REVOLUTIONIZING HIGH-CURRENT POWER MANAGEMENT: THE TRANS-INDUCTOR VOLTAGE REGULATOR (TLVR) SOLUTION

Introduction

The Trans-Inductor Voltage Regulator (TLVR) has emerged as a promising topology for powering low-voltage, high-current, multi-phase applications such as data centres, storage systems, graphics cards, and personal computing. These systems require a reliable and efficient power delivery solution that can support processors, memory, and high-current ASICs and FPGAs.

Traditionally, non-TLVR multi-phase circuits have been used to meet these requirements. However, the increasing demands of these applications have led to the limitations of the traditional approach. In May 2019, the TLVR circuit was introduced in the TD Commons, proposing a novel approach that replaces the traditional inductors with trans-inductors (1:1 ratio transformers). This change dramatically improves transient response and voltage regulation and has been widely adopted in VR14 and related programs.

Despite the significant benefits of the TLVR topology, there has been little investigation of the magnetic components' actual performance, efficiency, manufacturability, and cost. This paper aims to address this gap by reviewing both the non-TLVR and TLVR topologies and magnetic structures. Additionally, the paper will examine the circuit waveforms and 3D finite element models and provide a detailed analysis of the trade-offs between the two approaches. The analysis will include an efficiency comparison based on simulation results.

Voltage regulator (Non TLVR)

Traditional voltage regulator modules (VRMs) commonly used in high-current applications like data centres and FPGAs employ a multi-phase buck regulator. This regulator typically consists of several tightly packed power stages, each with an inductor of around 6x10 mm or 6x12 mm size, and a height of 12 mm. The input voltage in these applications is around 12V, while the output voltage can be as low as 1.X V or 0.8 V.

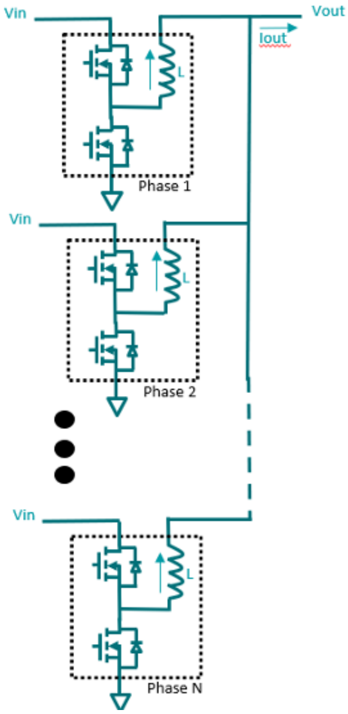

Figure 1: Generic multi-phase buck converter

During normal operation, one phase in the multi-phase buck regulator is turned on, while the others remain off, and continue to cycle through. While each phase will have a ripple current like that of a traditional buck converter, the currents into the output are summed, creating an overall smaller ripple. An example of the inductor current waveforms and output current ripple can be seen in *Figure 2.*

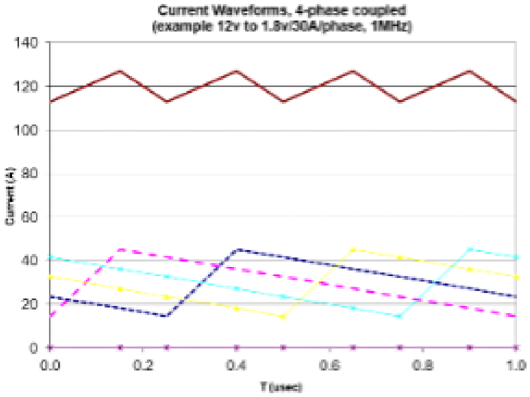

Figure 2: Typical Inductor Current Waveforms in VRM

During a transient period, the current per phase can increase rapidly, leading to a drooping in the output voltage before the converter can respond and regulate properly. This increase in load current can be seen in *Figure 3*.

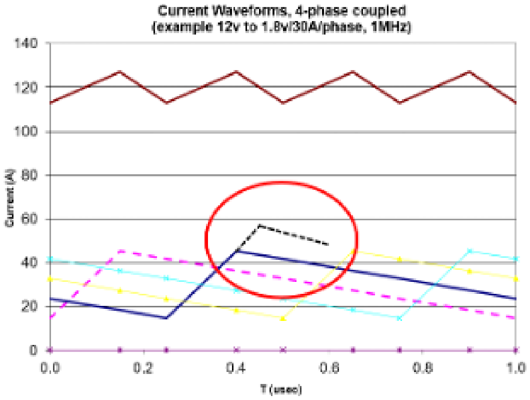

Figure 3: VRM Phase Current Transient

As the converter is not able to respond to the change in load current until the next phase switches on, the output voltage will temporarily droop, as seen in Figure 4. In sensitive processor circuits, this output voltage droop can become problematic, and novel converter approaches are needed to support more strict transient responses, especially as processor demands continue to increase.

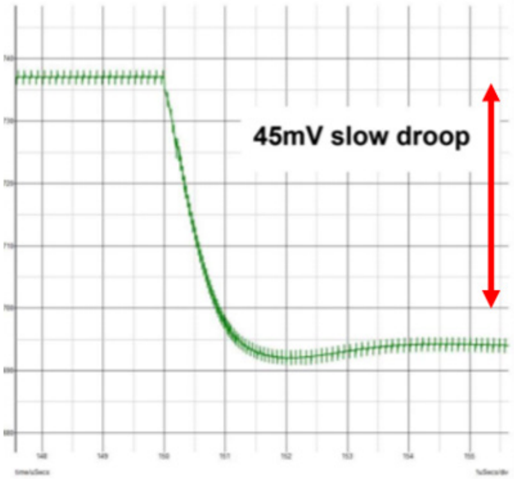

Figure 4: VRM Output Voltage Droop

Trans Inductor Voltage Regulator (TLVR)

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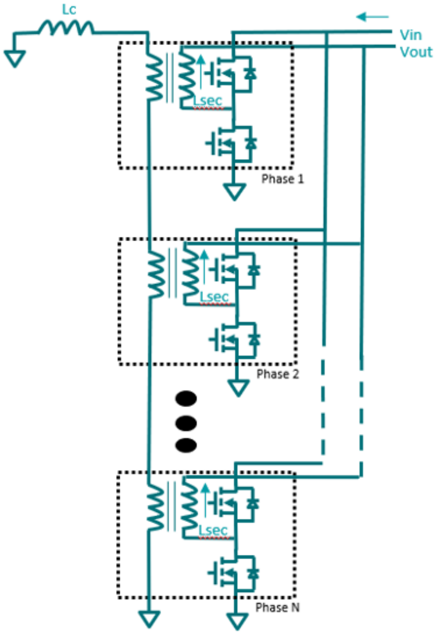

Figure 5: VRM Schematic Updated to Include TLVR

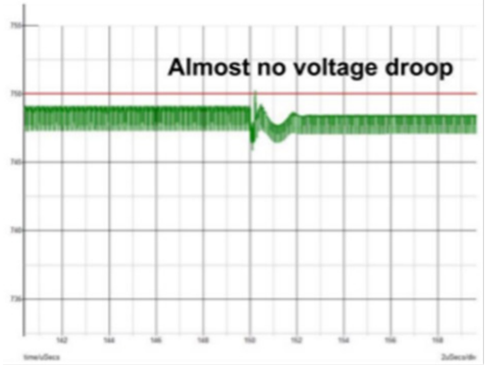

Figure 6: Reduced Output Voltage Droop with TLVR

In a TLVR circuit, all of the newly added secondary windings are placed in a series loop, with an external compensation inductor added to fine-tune the transient response. The schematic for a TLVR circuit is almost identical to the traditional VRM, with the only significant difference being the inclusion of the TLVR inductor. *Figure 5* shows the updated schematic of the TLVR circuit.

With the TLVR inductor in place, an increase in current from one phase is simultaneously coupled through all phases via the series connection of the secondary windings. This results in virtually no voltage droop, as shown in *Figure 6*. The TLVR structure significantly improves transient response and reduces output voltage droop compared to traditional VRMs.

Magnetic Structure

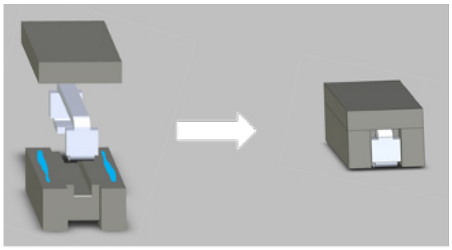

Figure 7: UI core bead for lower profile

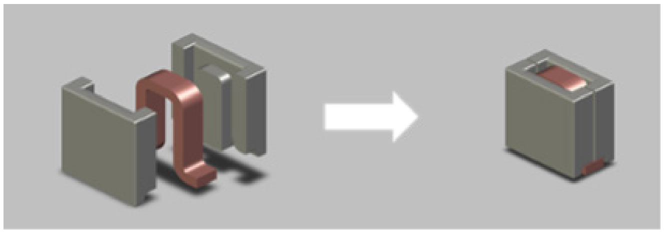

Figure 8: EE core bead for smaller footprint

The magnetic structure of TLVR inductors is very similar to that of traditional inductors used in VRMs. Traditional inductors have a simple construction consisting of two low loss ferrite core halves and a single turn lead. They are available in two varieties - an "E-E" core to minimize footprint while maximizing height or a "U-I" core to minimize height at the expense of footprint.

On the other hand, TLVR inductors utilize the same “E-E” core but have an additional single turn inner lead, which is shown in *Figure 8*. As a result, the overall layout of the TLVR circuit becomes relatively simple, with the inner leads routed in series with short copper runs, and a traditional VRM layout is used. Existing manufacturing processes can be used for the construction of TLVR inductors, making it a straightforward modification of the existing inductor construction.

Potential Challenges and Solutions with TLVR Inductors

TLVR inductors have shown great promise in revolutionizing power management solutions, thanks to their modified construction that allows for an additional winding resulting in higher efficiency and reduced output capacitor requirements. However, with any new technology, there are potential challenges that need to be addressed in order to fully realize the benefits of TLVR inductors. Three potential challenges that currently face TLVR inductors include mechanical stability, phase-phase isolation voltage, and added cost. Addressing these challenges is crucial for TLVR inductors to become a widely adopted technology.

Mechanical Stability

One challenge that arises when adding an additional winding to TLVR inductors is the mechanical stability of the inductor. Traditional “EE” core inductors have a limited width of 5 or 6 mm due to their height (often up to 12 mm) and small footprint, making them prone to placement issues in pick and place operations. TLVR inductors face the same challenge, but with the added complexity of ensuring that the inner and outer leads are coplanar. This requires a careful lead placement process during manufacturing and advanced optical inspection (AOI) to ensure tight coplanarity between the leads. To address this challenge, co-joined inductors can be manufactured to create a longer overall inductor without requiring spacing between inductor phases, thereby minimizing total solution space. However, further work is needed to validate the performance of this co-joined TLVR construction at the circuit level. *Fig. 9* illustrates the proposed co-joined TLVR construction.

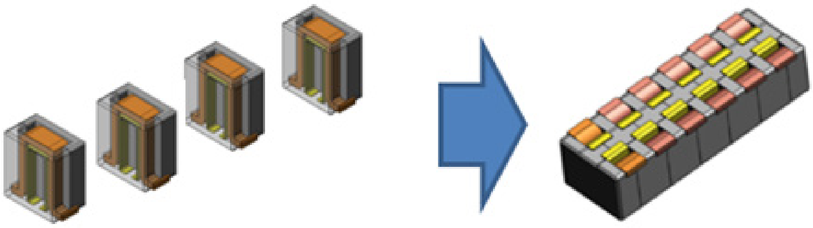

Figure 9: Proposed co-joined TLVR Construction

Phase – Phase Isolation Voltage

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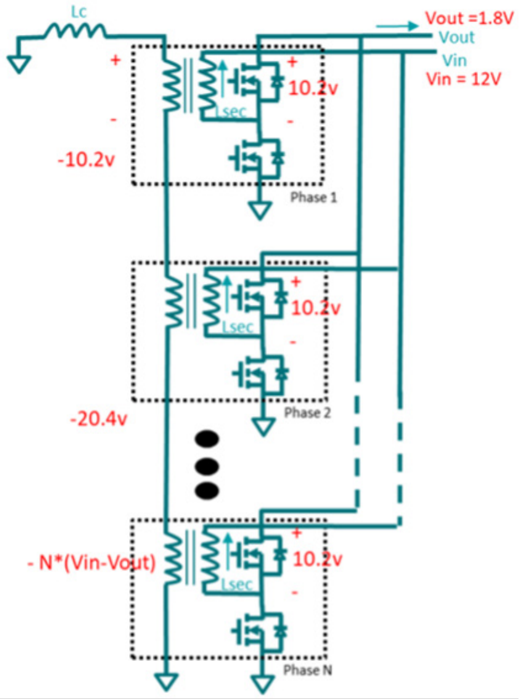


Figure 10: Potential Voltage Differentials across TLVR Windings

Increased Costs

The TLVR magnetic comes with the added complication of lead manufacturing, and potential adders for higher isolation, making it typically 15-50% more expensive than its traditional counterpart, depending on the nuances of the design. However, over time, it is expected that process improvements from individual manufacturers will close the cost gap.
At the converter level, the TLVR solution usually offers modest cost improvements overall due to reduced output capacitor requirements resulting from the reduced ripple.

Efficiency Comparisons

Many of the challenges faced in implementing TLVR technology have well-established mitigation strategies in place across the industry. However, the comparison in efficiency at the magnetic level is less highlighted. While traditional VRM inductor losses are well understood, the same loss mechanisms - fringing loss, core loss, and skin depth losses - are still present in the TLVR inductor, along with two added complications. The first complication is the creation of a small amount of proximity loss due to the two windings conducting simultaneously. The more significant issue is that a high-frequency ripple of Nphases*fsw is superimposed on top of the traditional buck inductor waveforms, resulting in excess loss not present in the VRM circuit.

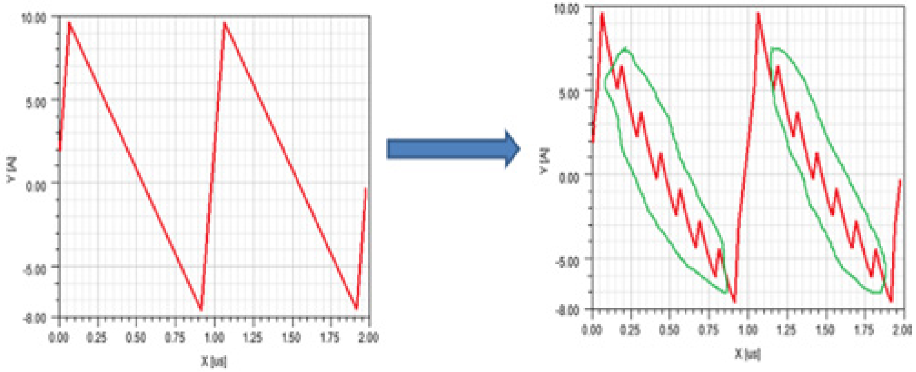
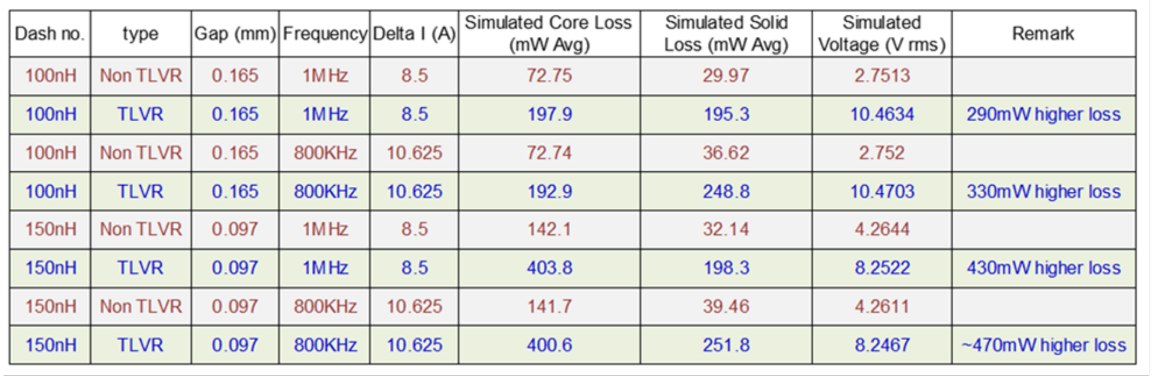


Figure 10: Potential Voltage Differentials across TLVR Windings

To estimate the added core loss, a first pass approach involves separating the low-frequency buck waveform from the high-frequency ripple and summing the loss. However, this approach has some potential drawbacks, such as core loss not being perfectly linear and depending on having an accurate core loss model for the much higher frequency. Furthermore, the high-frequency content introduces additional AC winding loss via fringing and proximity effects. When simulating similar E-E core constructions with both traditional VR windings and TLVR windings, the winding loss of the TLVR inductor can be as much as 11x higher. To obtain a more accurate understanding of TLVR inductor losses, several gap lengths and frequencies were simulated using commercially available software. These losses are summarized in *Appendix A*.

Based on these results, further work is needed to develop both lower loss, high-frequency core materials, and novel methods to alleviate AC winding effects such as fringing loss. Although these challenges are not yet fully understood, continued research and development in this area will be crucial for improving TLVR technology and increasing its adoption in the industry.



Dash no.	type	Gap (mm)	Frequency	Delta I (A)	Simulated Core Loss (mW Avg)	Simulated Solid Loss (mW Avg)	Simulated Voltage (V rms)	Remark
100nH	Non TLVR	0.165	1MHz	8.5	72.75	29.97	2.7513	
100nH	TLVR	0.165	1MHz	8.5	197.9	195.3	10.4634	290mW higher loss
100nH	Non TLVR	0.165	800KHz	10.625	72.74	36.62	2.752	
100nH	TLVR	0.165	800KHz	10.625	192.9	248.8	10.4703	330mW higher loss
150nH	Non TLVR	0.097	1MHz	8.5	142.1	32.14	4.2644	
150nH	TLVR	0.097	1MHz	8.5	403.8	198.3	8.2522	430mW higher loss
150nH	Non TLVR	0.097	800KHz	10.625	141.7	39.46	4.2611	
150nH	TLVR	0.097	800KHz	10.625	400.6	251.8	8.2467	~470mW higher loss

Appendix A

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