Multiphase Designs, Decisions, and Trade-Offs with Trans-Inductor Voltage Regulators

Alexandr Ikriannikov, Fellow in Analog Devices

Abstract

The recently introduced trans-inductor voltage regulator (TLVR) has gained popularity in multiphase DC-to-DC applications that supply power to low voltage high current loads, such as CPUs, GPUs, and ASICs. This trend is mainly based on the outstanding transient performance of this technology. TLVR also allows design and layout flexibility but has several drawbacks. This article illustrates how TLVR design choices affect performance parameters and discusses related trade-offs.

Current Ripple and Transient in TLVR Buck

Any improvements in the multiphase buck converter are of big interest to many high current applications. Transient improvements are of particular focus, as many CPUs, GPUs, and ASICs now have very aggressive transient specifications, while a high efficiency is also critical for energy savings and thermal performance.

Current ripple in inductors is an important parameter that influences the design choices: it affects efficiency and output voltage ripple, and indirectly involves the transient performance, solution size, and other performance metrics. Another critical characteristic is a current slew rate in transient, which is a fundamental limiting factor for transient performance. Very often, current ripple (and therefore efficiency) and transient performance (direct impact on the amount of the output capacitance, etc.) cause a trade-off for the design decisions.

The conventional multiphase buck converter with discrete inductors (DL) is shown in Figure 1a. The appropriate phase shift is assumed between all phases for the optimal interleaving of the waveforms. One of the alternatives is to replace DLs with coupled inductor (CL), shown in Figure 1b.[1–3,5] Another alternative is shown in Figure 1c and was called TLVR, where the tuning inductor L_c affects both current ripple and transient.[4,6,7,10] The TLVR approach is based on adding secondary windings to the discrete inductors and linking the phases by electrical connections of the secondary windings. This has an ideology similar to coupled inductors: averaging the AC waveforms between all the linked phases to get a better current ripple for a certain transient slew rate, but the effective coupling inductance of TLVR is limited because it has to be rated for the full phase current. The drawback is a result of the fact that the TLVR transformer does not pass the DC level of the current, so it is not canceled between the phases as it happens in magnetically coupled inductors. This article will focus on more details and particular trade-offs for TLVR, which were not possible to include to a previous study due to the paper size limitations.[9]

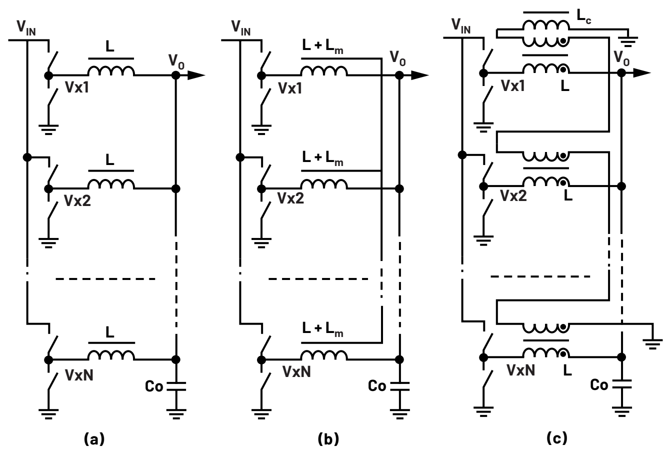

Figure 1. A multiphase buck converter with (a) discrete inductors (DL), (b) coupled inductors (CL), and (c) TLVR.

Possibly, the first mathematical model with equations for ripple and current slew rate in TLVR was shown.[7] While this is very helpful math that works for any circuit conditions (any duty cycle $D = V_O/V_{IN}$ or a number of phases N_{ph}, etc.), it has some limitations. For example, low L_c values (tuning inductor in Figure 1c) cause increased error that becomes infinite when $L_c = 0$, etc. The corner with low L_c values is more critical than L_c = open corner because the main reason to use TLVR is transient improvement, which implies a reasonably low L_c value.

A more accurate TLVR derivation was shown, where the derived equation can produce the current slew rate in a steady state (for current ripple) or transient by assigning appropriate Vx states.[10] The derivation was done for a more accurate equivalent TLVR schematic (Figure 2). This model has an extremely good correlation with simulations in any corner cases, but the current slew rate in a steady state is valid only for the $D < 1/N_{ph}$ range. The latter is acceptable because it was shown that TLVR has the maximum current ripple increase from DL baseline exactly for the $D < 1/N_{ph}$ region and approaches DL ripple when the N_{ph} is sufficiently high.[9,10]

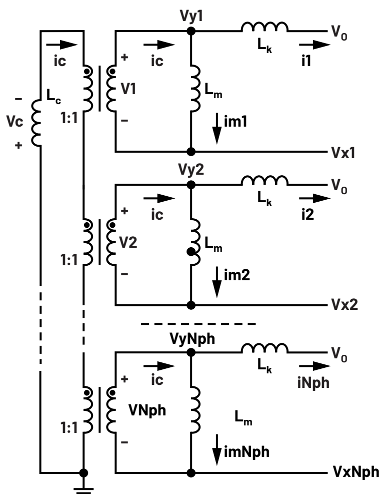

Figure 2. A TLVR model.[10]

Typically, the TLVR value is shown in the data sheet in the same way as a discrete inductor DL, from which TLVR is derived. The model in Figure 2 assumes that TLVR total value, or the self-inductance, is split into a typically small L_k and the rest effectively becomes a mutual inductance for the TLVR transformer L_m = TLVR-L_k (Equation 1).

This current slew rate in TLVR, based on the model in Figure 2, can be expressed as Equation 2, where L_k is a TLVR leakage between the main and auxiliary windings. The V_{x1} voltage is assigned to the phase of interest, while all other Vx nodes are assumed at the same voltage (V_{IN} or 0). The corresponding node voltage V_{y1} is shown in Equation 3. Equation 2 can be used for the direct calculation of the maximum transient slew rate in TLVR, forcing $V_{x1} = V_x$ and assigning these voltages to either V_{IN} (ramping up) or 0 (ramping down). Also, the current slew rate in Equation 2 can be used for a steady state ripple calculation in Equation 4, where $V_{x1} = V_{IN}$ and all other switching nodes are $V_x = 0$. Equation 4 is valid only for $D < 1/N_{ph}$ though, as it assumes a single and the same slew rate for the whole turn on time D/F_s.

$$TLVR = L_k + L_m \tag{1}$$

$$\frac{dIL_{TLVR}\,(V_{x1}, V_x)}{dt} = \frac{V_{y1}\,(V_{x1}, V_x) - V_o}{L_k} \tag{2}$$

$$V_{y1}\,(V_{x1}, V_x) = \frac{\dfrac{V_{x1} + (N_{ph} - 1)\,V_x - N_{ph}V_o}{L_c L_k \left\{\dfrac{N_{ph}}{L_c} + \dfrac{1}{L_k} + \dfrac{1}{L_m}\right\}} + \dfrac{V_o}{L_k} + \dfrac{V_{x1}}{L_m}}{\dfrac{1}{L_k} + \dfrac{1}{L_m}} \tag{3}$$

$$\Delta I_{TLVR} = \frac{V_{y1}\,(V_{IN}, 0) - V_o}{L_k}\,\frac{D}{F_s} \tag{4}$$

$$FOM = \frac{SR_{tr}}{SR_{st\_state}} \tag{5}$$

$$FOM_{TLVR} = \frac{V_{y1}\,(V_{IN}, V_{IN}) - V_o}{V_{y1}\,(V_{IN}, 0) - V_o} \tag{6}$$

As it was shown, figure-of-merit (FOM) is a very good indication of the system performance, and maximizing the FOM is generally a good direction to achieve the best trade-offs.[9,10] Notice however that the high FOM by itself does not guarantee that every parameter in specifications for a particular application will be satisfied: high FOM is only an indicator of a good design. Defining FOM as Equation 5, which is appropriate to use for the $D<1/N_{ph}$ range, we can express TLVR FOM as Equation 6.

For the comparison, CL equations will be used (not shown here), while the focus will be on the TLVR performance and trade-offs.[5,10] The notch coupled inductor (NCL) structure will be also used as a benchmark, compared to a particular TLVR = 150 nH solution that is footprint and size compatible.[10]

TLVR Trade-Offs

The key TLVR performance parameters as a function of tuning inductor L_c are shown in Figure 3, based on 12 V to 1.8 V 6-phase design (F_s = 300 kHz for the current ripple). TLVR = 150 nH is the maximum possible value to just barely meet the I_{sat}/ph spec in a given size and therefore minimize the TLVR ripple and maximize efficiency. The DL = 150 nH is also plotted as a baseline for TLVR = 150 nH, while NCL = 6× 25 nH (L_m = 375 nH) parameters are also plotted for comparison. The actual design point L_c = 120 nH is highlighted on all TLVR curves in Figure 3.

The change in TLVR parameters needs to be considered in the content: Figure 3 shows (a) FOM, (b) current transient slew rate, and (c) current ripple as a function of L_c with the same horizontal scale. Notice that as L_c increases—all TLVR curves are asymptotically approaching the DL performance. The FOM of TLVR is increasing with lowering the L_c value, as the transient slew rate is increasing a lot, but it comes with the expense of the further current ripple increase from the already significant ripple of the DL baseline, see Figure 3c. TLVR FOM is plotted without taking into account the reduction of ferrite when the secondary winding with isolation is added to the initial DL. As expected, the TLVR ripple is always larger than the DL baseline.[8–10]

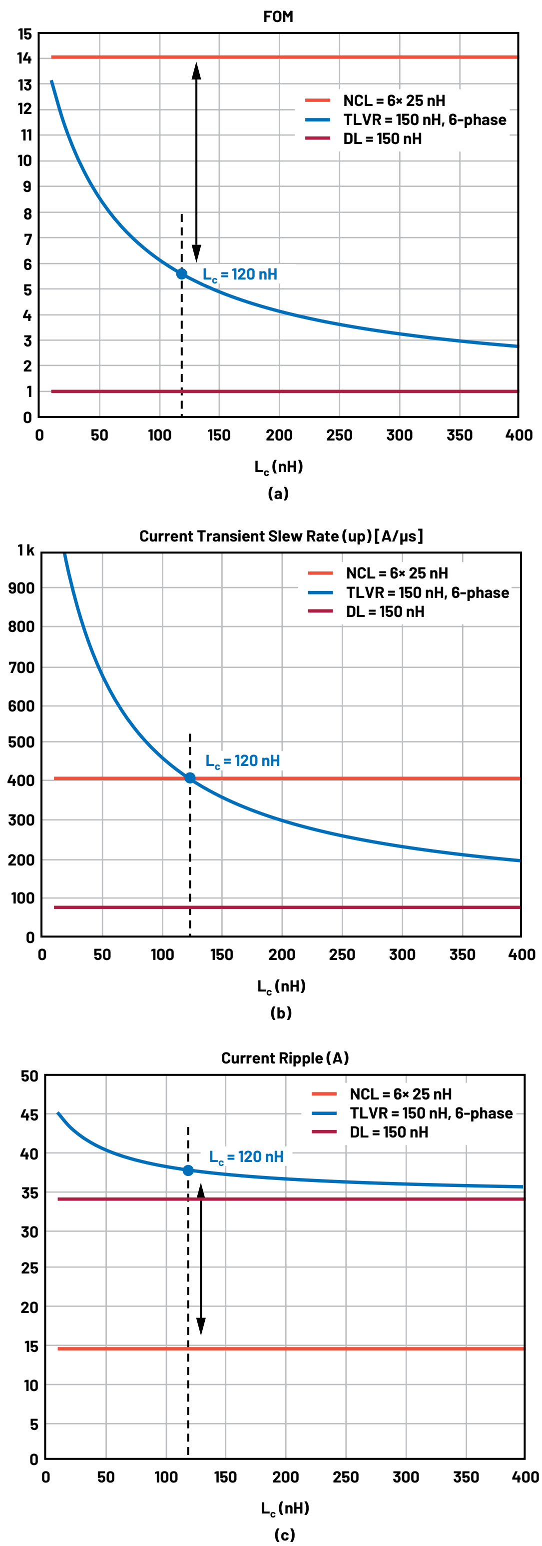

Figure 3. TLVR trade-offs vs. L_c: (a) FOM, (b) current slew rate (up), and (c) current ripple. The actual design point L_c = 120 nH is highlighted. 12 V to 1.8 V, 6 phases, F_s = 300 kHz.

Figure 4 shows FOM, transient slew rate, and current ripple as a function of TLVR value (effectively L_m). It is important to notice that while mathematical curves are plotted: the I_{sat} spec for TLVR is a full I_{sat} per phase (I_{sat} = 65 A for TLVR = 150 nH in the tested solution), while I_{sat} for L_m of the NCL is significantly lower (conservative I_{sat} = 25 A for L_m = 375 nH that has to withstand current unbalance between phases). Therefore, in the same given size of the tested solution: TLVR curves above 150 nH and NCL curves above 375 nH are only theoretical (a larger size would be needed to expand these values). As electrical models of TLVR and CL are similar, and the related curves as a function of L_m might be close to each other, the key point is that the mutual inductance in a given space will always be limited very differently for TLVR and CL.[10] This puts a realistic comparison perspective between TLVR and NCL in the same specified volume.

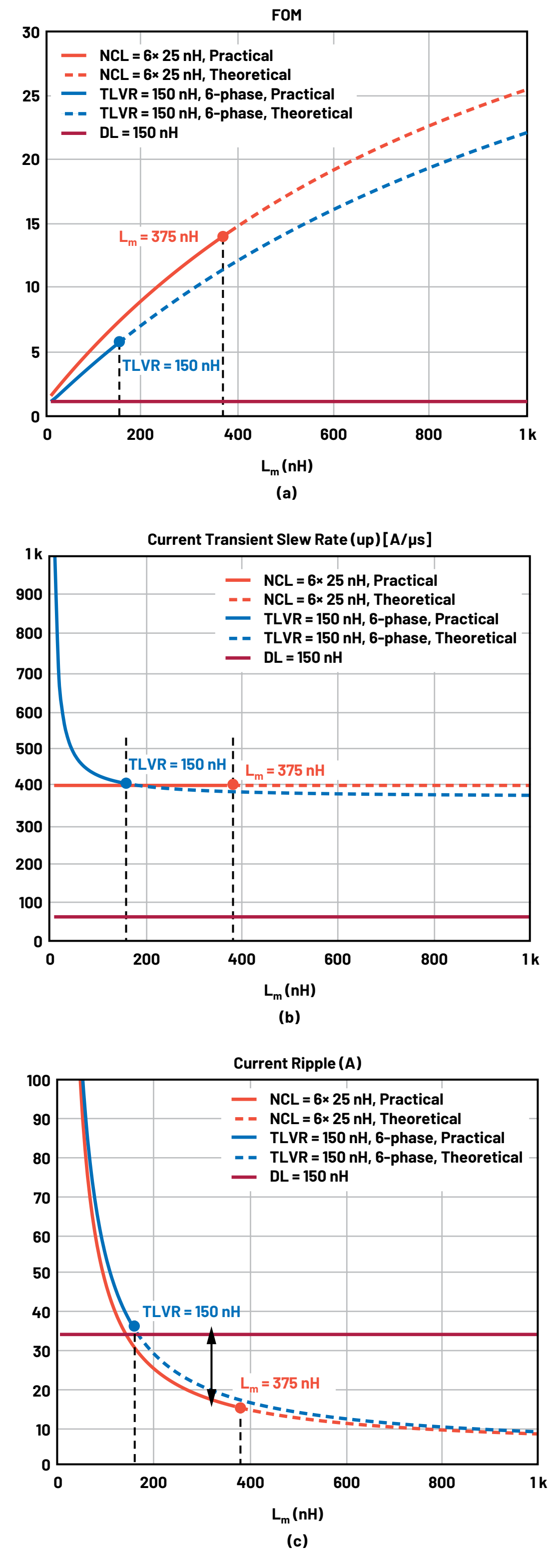

Figure 4. TLVR trade-offs vs. TLVR value (L_m): (a) FOM, (b) current slew rate (up), and (c) current ripple. L_c = 120 nH, maximum in the given size TLVR = 150 nH and L_m = 375 nH (for NCL) are marked. 12 V to 1.8 V, 6 phases, F_s = 300 kHz.

As expected for both TLVR and NCL, an increase of L_m results in a larger coupling coefficient and a larger FOM in Figure 4a.[10] The transient slew rate is generally defined by the leakage inductance L_k in NCL and the tuning inductor L_c in TLVR, not L_m, so the curves in Figure 4b are mostly flat. However, when the TLVR value (effective L_m) becomes too small—it starts effectively shorting the L_c in parallel and the transient slew rate increases rapidly.

Figure 4c confirms that increasing L_m is very beneficial for both TLVR and NCL in terms of the current ripple reduction (while L_m increase does not degrade the transient, see Figure 4b). The current ripple curves are very similar for TLVR and NCL as a function of L_m, which is expected from similarity of the electrical models, but the limits for L_m value are dramatically different.[10] Of course, most of the difference comes from the required I_{sat} rating for L_m in a given size, so the NCL has a significantly smaller current ripple than related TLVR.

Experimental Results

NCL was designed to fit on the same TLVR footprint and also match all other outer dimensions of TLVR solution.[10] Figure 5 shows the two tested solutions on the same board (NCL does not need L_c).

Both TLVR and NCL are very fast solutions, as expected from the slew rate numbers (Figure 3b and Figure 4b). The purposely same transient performance was verified, where even lowering the F_s to 300 kHz still did not cause feedback bandwidth limitation in 6-phase solutions where phases are coupled to each other.[8]

As NCL has a significantly higher FOM than TLVR (Figure 3a), then matching the transient performance results in NCL having a ~2.6× smaller current ripple. A corresponding efficiency comparison is shown in Figure 6, where TLVR performance is challenged by the large current ripple peak to peak.

As leakage of CL and especially NCL is typically much lower than TLVR value, it is also expected that current capability per phase is also much higher for CL and NCL: TLVR = 150 nH example had I_{sat} = 65 A (per phase), while NCL = 6× 25 nH in the same volume showed I_{sat} > 300 A per phase.

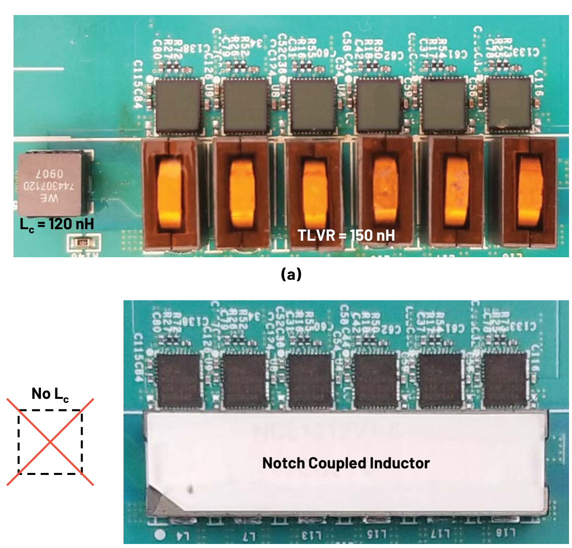

Figure 5. Solutions on the same board: (a) TLVR and (b) NCL.

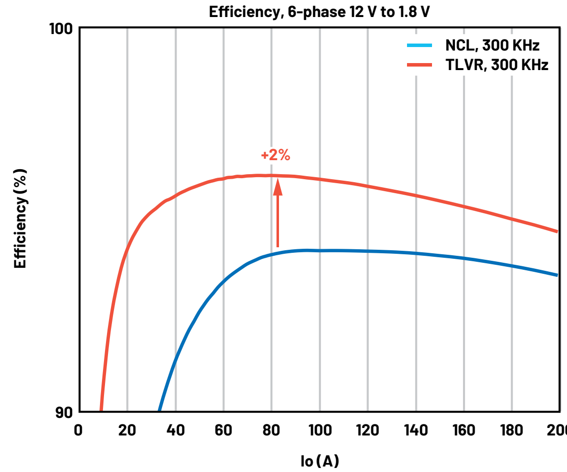

Figure 6. Efficiency vs. Io for 6-phase 12 V to 1.8 V solutions on the same board: (a) TLVR and (b) NCL.

Conclusion

TLVR generally has FOM~2 and from that perspective is an improvement from the discrete inductor baseline with FOM = 1. The advantage comes from the fact that TLVR improves the transient performance at a faster rate as compared to an increase in the current ripple. However, TLVR always improves only transient while creating several drawbacks. For example, TLVR current ripple is always higher than in DL with the same value due to the linking between the phases with low effective magnetizing inductance and L_c. This creates a bad efficiency impact especially considering a reduction in ferrite cross section when the secondary winding with high voltage isolation is added. The resulting additional loss of inductance value due to the loss of ferrite (assuming the same I_{sat} as in original DL) is not considered in this article. The secondary TLVR windings connected in series also cause a potential high voltage concern, and typically result in a cost increase of the magnetic components.[8]

The transient current slew rate of TLVR is typically set by L_c, but if L_m is low enough: then L_m is effectively shorting L_c to make an even faster transient but with a very big current ripple punishment that affects the efficiency.

Generally, TLVR behaves similarly to a coupled inductor; however, a full current rating for TLVR limits effective L_m and makes it underperform significantly. In the same volume, CL or NCL can achieve a much higher FOM and therefore performance due to a typically several times higher L_m. As a result, NCL shows a dramatically better efficiency in the considered example, while slightly improving the transient performance of TLVR at the same time.[10] This is also achieved without the cost impact or high voltage concerns of the TLVR approach.

A big advantage of I_{sat} current capability per phase for NCL vs. TLVR comes as a bonus (>4.5× difference in example above).

References

[1] Aaron M. Schultz and Charles R. Sullivan. "Voltage Converter with Coupled Inductive Windings, and Associated Methods." U.S. Patent 6,362,986, March 2001.

[2] Jieli Li. "Coupled Inductor Design in DC-to-DC Converters." M.S. thesis, 2001, Dartmouth College.

[3] Pit-Leong Wong, Peng Xu, P. Yang, and Fred C. Lee. "Performance Improvements of Interleaving VRMs with Coupling Inductors." *IEEE Transactions on Power Electronics*, vol. 16, no. 4, July 2001.

[4] Ming Xu, Yucheng Ying, Qiang Li, and Fred C. Lee. "Novel Coupled-Inductor Multiphase VRs." IEEE, 2007.

[5] Alexandr Ikriannikov. "Coupled Inductor Basics and Benefits." Analog Devices, 2021.

[6] S. Jiang, X. Li, M. Yazdani, and C. Chung. "Driving 48 V Technology Innovations Forward—Hybrid Converters and Trans-inductor Voltage Regulator (TLVR)." IEEE, 2020.

[7] "Multiphase Buck Converter with TLVR Output Filter." Infineon Technologies, February, 2021.

[8] Alexandr Ikriannikov. "TLVR High Voltage Considerations." Power Systems Design, 2021.

[9] Alexandr Ikriannikov. "Evolution and Comparison of Magnetics for the Multiphase DC-DC Applications." IEEE, March 2023.

[10] Alexandr Ikriannikov and Di Yao. "Converters with Multiphase Magnetics: TLVR vs CL and the Novel Optimized Structure." PCIM Europe, May 2023.

About the Author

Alexandr Ikriannikov is a fellow in the Communications and Cloud BU at Analog Devices. He received his Ph.D. in electrical engineering from Caltech in 2000, where he studied power electronics from Dr. Cuk. His graduate school projects ranged from power factor correction for AC-to-DC applications to 15 V to 400 V DC-to-DC for Mars rovers. After graduate school he joined Power Ten to redesign and optimize multi-KW AC-to-DC power supplies, then in 2001 joined Volterra Semiconductor concentrating on low voltage high current applications and coupled inductors. Volterra was acquired by Maxim Integrated in 2013, which is now part of Analog Devices. Currently, Alexandr is a senior member of IEEE. He holds more than 70 issued U.S. patents plus more pending and has authored multiple publications in the field of power electronics.

TA24848-10/23