Unexpected Bi-Directional Operation of Phase-Shift Full-Bridge Converter in Parallel Operation System

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***Abstract* — This paper discusses the effects of unexpected bi-directional operation of Phase-Shift Full-Bridge Converter in cold redundancy (CR). According to growing trends for high efficiency at light-load, cold redundancy method is strongly required in parallel operation system. However, because of unexpected backward operation, the voltage stress of primary switches is severely increased.**

In this paper, the period of mode change from normal operation to backward operation is investigated. The detailed operations in backward mode are described and the main factors of the severe voltage stress are analyzed. Furthermore, characteristics of switch to reduce higher voltage stress are also presented in terms of selecting switches. The validity of this study is confirmed by the experimental results of prototype 1.6kW converters.

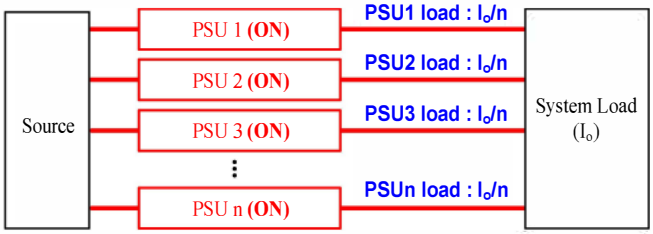
I. INTRODUCTION

When a server system having a single power supply is turned off by the hardware failure, the system stops operating and loses data in system. Therefore, the parallel operation is generally applied to prevent data loss and to secure the system reliability in the distributed power system (DPS). In the real condition, the power supplies in parallel system are usually operated under light-load condition because server system has an enough design margin for power supplies and power supply has the distributed system load. Furthermore, Climate Savers Computing Initiative (CSCI) sets the highest efficiency guideline on half load condition and the guideline on 20% load condition is also presented according to the requirements for computer, telecom, and network equipment manufacturers [1]. Recently, 10% load condition is added. It indicates that efficiency under the light-load condition becomes more and more important.

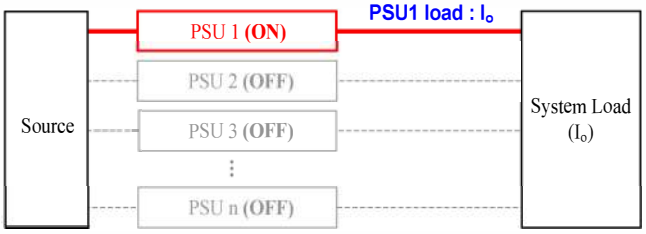
In the general parallel system, all power supplies are operated regardless of load conditions as shown Fig. 1(a). The system load is equally distributed to all power supplies over the entire load range. Because all PSUs are operated at the same time, system stability increases. However, the efficiency at light-load condition is low because of load-independent loss such as switching loss of switches and core loss of magnetics. Therefore, the technique to reduce the power consumption at light-load condition has been required.

Recently, a new control method to improve light-load efficiency is proposed, as called 'Cold Redundancy (CR)' [2]. Cold Redundancy method controls the number of operating power supply at light-load condition shown Fig. 1(b). The operation is same to the general operation method except for the light-load condition. When the server system is operating at light-load condition, only one power supply is operated and the load condition of the power supply is close to the half load designed for maximum efficiency. Furthermore, because the control circuit of other power supplies is not operated, it can also reduce the power consumption of control circuit. Therefore, parallel system with Cold Redundancy method shows better efficiency at light-load condition than in general parallel operation.

However, there is one requirement in parallel operation with Cold Redundancy method. The quick response of non-operated PSUs is strongly required when the server system load changes from the light-load condition to heavy-load condition or the operated PSU is turned off by some hardware failures. This requirement is essential to keep stability of parallel operation system with Cold Redundancy. To meet the requirement, non-operated PSUs start to work with full duty-ratio and without soft-start function. Thus, overshoot of output voltage can occur in this condition. Because of the overshoot, the direction of output inductor current changes to negative. As a result, the unexpected operation occurs because of the negative current of output inductor, as called 'backward mode'. In backward mode, voltage of switches is much increased because the current flow direction is reversed.



(a) General parallel system



(b) Parallel system with CR method at light-load condition

Fig. 1 Parallel operation of server system

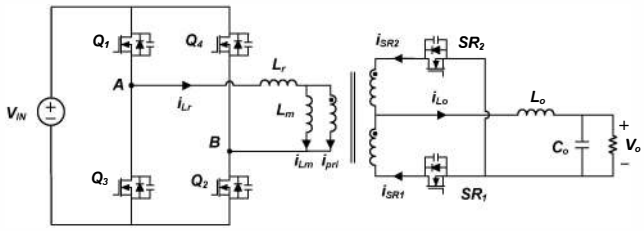
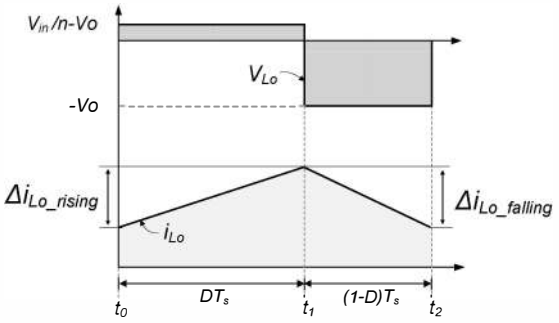
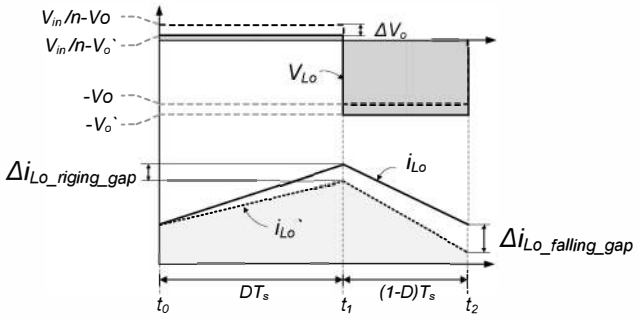


Fig. 2 Conventional PSFB converter



(a) in steady state



(b) in mode transition

Fig. 3 Output inductor current waveform

In this paper, the unexpected operation called as 'the backward operation' of phase-shifted full-bridge (PSFB) converter is defined and a comparison with the forward mode is also presented. Moreover, increased voltage stress of switches is analysed in the backward mode regarding the characteristics of switches. And the method to reduce stresses is also proposed. The analysis and operations are proved by an experimental prototype converter with the capability of 1.6kW.

II. ANALYSIS

A. Mode change from forward mode to backward mode

Before the mode analysis, the main factors making the mode change from the forward mode to the backward mode are explained. The mode depends on the output inductor current. When output inductor current flows toward the load, it is the forward mode. On the contrary, when the output inductor has the current toward the source, it is the backward mode.

Fig. 2 shows a conventional PSFB converter with external inductor on primary side [3]. In PSFB converter, Fig. 3(a)

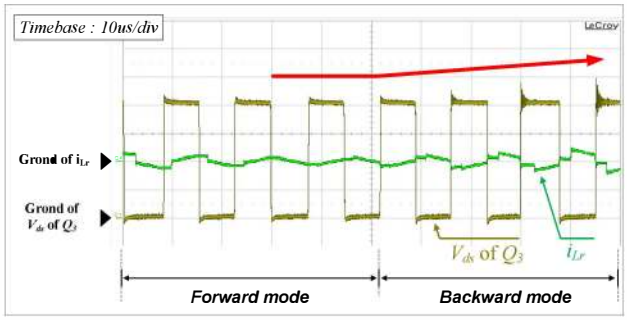


Fig. 4. Waveforms for entering backward mode

shows the voltage and current waveform of output inductor in the steady state of the forward mode. The rising and falling variation of i_{Lo} can be expressed as

$$\Delta i_{L_o\_rising} = \frac{\frac{V_{in}}{n} - V_o}{L_o} \times DT_s, \quad (1)$$

$$\Delta i_{L_o\_falling} = \frac{-V_o}{L_o} \times (1-D)T_s, \quad (2)$$

where V_o is output voltage, V_{in} is input voltage, D is duty ratio, L_o is output inductance, n is turn ratio of transformer, and T_s is switching period. The start and finish point of current waveform during one cycle are same because of the voltage-second balance.

However, in Cold Redundancy, power supply in idle mode need to quickly change to the normal operation in order to maintain system stability. The power supply in idle mode is operated without soft-start function and with full duty-ratio for quick response. Therefore, the overshoot occurs because the output voltage has very short rising time. The mode transition starts from the voltage overshoot. Fig 3(b) shows voltage and current waveform of output inductor in transient period to enter the backward mode as the dotted line. And the waveforms in steady state are expressed as the solid line same to Fig. 3(a). The difference is caused by the increased output voltage, V_o'. The difference of i_{L_o} during the rising time can be expressed as

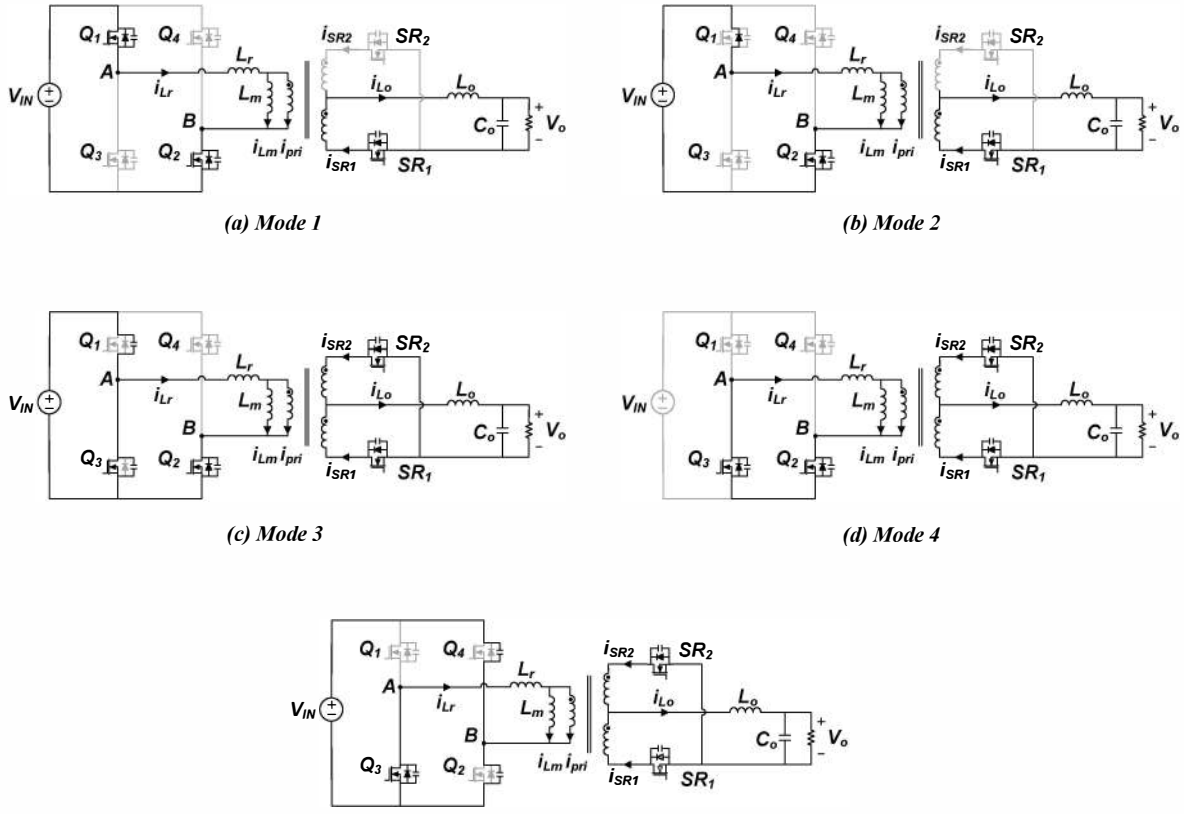
$$\Delta i_{L_o\_rising\_gap} = \frac{V_o' - V_o}{L_o} \cdot DT_s. \quad (3)$$

The gap of i_{L_o} during one cycle is presented as

$$\Delta i_{L_o\_falling\_gap} = \frac{V_o' - V_o}{L_o} \cdot T_s. \quad (4)$$

Because V_o is increased, $\Delta \boldsymbol{i_{L_o\_rising}}$ becomes smaller and $\Delta \boldsymbol{i_{L_o\_falling}}$ becomes bigger in (1) and (2). Therefore, the finish point of inductor current is no longer same as start point during one cycle and the current value in finish point is lower than start points. The unbalancing period is kept until inductor current meets the zero. When the inductor current direction is changed to negative, the mode change is finished and the backward mode starts. The increased output voltage keeps the unbalancing between start and finish point until the output voltage goes back to the setting voltage.

Fig. 4 shows a waveform during the transient time to enter the backward mode from the forward mode. Q_3 is low side switch of leading-leg and i_{Lr} is current of external



(a) Mode 1 *(b) Mode 2*

(c) Mode 3 *(d) Mode 4*

(e) Mode 5

Fig. 5. Equivalent circuit of PSFB converter in the backward mode

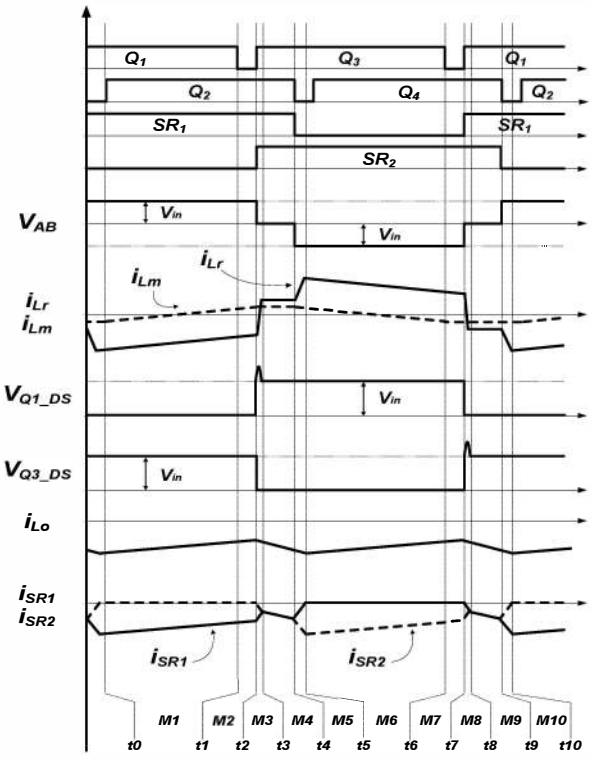


Fig. 6. Key waveforms of PSFB converter in the backward mode

resonant inductor. Mode change is expressed by i_{Lr} including information of i_{Lo}. In the forward mode, when Q_3 is turned off, i_{Lr} has the positive value. However, in backward mode, i_{Lr} is negative value in same condition. After the mode is changed to the backward mode, the arrow indicates that voltage stress of Q_3 is getting higher and higher.

B. Analysis of the backward mode

The unexpected backward mode of PSFB converter is similar to current-fed push-pull converter. The current-fed push-pull converter with diodes on secondary side has been studied already [4]. In this paper, the diodes on secondary side are replaced with the synchronous rectifier (SR) and the phase-shifted gate signals are applied to the full-bridge switches on the primary side.

Each switching period is subdivided into 10 modes and those equivalent circuits are expressed in Fig. 5. And Fig. 6 shows the key waveforms of PSFB converter in backward mode. This paper shows the analysis of mode 1 ~ 5 because the operations from mode 6 to mode 10 are the same except for the direction.

The analysis is based on the assumptions as follows:

1) All the active power devices are ideal switches with parallel body diodes and parasitic capacitors.

2) The parasitic capacitors of switches on each side is same.
3) The transformer is an ideal with parallel magnetic inductance and turn ratio is n:1:1.
4) L_r is the external inductor in order to expand the zero-voltage-switching (ZVS) range.
5) Q_1 and Q_3 are the leading-leg switches and Q_2 and Q_4 are the lagging-leg switches.

Mode 1 ($t_0 \sim t_1$): After Q_2 is turned on, the mode 1 starts. And Q_1 and SR_1 were turned on in previous mode. The primary current starts to increase. But the direction of current is negative and the absolute value is decreased. The output inductor current flows through SR_1. And i_{L_o} has the negative direction in this period. Key equations of this mode can be presented as follows:

$$i_{pri} = n\left(i_{SR_2} - i_{SR_1}\right) = ni_{L_o}, \tag{5}$$

$$i_{L_r} = i_{L_m} + i_{pri} = i_{L_m} + ni_{L_o}, \tag{6}$$

$$\Delta i_{L_m} = \Delta i_{L_r} = \frac{V_{in}}{L_m}(t_1 - t_0), \tag{7}$$

where i_{pri} is the ideal transformer current on primary side, i_{L_m}, i_{L_r} and i_{L_o} are the inductor current of L_m, L_r and L_o respectively, i_{SR_1} and i_{SR_2} are the current of SR_1 and SR_2.

Mode 2 ($t_1 \sim t_2$): This mode is almost same as Mode 1. At t_1, Q_1 is turned off. And Q_2 and SR_1 keep their status. The current of L_r flows through the body diode of Q_1 because of the negative current direction. So, $\boldsymbol{V_{DS}}$ of Q_3 is unchanged and the current slope equation is the same as Mode 1. In forward mode, the preparation of ZVS of leading-leg switches is implemented. However, output capacitance (C_{oss}) of leading-leg switches cannot be discharged due to the direction of $\boldsymbol{i_{L_r}}$ in the backward mode. In conclusion, ZVS of the leading-leg switches cannot be realized.

Mode 3 ($t_2 \sim t_3$): At t_2, gate signals of Q_3 and SR_2 are changed to high. And Q_2 and SR_1 keep the status. In backward mode, ZVS operation of Q_3 cannot be implemented and voltage stress is higer than the forward mode. However, the turning-on time of Q_3 and SR_2 are different because of the stored charge in C_{oss} of switches. In mode 3, SR_2 is only turned on. Because of the timing gap, i_{L_r} is increased rapidly. The equation of i_{L_r} is shown as follows:

$$\Delta i_{L_r} = \frac{V_{in}}{L_r}(t_3 - t_2). \tag{8}$$

And the $\Delta i_{L_m} = 0$ because v_{L_m} is zero.

The dramatic change of i_{L_r} makes the high voltage stress of Q_1 due to a reverse recovery characteristic of body diode. Normally, the body diode of switches has worse reverse recovery characteristics than diodes, such as the fast recovery diode and ultra-fast recovery diode. Furthermore, the reverse transfer capacitance (C_{rss}) of switches also affects the slope of drain-source voltage of Q_3. On the secondary side, SR_1 and SR_2 are commutated first.

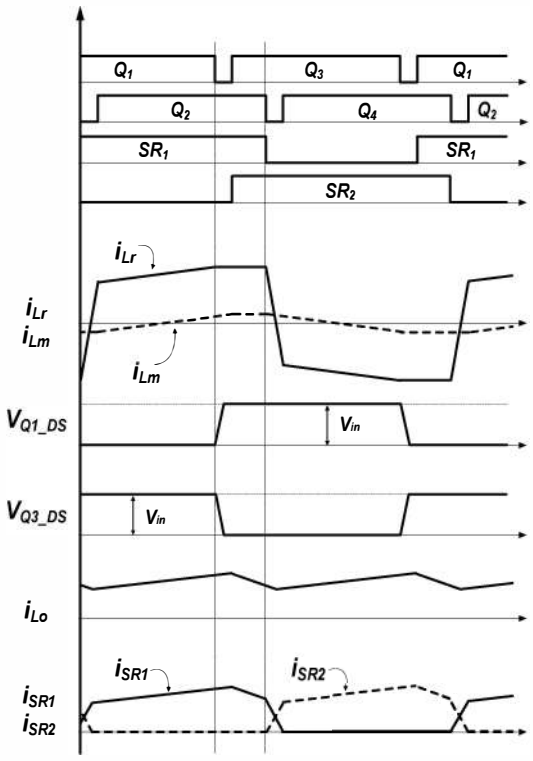


Fig. 7. Key waveforms of PSFB converter in the forward mode

Mode 4 ($t_3 \sim t_4$): This period is same as the freewheeling period in forward mode. The voltages of L_r and L_m are zero and i_{L_r} and i_{L_m} maintain the value. At t_3, the value of i_{L_r} is determined by the slope of i_{L_r} during mode 3 and i_{SR_1} and i_{SR_2} are determined by i_{L_r} from (5) and (6).

Mode 5 ($t_4 \sim t_5$): At t_4, Q_2 and SR_1 are turned off and the freewheeling period is finished. On secondary side, i_{SR_1} has the rapid decrease once more and i_{L_r} are also changed. The second commutation occurs and the slope of i_{L_r} has positive value because of (5). After the change, the slopes of i_{L_r} and i_{L_m} are same as mode 1 with opposite direction. And the output capacitor of lagging-leg switch Q_4 is discharged from i_{Lr}. Therefore, ZVS of the lagging-leg switches Q_2 and Q_4 can be achieved better than the forward mode.

C. Analysis of the switch voltage stress

The backward mode has operational differences from the forward mode as shown in Fig. 7. There are three differences. First, the current flow and power transfer are basically opposite to the forward mode. Second, ZVS operations are different. In forward mode, ZVS of leading-leg switches are achieved easily but lagging-leg switches are harder than leading-leg switches [5]. However, in backward mode, ZVS of lagging-leg switches are easier than leading-leg switches and even leading-leg switches are under hard-switching condition. Finally, in the backward mode, the commutation between SR switches is added on mode 3 because the current of i_{Lr} has a dramatic change. In aspects of voltage stress, the notable

difference is ZVS of leading-leg switches. From the difference, the increased voltage stress on primary side is explained.

In mode analysis, i_{Lr} flows through the body diode of Q_1 during mode 2. At the end of mode 2, gate signals of Q_3 and SR_2 simultaneously change to high in logic level. Because of the difference between V_{ds} of Q_3 and SR_2, SR_2 is only turned on and the period is expressed as mode 3. At the start of mode 3, i_{Lr} has a sharp change according to (8) and its direction is also changed. And the body diode of Q_1 is turned off because of the dramatic current change. In turn-off time of diode, reverse recovery current (I_{RR}) and maximum repetitive reverse voltage (V_{RRM}) are determined by reverse recovery charge (Q_{rr}) and reverse recovery time (t_{rr}) of inner body diode of switches [6]. Especially, V_{RRM} is directly shown as the voltage stress of switches. Therefore, the voltage stress of switches in backward mode is able to reduce by considering characteristics of body diode of switches. When the switches having small t_{rr} and Q_{rr} are implemented, the voltage stress of primary switches can be decreased.

In the backward mode, the leading-leg switches are operating under the hard-switching condition. Therefore, C_{rss} is the main factor to set the slope of drain-source voltage of turn-on switch [7]. The voltage stress of switches depends on the slope of V_{DS}. Therefore, the voltage stress is also changed by the C_{rss} of switches. When switch having small C_{rss} is applied, the switch has the dramatic slope of V_{DS} and voltage stress can be increased compared with switches having large C_{rss} are applied.

Furthermore, the sharp voltage stress of turn-off switch causes the negative voltage stress of another switch on the same leg. In backward mode, the driver IC is damaged by the negative voltage of turn-on switch. Moreover, it leads the critical damage of the switches.

III. Experimental Verification

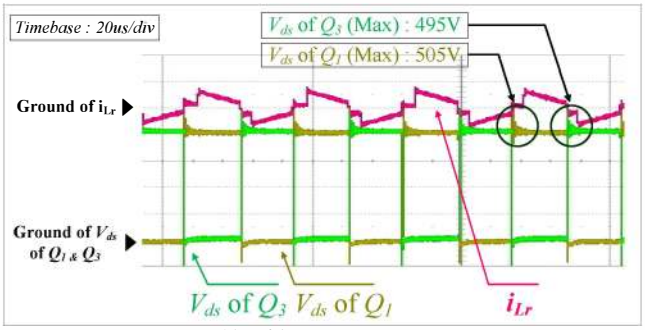
The PSFB converter to compare the voltage stress of switches having the different characteristics of inner body diode and C_{rss} are realized with the following specification.

- Input voltage : V_{in} = 400V$_{dc}$
- Output voltage : V_o = 12V
- Maximum output current : $I_{o(max)}$ = 133A
- Maximum power : $P_{o(max)}$ = 1.6kW
- Switching frequency : f_s = 70kHz

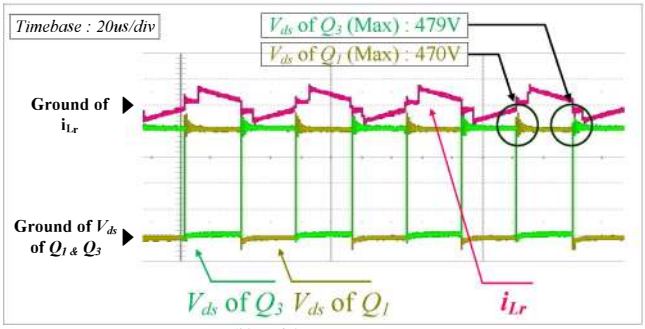
Table 1 indicates the key characteristics of switches. In Table 1, C_{rss} of IPP60R125C6 is same to C_{rss} of IPP65R110CFD. However, characteristics of body diode such as t_{rr} and Q_{rr} are larger than IPP65R110CFD. In comparison between IPP60R125C6 and IPP60R125CP, t_{rr} and Q_{rr} of two switches have similar values but Crss of IPP60R125C6 is larger than IPP60R125CP. Two switches that all characteristics are similar except for one factor are selected and peak voltage of power supplies with selected switches is compared.

TABLE I. Comparision Between The Presented Switches

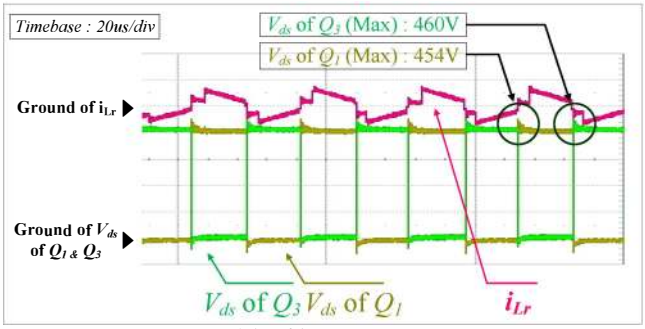
No.	Part Number	$R_{ds(on)}$ [ohm]	C_{oss} [pF]	C_{rss} [pF]	t_{rr} [ns]	Q_{rr} [µC]
1	IPP60R125CP	0.125	120	1.2	430	9
2	IPP60R125C6	0.125	125	13	510	10
3	IPP65R110CFD	0.110	160	13	150	0.8



(a) With IPP60R125CP



(b) With IPP60R125C6



(C) With IPP65R110CFD

Fig. 8. Waveforms of voltage stress on the backward mode

Fig. 8 shows the drain-source voltage of leading-leg switches Q_1, Q_3 and i_{Lr} in backward mode. As shown in Fig. 4, comparison between the presented switches the voltages across primary switches have the maximum level when the direction of i_{Lr} is changed. The comparison between IPP65R110CFD and IPP60R125C6 is tested in order to show the effect of body diode of switch. The voltage stress of Q_3 is 460V when IPP65R110CFD is used as the switches on primary side as shown in Fig. 8(c). And Fig. 8(b) presents that voltage stress of Q_3 is 479V when IPP60R125C6 is

applied. The voltage stress of primary side switches in backward mode is decreased with the small t_{rr} and Q_{rr}.

IPP60R125CP and IPP60R125C6 are compared to show the effect of C_{rss}. The voltage stress of Q_3 is 495V with IPP60R125CP as shown in Fig. 8(a). Therefore, low C_{rss} makes the slope of V_{DS} sharply and the sharp slope of voltage is shown as the voltage stress of switches. In conclusion, the switch with small t_{rr} and Q_{rr} and large C_{rss} has the lowest voltage stress as expected from the analysis of voltage stress. And the effects of two factors, body diode characteristics and $C_{rss,}$ are shown as the almost same voltage stress.

Furthermore, when high voltage spike is getting small, the negative voltage stress is also getting small. The damage of gate driver IC by the negative voltage spike is also prevented by selecting the proper switches.

IV. CONCLUSION

In this paper, the unexpected operation of PSFB Converter called as 'the backward operation' is analyzed in Cold Redundancy. The mode change from forward mode to backward mode is explained and the difference between the forward and backward mode are studied through the mode analysis of backward mode. Among the differences between two modes, the ZVS condition of leading-leg switches depends on the voltage stress of leading-leg switches.

Two factors making the voltage stress of primary switches, reverse recovery of body diode and C_{rss}, are described from the voltage stress analysis. The switches with small t_{rr} and Q_{rr} reduce the voltage stress of leading-leg switches. On the other hand, the switches having small C_{rss} increase the voltage stress sharply. And the effects of reverse recovery of body diode and C_{rss} characteristic are proved from the experiments with the 1.6kW prototype PSFB converter.

ACKNOWLEDGMENT

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