TLVR Inductors

The Basics, and How They Improve Multiphase DC-DC Converters

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Introduction

Over the past few decades, the rise of power-hungry silicon (GPUs, CPUs, ASCIs, FPGAs, etc.) has led to the adoption of multiphase DC-DC converters as a standard power delivery solution in voltage regulator modules (VRMs) due to their high-current capability and fast response times. However, the surge of demanding applications such as machine learning, cloud computing, data analysis, graphics processing, crypto mining, etc. has not only pushed the current demand in such applications up to hundreds of amps, but also the required response time to meet such demand down to the microsecond. This push for faster processing time has created a need to realize a faster power delivery solution capable of responding to fluctuations in load as quickly as possible.

A trans-inductor voltage regulator (TLVR) is a topology that pushes the transient response time of multiphase DC-DC converters further down by coupling all phases together through a series of secondary windings. In this paper, a high-level overview of the TLVR functionality is explored, as well as the internal composition of the TLVR inductor.

What is a Multiphase DC-DC Converter?

In a high-power application like supercomputers, workstations, datacenters, etc., when a heavy load is switched from a sleeping state or low power state to a full load state, the DC-DC converter seeks to meet this demand by increasing the current throughput. During this transient, the initial current rise from a sleeping state current to the full load current is supplied by the inductor and output capacitor of the converter. However, due to the parasitic effective series resistance (ESR) and effective series inductance (ESL) of the capacitor, a voltage drop at the output side would occur as more current is drawn by the load [1].

While the parasitic ESR and ESL values could be small, depending on the quality of the capacitor, this voltage drop can be significant as it is proportional to the amount of current fed to the load. Some cores require an extremely tight voltage deviation (the percentage drop from the nominal voltage) of ±3%. Since it is common for processors to require voltages between 0.9V and 1.3V, the voltage deviation in such cases cannot exceed a few tenths of a millivolt. The output voltage will keep dropping until the inductor supplies enough current to recharge the capacitor and satisfy the load demand. Therefore, the control system is designed such that the feedback loop senses this voltage drop and responds by sending a control signal to the power MOSFETs, driving more current through the inductor before the voltage drops to a critical level. However, how fast the inductor reacts to this change in current depends heavily on its inductance value.

From the equation below, the rate of current change with respect to time is inversely proportional to the inductance (L) of the inductor. Therefore, the larger the inductance, the smaller the rate of current change with respect to time. Therefore, it will take the inductor longer to reach the current value needed to recharge the capacitor and meet the load requirement.

$$\frac{V_L}{L} = dI_L/dt$$

Eq. [1]: Rate of current change relationship with inductance (L) and Inductor's voltage

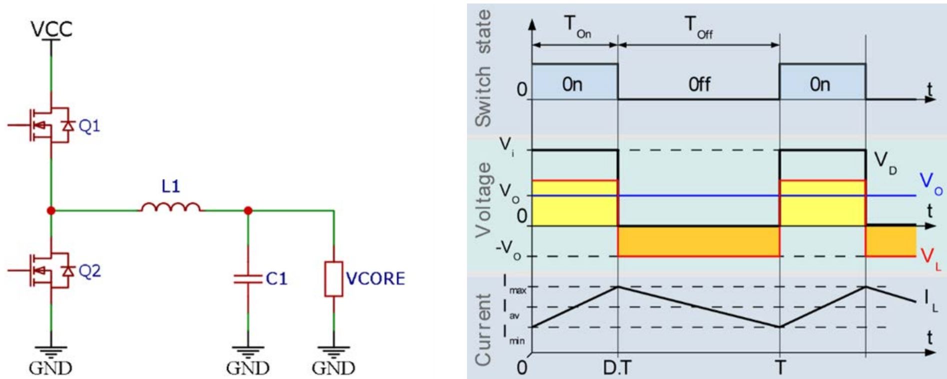

Figure [1]: Single phase Buck DC-DC converter and control signals.[2]

One solution to such a problem is to use a multiphase DC-DC converter where multiple single-phase buck converters are used in parallel. This gives the designers the flexibility of simultaneously using multiple smaller inductors to drive the load, rather than using a single large inductor.

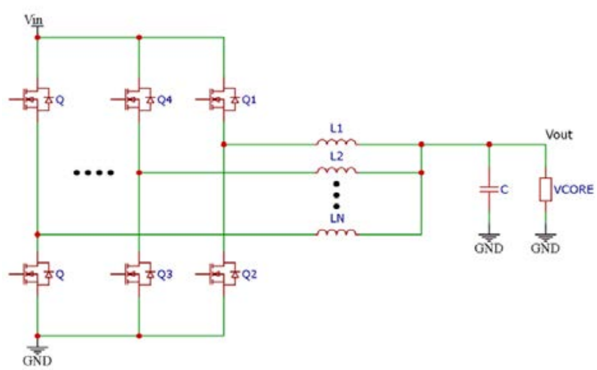

Figure [2]: An N-phase Multiphase Buck DC-DC converter.

In this scheme, the inductors are operated in an interleaved way, where the control signals of the different phases are shifted such that only one phase is active at a given time, as illustrated in Figure [3].

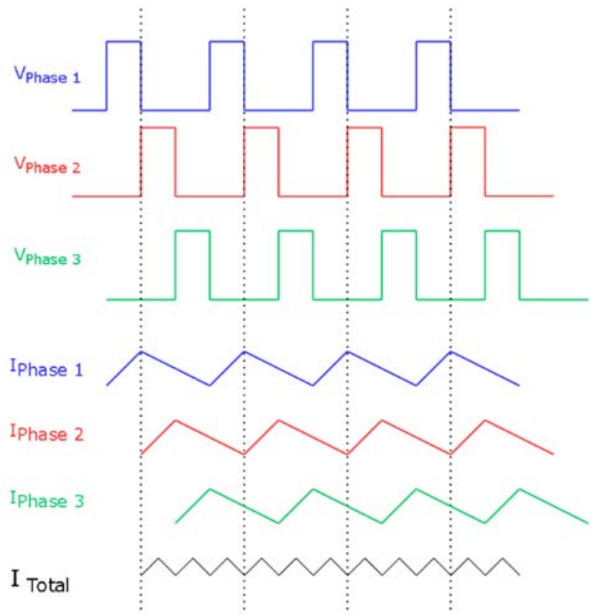

Figure [3]: An example of the inductor's voltages and currents in a 3-phase DC-DC converter.

The current fed to the load is the sum of all different phases' currents. By comparing the total current (I_{total}) in the multiphase converter to the current in any of the single phases, a significant reduction in the overall peak-to-peak ripple current can be realized. Additionally, as equation [1] illustrates, the flexibility of utilizing lower inductances for each phase allows the current to quickly rise. This results in a faster transient response and a lower voltage drop during load transients, which is another benefit that multi-phase DC-DC converters offer over single-phase converters. Moreover, each phase's current strain is reduced, enabling the use of smaller inductors in high-density designs. In the context of high-current designs, this leads to an overall increase in efficiency, reliability, and ease of thermal management due to the reduced AC and DC losses [4].

The Drawback of Traditional Multiphase DC-DC Converters

In a multiphase DC-DC converter, the feedback control system usually adjusts the duty cycle as a response to the load transients sensed at the output. In the simplest control schemes, a single phase reacts to the feedback system as more current is supplied to the output. To fully meet the new current demand, the control system needs more time to adjust all phases since they are sequentially triggered, one after the other, as Figure [3] depicts.

Although the converter can supply higher current demand to the output, there is room to minimize the overall response time of the converter by optimizing how each phase is triggered as a response to the load transients. TLVR is one of the newly emerging methods that attempts to optimize the response time of multiphase DC-DC converters.

What is a Trans-Inductor Voltage Regulator (TLVR)?

TLVR is a multiphase DC-DC converter topology that allows a faster transient response by utilizing a series connection of secondary windings that couple all phases together, allowing a simultaneous induction of current across all phases in response to an increase in load.

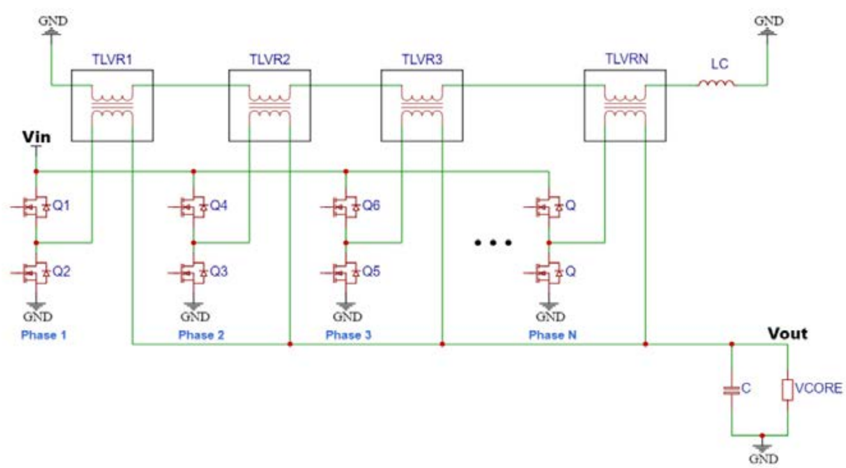

Figure [4]: Multiphase TLVR topology.

TLVR has a similar structure to the conventional multiphase DC-DC converter, with a slight difference between the two. In this topology, each inductor is magnetically coupled to a secondary winding, forming what is known as a TLVR inductor. Just to alleviate any uncertainty, a “TLVR inductor,” also sometimes referred to as a “TLVR transformer,” is the passive component encompassing the primary and secondary windings, as shown in Figure [5] below, while “TLVR” refers to the complete DC-DC converter topology shown in Figure [4].

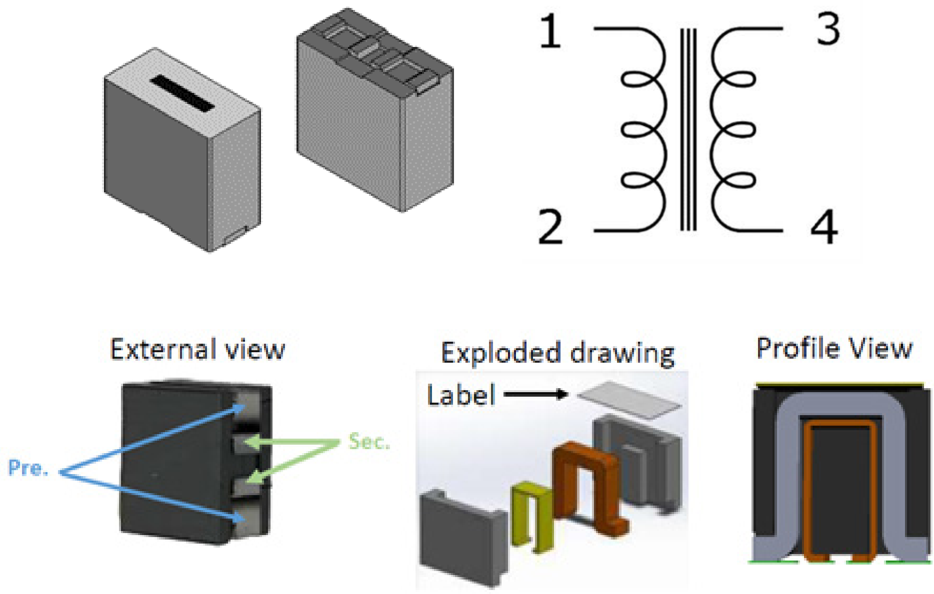

Figure [5]: TLVR inductor construction and equivalent schematic.

As Figure [5] depicts, a TLVR inductor is a transformer where the primary and the secondary windings are composed of two copper clips to minimize DC losses. Both clips are contained within a magnetic core made of ferrite or iron-based material, coupling both primary and secondary magnetically. Therefore, the non-ideal transformer model can be used to represent the functionality of each TLVR inductor. The model includes an ideal transformer, magnetizing inductance (L_m) and leakage inductance (L_{Leak}) which are not shown in Figure [4]. Please refer to [Exploring Transformer Basics Understanding Transformers: Part 1] for more insight about the transformer's non-ideal model.

How Does the TLVR Work?

TLVRs operate similarly to traditional multiphase converters. However, the key difference in the TLVR configuration is the utilization of the primary winding of each TLVR inductor as an output inductor for each phase. As depicted in Figure [3], the primary windings are subjected to staggered square wave voltage waveforms, such that only one phase is active at a given time. This creates a current waveform through each inductor, as shown in Figure [6B]. The secondaries of all phases are interconnected in series to a compensation inductor (L_c), as Figure [4] illustrates. Each primary winding's voltage is reflected on the corresponding secondary winding due to the 1:1 coupling. Since all secondaries are connected in series, the compensation inductor (L_c) sees the sum of all these waveforms.

Consequentially, as shown by the black waveform in Figure [6C], a triangular current waveform is generated in the secondary windings with a frequency [N] times higher than the switching frequency, where [N] is the number of phases. The size of the compensation inductor (L_C) and the duty cycle dictate the peak-to-peak current ripple in the secondary. This current is reflected from the secondary back to all primary windings, superimposing a triangular waveform on the original primary currents, creating the black waveforms shown in Figure [6D].

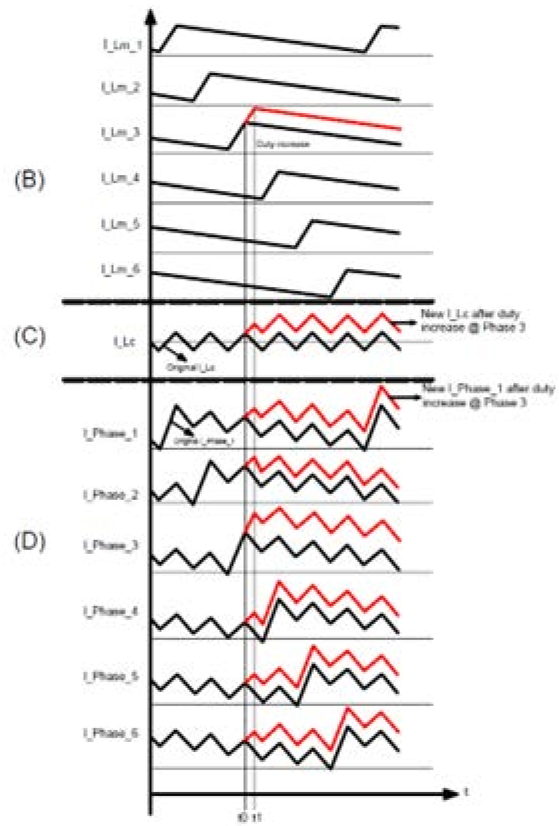

Figure [6]: Currents through different phases in a 6-phase TLVR and their reaction to increase in load [3]

When there’s a load change, such as a processor handling an intense task, the converter must supply more current as fast as possible. As was illustrated earlier, while more current is drawn from the converter, the voltage at the output starts dropping due to the parasitic ESR and ESL of the capacitor. The feedback control loop senses this drop and responds by increasing the drive level of whichever phase is active at that time, sourcing more current through that phase to limit the voltage drop and meet the new load demand.

An example of this phenomenon is shown by the red waveform in Figure [6B], where phase #3 reacts to a change in load, increasing the current through it. This additional current is reflected on the secondary winding, leading to an increase in the current already present, as shown by the red waveform in Figure [6C]. Here is where TLVRs excel over traditional multiphase converters: Since the secondary is coupled with all other phases, this new current waveform is reflected on all primary windings, leading to an instantaneous increase in current across all phases, as shown in red in Figure [6D]. This is achieved by the response of one phase to the feedback system, inducing a current through the other phases, hence the “trans-inductor” in the TLVR name. The collective response of all phases to changes in load circumvents the time the controller needs to trigger each of the other phases, leading to a faster transient response [3].

Why Abracon TLVR Inductors?

Abracon offers a wide selection of TLVR inductors through its ATL family. Well suited to meeting all customer needs, the ATL family is available in industry standard sizes between 9x6mm and 12x6mm with saturation current rating up to [160] amps. Abracon TLVR inductors use the same standard footprints that are being employed by some of the high-power inductors that are typically found in the traditional DC-DC converters, giving the designer the flexibility of swapping between the TLVR configuration and the traditional multiphase converter in the same build. In addition, Abracon supports custom TLVR solutions tailored to meet specific customer requirements, and is poised to support next generations product needs.

Conclusion

The emergence of various applications that require faster, high-load transients has necessitated the need for solutions that meet such rigorous requirements. The multiphase TLVR topology has emerged as a new design technique that improves upon the classical multiphase DC-DC converter by coupling all phases through a series connection of secondary windings, allowing all phases to concurrently respond to changes in load, leading to a much faster transient response time. Abracon's family of TLVRs can help engineers work within the design specs through its comprehensive portfolio, allowing a swift transient response while minimizing voltage drop. For more information about Abracon's TLVR Inductors, please click here.

Typical TLVR Inductors' Parameters

Primary and secondary inductances (L_{pri}/ L_{sec}): refer to the inductances of the primary or secondary windings of the TLVR. Since TLVR inductors typically have a 1:1 turn ratio, both inductances' values should be the same. The choice of the inductance value is mainly dependent on the duty cycle and the amount of current ripple allowed.

Full Load inductance (L_{Full}): the inductance of the TLVR when it is run at saturation current.

Temperature rise current (I_{rms}): the current that causes the temperature of the TLVR to rise by certain degrees. 40°C is the typical industry standard.

Saturation current (I_{sat}): the current that causes the inductance to drop by a certain percentage from its nominal value. Typical percentages are 20% and 30%. Saturation is usually measured at room temperature. However, some manufacturers include saturation measurement at higher temperatures, such as 100°C and 125°C.

Leakage inductance (L_{Leak}): Since the primary and secondary inductors are not perfectly coupled, some of the magnetic field is not linked between the two inductors. The amount of imperfect coupling can be quantified through leakage inductance. While its typical value is in the nano Henry range, it's important to take note of leakage as it will appear as a voltage drop across the isolation boundary. Some manufacturers use the coupling coefficient as an alternative.

DC resistance (DCR): Refers to the resistance of the copper conductor inside the TLVR. This parameter has a direct impact on the efficiency of the converter as it is the main contributor to the DC losses (I2 *DCR). For more details about the impact of DCR in DC-DC converter please refer to DC-DC Converters & the Importance of DCR-Optimized Inductors

References

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