Design and Comparison of Two Front-end Dc/Dc Converters: LLC Resonant Converter and Soft-switched Phase-shifted Full-bridge Converter with Primary-side Energy Storage Inductor

Chen Zhao, Xinke Wu, Zhaoming Qian (IEEE Senior Member)
College of Electrical Engineering, Zhejiang University
38# Zheda Road, Hangzhou, China, 310027
chanezhao@zju.edu.cn

***Abstract*-This paper presents detailed design and comparison of two front-end Dc/Dc converters which are suitable especially for the medium-power level applications with low output voltage and high output current both. Where, the LLC resonant converter drawn more and more attention recently shows its essential advantages in high conversion efficiency and high power density. However, due to the variable-frequency control strategy, its slow response especially in burst-mode with light-load or null-load makes the design more difficult. On the oppose side, the soft-switched Phase-Shift (PS) Full-bridge (FB) converter with primary-side energy storage inductor proposed in the foregoing work can be operated in CCM, BCM and DCM respectively according to the different designs. Where, the optimum design consideration indicates that the BCM and DCM operation modes can help to obtain high conversion efficiency. Additionally, thanks to the conventional phase-shift control strategy, it can obtain fast response during the burst-mode with light/null load. Finally, two lab-made prototypes of these two Dc/Dc converters (300Watts, 100 kHz) are built up to verify the theoretical analysis and comparison.**

I. INTRODUCTION

Nowadays, with the rapid development of the consumer electronics, the requirement of reducing the package size of power supply adapter is going to be more and more important. Usually, only the natural convection cooling is allowed for the power supply adapters. Although the adapter's package size is increasing along with the increasing of the power level, the ratio of the package's surface area to volume would reduce still, which leads to the reduction of the effective heat dissipating capability directly. Therefore the conversion efficiency of the power supply adapters must be pushed up further in order to meet the rigorous thermal limitation. Otherwise, the power density has to be reduced to ensure the reliability of the heat dissipation, which is undesirable for the power supply design obviously.

For the medium-power level application area, the two-stage configuration, which consists of PFC stage and front-end Dc/Dc stage, is usually more appropriate and can be optimum designed separately for the power supply adapter to get high conversion efficiency and power density. Theoretically to say, all the Dc/Dc topologies can be utilized to implement the front-end Dc/Dc stage. Recently, the LLC resonant converter has drawn more and more attention to be the front-end Dc/Dc converter due to its essential advantages in high conversion efficiency and high power density [1,2…6]. Moreover, thanks to the DC block effect of the series resonant capacitor, the half-bridge can be utilized at the primary-side to reduce the converter size and cost. Two primary-side switches can be operated under ZVS condition both without any auxiliary circuit. Furthermore, when the converter operated with the switching frequency lower than the resonant frequency (f_S), the secondary-side rectifier can be operated under ZCS condition to reduce the switching loss (if the Synchronous Rectifier is used) and the reverse-recovery loss (for the diode rectifier or the body-diode of the Synchronous Rectifier). However, its narrow bandwidth deteriorates the dynamic response seriously. Large capacitance is necessary to be employed at the output side to avoid the considerable voltage drop when the output load is shifted from null load to full load. Then, the power density would have to be reduced. Much worse is that the control circuit would be shut down by error due to the undesirable decrease of the DC bias, which is caused by the slow dynamic response when the converter is operated in the burst-mode with light load or null load.

Besides the LLC resonant converter, some full-bridge converter with energy storage inductor shows advantages both in conversion efficiency and power density as well [7,8,9,10]. Based on [8,9,10,11], foregoing work shown in [12,13] proposes a synchronous rectified soft-switching full-bridge converter with primary-side energy storage inductor, which is especially fit for low output voltage and high output current application areas. All the primary-side full-bridge switches can be operated under soft-switching condition without any auxiliary circuit, ZVS for the leading leg switches and ZCS for the lagging leg switches separately. Employing a simple L-C network can help the lagging leg switches achieving ZVS easily. The secondary-side rectifiers can be operated under ZCS as well as the LLC resonant converter. Although compared to the LLC resonant converter this full-bridge converter has a little disadvantage in the size as the front-end Dc/Dc converter, the conventional PWM phase-shift control strategy with wide bandwidth can ensure fast dynamic response.

This paper focuses on the detailed comparison of these two front-end Dc/Dc converters mainly in three interesting parts, such as the conversion efficiency, the amount of key power components and the whole prototype's size, and the dynamic

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response. The comparison results, which present several key characteristics of these two converters, are supposed to be the reference guide for the power supply adapter engineers and help them to simplify the design and implementation procedures effectively. Section II of this paper shows the comparison based on the theoretical analysis. Two lab-made prototypes (300Watts, 100kHz) are optimum designed and built up in order to present the experimental comparison in section III.

II. Theoretical Analysis and Comparison Of These Two Front-End Converters

A. Loss Evaluation and Conversion Efficiency Comparison

1) Topologies of these two converters

Fig.1 and Fig.2 shows the basic topologies of the half-bridge LLC resonant Dc/Dc converter and the soft-switched full-bridge Dc/Dc converter with primary-side energy storage inductor separately. In Fig.1, the primary-side half-bridge consists of MOSFET Q_1 and Q_2. The resonant tank consists of the series resonant inductor Lr and the resonant capacitor Cr. The Lm represents the magnetizing inductor of the power transformer. SR_1 and SR_2 are the synchronous rectifiers at the secondary-side for reducing the conduction loss in the high output current applications. The capacitive output filter Co is utilized. The output load is represented by Ro. In Fig.2, Q_1~Q_4 are the primary-side full-bridge switches paralleled with D_{c1}~D_{c4} as their body diodes. C_{oss1}~C_{oss4} are their parasitic paralleled capacitors. L_R is the equivalent series inductor which consists of the added series energy storage inductor L_r and the primary-side leakage inductor of transformer L_{k_p}. It means that this converter can accommodate L_{k_p} to be a part of energy storage inductor. The L_{k_s} is the secondary-side leakage inductor of transformer. SR_1 and SR_2 are the synchronous rectifiers at secondary-side paralleled with D_{sr1} and D_{sr2} as their body diodes. C_{sr1} and C_{sr2} are their parasitic paralleled capacitors. It employs capacitive filter Co as well as the LLC resonant converter.

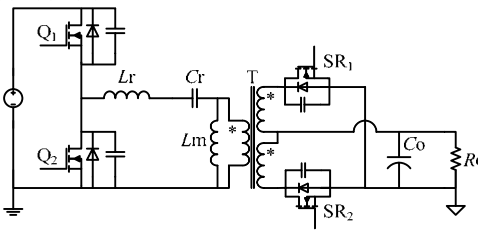

Fig.1 the topology of LLC resonant converter

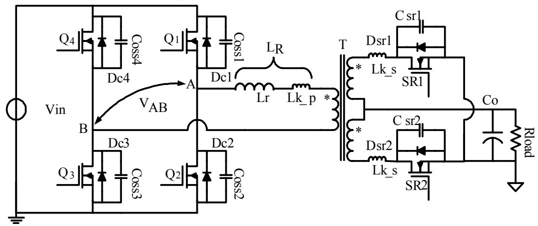

Fig.2 the topology of soft-switched full-bridge converter with primary-side energy storage inductor

2) Basic design specifications

In order to ensure the comparison results to be reasonable, the basic design specifications of these two front-end Dc/Dc converters should be same and as given in Table I.

TABLE I
BASIC DESIGN SPECIFICATIONS

V_{IN_min}	V_{IN_max}	V_O	I_{O_max}	T_S	f_S
350V	400V	12V	25A	10 us	100 kHz

Generally, the input voltage range for the front-end Dc/Dc converter is necessary to be considered for the hold-up time requirement of the adapter. For the two-stage configuration, the input voltage of the Dc/Dc stage can usually be regulated by the front PFC stage. Thus, the front-end Dc/Dc converter can be operated with V_{IN_max} during the normal operation mode.

3) The comparison of conversion efficiency

This section focuses on the loss evaluation and the efficiency comparison between these two converters with normal bus voltage input and full-load output. Thanks to the burst-mode, the conversion efficiency with light-load output (<1W) and null-load loss can be improved dramatically. However, they are usually hard to be evaluated thru the theoretical analysis. Thus, comparing them based on the experimental results directly may be a more reasonable and acceptable method. It is shown in the following section.

For the full-load loss evaluation with normal bus voltage, there are about six key parts that should be taken into account: *a*) Conduction and driving losses of the primary-side switches; *b*) Resonant or energy storage inductor loss; *c*) Transformer loss; *d*) Conduction and driving loss of the secondary-side SRs; *e*) Conduction loss in filter capacitors and *f*) Soft switching auxiliary circuit loss. We define the LLC resonant converter to be the converter I and the other one to be the converter II.

a) Conduction and driving losses of the primary-side switches

Because the half-bridge and the full-bridge are utilized for the converter I and II separately, it is obviously that the primary-side switches' driving loss of the converter II is twice of that of converter I if the same type MOSFETs are used.

The detailed operation principle can be obtained from the foregoing work [7,12,13]. For the conduction loss, the RMS value of the primary-side current can be expressed in (1) for converter I and in (2) for the converter II.

$$I_{rms\_p\_LLC} = \frac{\pi V_o \sqrt{2(Q^2 m^2 + n_T{}^4)}}{4 R_o n_T Q m} \tag{1}$$

Where, V_O is the output voltage; Q is the quality factor, m is the ratio of Lm to Lr; n_T is the turn ratio of transformer; R_O is the output load.

$$I_{rms\_p\_SSFB} = \frac{\sqrt{3}}{3}\frac{2I_o}{n_T} \tag{2}$$

Where, I_O is the average of the output current.

Although the lagging leg switches of the converter II can achieve ZCS condition easily, a simple L-C network [15,16,17] is still necessary to help MOSFETs achieve ZVS condition to reduce switching loss. However, the auxiliary L-C network increases the current stress in the lagging leg switches and the RMS value of the current can be expressed in (3).

$$I_{rms\_aux} = \frac{\sqrt{3}}{3}\frac{V_{in}T_s}{8L_{aux}} \tag{3}$$

Where, V_{in} is the input voltage; T_S is the switching period; L_{aux} is the auxiliary inductance.

It is supposed that CoolMOS SPI15N60 from Infineon is used as the primary-side switches of these two Dc/Dc converters both. Then, based on (1), (2) and (3), the conduction loss can be obtained easily and the comparison marked as "Pri-Swi" can be derived as shown in Fig.3

b) *The resonant or energy storage inductor loss*

As usual, both the resonant inductor loss of converter I and the energy storage inductor loss of the converter II consist of winding loss and core loss. With the designed peak flux density and the selected type of core [7,12,13], the core loss always can be derived by the loss curves from the magnetic component datasheet. On the other side, according to (1) and (2), the winding loss also can be evaluated when the winding structure and characteristic are given or optimum designed. It is supposed that RM8/TP4B is used as the resonant inductor of converter I and PQ2020/TP4B is used as the energy storage inductor of the converter II. The loss comparison between these two inductors marked as "inductor" can be derived as shown in Fig.3.

c) *The transformer loss*

Being similarly with the inductor mentioned above, the transformer loss consists of winding loss and core loss as well. Due to the utilization of the capacitive output filter, the voltage stress across the transformer is always clamped by the output voltage. (4) shows the peak flux density of the transformer. Thus, thus core loss also can be obtained by the loss curves from the magnetic component datasheet.

$$\Delta \boldsymbol{B_T} = \frac{\boldsymbol{n_T V_O T_S}}{4\boldsymbol{n_P A_{CT}}} \tag{4}$$

Where, n_P is the primary-side winding turn of the transformer, A_{CT} is the effective section area of the transformer core.

In order to estimate the transformer winding loss, besides the RMS value of the primary-side current as shown in (1) and (2), the RMS value of the current in the secondary-side winding is necessary as well. (5) and (6) express the RMS value of the secondary-side current in the single winding of the converter I and the converter II respectively [7,12,13]. It is supposed that RM12/TP4B is used as the transformer core for these two front-end Dc/Dc converters both. Thus, the transformer loss comparison marked as "Transformer" can be obtained as shown in Fig.3.

$$I_{rms\_ss\_LLC} = \frac{V_o}{4R_oQm}\sqrt{\frac{(5\pi^2 - 48)n_T^{\,4}}{3} + \pi^2Q^2m^2} \tag{5}$$

$$I_{rms\_ss\_SSFB} = \frac{\sqrt{6}}{3}I_o \tag{6}$$

d) *The conduction and driving loss of the secondary-side SRs*

Based on (5) and (6), the conduction loss of SRs at the secondary-side can be derived easily as well. The driving loss can be expressed in (7).

$$\boldsymbol{P_{Dr} = Q_g V_{GS} f_S} \tag{7}$$

Where, Q_g is the gate charge total of MOSFET, which can be obtained from datasheet easily, V_{GS} is the driving voltage across the gate and the source.

It is supposed that Power Trench MOS FDI038AN06A0 from Fairchild is used as the synchronous rectifier at the secondary-side. Thus, the loss comparison result marked as "Sec-SRs" can be gotten as shown in Fig.3.

e) *The conduction loss of the filter capacitors*

Due to the utilization of the capacitive filter at the secondary side both for these two converters, large output current ripple flows into the electrolytic capacitor and its ESR suffers considerable conduction loss which should be taken into account. (8) shows the RMS value of the secondary-side current flowed in the output filter capacitors. Based on the value of the ESR from the capacitor's datasheet, the conduction loss of output filter capacitor can be derived and comparison result marked as "Cout" is shown in Fig.3.

$$I_{rms\_Co} = \sqrt{2I_{rms\_ss}^{\ 2} - I_o^{\ 2}} \tag{8}$$

f) *The other soft switching auxiliary circuit loss*

For the converter I, the primary-side half-bridge switches can achieve ZVS without any other auxiliary circuit. But for the converter II, although the lagging leg switches can achieve ZCS easily, the ZVS is more important for MOSFET to reduce the turn-on switching loss. Thus, a simple L-C network [15,16,17] is needed to be an auxiliary circuit for the lagging leg switches' load-independent ZVS condition. Then its total loss can be approximately considered as the sum of winding loss and core loss of the auxiliary inductor. It is supposed that PQ2020/TP4B is used as the auxiliary inductor. Thus, the loss evaluated result marked as "Auxiliary" can be found in Fig.3 as well.

g) *The loss analysis and comparison results*

Based on the theoretical analysis above, Fig.3 shows the loss evaluation and comparison results of these two converters. It can be seen that the converter I is a little better than the converter II in the conversion efficiency when they are operated with normal bus voltage input and full-load output both. Fig.4 shows the loss percentage of every key considered part for these two converters respectively. It can be seen that the transformer loss, the SRs' loss and the primary-side switches' loss are the top 3 loss of the total when these two front-end Dc/Dc converters are used in medium power level applications with low output voltage and high output current. This comparison result can be a reference guide for the power supply adapter engineers and indicates that these three parts should be design carefully especially during the optimum design procedures.

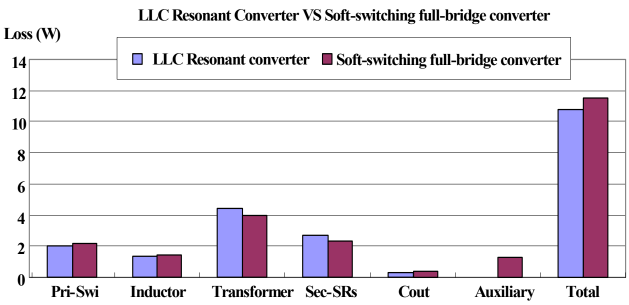

Fig.3 the loss evaluation and comparison results of these two converters

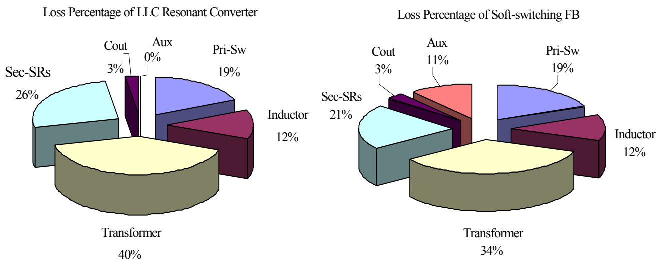

Fig.4 The loss percentage analysis of these two converters

B. *The amount of components and the size comparison*

1) *The amount of components*

Besides the requirement of the conversion efficiency, the power density and the cost also are very important aspects in the design and implementation of the power supply adapter. Table II lists the components, which are utilized to implement these two front-end Dc/Dc converters and obtain the high conversion efficiency as the theoretical estimation mentioned above, and it indicates the difference in the cost and the size of between these two converters as well.

2) *The size comparison*

Fig.5 shows the real dimension of these two converters based on the practical measurement. Fig.6 and Fig.7 show the prototypes pictures. Although they have not been optimum designed enough especially in the PCB layout and the package, the size comparison based on the Fig.5~Fig.7 still can indicate the difference between these two converters in the power density. Converter I has some advantage than converter II in the aspects of power density and cost.

C. *The comparison of dynamic response*

Thanks to the burst-mode, the light-load (<1W) efficiency and the null-load loss can be improved a lot. It is easy to achieve the goal that light-load (0.5W) efficiency is higher than 50% and null-load loss is less than 0.5Watts. However, the slower dynamic response would lead to the lower burst-frequency. Then, the DC bias would probably decrease to shut down the control circuit. Furthermore, considerable voltage drop appears when the output load shifted from null-load to full-load. Although the larger capacitance of output filter can alleviate the issue of voltage drop, power density reduces as well.

TABLE II
KEY COMPONENTS LIST OF TWO FRONT-END DC/DC CONVERTERS

Components	Converter I		Converter II	
	Type	Amt.	Type	Amt.
Primary-side Switches	SPI15N60	2	SPI15N60	4
Secondary-side SRs	FDI038AN06	4	FDI038AN06	6
Inductor	RM8/TP4B	1	PQ2020/TP4B	1
Transformer	RM12/TP4B	1	RM12/TP4B	1
Output Capacitor	Nichicon/HZ	4	Nichicon/HZ	4
Control IC	L6599D	1	UCC3895	1
Driving IC	N/A	0	IR2113	2
Auxiliary Circuit	N/A	0	PQ2020	1

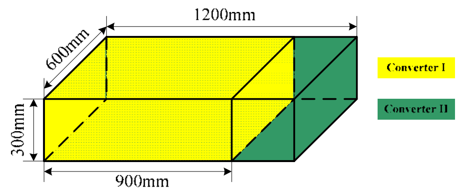

Fig.5 Measured dimension of two prototypes

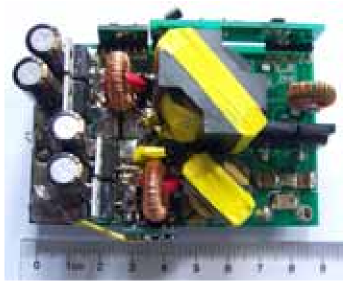
Fig.6 the picture of converter I prototype

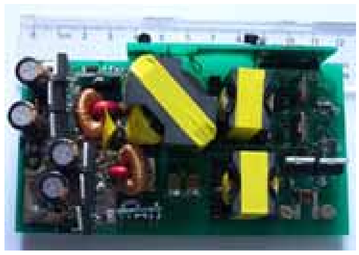
Fig.7 the picture of converter II prototype

For the converter I, because the variable frequency control strategy is employed, its narrow bandwidth results to the slow dynamic response. Thus, when the converter I operated in the burst-mode with light load or null load, the burst frequency is slow and needed to be design carefully. Fig.8 shows the key experimental waveforms of the converter I when operated in the burst mode. It is clearly that the burst frequency is about 40Hz with 0.5W- load output and 2.5Hz with null-load output. The Dc bias nearly has about 1.8V voltage ripple when it operated with null-load output, which means the risk of shut down by error for the control circuit. Thus, both of the output capacitance and the Dc bias capacitance should be designed large enough.

On the oppose side, converter II employs the conventional PWM phase shift full-bridge control strategy. It has some similar characteristics with the traditional Buck converter in DCM. Thus, the wide bandwidth of converter II can make the dynamic response to be fast enough.

Therefore, for the aspect of dynamic response consideration, the converter I has a little more difficult than that the converter II has.

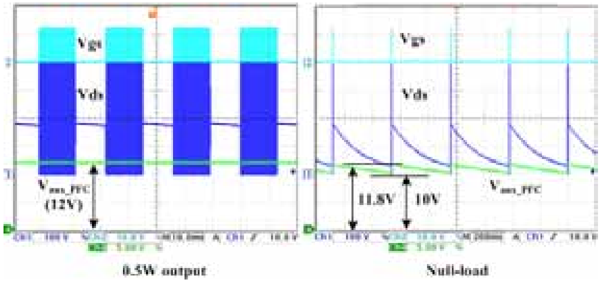

Fig.8 key waveforms of converter I in Burst mode

III. Conversion Efficiency Measurement Results of Two Front-end Dc/Dc Converters

Based on the prototypes of these two front-end Dc/Dc converters (300W/100kHz), the conversion efficiency has been measured. Fig.9 shows the full-load efficiency comparison of these two converters with different input voltage. Fig.10 shows the efficiency comparison with normal bus voltage (400V for converter I and 350V for converter II) [7,12,13] and different output load. According to the experimental results, although the converter I is a little better than the converter II in the aspect of conversion efficiency as the theoretical analysis and the comparison mentioned above, both of them can obtain high conversion efficiency as a front-end Dc/Dc converter for the power supply adapter in medium power level applications.

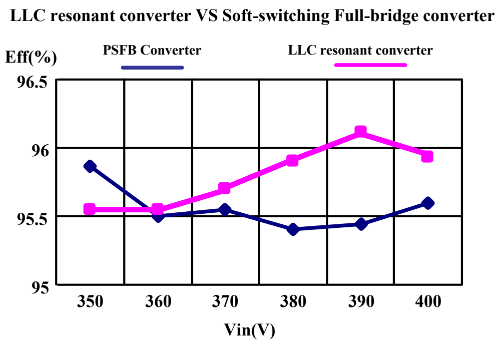

Fig.9 Efficiency comparison with different input voltage

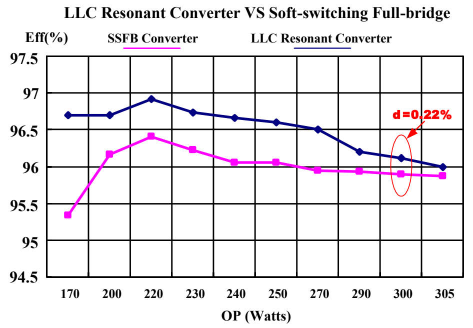

Fig.10 Efficiency comparison with different output voltage

IV. Conclusion

This paper focuses on the comparison between the LLC resonant converter and the soft-switched phase shift full-bridge converter mainly in three parts when they are used as the front-end Dc/Dc converter of the power supply adapter for the medium power level applications. LLC resonant converter definitely shows better performance in conversion efficiency and power density, no matter in the theoretical analysis or in the experimental results. But its relatively narrow bandwidth increases the difficult in dynamic response consideration. Large output capacitance and Dc bias capacitance are needed to guarantee the acceptable output voltage drop during the load shift and the control circuit operation during the burst mode.

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