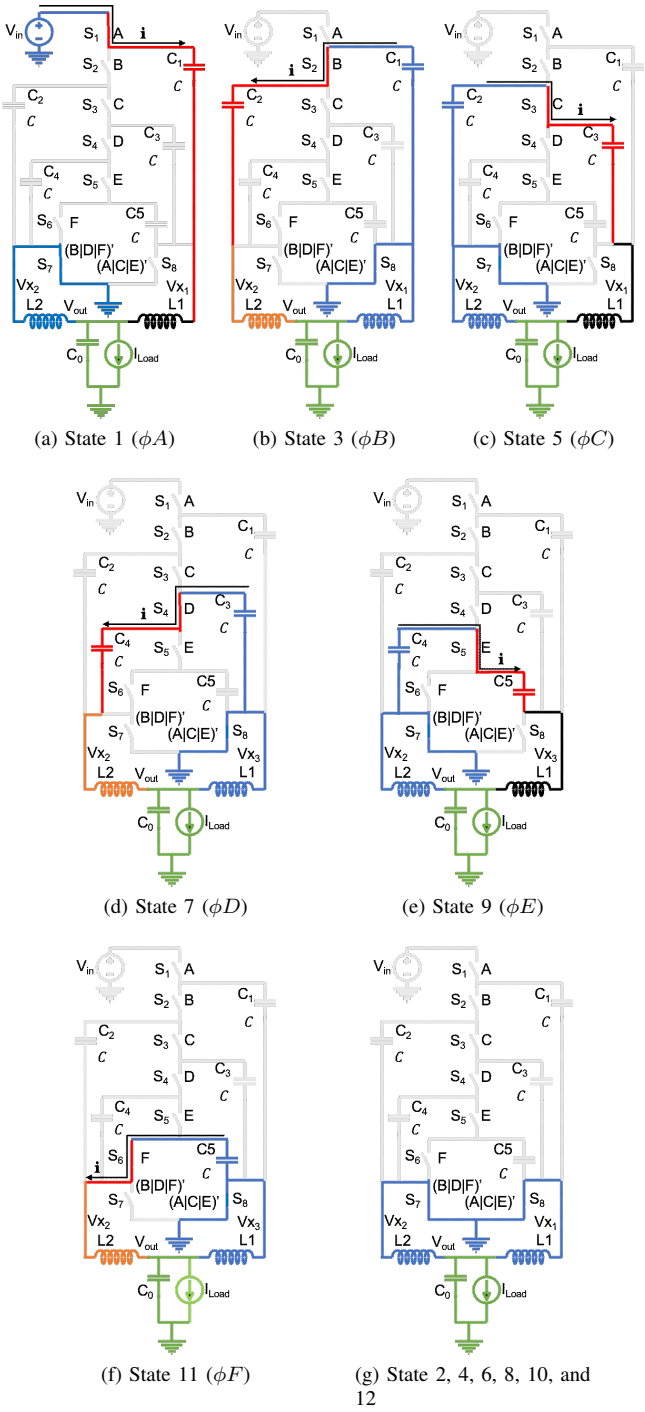
network voltage mismatches. Two strategies to overcome this problem are to employ a split-phase control [10], or a capacitor sizing method [11]. Both of these strategies rely on small variations in capacitance values for flying capacitors. However, as the capacitors in the SC network are biased at different voltages their capacitance are subjected to non-linear and unpredictable changes [12], which in turn negates the benefits of the hybrid topologies.

To benefit from state-of-the-art designs and overcome the challenges in previous DIH converter implementations, in this work a DIH converter is operated in a multi-phase manner to form a multiphase dual-inductor hybrid (MP-DIH) converter . This work demonstrates a new strategy to completely eliminate hard-charging for the even-level DIH converter and maintain high efficiency even with 20% of capacitance mismatches of the flying capacitors. Operation of the converter is explained in Section II with a loss comparison of dual-phase and multiphase topology due to capacitance mismatch. Experimental results are included in Section IV. Finally, the work is summarized and concluded in Section V.

II. OPERATION OF MP-DIH CONVERTER

The proposed MP-DIH converter operation can be applied to any DIH converter topology that has an even number of levels. The number of non-overlapped phases equals the number of the converter's levels (ignoring the zero level). In this work, a six-level version of the topology shown in Fig. 1 is demonstrated as a proof of concept. This 6-to-1 MP-DIH converter has two inductors L_{1-2}, five capacitors C_{1-5}, and eight switches S_{1-8}. Its operation can be explained using the illustrations of states and operational waveforms in Fig. 3. In State 1, a charge drawn from the input by C_1 and L_1 is stored in C_1. It is then sequentially transferred to C_2, C_3, C_4, and C_5 in other odd states with the operation of $L_1$and L_2. In each odd state other than State 1 and 11, two capacitors and one inductor form a conducting branch where the inductor enables a soft charge transfer from the higher-level capacitor to the lower-level one, e.g. from C_1 to C_2 using L_1 in State 3. In State 1 and 11, C_1 receives the charge from the source and C_5 delivers the charge to the load, respectively. These odd states are also labeled as the six identical non-overlapped phases A-F evenly distributed over an operational cycle T. For even states, all the capacitors are inactive and open-circuited. Inductor L_1 (L_2) free-wheels the stored charge to the output when S_8 (S_7) is activated during even states and during odd states when L_2 (L_1) is getting charged. The operational PWM signals, related capacitor voltage and inductor current ripple waveforms are shown in Fig. 3a.

To simplify the analysis on the steady-state voltages V_{C1} to V_{C5} of the capacitors C_{1-5}, we first assume small voltage ripples across the capacitors and inductor volt-second balance. Similar to a regular 6-to-1 Dickson SC converter, C_{1-5} have their steady-state voltages gradually decreased by $\frac{V_{in}}{6}$ from $V_{C1} = \frac{5V_{in}}{6}$ to $V_{C5} = \frac{V_{in}}{6}$. Switching nodes V_{X1} and V_{X2} swing from 0 to $\frac{V_{in}}{6}$ in states 1,5,9 and 3,7,11, respectively.



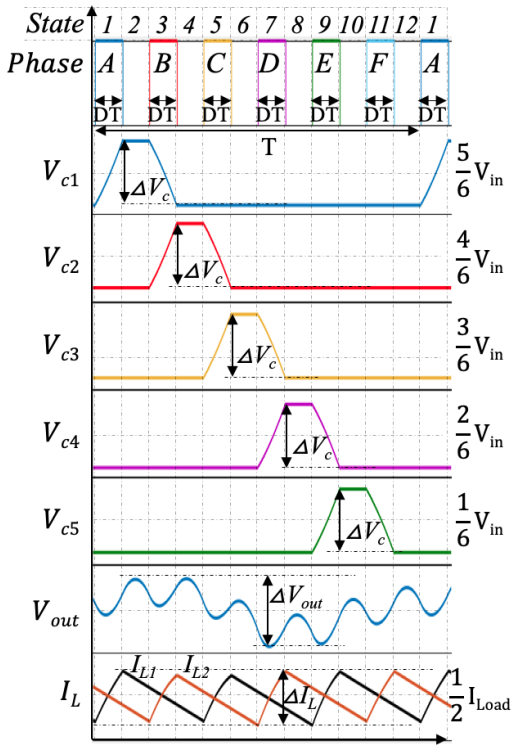
(a) State 1 (ϕA) (b) State 3 (ϕB) (c) State 5 (ϕC)

(d) State 7 (ϕD) (e) State 9 (ϕE)

(f) State 11 (ϕF) (g) State 2, 4, 6, 8, 10, and 12

Fig. 2. Operating states of the proposed MP-DIH converter

Therefore, each inductor blocks only $\frac{V_{in}}{6}$ and is effectively switched at a frequency three times higher than that of S_{1-6}. This creates an opportunity to select an inductor of lower inductance, and thus lower equivalent series resistance (ESR) for the same size, while sacrificing switching loss for only $S_{7,8}$, i.e. $S_{7,8}$ is operated at 3X the fundamental switching frequency.



(a) Operational waveforms

Fig. 3. Operational waveforms of the proposed MP-DIH converter

As can be seen in Fig. 6, on top of the high-frequency ripple, associated with switching nodes $V_{X1,2}$, $I_{L1,2}$ and V_{out} also have a low-frequency ripple at the operational frequency of the high-side switches, i.e. $1/T$. This phenomenon is caused by the different impedance and as a result, different voltage swing seen by the inductors in States 3, 5, 7, and 9 compared with States 1 and 11 [11]. Particularly, L_1 (L_2) only sees one capacitor C_1 (C_5) when it gets charged in State 1 (11), while in all other odd phases the inductors see two capacitors in series at switching nodes $V_{X1,2}$. Since the voltage swing difference created by equivalent capacitor mismatch only causes a small predictable perturbation in the fundamental operations of the converter, it does not alter either the charge balance of C_{out} and C_{1-5} or the volt-second balance of the inductors achieved in the entire period.

General steady-state values of the output and flying capacitor voltages for an MP-DIH converter are given as:

$$V_{out} = \frac{DV_{in}}{2} \quad \text{and} \quad V_{C_k} = \frac{(N-k)V_{in}}{N} \tag{1}$$

where, k=1, 2,...., N-1

One can calculate from this analysis that for an N-level N-phase operation, the maximum duty cycle D is limited to $\frac{1}{N}$ due to non-overlapping phase distribution. In other words, the conversion ratio $\frac{V_{in}}{V_{out}}$ is limited to $2N$. However, the converter is still capable of supporting a wide range of conversion ratios from a 40V-54V input supply to an output voltage up to 3.33V-4.5V, covering the 1V-2V range typically required in data center and telecommunication systems. It is also noted that, for the same voltage conversion ratio as a three-level Buck converter the voltage stress across each high-side switch of the MP-DIH converter is $\frac{2V_{in}}{N}$, significantly lower than the three level Buck converter's switch stress of $\frac{V_{in}}{2}$ [6], [7], [8]. This difference brings advantages in both switching loss and conduction loss, i.e. allowing switches with lower breakdown voltage and on resistance, promising a higher efficiency for a larger conversion ratio.

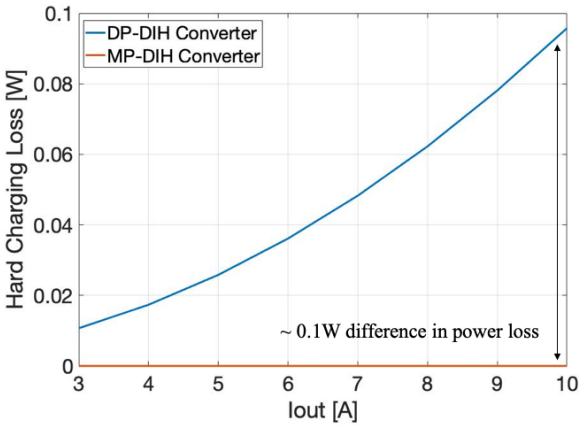


Fig. 4. Simulated hard charging loss comparison between dual-phase and multiple-phase operations

III. COMPLETE SOFT-CHARGING FEATURE

As illustrated above, as the flying capacitors are only charged or discharged directly by an inductor, this MP-DIH converter completely eliminates all the hard-charging in the circuit without any split phase operation. More importantly, this natural complete soft-charging feature is robustly achieved regardless of the flying capacitance mismatches and variations that are unavoidable due to variations in DC bias, temperature, and manufacturing tolerance. Compared with the previous dual-phase DIH converter reported in [10] that relies on capacitor matching, this feature is a very significant improvement. As shown in Fig. 4, the hard charging loss in the dual phase operation of DIH converter can increase rather exponentially than linearly as the output current increases. In contrast, the multiple-phase operation would introduce almost zero additional loss from hard charing of flying capacitors. This loss discrepancy accounts for ~10% of the total converter loss, or 1% difference in efficiency at 10A load current. This analysis assumes stacking of 4 pieces of a popular TDK ceramic capacitor CGA5L3X7R1H105K160AB ($1\mu F$, 50V, X7R,1206) with capacitance degradation of -70%, -65%, -55%, -35% and -10% at 40V, 32V, 24V, 16V and 8V DC bias voltage , respectively. Stacking multiple capacitors in parallel to minimize the equivalent series resistance would likely increase the mismatch and make the issue worse. Therefore, applying multiple phase operation is beneficial to help the system naturally immune to the hard-charging loss injected by capacitor degradation and mismatch.

TABLE I
PARTS LIST

Item	Design Selection
Flying Capacitors C_{1-5}	2.2, 1.5, 1.5, 1, 1μF, X7R, 1812/1210, TDK
Output Capacitor C_0	6.8μF, X5R, 0603, 10V, TDK
Inductors L_1, L_2	1.5μH, IHLP-5050CE-01
High Side Switches, S_{1-6}	EPC2014C
Low Side Switches, $S_{7,8}$	EPC2023
$S_{7,8}$ Paralleled Diodes, $D_{7,8}$	CRS08, 30 V, 1.5 A
Gate Drivers	LM5113, LM5114
Signal Isolators	Si8422, Silicon Labs
Microcontroller	TMS320F28377 Delfino, TI

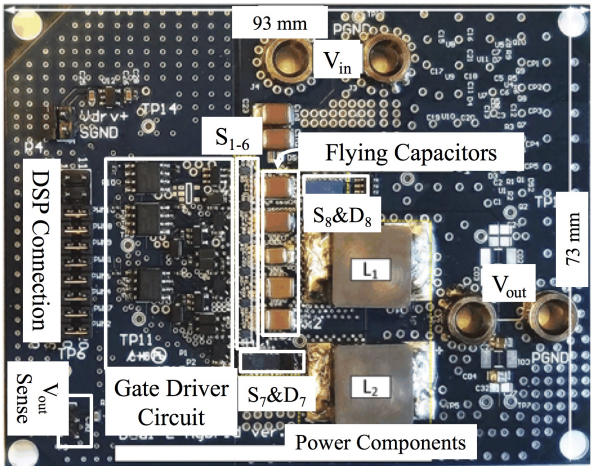


Fig. 5. Prototype Board

IV. EXPERIMENTAL RESULTS

To verify the feasibility of this novel topology and operation, a 48V 20W prototype has been implemented using the components listed in Table I. With a switching frequency of 150 KHz applied to S_{1-6} , $S_{7,8}$ and $L_{1,2}$ are switched effectively at 450 KHz, as described in Section II. The operational waveforms of I_{L1}, I_{L2}, V_{X1}, V_{X2}, and V_{out} are captured in Fig. 6, while capacitor voltages V_{C1-5} for one operational cycle with 12 states shown in Fig. 7. These measured waveforms verify intended converter operations and analysis of Section II.

As shown in Fig. 8 and Fig. 9, the converter is also demonstrated to maintain efficiency higher than 90% over most of the 1A-8A load range for wide ranges of input voltages, 40V-54V, and output voltages, 1.4V-2V, with a peak efficiency of 92.4% at 40V-1.8V/4A and 92.1% at 48V-1.8V/4A. At a mid load of 4A for 48V-to-1.8V conversion, the converter is analyzed to have switching loss, magnetic component loss, conduction loss and non-ideal parasitic loss of 40%, 37%, 20%, and 3%, respectively, as given in the Fig. 10. It can be concluded that to further increase the efficiency of this Multiphase Dual Inductor Hybrid (MP-DIH) Converter, a customized and more optimizedinductor design is required. Moreover, a soft-switching approach and discontinuous conduction mode (DCM) operation are necessary for better efficiency at light load operations.

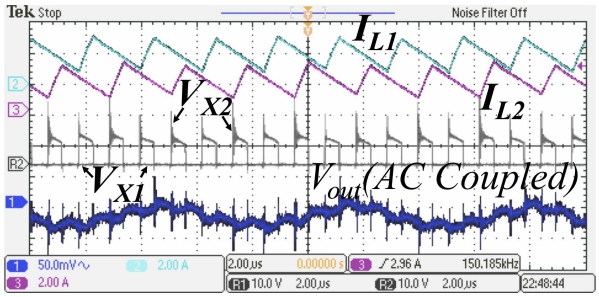


Fig. 6. Operational waveforms of prototype at 48V-1.8V/4A.

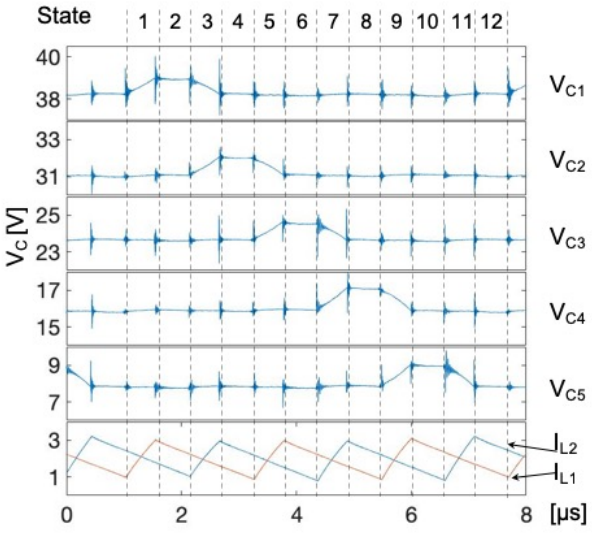


Fig. 7. Flying capacitor voltage with no hard-charging.

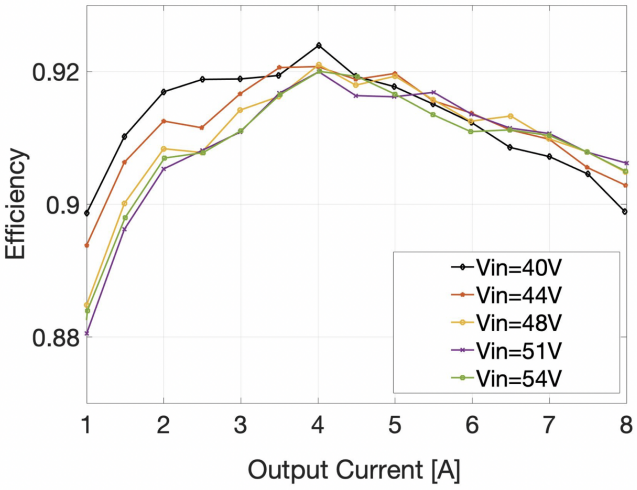


Fig. 8. Measured efficiency for different input voltages at $V_{out} = \mathbf{1.8V}$ regulated

V. CONCLUSION

In this paper, a novel multi-phase 6-to-1 dual-inductor hybrid converter topology is presented, together with operation analysis and experiment results. By connecting each branch in the circuit separately in multiple phases, the converter

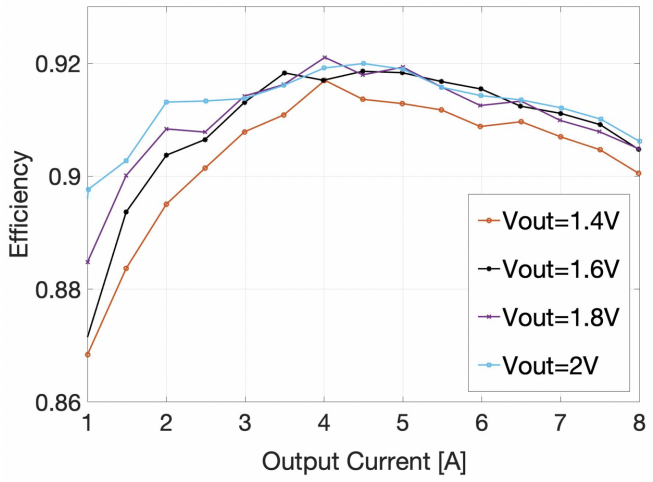


Fig. 9. Measured efficiency for different output voltages at V_{in} = **48V**regulated

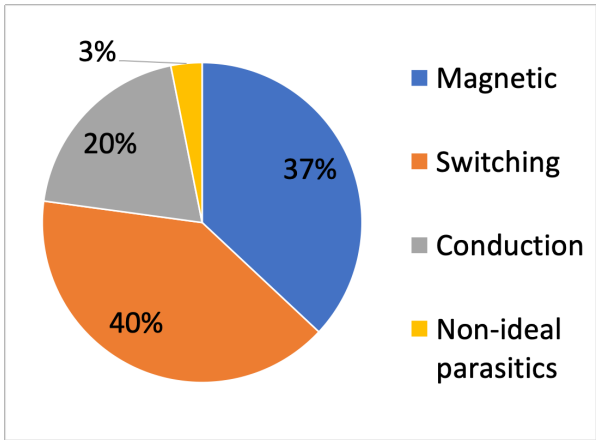


Fig. 10. Loss breakdown at 1.8V/4A output

is capable of robust full soft-charging of flying capacitors regardless of unavoidable capacitance mismatches and variations. A 92.4%-efficient 20W 48V-to-1.8V prototype converter successfully demonstrates the intended operation and characteristics including capacitor voltage ripples, inductor currents and output voltage regulation. In addition, a numerical loss breakdown analysis is suggested following by optimization direction.

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