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# Magnetic Integrated Trans-Inductor Voltage Regulator

## ABSTRACT

To meet the high and fluctuating power demand of ASICs, a state-of-the-art technique, trans-inductor voltage regulator (TLVR) has been proposed. However, this TLVR requires a compensation inductor in series with the secondary winding of its inductor/transformer to produce an additional coupling current to achieve a fast transient response. Therefore, the TLVR needs additional layout space and the compensation inductor imposes additional cost and power loss. This disclosure describes a magnetic integrated trans-inductor voltage regulator (MITLVR) that integrates the transformer and the compensation inductor into a magnetic component. This topology can achieve ultra-fast transient performance as TLVR but without an additional magnetic component in series with secondary winding. It provides a higher power density and cost-saving solution compared with existing TLVR and is suitable for xPU applications.

## KEYWORDS

- Multi-phase voltage regulator
- Decoupling capacitor
- Trans-inductor
- Transient response
- Load transient
- Voltage regulator bandwidth
- Trans-inductor voltage regulator
- Pulse width modulation (PWM)

## BACKGROUND

Ultra-high current demand ASICs are widely used in data centers, e.g., for AI/ML applications. These typically consume significantly high and rapidly fluctuating current, e.g., about a thousand amperes, and >10,000A/us di/dt slew rate. Due to many factors such as control bandwidth limitation and power density requirement, traditional multi-phase voltage regulators have transient performance limitations. In order to satisfy the power requirements of ASICs, a state-of-the-art technique, trans-inductor voltage regulator (TLVR) was proposed in [1]. The TLVR uses a winding coupling technique by the secondary winding of a transformer in a series loop to efficiently provide an extremely fast transient response that matches the demands of the load in amperage and bandwidth. However, the TLVR requires a compensation inductor in series with secondary winding to produce an additional coupling current to achieve a fast transient response. The compensation inductor not only occupies additional layout space but also makes additional cost and power loss.

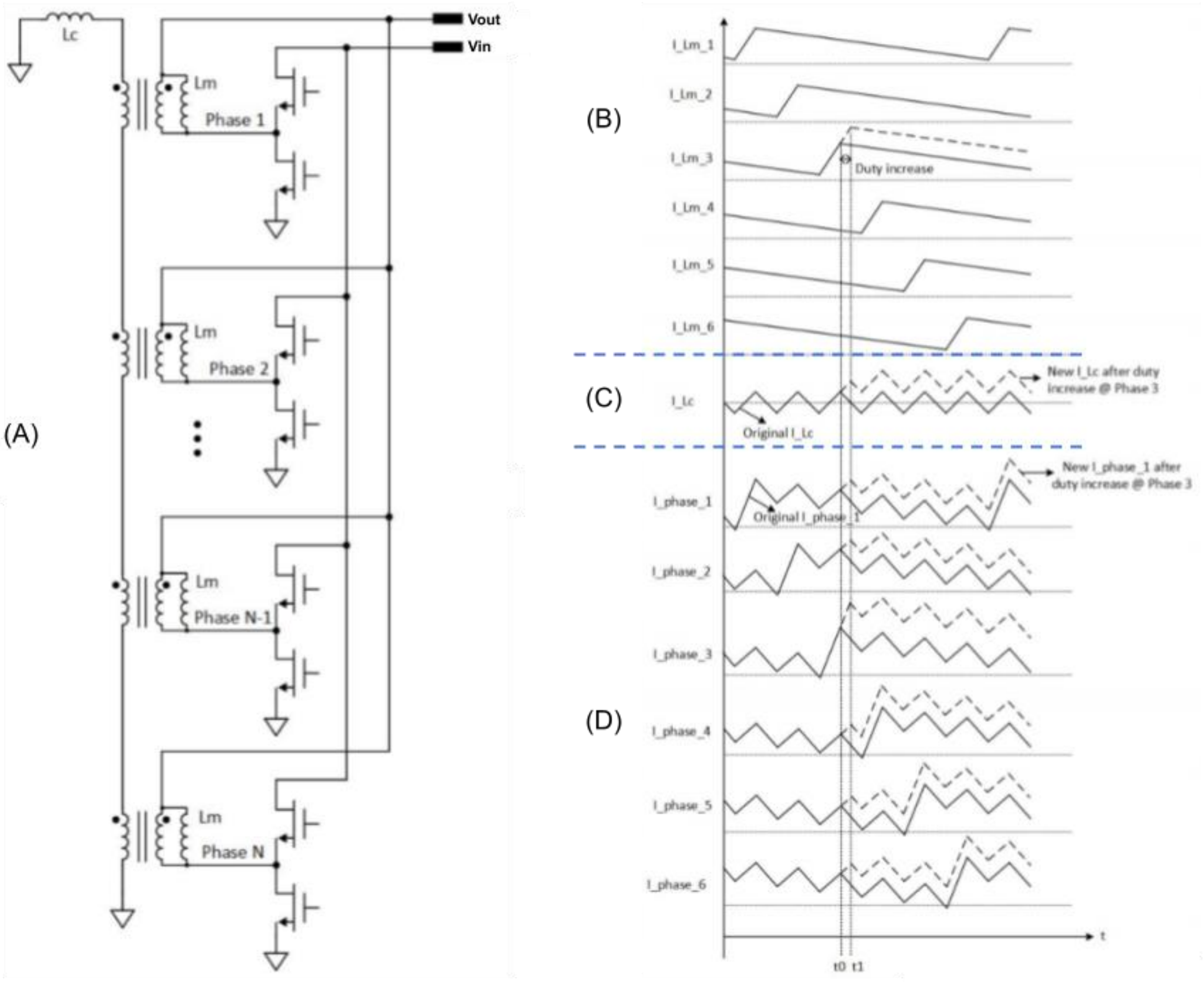

**Fig. 1: Transient operation of a TLVR. (A) Single-secondary TLVR (B) Currents through the magnetizing inductor of each phase (C) Current through the primary windings (D) Output current of each phase.**

Fig. 1 illustrates an N-phase single secondary TLVR, as described in [1]. The TLVR is such that each of its phases has an output inductor that is the primary winding of a transformer whose secondary windings are all connected in a series loop with a compensation inductor Lc. The secondary winding of a transformer is strongly coupled to the primary winding of the transformer with negligible leakage. Namely, the coupling coefficient Kps is close to unity. The primary to secondary turns ratio is typically 1:1 (or higher). The primary windings, connected in a series loop, have an additional compensation inductor Lc, and are grounded.

Fig. 1B-1D illustrate the transient operation of a single-secondary TLVR. When a fast load transient event appears at the multi-phase trans-inductor voltage regulator output, the duty cycle of the TLVR changes the PWM waveforms by a PWM controller such that all phases respond with a changed current. Since the PWM duty cycle changes, the magnetizing current I_Lm_x (Fig. 1B) changes through the magnetizing inductor, at the same time, the current I_Lc (Fig. 1C) through the compensation inductor also changes. Since the per-phase currents (Fig. 1D) are composed of the I_Lc and I_Lm_x, each phase current changes at the same time. This results in the fast transient response of the TLVR. Namely, the TLVR's equivalent output transient inductance is relatively lower than traditional multiphase VR implementation.

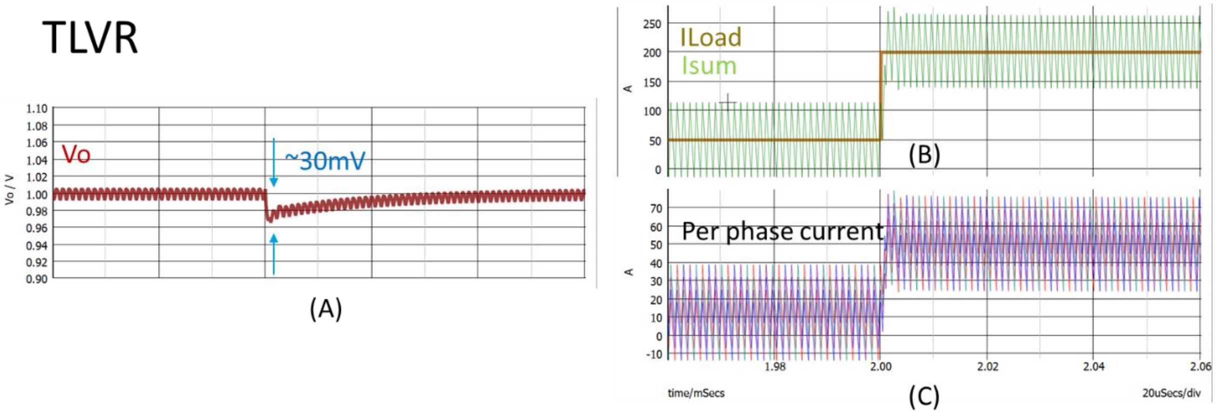

**Fig. 2: Transient response of a TLVR. (A) Output voltage response of the TLVR (B) Load transient and Current response of the TLVR (C) per phase current**

Fig. 2 illustrates the transient response of a four-phase TLVR with a 500 kHz PWM driver waveform, a compensating inductance Lc of 100 nH, and 3 mF MLCC decoupling capacitors. Fig. 2 (B) and (C) illustrate the load transient, which goes from 50 Amperes to 150 Amperes at a rate of 1 Amperes per nanosecond and the current output of the TLVR, which shows that the TLVR output current tracks load current quickly. Fig. 2 (A) illustrates the output voltage of the TLVR, which shows the voltage droop of only 30mV. In the other words, TLVR provides an extremely fast transient response.

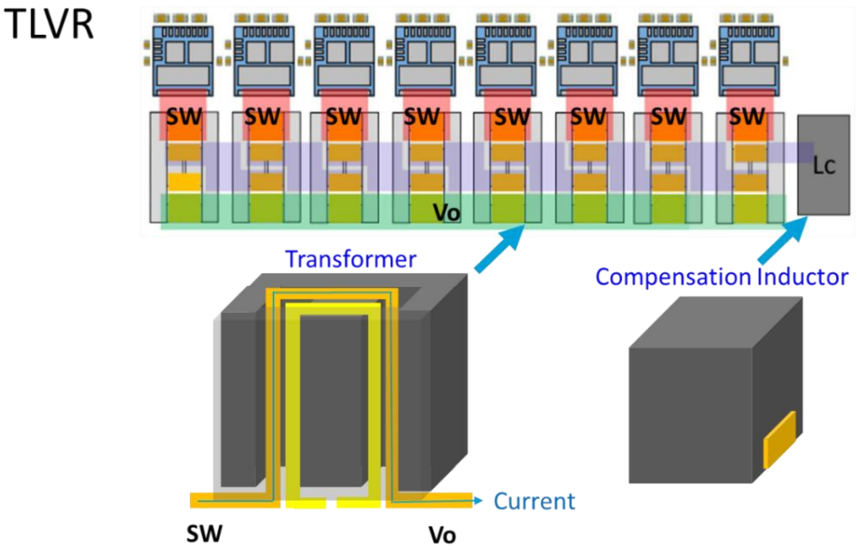

**Fig. 3: Physical Layout of a nine-phase single-secondary TLVR**

However, as shown in Fig. 3, the TLVR requires a compensation inductor in series with the secondary winding to produce an additional coupling current to achieve a fast transient response. Therefore, in TLVR design, the PCB layout needs to reserve additional space for the compensation inductor that might pose challenges for high-speed signal routings, especially for applications with lots of high speed IOs.

For example, in a server platform design, the TLVRs are placed close to the keep-out zone of the CPU in order to save the conduction loss of the power delivery path. Due to the additional compensation inductor of the TLVR occupying some layout space, the high-speed IO routing becomes crowded. This also raises challenges for high-speed signal routing. Moreover, the compensation inductor also makes additional cost and power loss.

## DESCRIPTION

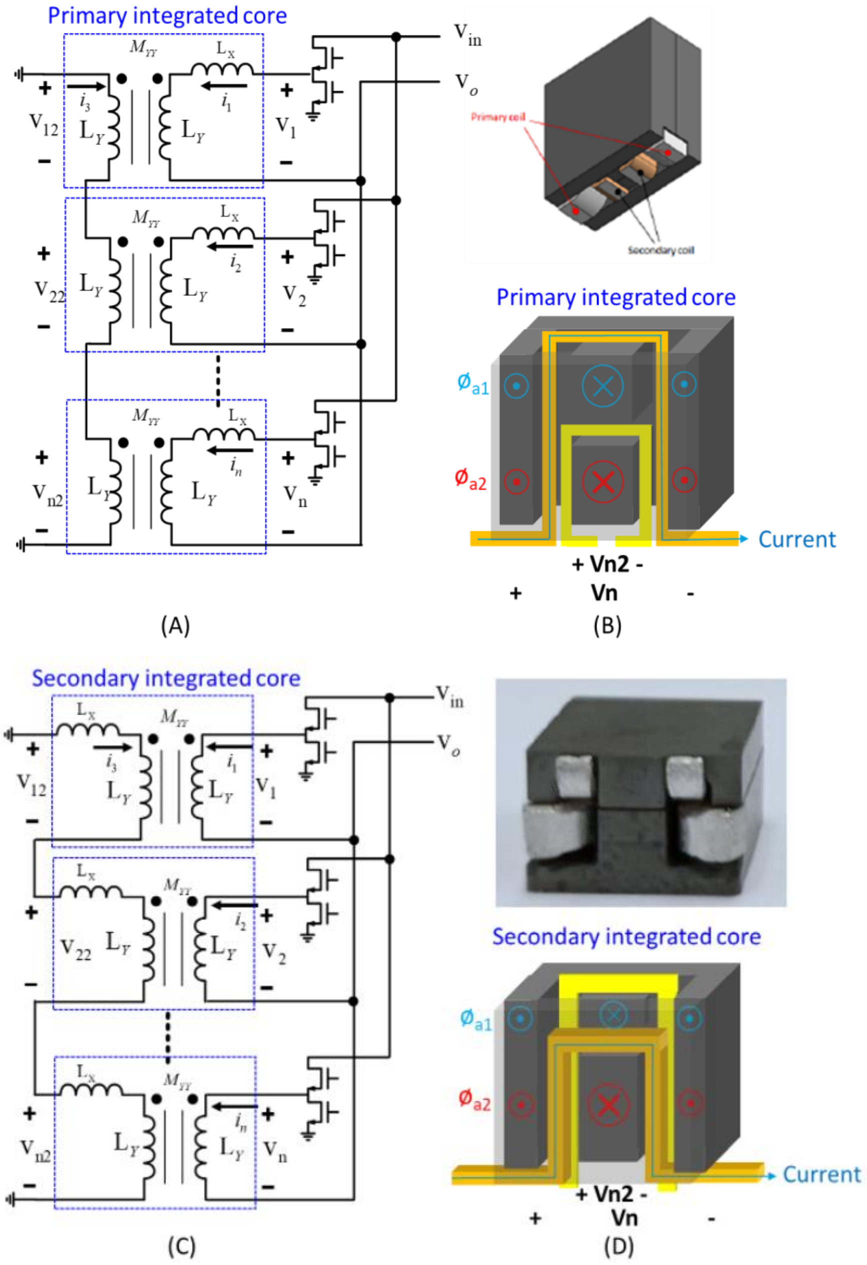

**Fig. 4: Magnetic integrated trans-inductor voltage regulators (MITLVR). (A) Primary integrated type (B) A physical primary integrated core structure (C) Secondary integrated type (D) A physical secondary integrated core structure.**

This disclosure describes a multi-phase N-phase Magnetic integrated trans-inductor voltage regulator (MITLVR), as shown in Fig. 4. Fig. 4(A) illustrates an N-phase primary integrated type MITLVR. Fig. 4(C) illustrates an N-phase secondary integrated type MITLVR. The MITLVR is such that each of its phases has an inductor Lx integrated with a transformer with self-inductor Ly and mutual inductor Myy. The transformer is strongly coupled with negligible leakage. Namely, the self-inductor Ly and mutual inductor Myy are almost equal, and the coupling coefficient is close to unity.

In the primary integrated type as shown in Fig. 4(A), the primary side winding of each transformer is connected in a series with an inductor Lx to a half-bridge switching note. Secondary windings of the transformers are connected in series and then grounded directly. Fig. 4 (B) illustrates the physical structure of a primary integrated core, there are two middle core legs with air gaps that carry two magnetic fluxes ϕa1 and ϕa2 separately. Since the magnetic reluctance of air gaps are much larger than the magnetic reluctance of the core, most of fluxes ϕa1 and ϕa2 go through the outer legs. There is no coupling effect between the two middle core legs. ϕa1 represents the flux through the inductor Lx and ϕa2 represents the flux through the transformer. In the other words, the inductor Lx and the transformer can be designed independently by sizing middle core legs and their air gaps. The dark yellow winding represents the transformer primary winding which is series with an inductor Lx, and the light yellow winding represents the secondary winding of the transformer.

In the secondary integrated type as shown in Fig. 4(C), the secondary side winding of each transformer is connected in a series with an inductor Lx and then all inductors Lx are all connected in a series loop and then grounded directly. Fig. 4(D) illustrates the physical structure of the secondary integrated core. Similarly, two middle core legs with air gaps carry two magnetic fluxes ϕa1 and ϕa2 separately. There is no coupling effect between two middle core legs. ϕa1 represents the flux through inductor Lx and ϕa2 represents the flux through the transformer. By sizing core legs and air gaps, the inductor Lx and the transformer can be designed separately. Compared with the primary integrated core, the difference is that the primary winding (dark yellow) only crosses to the transform core leg but the secondary winding (light yellow) crosses two legs and is in series connection, so the inductor Lx is in series with the secondary winding of the transformer.

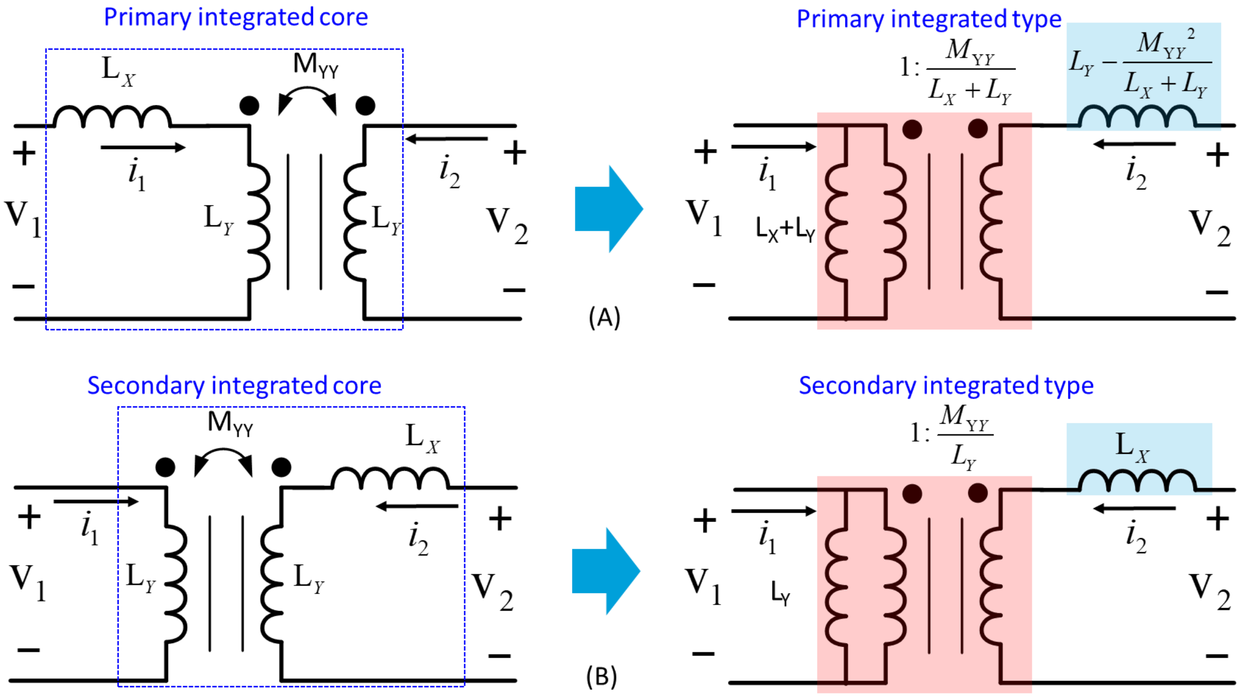

**Fig. 5: Integrated core equivalent circuit. (A) Primary integrated type (B) Secondary integrated type**

Fig. 5 illustrates integrated core equivalent circuits. The primary integrated type and the second integrated type MITLVR can be identical with an inductor in series to the secondary winding of a transformer and a parallel inductor connected to the primary winding. Each equivalent series inductance, equivalent parallel inductance, and the equivalent turns ratio of the transformer can be expressed by a function of the physical inductance Lx, self-inductor Ly and mutual inductor Myy, respectively.

Based on the equivalent circuit characteristic, the MITLVR can achieve the same or similar performance as traditional TLVR. For example, if the physical self-inductance Ly is designed close to mutual inductance Myy (strongly coupling) in the secondary integrated type MITLVR, the equivalent turns ratio of the transformer will be close to unity and inductance Lx will replace the TLVR’s compensation inductance Lc divided by phase number N. The MITLVR can achieve the fast transient response without the additional series compensation inductor.

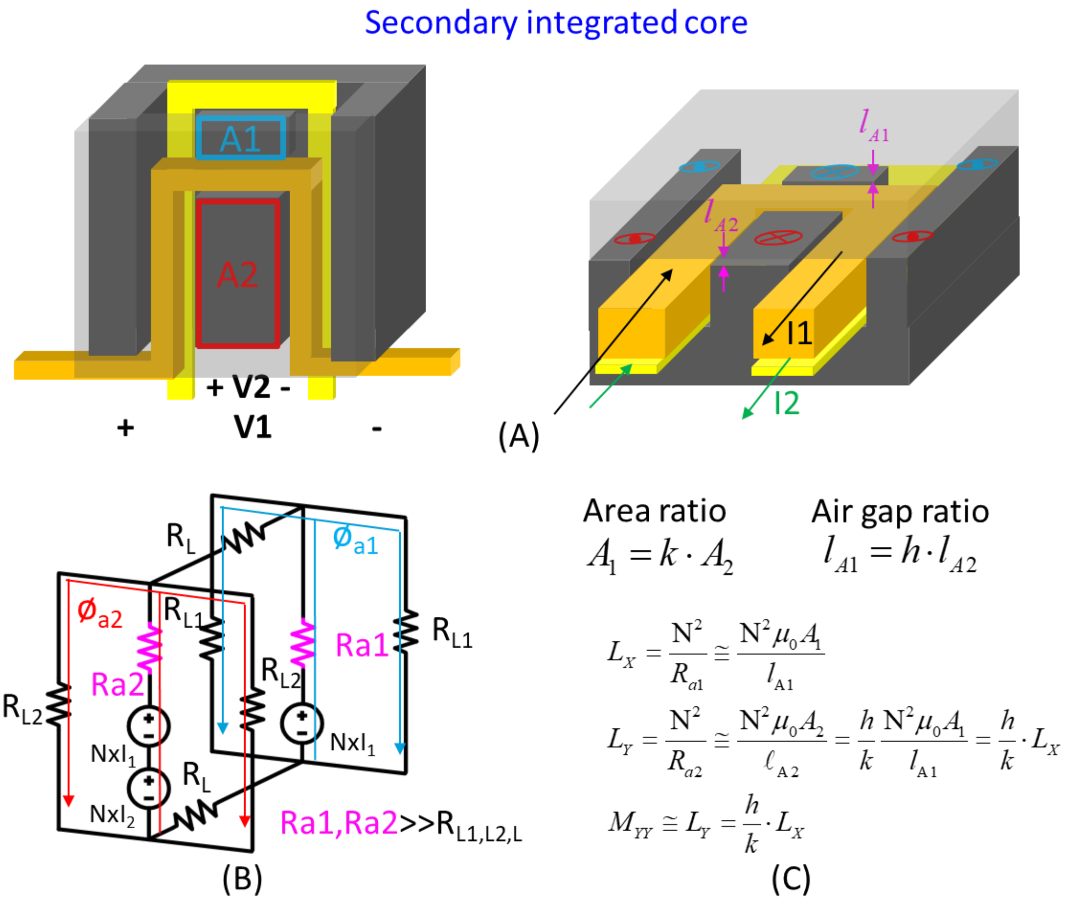

**Fig. 6: Secondary integrated core. (A) Physical structure (B) Magnetic reluctance model (C) Inductor Lx/self-inductor Ly/ mutual inductor Myy equations.**

Fig. 6 illustrates a secondary integrated core modeling. Fig. 6(A) illustrates the physical structure for a secondary integrated core, where the A1 and A2 represent the middle core leg cross-sectional areas, respectively. lA1 and lA2 represent the lengths of air gaps inside the middle core legs. Fig. 6(B) illustrates a magnetic reluctance model for a secondary integrated core. Ra1 and Ra2 express the magnetic reluctance of two air gaps and RL1 / RL2 / RL represent the equivalent magnetic reluctance of the core.

Fig. 6(C) illustrates the relation between inductance and physical parameters, where k and h are the ratios of cross-sectional areas and air gaps; N is the number of turns; and u0 is the permeability of air. Here, since the magnetic reluctance of air is much larger than the magnetic reluctance of the core, the inductance is dominated by the cross-sectional area of the air gap and the length of the air gap. The inductance Lx or Ly can be sized by k and h once one of the values is defined.

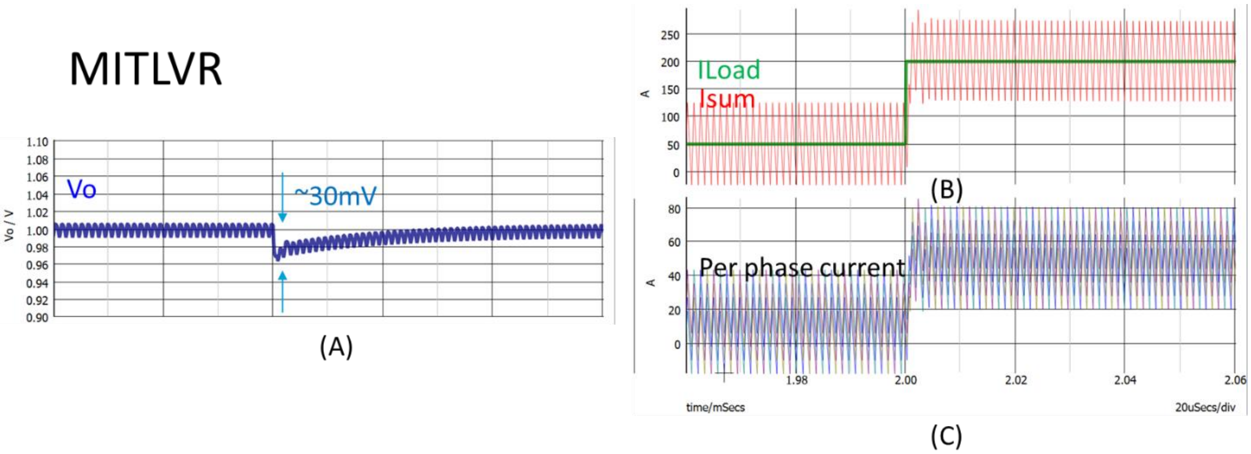

**Fig. 7: Transient response of a secondary integrated type MITLVR. (A)Output voltage response of the MITLVR (B) Load transient and Current response of the MITLVR (C) per phase current**

Fig. 7 illustrates the transient response of a secondary integrated type four-phase MITLVR with a 500 kHz PWM driver waveform, a series inductor of 25 nH (the TLVR’s compensation inductance Lc of 100nH divided by phase number 4), and 3 mF MLCC decoupling capacitors. Figs. 7(B) and 7(C) illustrate the load transient, which goes from 50 amperes to 150 amperes at a rate of 1 ampere per nanosecond and the current output of the MITLVR, which shows that the MITLVR output current tracks the load current quickly. Fig. 7(A) illustrates the output voltage of the MITLVR. As seen, the voltage droop is almost the same as that of Fig. 2. In the other words, the MITLVR described herein provides a similarly ultra-fast transient response as the TLVR of Fig. 1.

## CONCLUSION

This disclosure describes a magnetic integrated trans-inductor voltage regulator (MITLVR) that integrates the transformer and the compensation inductor into a magnetic component. This topology can achieve ultra-fast transient performance as TLVR but without an additional magnetic component in series with secondary winding. It provides a higher power density and cost-saving solution compared with existing TLVR and is suitable for xPU applications.

## REFERENCES

1. "Fast multi-phase trans-inductor voltage regulator", Technical Disclosure Commons, (May 09, 2019) https://www.tdcommons.org/dpubs_series/2194