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Predicting Individual Phase Current in Couple Inductor Based Voltage Regulators (VRs)

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Abstract

Coupled inductor is one appealing technology to improve transient response and reduce output decoupling significantly in interleaved multi-phase voltage regulators (VRs). One known problem is that there is no mature solution yet to sense the individual phase current accurately in a lossless way for couple inductor based VRs design. This will impact VR some normal function in one phase mode. This paper proposes a new solution to this problem and simulation is conducted to verify effectiveness of the proposal.

Keywords

Current Sensing, Couple Inductor, Voltage Regulator (VR)

1. Introduction

According to the microprocessor's roadmap, there are several stringent challenges for the future microprocessor voltage regulators (VRs): high output current, low output voltage, high current slew rate and low droop resistance. These challenges require the VRs to have both higher steady state performance and faster transient performance. To improve above issues in today's multiphase non-coupled VRs, inverse coupled inductor VRs are proposed mainly to improve transient response significantly so that both real estate and cost could be saved on output decoupling [1] [2]. Some studies also show that inverse coupled inductor could also help improve converter conversion efficiency if keeping same transient response as non-coupled multiphase VRs [3] [4]. With all these advantages, one known issue for couple inductor based VR design is that there is no good solution yet to accurately sense each individual phase current of VR because of coupling effect between different phases [5]. As shown in **Figure 1(a)**, typically a lossless DCR sensing method is widely adopted in conventional couple inductor based VR design to get total output current information of all the phases with right time constant match. However, as shown in **Figure 1(b)**, the sensed voltage V_{c1} and V_{c2} does not exactly conform to individual phase current i_1 and i_2 [5]. This deviates from the perception that V_{c1} and V_{c2} should be strictly proportional to i_1 and i_2. This method can ensure a normal function of VR which depends on total current of multiphase, however, knowing individual

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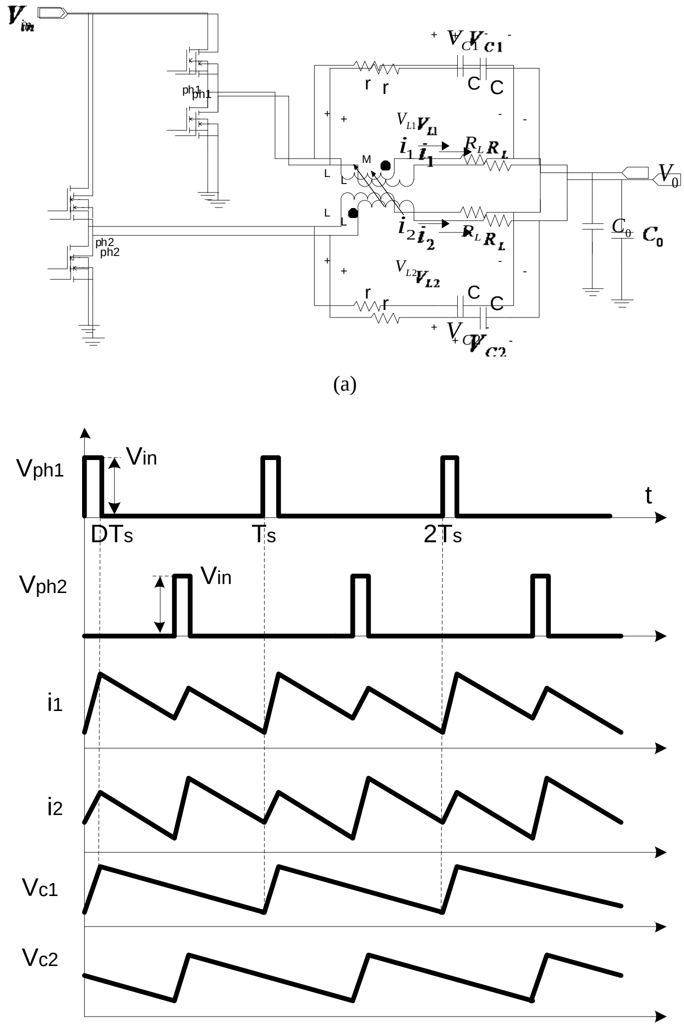

(a)

(b)

Figure 1. Traditional 2-phase coupled inductor VR with lossless current sense: (a) circuit; (b) inductor current and sensed voltage at capacitor.

phase current is of great importance for phase current balance, power monitor and especial for load line control when VR works under one phase mode (under light load mode).

This paper proposes one new method to sense individual phase current of couple inductor based VRs in a lossless way. Detailed working principle is analyzed and simulation is also conducted to verify the theoretical analysis. Even this method is initially proposed for couple inductor application, it's proved that it's a universal method which could be applied to both couple inductor and non-couple inductor multiphase buck voltage regulators.

2. Proposed New Current Sensing Method and Its Working Principle

2.1. Proposed Method

As shown in **Figure 2** and **Figure 3**, the proposed new current sensing method consists of following ingredients:

- One interleaved two-phase coupled inductor VR as shown in **Figure 2**. it replaces couple inductor in **Figure 1** with an equivalent circuit model. Detailed deduction could be found in [5] and is not described here.
- For coupled inductor, M is the mutual inductance, L is self inductance, L_k is the leakage inductance and $L_k = \left(1-k^2\right)L$, and k is the coupling coefficient defined as $k = M/L$. R_L is DCR of inductor individual winding.

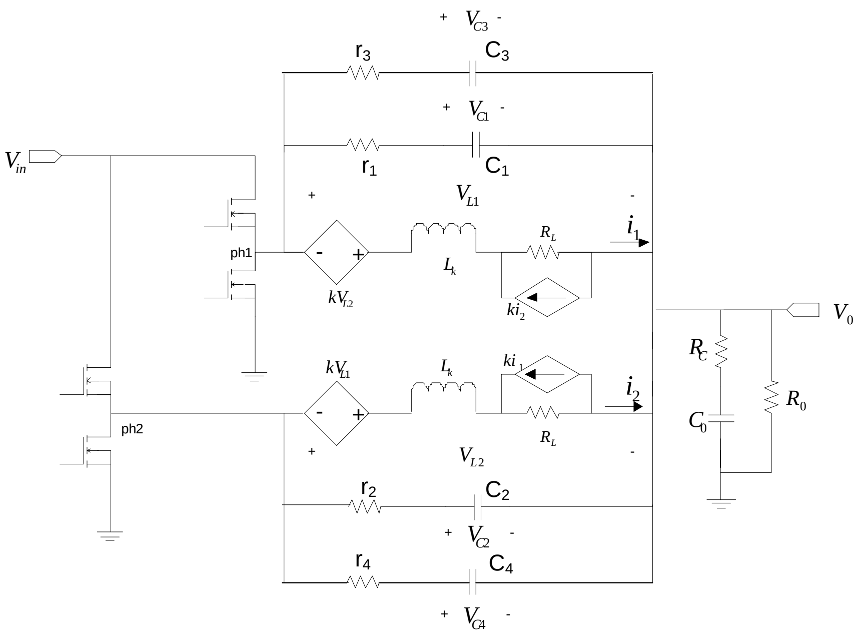

Figure 2. New current sensing for 2-phase coupled inductor VR.

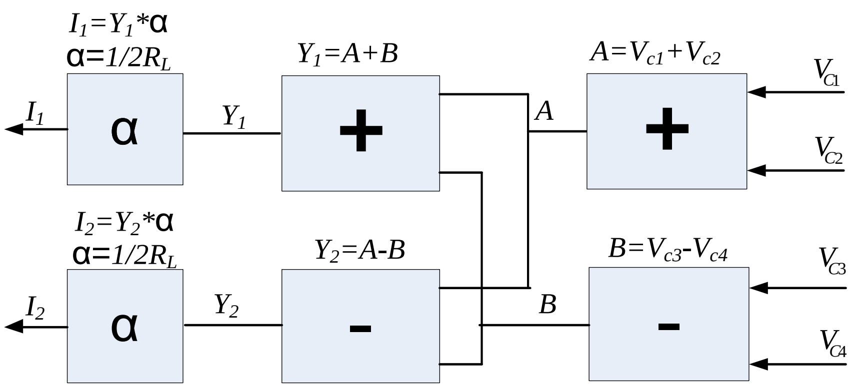

Figure 3. Function diagram to get individual phase current.

- Two groups of DCR current sensing networks. Group 1 consists of r_1, C_1, r_2, C_2; group 2 consists of r_3, C_3, r_4, C_4. There is relationship: $r_1 = r_2$, $C_1 = C_2$, $r_3 = r_4$, $C_3 = C_4$. V_{c1}, V_{c2}, V_{c3} and V_{c4} are voltages across C_1, C_2, C_3 and C_4 respectively.
- Function block including adder, subtracter, proportional amplifier as shown in **Figure 3** to get final individual current i_1 and i_2. The function block could be implemented in either analog or digital way and also could appear in other form/combination so long as it can achieve same mathematic result.

2.2. Working Principle

By comparison, proposed method adopts two groups DCR sensing networks instead of one in conventional multiphase buck regulator design. From **Figure 2** and **Figure 3**, following equations could be derived [5]:

$$v_{L1} = L_k \frac{\mathrm{d}i_1}{\mathrm{d}t} - kv_{L2} + R_L\left(i_1 + ki_2\right) \tag{1}$$

$$v_{L2} = -kv_{L1} + L_k \frac{\mathrm{d}i_2}{\mathrm{d}t} + R_L\left(ki_1 + i_2\right) \tag{2}$$

where M, L_k, L and k have same definition as aforementioned. i_1 and i_2 are individual phase current, v_{L1} and v_{L2} are voltage across L_1 and L_2 respectively. If transforming Equations (1)-(2) from time-domain to s-domain, following equations could be obtained:

$$V_{L1}(s) = sL_k I_1(s) - kV_{L2}(s) + R_L(I_1(s) + kI_2(s)) \tag{3}$$

$$V_{L2}(s) = -kV_{L1}(s) + sL_k I_2(s) + R_L(kI_1(s) + I_2(s)) \tag{4}$$

The voltage across C_1, C_2, C_3 and C_4 could be represented by Equations (5)-(6):

$$V_{C1}(s) = \frac{V_{L1}(s)}{1 + sr_1C_1}, \quad V_{C2}(s) = \frac{V_{L2}(s)}{1 + sr_2C_2} \tag{5}$$

$$V_{C3}(s) = \frac{V_{L1}(s)}{1 + sr_3C_3}, \quad V_{C4}(s) = \frac{V_{L2}(s)}{1 + sr_4C_4} \tag{6}$$

With the fact of: $r_1 = r_2$, $C_1 = C_2$, $r_3 = r_4$, $C_3 = C_4$, the relationship of the voltages across the sensing capacitors can be obtained as:

$$V_{C1}(s) + V_{C2}(s) = R_L \frac{I_1(s) + I_2(s)}{1 + sr_1C_1}\left(1 + s\frac{L_k}{R_L(1+k)}\right) \tag{7}$$

$$V_{C3}(s) - V_{C4}(s) = R_L \frac{I_1(s) - I_2(s)}{1 + sr_3C_3}\left(1 + s\frac{L_k}{R_L(1-k)}\right) \tag{8}$$

If r_1 and C_1 are selected such that:

$$r_1C_1 = \frac{L_k}{R_L(1+k)} = \frac{(1-k)L}{R_L} \tag{9}$$

Then Equation (7) becomes:

$$V_{C1}(s) + V_{C2}(s) = R_L(I_1(s) + I_2(s)) \tag{10}$$

If r_3 and C_3 are selected such that:

$$r_3C_3 = \frac{L_k}{R_L(1-k)} = \frac{(1+k)L}{R_L} \tag{11}$$

Then Equation (8) becomes:

$$V_{C3}(s) - V_{C4}(s) = R_L(I_1(s) - I_2(s)) \tag{12}$$

In time-domain, (10) and (12) can be expressed as:

$$v_{C1}(t) + v_{C2}(t) = R_L(i_1(t) + i_2(t)) = A(t) \tag{13}$$

$$v_{C3}(t) - v_{C4}(t) = R_L(i_1(t) - i_2(t)) = B(t) \tag{14}$$

From (13) and (14), we can get the individual phase current as following:

$$i_1(t) = \frac{A(t) + B(t)}{2R_L} \tag{15}$$

$$i_2(t) = \frac{A(t) - B(t)}{2R_L} \tag{16}$$

It can be seen that the key to get individual phase current is depended on two steps: first, choose right *RC* parameters to satisfy Equations (9) and (11); second, derive individual phase current according to Equations (13)-(16). By the way, all above equation derivation is based on couple inductor design with coupling coefficient *k*. it's obvious the condition of $k = 0$ is corresponded to non-couple inductor design, which indicates this method actually applies to non-couple inductor multiphase VRs as well.

3. Simulation Results

Since there is no existed IC solution in industry yet to support the concept verification, simulation is used here as an alternative way to verify the proposed method in this paper.

3.1. For Couple Inductor Design

One simulation is conducted for a typical coupled inductor $(k = 0.6)$ based two-phase interleaved VR design by using Hspice tool. Key parameters are shown as following:

Inputvoltage: V_{in} = 12.6 V; Output voltage: V_o = 1 V; Coupling coefficient: k = 0.6; Self inductance: L = 1 uH; Individual Inductor DCR: R_L = 1mohm; Per-phase switching frequency: $f_{sw} = 300$ kHz.

Current sense network is designed to satisfy (9) and (11): $r_1 = r_2$ = 4 kohm, $C_1 = C_2$ = 0.1 uF, $r_3 = r_4$ = 4 kohm, $C_3 = C_4$ = 0.4 uF.

3.2. Simulation Results

Figure 4 shows that voltage across C_1 and C_2 cannot represent individual phase current i_1 and i_2, but sum of voltage across C_1 and C_2 can represent total output current. **Figure 5** shows that voltage across C_3 and C_4 cannot represent individual phase current i_1 and i_2 either, but (V_{c3}-V_{c4}) can represent (i_1-i_2) according to above analysis even it's not straightforward yet.

As show in **Figure 6**, $i_{(v1)sim}$ and $i_{(v2)sim}$ are individual phase#1 and phase#2 current directly probed from inductors L_1 and L_2 in simulation circuit which is not feasible to test in practice; $i_{(v1)new}$ and $i_{(v2)new}$ are individual phase#1 and phase#2 current which is obtained by the proposed method. Waveforms for phase#1 and phase#2 current are identical even they are obtained from different way. This verifies the proposed method can accurately predict individual phase current for the couple inductor design.

3.3. For Non-Couple Inductor Design

To verify proposed method could be also applied to non-couple inductor design, the other simulation is conducted for a two-phase interleaved VR design with uncoupled inductor (k = 0). Following are key design parameters:

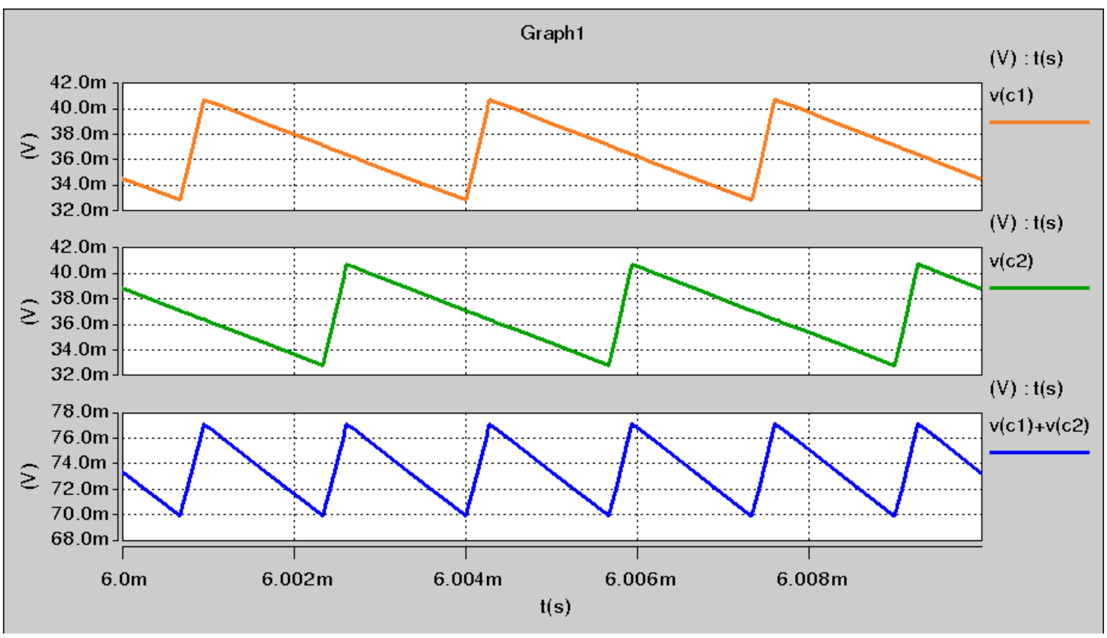

Figure 4. [$C_1 = C_2$ = 0.1 uF], v(c1), v(c2) and A(t) = v(c1) + v(c2) waveform.

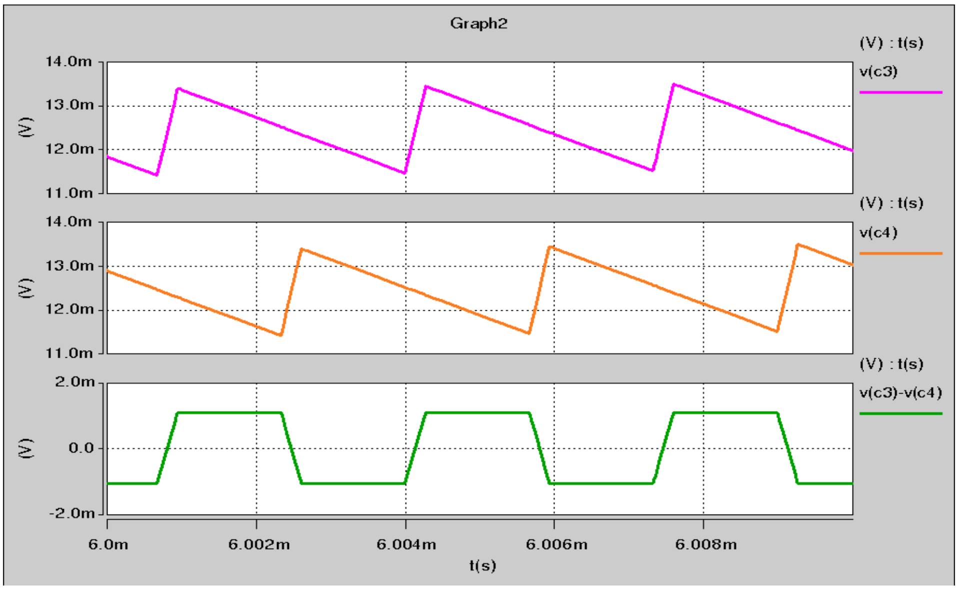

Figure 5. [$C_3 = C_4 = 0.4$ uF], v(c3), v(c4) and B(t) = v(c3) − v(c4) waveform.

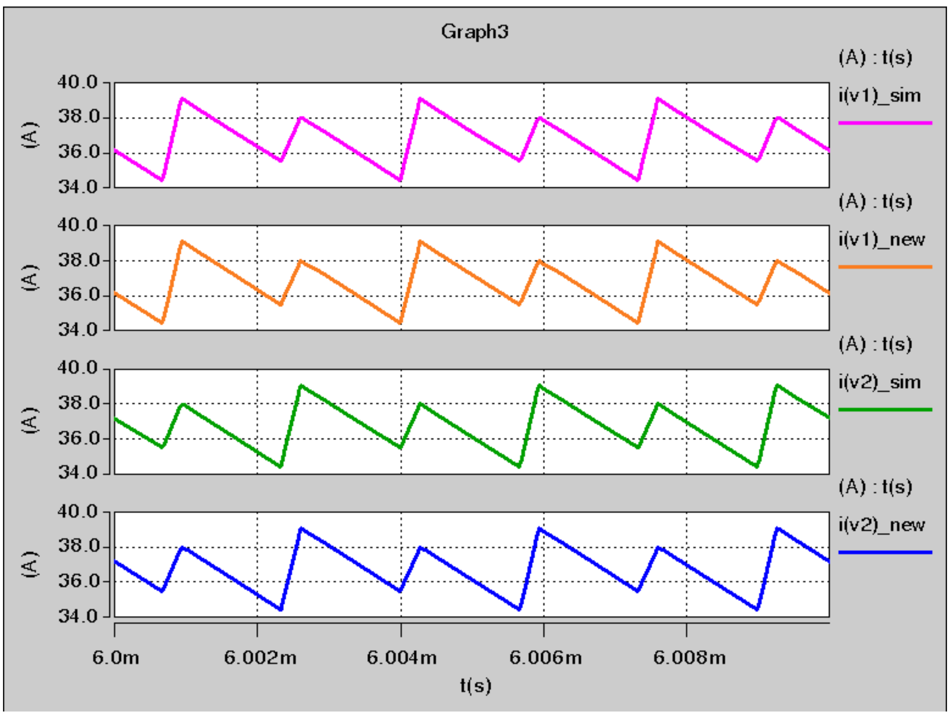

Figure 6. Probed phase current vs. derived phase current for couple inductor design.

Input voltage: $V_{in} = 12.6$ V; Output voltage: $V_o = 1$ V; Coupling coefficient: $k = 0$; Self inductance: $L = 1$ uH; Individual Inductor DCR: $R_L = 1$ mohm; Per-phase switching frequency: $f_{sw} = 300$ kHz.

Current sense network parameter is designed to satisfy (9) and (11): $r_1 = r_2 = r_3 = r_4 = 4$ kohm, $C_1 = C_2 = C_3 = C_4 = 0.25$ uF. For non-couple inductor design, two groups of sensing networks are identical, so $V_{c1} = V_{c3}$, $V_{c2} = V_{c4}$. **Figure 7** shows derived A(t) and B(t) waveforms. Typically, non-couple inductor design only need one group DCR sensing network to get individual phase current since V_{c1} and V_{c2} could represent actual phase#1 and phase#2 current. Purpose here is just to verify the proposed method can also apply to non-couple inductor design.

As shown in **Figure** 8, $i_{(v1)sim}$ and $i_{(v2)sim}$ are individual phase#1 and phase#2 current directly probed from

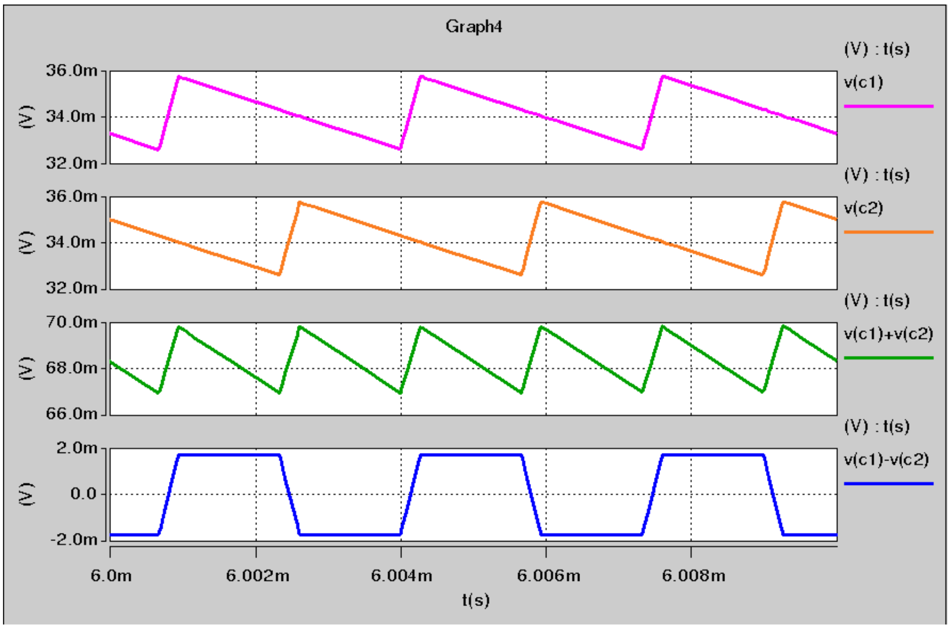

Figure 7. v(c1) = v(c3), v(c2) = v(c4), A(t) = v(c1) + v(c2) and B(t) = v(c1) − v(c2) waveform.

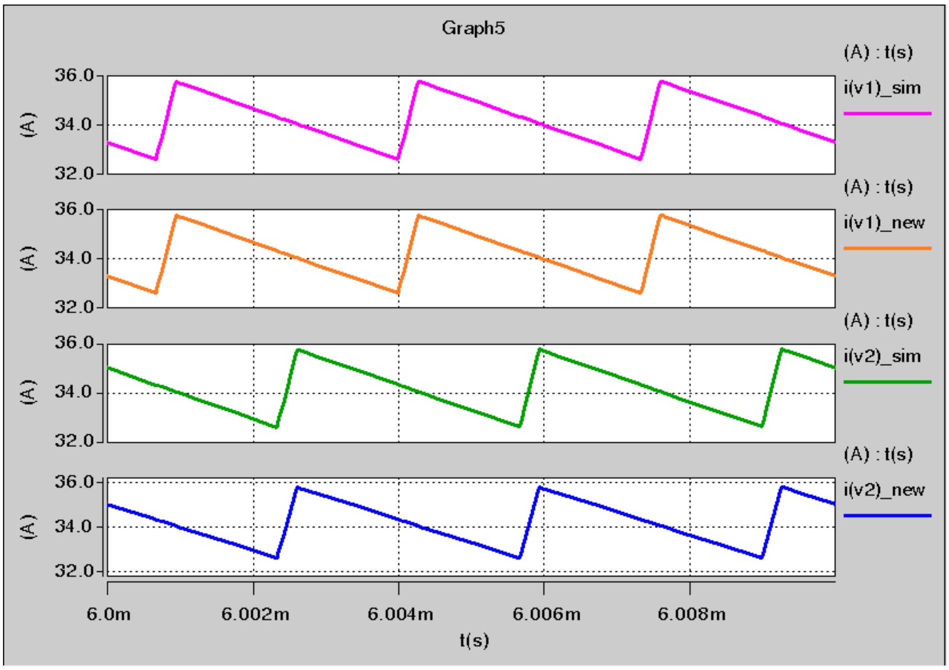

Figure 8. Probed phase current vs. derived phase current for non-couple inductor design.

inductors L_1 and L_2 in simulation circuit which is not feasible to test in practice; $i_{(v1)new}$ and $i_{(v2)new}$ are individual phase#1 and phase#2 current which is obtained by proposed method. Waveforms for phase#1 and phase#2 current are identical even they are obtained from different way, which verifies the proposed method can accurately predict individual phase current for non-couple inductor design as well

4. Conclusions

One new method is proposed to losslessly sense individual phase current for couple inductor based interleaved multiphase VR design. Working principle is analyzed in detail and simulation is conducted to verify all theoretical analysis. It proves that this method is a universal way both for couple and non-couple inductor designs.

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