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Multi-phase Interleaved LLC-SRC and Its Digital Control Scheme

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***Abstract*--This paper proposes a new 3-phase interleaved LLC resonant DC-DC converter and its control scheme. The proposed circuit consists of three conventional interleaved LLC resonant DC-DC converters and each converter operates with $\pi/3$ of phase difference respectively. Therefore the current ripple of the output capacitor can be significantly reduced and the life cycle of the converter will be extended. To verify the validity of the proposed converter and digital scheme, an experiment with a prototype 1kW (12V/84A) DC-DC converter was implemented and its results are presented in this paper.**

Index Terms—Interleaved DC-DC converter, LLC Resonant, Parallel converter operation

I. INTRODUCTION

Since it was first introduced in early 1990s, LLC-SRC (series resonant converter) has became a popular topology because of its outstanding performance such as the output regulation over wide line and load variations with small variations of switching frequency, ZVS capability for entire load range, low turn-off current, small resonant components using the integrated transformer, zero current switching (ZCS) and no reverse recovery loss on secondary rectifier and etc.[1-5]. Especially, its efficiency and power density are far superior to other DC-DC converter topologies. However, since it doesn't need inductive output filter and only needs capacitive filter in the output stage, the large ripple current at the output capacitors is inevitable. Therefore, LLC-SRC is optimal for high voltage and low current applications such as PDP sustaining power supplies [6-8]. Of course, it is also applied to the middle voltage and middle current applications like LCD power supply, but many extremely low ESR capacitors in parallel have to be required at the output stage to reduce the output ripple voltage as well as the current stresses of the output capacitors. The life cycle of DC-DC converter is dominated by the output capacitor. In order to overcome this problem, a two-phase interleaved LLC DC-DC converter was recently developed that can significantly reduce the output ripple current at the output capacitors.[9, 10] The theoretical output ripple current of 2-phase interleaving operation is about 1/5 of the conventional. However, it is insufficient to apply to the extremely high current applications like electrical vehicle power converters, battery charger, server power supplies and so on.

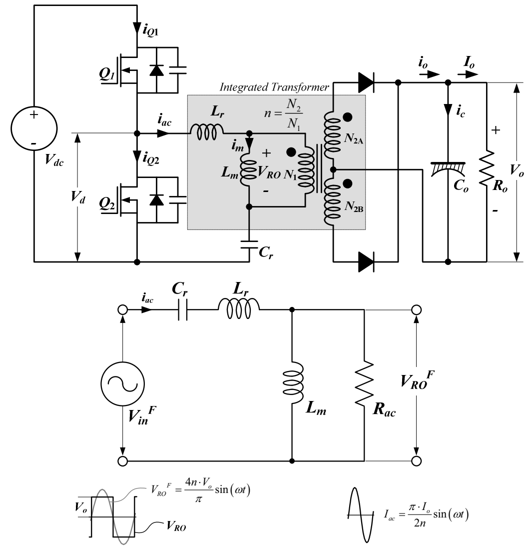

Fig.1. LLC series resonant converter

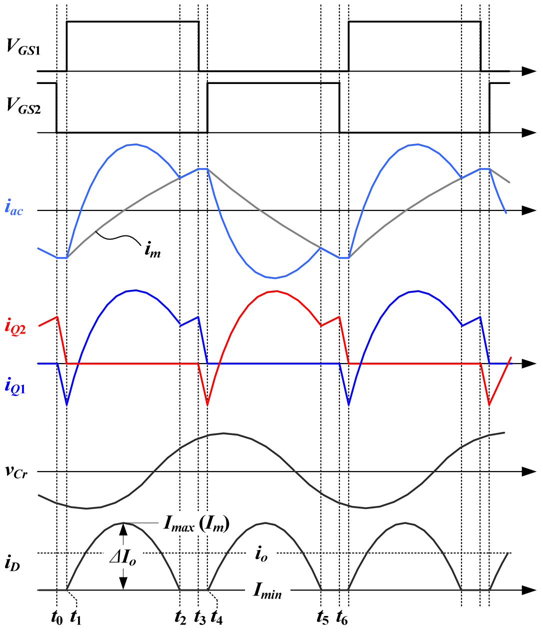

Fig.2. Theoretical waveform of LLC-SRC

In this paper, 3-phase interleaved LLC-SRC and its digital control scheme are proposed. Since the proposed converter consists of three LLC-SRCs and operates with interleaving control method, the low ripple current at the output capacitors can be realized. The validity of the proposed method during low voltage and high current output conditions was verified through experimental

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results with a 1kW (12V/83A) prototype set-up in this paper.

II. ANALYSIS OF LLC RESONANT TOPOLOGY

The LLC-SRC has same form as the conventional series resonant converter (SRC), the only difference is that the magnetizing inductance, L_m is included into the resonant components [11, 12]. The circuit diagram of the typical LLC-SRC and its equivalent circuit are shown in Figure 1 and the theoretical waveforms are shown in Figure 2 respectively. Two resonant circuits are formed in accordance with load conditions; one is formed by L_r, L_m and C_r at the no-load and the other is formed by L_r and C_r at heavy load condition. Therefore two different resonant frequencies need to be considered for analysis as follow;

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (1)$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \quad (2)$$

The quality factor, Qs is derived as;

$$Q_s = \frac{\sqrt{L_r / C_r}}{n^2 R_o} = \frac{Z_{r1}}{n^2 R_o} \quad (3)$$

where $n=N_1/N_2$ and Z_{r1} is the characteristic impedance at $f_s=f_{r1}$, and $R_o=V_o/I_o$ respectively.

The primary side resonant current consist of two components; the resonant current, i_{r1} and the magnetizing current, i_m. However the magnetizing current doesn't contribute the power conversion; the only resonant current is transferred to the output. If the switching frequency is below the first resonant frequency, f_{r1}, the secondary rectifier can softly commutates while the magnetizing current will be relatively high thereby, the reverse recovery loss can be removed. The ripple current at the output capacitor, ΔI_c will be extremely high in case of low voltage high current application. Let we assume $I_{\max} - I_{\min} = \Delta I_c$, then the current ripple ratio is defined as below;

$$\%\Delta I_c = \frac{\Delta I_c}{I_o} \times 100[\%] \quad (4)$$

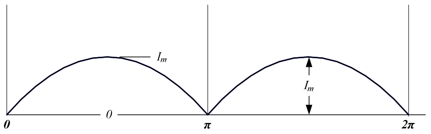
When the switching frequency, $f_s = f_{r1}$, the output current, I_o is derived by

$$I_o = \frac{1}{T}\int_0^T (I_{\max} - I_{\min}) \sin \omega t d\omega t + \mathrm{I}_{\min} \quad (5)$$

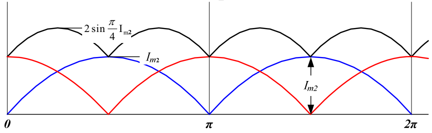
In case of single phase operation, the output current is

$$I_o = \frac{2}{\pi}\mathrm{I}_\mathrm{m} \quad (6)$$

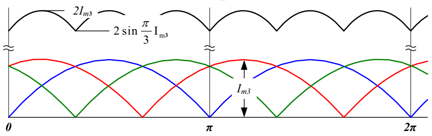
Therefore, the current ripple ratio, $\%\Delta I_c$ is π/2 (157.1%). If LLC-SRC is applied to a low voltage and high current application, the quality of output voltage will get worse and the output capacitors will easily deteriorated by large current stress. Therefore, LLC-SRC topology has been restrictively applied to high voltage and low current applications like PDP sustaining power supply.



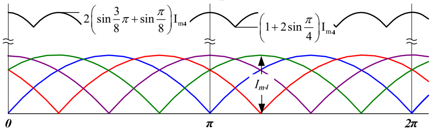
(a) 1-phase



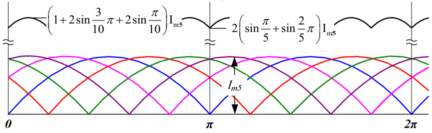
(b) 2-phase



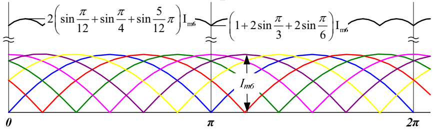
(c) 3-phase



(d) 4-phase



(e) 5-phase



(6) 6-phase

Fig.3. Interleaving operation simulation results

III. PROPOSED 3-PHASE INTERLEAVED LLC-SRC AND ITS CONTROL SCHEME

The output capacitor absolutely governs the life cycle of whole system in DC-DC converter. To ensure the longer life cycle, the current stress at the capacitors should be suppressed. However, the capacitor current ripple of LLC-SRC is inevitably high because its output filter consists only of capacitance. However, the output current ripple of LLC-SRC can be significantly reduced if multi phase interleaving control technique is applied [9, 10]. When the switching frequency, f_s is same as the first resonant frequency, f_{r1}, the non-powering period, t_2~t_4 in Figure 2 can be neglected. Figure 3 shows the output current simulation results from single phase operation to six-phase interleaving operation of LLC-SRC under the condition, $f_s = f_{r1}$. The calculated maximum current ($I_{\max}$), minimum current ($I_{\min}$), load current (I_o), capacitor ripple current (ΔI_c) and current ripple ratios ($\%\Delta I_c$) for each case are contained in Table 1 respectively. The obtained current ripple ratios for each case using equation (4) are shown in Figure 5. Figure 5 clearly shows the effectiveness of interleaving operation in LLC-

TABLE I. CALCULATION RESULTS

	I_{max}	I_{min}	I_o	ΔI_c	% ΔI_c
1-phase	I_m	0	$0.637I_m$	I_m	156.7%
2-phase	$1.414I_{m2}$	I_{m2}	$1.264I_{m2}$	$0.414I_{m2}$	32.8%
3-phase	$2I_{m3}$	$1.732I_{m3}$	$1.903I_{m3}$	$0.268I_{m3}$	14.1%
4-phase	$2.613I_{m4}$	$2.414I_{m4}$	$2.541I_{m4}$	$0.199I_{m4}$	7.8%
5-phase	$3.236I_{m5}$	$3.078I_{m5}$	$3.179I_{m5}$	$0.158I_{m5}$	5%
6-phase	$3.864I_{m6}$	$3.732I_{m6}$	$3.816I_{m6}$	$0.132I_{m6}$	3.5%

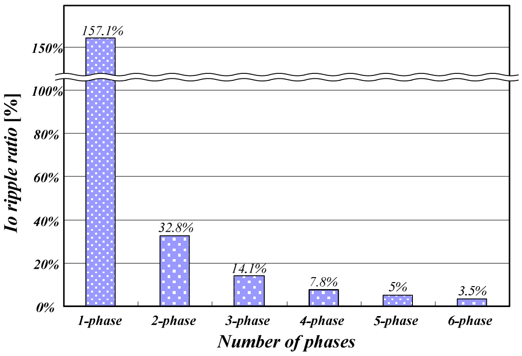


Fig.4. Current ripple comparison

SRC. The current ripple compare with single phase operation will be about 1/5 in 2-phase interleaving operation and about 1/11 in 3-phase interleaving operation respectively. Meanwhile, the effectiveness over 4-phases becomes smaller and smaller while the building cost becomes higher and higher. Over 4-phase interleaving operations are therefore impracticable. In consequence, it is desirable to choose between 2-phase and 3-phase operation in accordance with load condition in case of interleaving operation.

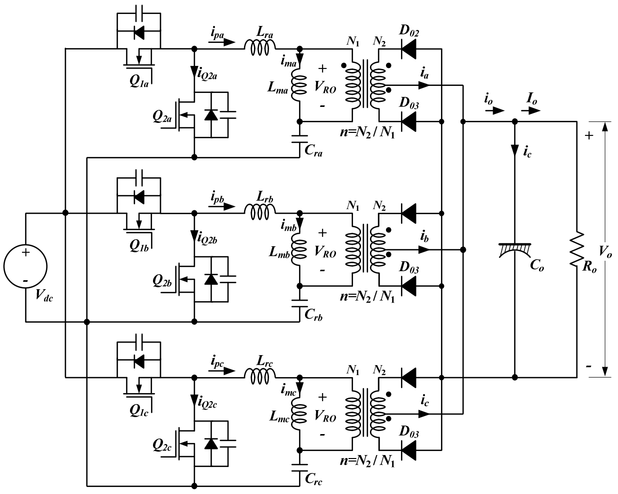


Fig.5. 3-Phase interleaved LLC-SRC

Figure 5 shows an example of 3-phase interleaved LLC-SRC. To realize the multi phase interleaved LLC-SRC, we proposed a new control scheme. Figure 6 shows a block diagram of multi-phase interleaving control scheme. The proposed control circuit is composed of a typical frequency modulator, MOD-3 CNT', digital comparators, and drive circuits. The typical frequency modulator generates a reference clock and its frequency is controlled by a compensation network. MOD-3 CNT' counts the input pulse and its output is compared with 0, 1 or 2 by three digital-comparators, CMP#A-C. The

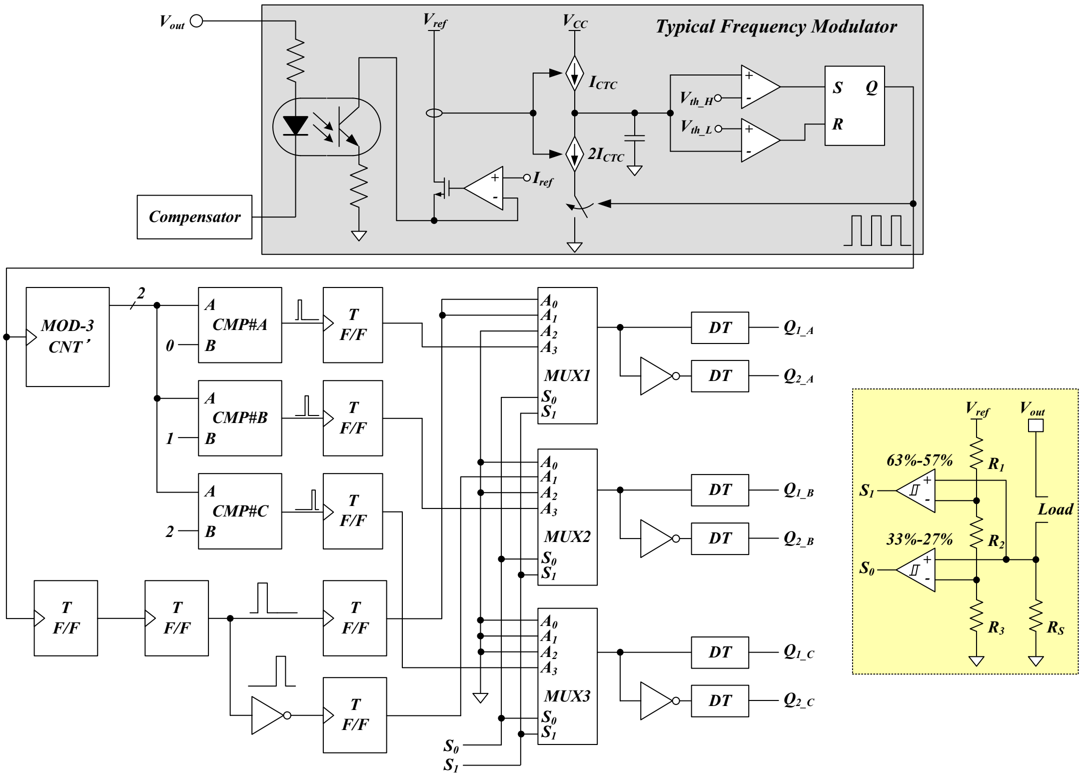
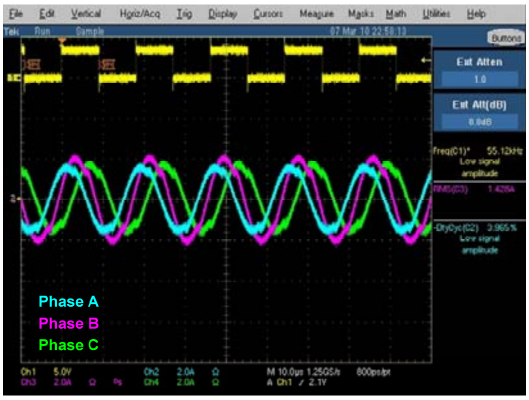
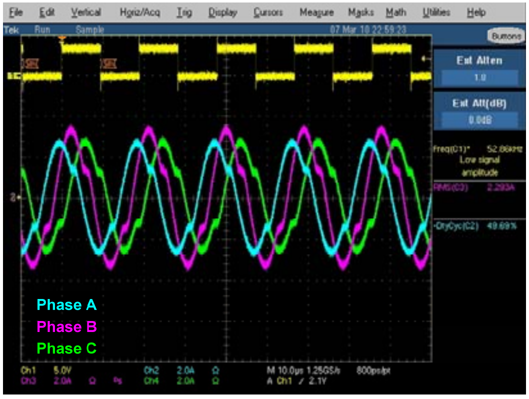


Fig.6. Proposed 3-phase interleaved control scheme



(a) at 50% load condition



(b) at full load condition

Fig. 7. Key waveforms of 3-phase interleaved LLC converter

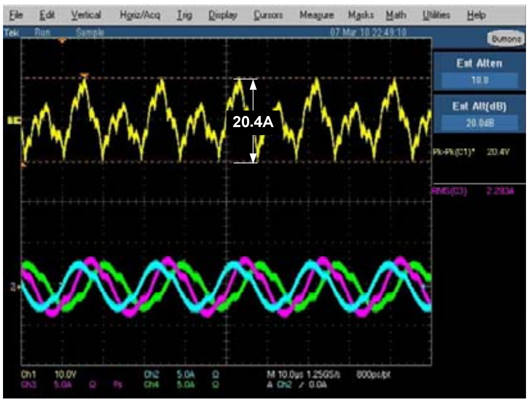


Fig. 8. Resonant currents and the ripple current of capacitor

output short pulses of each CMP are converted to the rectangular waveforms by T-F/F and each waveform has 60° of phase difference for 3-phase interleaving operation.

The proposed control scheme provides the phase management function. Since the output voltage is constant, the output power can easily be defined by sensing the load current. Two analog comparators in Figure 6 sense the load current and generate 2-bit signals, S_1 and S_2, of which states are determined by load condition. The digital MUXs select the input signal among A_0, A_1 and A_3 according to the state of S_1 and S_2. As a result, the phase management of multi-phase interleaving LLC-SRC can be achieved.

TABLE II. RESONANT PARAMETERS

C_{ra}, C_{rb}, C_{rc}	T_a		T_b		T_c	
	L_{ma}	L_{ra}	L_{mb}	L_{rb}	L_{mc}	L_{rc}
22nF	**1.03mH**	**327 μH**	**1.02 mH**	**308μH**	**998μH**	**312 μH**

IV. EXPERIMENTAL RESULTS

In order to verify the validity of the multi-phase interleaved LLC resonant converter, we implemented an experiment with a 1kW 3-phase interleaved LLC resonant converter wherein the input voltage is 400V and the output is 12V/84A. The resonant parameters are shown in table 2. Figure 7 shows the waveforms of the resonant currents at 50% load and full load conditions. The phase difference for each phase is 60°.

Figure 8 shows the waveforms of the resonant currents and the ripple current of capacitor at full load condition.

The ripple current, ΔI_c is measured as 20.4A and 24.3 % of $\%\Delta I_c$. Even though the obtained current ripple ratio is far from the calculated results due to non-powering period and the unbalance among the resonant currents, it is verified that the ripple current at the output capacitor can be dramatically reduced through interleaved operation. Because the DC gain characteristics for the load condition of each converter are inevitably not same, the current unbalance is occurred among the phases. Therefore the load sharing method for applying the phase management function has to be more studied as further step.

V. CONCLUSIONS

In this paper, a multi-phase interleaved LLC-SCR and its control strategy are presented. Since the output ripple current can be dramatically reduced by an interleaving operation, it is suitable for especially low voltage, high current applications such as server power supply systems while the conventional LLC-SRC is normally applied for high voltage low current applications. By reducing the current stress, a smaller capacitance is needed and the life cycle of the power supply can be extended.

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