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Inductor Characteristics Analysis in High Power Interleaved Buck Converter

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** Short Paper*

** Extended from a Conference: Preliminary results of this paper were presented at the IEEE ICCE-Asia 2016. This present paper has been accepted by the editorial board through the regular reviewing process that confirms the original contribution.*

Abstract**:** Inductor in high power converter system increases production cost, volume and core loss proportional to the power. To decrease these disadvantages, this paper analyzed the characteristic of parallel-inductor and coupled-inductor in interleaved system with simulation. As a result, it is confirmed that two-phase interleaved non-coupled buck-converter has the best characteristic among three types converter.

Keywords**:** Inductor, High power buck converter, Interleaved

1. Introduction

Since VRF (Variable Refrigerant Flow) was introduced for the first time in Japan 20 years ago, it has been able to operate air-conditioning and heating, and has been attracting attention as a heating and cooling system for medium and large-sized buildings. VRF system is basically larger and more complex than the multi-split type, unlike the chiller system which uses the existing duct. VRF, which is equipped with many compressors and interior evaporators, has complicated control system and it uses 380V commercial power [1]. However North America uses 575V high commercial power different from other country include Korea.

To cope with this, a power conversion device having a high power rated should be selected in power conversion system. Generally, the criteria for the rated power of power conversion device such as IGBT is selected considering the voltage variation rate, surge voltage and input voltage margin and semiconductor manufactures classifies 600V, 1200V, 1700V, 3300V incase of IGBT.

Because of 575V commercial voltage in North America, 1700 rated voltage IGBT is proper and it gives rise to increase the manufacture cost and difficulty the IGBT supply of power conversion system in VRF. The use of high voltage also increases the volume of power conversion system due to the increment of separation distance inside the module. It causes decrement not only productive capacity, but also system reliability so high power conversion system is required which reduce the high input voltage to low input voltage in industry.

Phase controlled rectifier is a type of AC to DC converter, which varies the output voltage. Phase controlled rectifier has advantage in maintain the output voltage in condition of input voltage variation. However supplement of the high power phase controlled rectifier devices is not easy and it can't provide good performance in PF(Power Factor) because of phase delay.

Switch mode power supply is required electrical insulation between input and output to protect users from the high voltage and leakage current accident. High frequency transformer is used for isolation. But transformer volume and product cost is raised because core and wire cross-section area of transformer should be wide in high power system.

As a result that topology for easy configuration is required. Along with the transformer, inductor also increase the manufacturing cost of the power conversion system with PWM switching in proportion to inductance, and the hysteresis loss increases in proportion to the core cross-sectional area as the volume increases [2].

To overcome these disadvantage interleaved structure has been studied. Interleaved structure has N-times switching frequency effect by superimposed current because of multiphase structure. Not only that phase difference from the distributed current by number of interleaved phase effects on setoff of current ripple and it causes the reduction of output filter capacity and volume according converter output current decrement [3].

High power interleaved buck-converter has not been published so far. This paper analyses and verifies the dynamic characteristic of normal-inductor and coupled-inductor by simulation with POWERSIM in interleaved system to apply the interleaved buck-converter to conditioning equipment power conversion system.

2. Inductor Loss Analysis of Buck-converter

2.1 Inductor Core Loss Analysis

Output current ripple of single buck-converter derived as Eq. (1).

$$\Delta i_{Lo} = \frac{V_o}{L}(1-D)T_s, \quad (1)$$

$$\lambda_{max} = L i_{max}, \quad (2)$$

$$\lambda_{max} = n\phi_{max} = nSB_{max}, \quad (3)$$

$$L i_{max} = nSB_{max}, \quad (4)$$

where D is duty cycle of converter, T_s is switching period of converter.

Eqs. (2)-(4) shows the relation among inductance, current and area using Area Product Approach in magnetic element design [4]. Where, λ_{max} is flux linkage max, ϕ_{max} is flux max, S is core cross-section area, B_{max} is magnetic flux density max. From the Eq. (4) it can be seen core cross-sectional area is proper to inductance in condition of other parameter is constant.

As a result of that using big inductance inductor increases the system volume. By Fig. 1 energy consumption of inductor for a cycle of switching is derived as Eq. (5). Eq. (7) shows flux linkage variation and Eq. (8) explain magnetic field.

$$W_{loss} = \int_{OC} v(t)i(t)\,dt, \quad (5)$$

where T_s is one cycle.

$$\lambda(t) = n\phi(t) = nSB(t), \quad (6)$$

$$\frac{d\lambda(t)}{dt} = nS\frac{dB(t)}{dt} = v(t), \quad (7)$$

$$H(t)l_m = ni(t), \quad (8)$$

Substituting Eqs. (7) and (8) to (5), core hysteresis loss of core by core cross-sectional area and B-H loop derived as Eqs. (9) and (10).

$$W_{loss} = Sl_m \int_{OC} HdB, \quad (9)$$

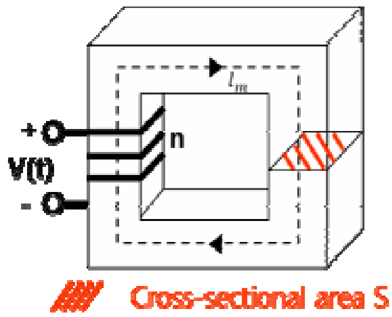

Fig. 1. Structure of Inductor.

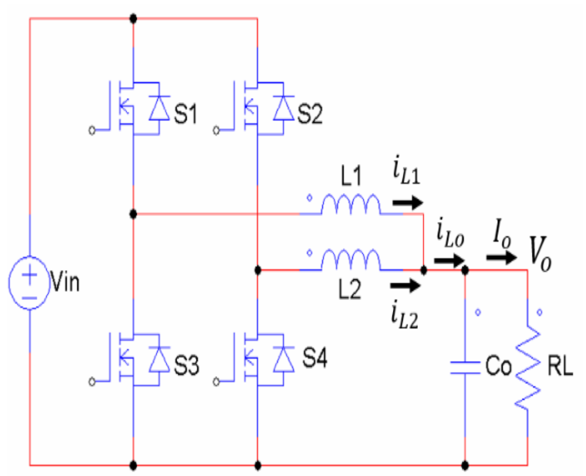

Fig. 2. Circuit of Two-phase interleaved buck converter (non-coupled type).

$$P_{loss} = Wf_s, \quad (10)$$

$$P_{loss} = Sl_m f_s \int_{OC} HdB, \quad (11)$$

where Sl_m is volume of the core, f_s is switching frequency and $\int_{OC} HdB$ is hysteresis loop area.

By Eq. (11), wide core cross-sectional area and high switching frequency increases energy loss and it occurs as heat. Accordingly, it can be seen that volume of system is proportionally increased by inductance and core loss is raised proportional to core cross-sectional area.

2.2 Two-phase Interleaved Buck-converter (Non-coupled Type)

The ripple current of inductor 1 and inductor 2 is explained by Eq. (12) in two-phase interleaved buck converter (non-coupled type) when L1 and L2 is equal as L. [5]

$$\Delta i_L = \frac{V_o}{L}(1-D)T_s, \quad (12)$$

where $L = L_1 = L_2$.

Output current is explained as $i_{Lo} = i_{L1} + i_{L2}$ and current

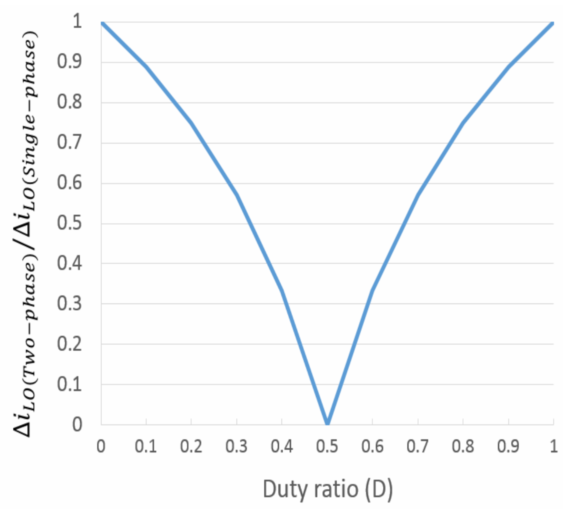

Fig. 3. Output current ripple of two-phase interleaved buck converter normalized with respect to that of single-phase case.

ripple occurs two times during a period (T_S). In other words, output current ripple frequency is double times of switching frequency.

$$\Delta i_{Lo} = \frac{V_o}{L}(1-2D)T_s\,, \tag{13}$$

Output current ripple is shown as below: Output current ripple of two-phase system is lower than single-phase system, comparing Eqs. (1) and (13). Fig. 3 explains that two-phase output current ripple is reduced than single-phase one when D is as close as 0.5.

2.3 Two-phase Interleaved Buck-converter (Coupled Type)

Eqs. (14) and (15) indicate inductor and output current ripple. [6]

$$\Delta i_L = \frac{V_o}{L_{lk}}\left(\frac{1-D-kD}{1+k}\right)T_s\,, \tag{14}$$

$$\Delta i_{Lo} = \frac{V_o}{L_{lk}}(1-2D)T_s$$

$$k = \frac{L_m}{L_s}\,, \tag{15}$$

$$L_s = L_m + L_{lk}$$

where k is coupling coefficient, L_s is self inductance, L_m is magnetizing inductance, and L_{lk} is leakage inductance.

Eq. (15) is the same with Eq. (13), where $L_{lk} = L$. It is obvious that inductor current ripple of coupled system is lower than non-coupled system from Eqs. (14) and (14).

By Fig. 5 it is clear that coupled inductor current ripple is decreased that coupled-inductor in condition of $L = L_{lk}$, D is much closer to 0.5 and k is closely approach to 1.

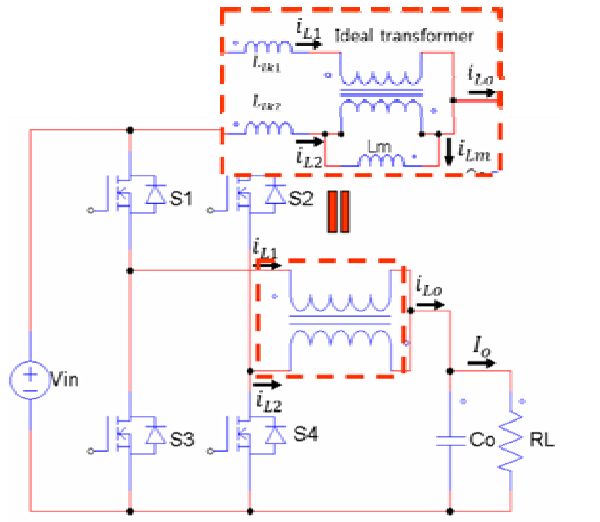

Fig. 4. Two-phase interleaved buck converter (coupled type).

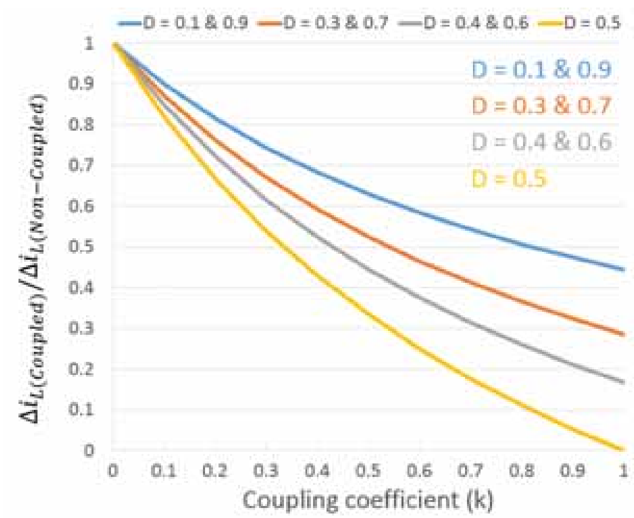

Fig. 5. Inductor current ripple of two-phase interleaved (coupled type) buck converter normalized with respect to the non-coupled case.

Table 1. Current Ripple comparison.

	Inductor Current Ripple Δi_L	Output Current Ripple Δi_{Lo}
Sigle Phase	$\frac{V_o}{L}(1-D)T_s$	$\frac{V_o}{L}(1-D)T_s$
Two phase (non coupled)	$\frac{V_o}{L}(1-D)T_s$	$\frac{V_o}{L}(1-2D)T_s$
Two phase (coupled)	$\frac{V_o}{L_{lk}}\left(\frac{1-D-kD}{1+k}\right)T_s$	$\frac{V_o}{L_{lk}}(1-2D)T_s$

Table 1 shows inductor and output current characteristic of 3 type system.

Table 2. Buck converter specification.

Parameters	Values
INPUT VOLTAGE (V_{in})	776.5 [v]
OUTPUT VOLTAGE (V_o)	349.4 [V]
OUTOUT POWER (P_o)	17 [KW]
OUTPUT CURRENT (I_o)	49 [A]
DUTY RATIO (D)	0.45
SWITCHING FREQUENCY (f_s)	10 [KHz]
EQUIVALENT RESISTANCE OF INDUCTOR (R_L)	7.12 [Ω]
OUTPUT CAPACITANCE (C_o)	40 [μF]

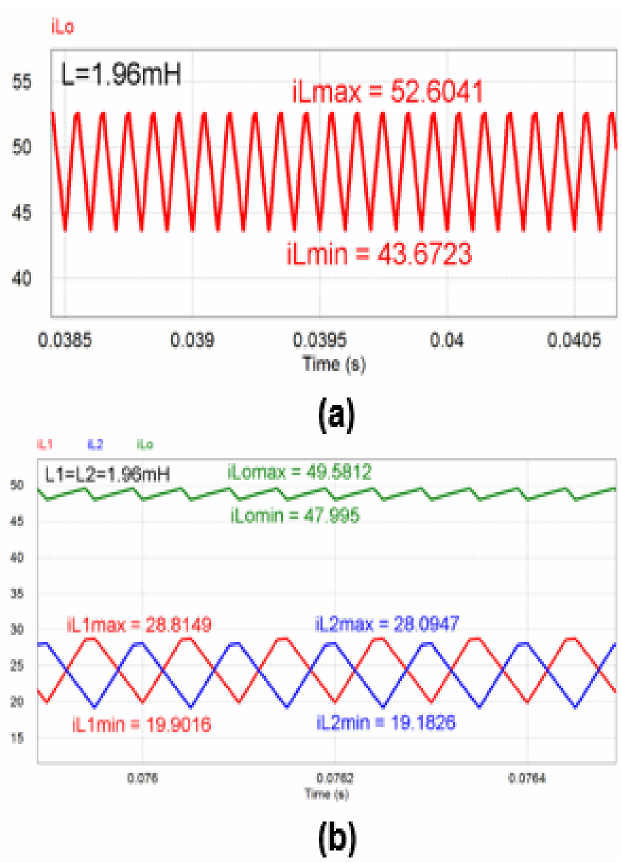

Fig. 6. Output current of single and two-phase buck converter (a) single phase, (b) two phase.

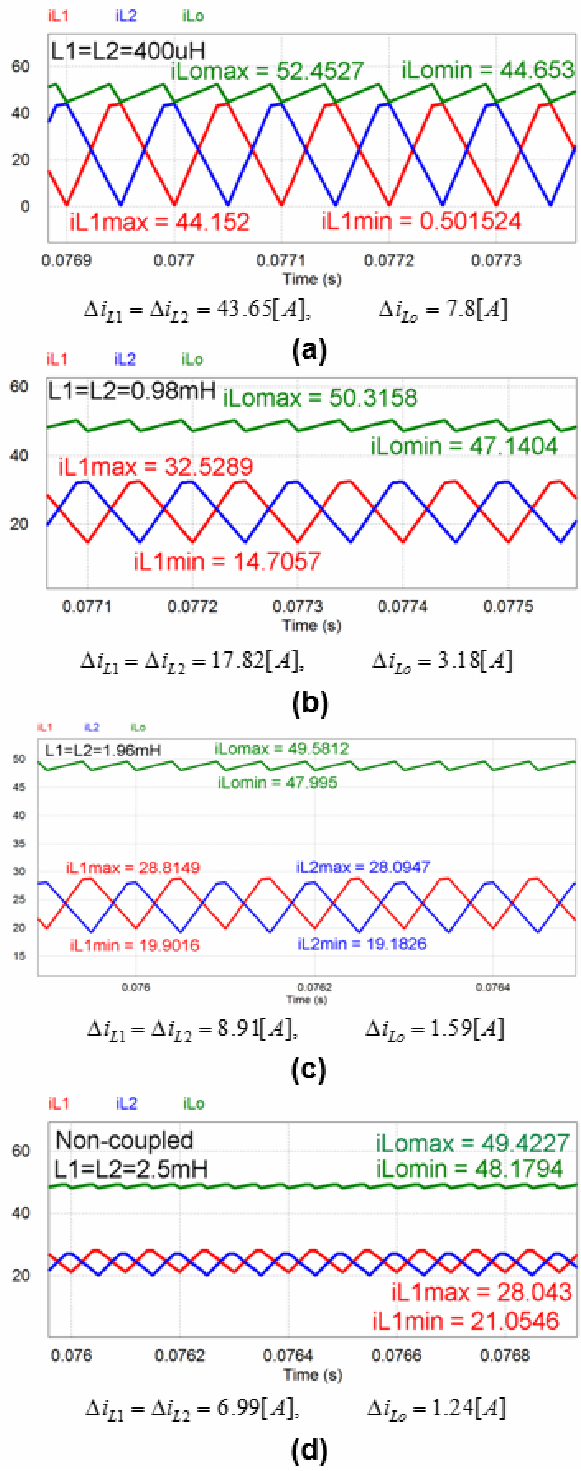

Fig. 7. Output & inductor current by L variation (a) $L_1 = L_2 = 400\mu H$ **, (b)** $L_1 = L_2 = 0.98mH$ **, (c)** $L_1 = L_2 = 1.96mH$ **, (d)** $L_1 = L_2 = 2.5mH$ **.**

3. Simulation

Table 2 shows the buck-converter specification used in the simulation to verify the system characteristic.

Generally, output current ripple designed about 20% of rated current, inductance and ripple current can be recalculated from Eq. (1) as $L = 1.96mH$ and $\Delta i_L = 8.93A$.

Fig. 6 compares output current of single-phase and two-phase interleaved(non-coupled type) buck-converter in condition of the same inductance($L = 1.96mH$). Single-phase buck-converter output current ripple is 8.93A at Fig. 6(a), two-phase interleaved buck-converter output current ripple is 1.59A at Fig. 6(b). Fig. 7 indicates inductor and output current by inductance changes in non-coupled system.

Fig 8 shows inductor and output current according inductance change in coupled type system.

Fig. 9 compares the characteristic of non-coupled and

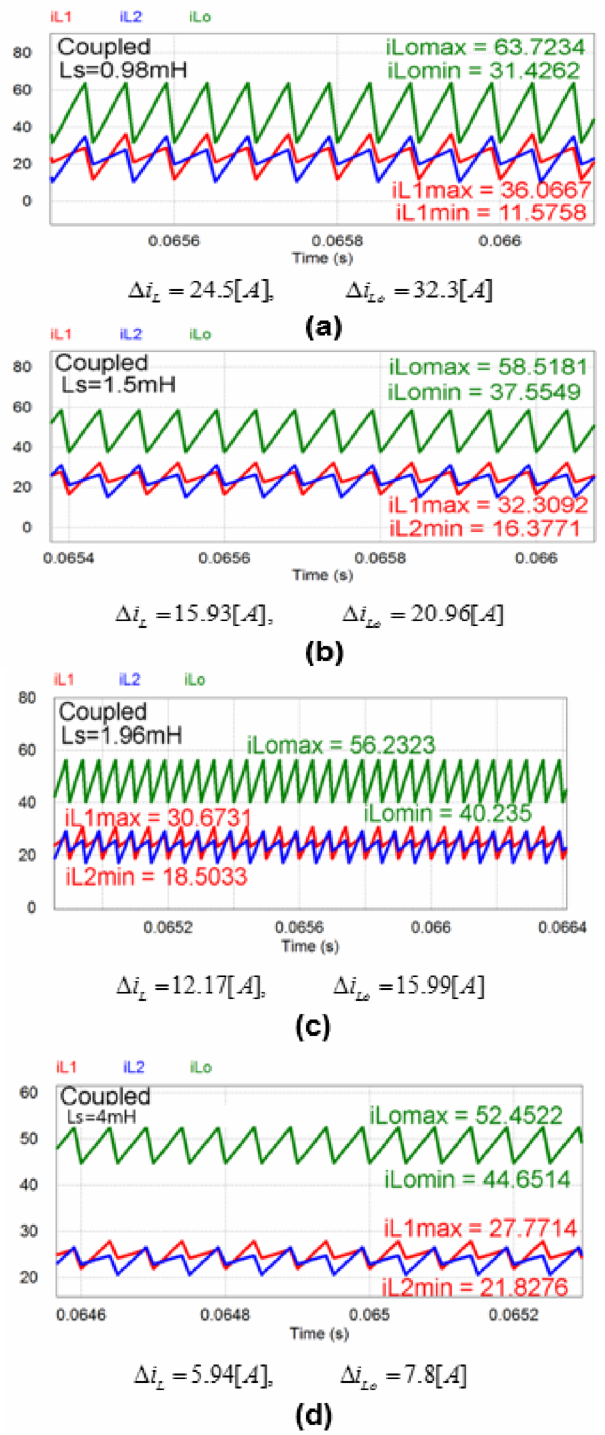

Fig. 8. Output & inductor current by L changes (k=0.9) (a) $L_1 = L_2 = 0.098mH$ **, (b)** $L_1 = L_2 = 0.15mH$ **, (c)** $L_1 = L_2 = 0.196mH$ **, (d)** $L_1 = L_2 = 0.4mH$ **.**

coupled type two-phase interleaved buck-converter in the condition of $L_{lk} = L$. The red and blue line indicate current ripple. Non-coupled inductor current ripple is 43.65A at Fig. 9(a) and coupled one is 5.94A at Fig. 9(b). (where, k=0.9).

Table 3 expresses the characteristic of 3 types systems. Because non-coupled system operates DCM(Discontinuous Current Mode) under 0.4mH, critical inductance is set to 0.4mH for non-coupled system.

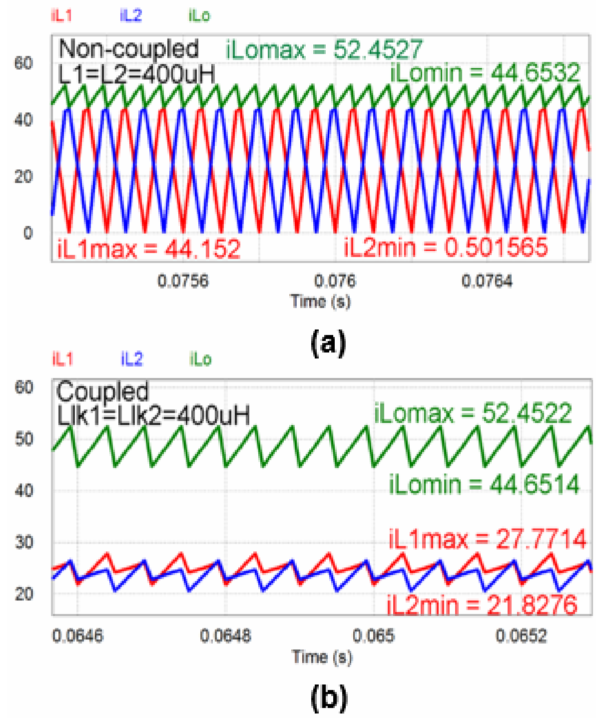

Fig. 9. Output current of non-coupled & coupled (a) two phase(non-coupled), (b) two phase(coupled).

Table 3. Characteristics of Systems.

	Sigle phase	Two phase (non-coupled)	Two phase (coupled)
L	**1.96 [MH]**	0.4 **[MH]**	**3.6 [MH]**
Δi_L	8.93 [A]	43.65 [A]	6.61 [A]
Δi_{Lo}	8.93 [A]	7.8 [A]	8.67 [A]

4. Conclusion

Increased inductance for high power conversion system proportionally increases system volume, production cost and core loss. This paper analyzed dynamic characteristic of parallel non-coupled inductor and coupled inductor in high power interleaved buck-converter. It is confirmed that two-phase interleaved non-coupled buck-converter has the best characteristic among three types converter.

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