A Zero Voltage Switching Phase Shift Full Bridge Converter with Separated Primary Winding

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Abstract

Generally additional leakage inductance and two clamp diodes are adopted into the conventional phase shift full bridge (PSFB) converter for reducing the voltage stress of secondary rectifier diodes and extending the range of zero voltage switching (ZVS) operation. However, since additional leakage inductance carries the ac current similar to the primary one, the core and copper loss oriented from additional leakage inductance can be high enough to decrease the whole efficiency of DC/DC converter. Therefore, in this paper, a new ZVS phase shift full bridge converter with separated primary winding (SPW) is proposed. Proposed converter makes the transformer and additional leakage inductor with one ferrite core. Using this method, leakage inductance is controlled by the winding ratio of separated primary winding. Moreover, by manufacturing the both magnetic components with one core, size and core loss can be reduced and it turns out the improvement of efficiency and power density of DC/DC converter. The operational principle of proposed converter is analyzed and verified by the 1.2kW prototype.

1. Introduction

The conventional zero voltage switching (ZVS) pulse width modulation (PWM) phase-shift full bridge (PSFB) converter is very attractive topology for medium-high power applications and it has some desirable features, such as low current/voltage stress and ZVS operation of all switches by utilizing the transformer leakage inductance and intrinsic capacitances of switches without any additional circuit. [1] ZVS operation of conventional PSFB converter is dependent on the load condition and it cannot be achieved at light load condition due to insufficient energy of leakage inductance. Hence, additional leakage inductance is appended to the primary side of PSFB converter for improving the ZVS operation range. However, the interaction between the junction capacitance of the rectifier and the additional leakage inductance causes severe voltage overshoot and oscillation across the rectifier after a commutation. Thus, it increases the rating of the rectifier devices and causes output voltage noise and electromagnetic interference noise. To prevent this problem, two clamp diodes are introduced to the PSFB converter with additional leakage inductance. [2] Fig. 1 shows the circuit diagram of PSFB converter with additional leakage inductance and clamp diodes.

In the PSFB as shown in Fig. 1, additional leakage inductance carries the AC current almost same with primary current of transformer and generally additional leakage inductor core is employed small one. Hence, flux swing of inductor core will be large so that the core loss as well as conduction loss can be increased.

In this paper, PSFB converter with separated primary winding is proposed to solve this problem. By separating the primary winding into two parts, center and outer side of EI core, proposed converter

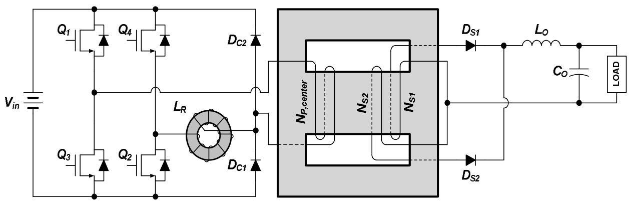


Fig. 1 Conventional PSFB

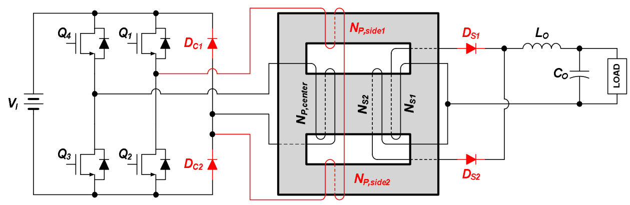


Fig. 2 Proposed PSFB with SPW

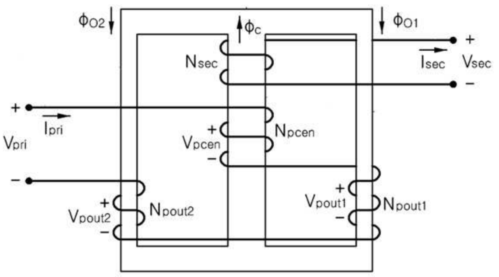
combines the additional leakage inductor and transformer in one ferrite core for producing the controllable value of leakage inductance which is suitable value for ZVS operation. Furthermore this PSFB converter with SPW can reveal the lower core loss than one of conventional converter. Therefore, it can improve the power density and efficiency. The operational principle, design will be discussed in next section.

2. Operational principle

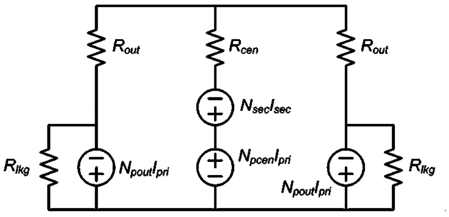
2.1 Analysis of transformer with separated primary winding transformer.

Fig.2 shows the circuit configuration of proposed ZVS PSFB converter with separated primary winding. The circuit configuration of proposed converter is based on the conventional PSFB with two clamp diodes. The difference with conventional one is that the primary winding of transformer is separated into two parts; $N_{Pcenter}$ and N_{Pout}. $N_{Pcenter}$ winds around the center leg of EI core and N_{Pout} around the side leg of EI core. $N_{Pcenter}$ is connected to the lagging leg and N_{Pout} to the leading leg.

For the analysis of the transformer with separated primary winding, Fig. 3 shows the transformer configuration and the magnetic equivalent circuit diagram of proposed transformer. It is supposed that Npout1=Npou2 to make the transformer core operate in a symmetrical condition. Then, the voltage between $N_{Pout}1$ and 2 is determined to the same value, $V_{Pout}=V_{Pout1}=V_{Pout2}$, and flux through the both outer legs is also determined to the same value, $\Phi_{out}=\Phi_{out1}=\Phi_{out2}$. From these assumptions, the voltage



(a) Transformer configuration of proposed PSFB with SPW



(b) Magnetic equivalent circuit diagram of SPW

Fig. 3 Circuit diagram of transformer with SPW

of primary side of transformer is determined as follows:

$$V_{pri} = V_{Pcen} + 2V_{Pout} \tag{1}$$

When positive voltage is given to the primary side of transformer, flux of the transformer core will increase along with the direction as shown in Fig. 3-(a). Flux will vary with the time as follows:

$$p < \Phi_{center} >= p < 2\Phi_{out} > \tag{2}$$

P<x> means the variation ratio of "x" per time. From (2), it is derived the voltage ratio between $V_{Pcenter}$ and V_{Pout} as follows:

$$\frac{V_{Pcen}}{N_{Pcen}} = 2\frac{V_{Pout}}{N_{Pout}} \tag{3}$$

From (1)-(3), voltage ratio between primary side and secondary side of transformer is derived as follows:

$$\frac{V_{\sec}}{V_{pri}} = \frac{N_{\sec}}{N_{Pcen} + N_{Pout}} \tag{4}$$

From (4), When it is supposed that $N_{pri}=N_{Pcen}+N_{Pout}$, proposed PSFB with separated primary winding can operate as same way with the conventional PSFB converter which has transformer that of primary turn ratio is N_{Pri}.

Main concept of the proposed separated primary winding is

1) Both primary winding are magnetically coupled.
2) Using the bad coupling coefficient of outer primary winding, it is produced larger leakage inductance without additional leakage inductance for ZVS operation.
3) The leakage inductance is controlled by the turn ratio of the outer side.
4) By combining the additional leakage inductance with transformer, the loss oriented from additional leakage inductance can be decreased and it brings about the improvement of efficiency.

2.2 loss comparison with additional leakage inductor

In case of conventional PSFB, square wave voltage is given to the additional leakage during the commutation period. Since leakage inductance is designed as small enough to satisfy the ZVS condition as possible, large input voltage encounters with leakage inductor during short commutation period. Previous research on core loss mentioned that when abrupt square wave is given to the core, another loss except hysteresis loss become dominant factor [3]. Furthermore, another loss will increase as the period which voltage is given decrease. The loss ratio is expressed as follows:

$$\frac{P_c^{square}}{P_c^{\sin}} = \left\{\frac{A}{8\pi\rho}(4fB_o)^2\frac{1}{D}\right\} / \left\{\frac{A}{16\pi\rho}(2\pi fB_o)\right\} = \frac{8}{\pi^2 D} \tag{5}$$

$$\frac{P_{ex}^{square}}{P_{ex}^{\sin}} = \left\{3.5\sqrt{\frac{2\pi A\alpha n_o}{\rho}}(fB_o)^{3/2}\right\} / \left\{8\sqrt{\frac{A\alpha n_o}{\rho}}(fB_o)^{3/2}\frac{1}{\sqrt{D}}\right\}$$

$$= \frac{4}{3.5}\sqrt{\frac{2}{\pi}}\frac{1}{\sqrt{D}} \tag{6}$$

where $B_o = \frac{V_o}{2\pi fNA}$

Generally, additional leakage inductance is embodied by the toroidal core which has small cross section area. Hence the size or loss will be increased according to the loss analysis.

However, in case of proposed separated primary winding, additional leakage inductance is expressed with transformer core which have large cross section area. Therefore loss can be decreased compare to the one of conventional PSFB.

2.3 Leakage inductance design

Leakage inductance of transformer is actually distributed throughout the windings of a transformer because of the flux set-up by the primary winding, which does not link the secondary, thus giving rise to leakage inductance in each winding without contributing to the mutual flux. According to the literature, leakage inductance is influenced by the winding method; i.e. winding length, winding layer. It means that if winding method is well-designed, leakage inductance can be controlled. In the proposed converter, primary winding is divided into two parts. Outer primary winding will have many parts which do not link the secondary. Hence, by setting the winding ratio of outer primary winding, leakage inductance is constructed to desired value which is suitable for ZVS operation.

3. Design consideration of PSFB with SPW

3.1 Turn ratio of transformer, n=Np/Ns

As mentioned previous section, proposed PSFB with SPW can operate as same way with the conventional PSFB. Hence, voltage conversion ratio is shown as follow:

$$\frac{V_{out}}{V_{in}} = \frac{2D}{n} \tag{7}$$

When turn ratio is designed as $N_{pri}=N_{Pcen}+N_{Pout}$, total turn ratio of transformer can be decided from (7). When minimum input voltage is given to the converter, converter is operated with maximum duty ratio. Hence turn ratio is expressed as follows:

$$n = \frac{N_{pri}}{N_{\sec}} = 2D_{\max}\frac{V_{in\min}}{V_{out}} \tag{8}$$

The selection of turn ratio of primary side, N_{Pcen} and N_{Pout}, is related with leakage inductance. Since the transformer with SPW produces the leakage inductance using the bad coupling coefficient of outer primary winding, primary winding ratio between center and outer side should be selected according to the ZVS condition.

3.2 Additional leakage inductance

To decide the turn ratio of outer primary, ZVS condition of proposed converter should be discussed at first as mentioned prior section. It is assumed that the magnetizing inductance is large enough to ignore the effect of magnetizing current for ZVS operation. The ZVS condition of proposed converter can be expressed as $(L_{lkg}+L_R)i_{Lr}^2(t_2)\ge 2C_sV_{in}^2$ and can be rewritten as follows:

$$i_{Lr}(t_2)\ge\sqrt{\frac{2C_s}{L_{lkg}+L_R}}V_{in} \tag{9}$$

It is assumed that the output capacitance of power switch, Cs is 780nF. To achieve the ZVS operation at half load condition, $L_{lkg}+L_R$ is selected to 10uH.

Table 2 shows the resonant inductance which is made by SPW. It can be seen that the measured inductance is proportional to N^2. Outer turns are selected to 8 turns to meet ZVS operation at 60% load condition.

Table 1. Leakage inductance according to outer primary winding

Outer turns	Inductance
7	7.8u
8	12.6u
9	14.5u
10	16.8u

4. Experimental results

To verify the proposed PSFB with SPW, the 1.2kW prototype is built with following specification

- Input voltage Vin : 320~400Vdc,
  Normal operation voltage: 400Vdc
- Output voltage Vout : 12V, 100A
- Maximum output power Po : 1200W
- Switching frequency : 86kHz
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Fig. 4 shows the experimental results of proposed PSFB with SPW under full load condition. Fig. 4 gives the key waveforms of primary voltage of transformer, primary leakage current and the voltage of secondary synchronous rectifier (SR). As can be seen in Fig. 4, ZVS operation of all switches is well achieved as shown in primary voltage of transformer. The voltage overshoot is observed at the voltage of SR. Since the outer primary side is linked with center side of transformer, leakage inductance cannot totally be isolated by the clamp diodes during the commutation period. Hence, by the resonance between output capacitance and leakage inductance, the voltage of SR has to have some voltage overshoot.

Fig. 5 shows the efficiency comparison table of the proposed converter and conventional converter. The proposed converter shows the 0.6% higher efficiency than conventional one. It means that the proposed PSFB converter wish SPW reduce the loss of additional leakage inductor so that whole efficiency can be increased.

Table 2. Used component list

Switching frequency (fs)	86kHz
Primary switches	SSP20N60C3
Primary clamp diode	ES1J
Turn ratio of transformer (N_p:N_{s1}: N_{s2})	24 : 1 : 1
Magnetizing inductance (L_m)	1.68mH
Leakage inductance (L_{lkg})	2.2uH
Additional resonant inductance (L_R)	8.25uH
Synchronous rectifiers	IRFB3907
Output inductance	1.2uH
Output capacitance..	990uF
Turn ratio of primary (N_{pcen}:N_{pout})	16:8

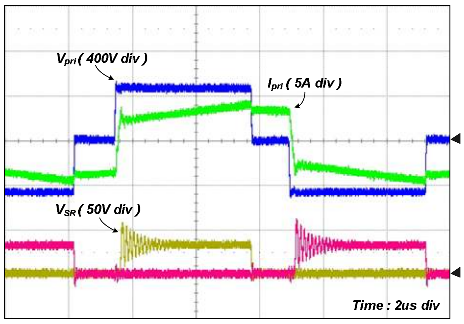

Fig. 4 Experimental results of proposed PSFB with SPW

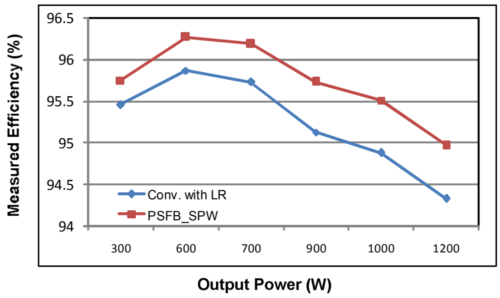

Fig. 5 Efficiency comparison with load variation

5. Conclusion

A new PSFB converter with SPW is proposed in this paper. Proposed PSFB converter with SPW combines the additional leakage inductor to the transformer by using the separated primary winding. By simply setting the outer turn ratio, leakage inductance is designed for the ZVS operation of converter. Furthermore the loss is decreased as additional leakage inductor is built in transformer without extra core. These advantages bring about the improvement of whole efficiency and the reduction of size and cost. Therefore, proposed PSFB with SPW is very desirable converter for high power, high power density and high efficiency system.

Acknowledgment

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