Analysis of MOSFET Failure Modes in Bi-directional Phase-Shift Full-Bridge Converters

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Abstract – This paper presents an analysis of the mechanism of failure modes in bi-directional phase-shift full-bridge converters, composed of MOSFET, based on the circuit operation and parasitic parameters of MOSFET. In addition, the relation between circuit operation and parameters is suggested through an experimental comparison. From this relation, the suitable ranges of parameters for stable performance are analyzed. The design criteria of the bi-directional phase-shift full-bridge converter are presented and evaluated from the experimental verification.

Keywords: Bi-directional Full-bridge converters, Bi-directional Phase-shift, Failure modes, MOSFET fault, MOSFET failure modes

1. Introduction

As the development of vehicle to grid systems and renewable energy sources or battery energy storage systems has been actively progressing, the bi-directional converter has continued to receive attention as the effective power transfer unit from the battery to the energy source [1-4].

Among the various types of bi-directional converter topologies, the bi-directional phase-shift full-bridge (PSFB) topology with dual active bridge (DAB) as shown in Fig. 1 is regarded as a preferred option with its advantages such as isolation among energy sources, medium / high power capacity with high efficiency, stability, and reliability [1, 7-12].

The elements affecting performance and stability of the bi-directional PSFB converter can be listed as controller configuration, design of magnetic components, and selection of switching devices. Among these, MOSFETs substantially influence the characteristics of the overall performance. Especially, in the case of bi-directional operation, the primary and secondary sides of PSFB converters consist of MOSFETs, so that the effect of parasitic components becomes more serious [7]-[12].

The important considerations in selecting the MOSFET applied to the bi-directional PSFB converters are parasitic output capacitance (C_{oss}) for resonant condition, conductive resistance ($R_{ds,on}$) to reduce conduction losses, and gate drive charge (Q_g) for stable gate drive. Also, in particular reverse-recovery characteristics of body diode (t_{rr} or Q_{rr}) and gate charging capacitance (C_{gd}) are additionally considered. As the body diodes are used to rectify the

Fig. 1. Configurations of bi-directional PSFB converter using MOSFETs

secondary side of the PSFB converter in the DAB structure, the reverse-recovery current (I_{rr}), which is determined by the reverse-recovery characteristics of the DAB structure, is reflected on the primary side and added to the voltage stress of the switching devices [12-15].

Moreover, the failure of devices in the secondary side also occurs in the operation of the rectifier. In addition, the gate charging capacitance (C_{gd}) is important to ensure the stable gate driving of MOSFET from the instantaneous voltage/current stress caused by the increased parasitic parameters and I_{rr} . Considering the above-mentioned phenomena, the appropriate design process of the bi-directional PSFB converter should be performed. However, the failure modes occasionally appear in this converter because of the insufficient consideration of the design criteria of the parameters [1, 6-9, 14].

Therefore, in this paper, the analysis of the mechanism of the failure modes in the bi-directional PSFB converter using MOSFET is presented on the basis of the operation of the circuit and parasitic components of MOSFET. Based on the result of the analysis, each parameter that affects the failure modes is described. By considering these parameters, desirable MOSFETs for achieving high efficiency in the PSFB converter are determined, and appropriate MOSFETs are reclassified for the stable

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operation of the bi-directional type.

In this procedure, an experimental comparison is carried out to evaluate the parameters of the selected MOSFETs on the circuit operation, considering transient characteristics of the bi-directional PSFB converter.

2. Analysis of Failure Modes Mechanism

Failure modes in the bi-directional PSFB converter mainly occur in two conditions of circuit configuration, such as the transient in the circuit operation and the false operation of the MOSFETs in the full-bridge configuration by the reverse recovery current of the body diode [1].

2.1 Failure mode in circuit operation

The circuit operation of the PSFB converter can be divided into the leading-leg transition and the lagging-leg transition. In the conversion of both operations, the transient voltage spike, after freewheeling in the primary side and commutating in the secondary side by the circuit operation, induces the failure modes of the MOSFETs and the body diodes as shown in Fig. 2 [1].

In the leading leg transition, the filter inductor current simultaneously charges and discharges the output capacitance

Ch1: $V_{AB,pri}$ (200V/div) / Ch2: $I_{Lr,pri}$ (2A/div) / Ch3: V_{out} (100V/div) [Time: 2us/div]

(a) Transient voltage spike in primary side

Ch1: $V_{AB,pri}$ (500V/div) / Ch3: $V_{ds,Sa}$ (100V/div) / Ch4: $I_{ds,Sa}$ (10A/div) [Time: 1us/div]

(b) Transient voltage spike in secondary side

Fig. 2. Transient voltage spike due to the circuit operation

(a) Leading leg

(b) Leading leg

Fig. 3. Equivalent circuit in the operation of bi-directional PSFB

of the switches in the primary and secondary sides of PSFB. In this process, the converter consists of an LC resonant network and it generates current resonance. In the resonant condition, the voltage across the primary switches and the rectified voltage in the secondary side are linearly decreased. The currents through both inductors can be treated as current sources, because the filter inductor and the magnetizing inductor of the transformer are relatively larger than the resonant inductor. The current flowed from the current sources linearly discharges the energy stored in the capacitors without the transient voltage.

In the lagging leg transition, on the other hand, the LC resonant circuit with the input voltage source induces the voltage spike.

Both transient operations of the bi-directional PSFB converter can be represented by the equivalent circuits as shown in Fig. 3. Fig. 3(a) indicates the equivalent circuit of the leading leg transition. In this condition, $2C_{oss,pri}$ and $2C_{oss,sec}$, which are respectively parasitic capacitors of two MOSFETs in primary bridge and secondary bridge rectifier, construct a parallel configuration. The current through the primary resonant inductor $I_{Lr,pri}$ and the current $I_{L,sec}$, which current of the filter inductor with a secondary resonant inductor, charge and discharge the capacitor simultaneously.

Since $I_{L,sec}$ can be treated as the current source, the energy stored in the capacitors is discharged without the transient state. At that time, the equivalent parameters can be represented as follows:

$$I_{L,sec} = I_{Lr,sec} + (I_{Lf,sec} / n) + I_{Lm} \quad (1)$$

On the other hand, as shown in Fig. 3(b), the equivalent inductor L_e , which is the sum of the primary resonant inductor $L_{r,pri}$ and the reflected secondary resonant inductor $L_{r,sec}$, and $2C_{oss,sec}$ consist of an LC resonant network in the lagging leg transition. In this equivalent circuit, the

equivalent inductor L_e is defined as follows:

$$L_e = L_{r,pri} + (L_{r,sec} / n^2) \quad (2)$$

The equivalent LC resonant network generates the voltage resonance with the input voltage source. Thus, the voltage oscillation is induced and it can be represented as follows:

$$V_C(t) = V_S - V_S \cos\{\omega_0(t-t')\} \quad (3)$$

As the voltage resonance effects to the rectifying voltage of the secondary side, the voltage stress affects on MOSFETs in the secondary bridge as well as in the primary bridge. The voltage stress on the secondary bridge can be expressed as follows:

$$\begin{aligned} V_{rec,sec}(t) &= \frac{N_2}{N_1} \cdot V_{C,pri}(t) \\ &= \frac{N_2}{N_1} \cdot [V_S - V_S \cos\{\omega_0(t-t')\}] \end{aligned} \quad (4)$$

where ω_0 is the resonant frequency of the LC network in the lagging leg transition as defined in (5)

$$\omega_0 = \frac{1}{\sqrt{(L_{r1} + L_{r2} / n^2)(2C_{oss,sec} / n^2)}} \quad (5)$$

In this transient analysis, not only C_{oss} but also the ratio between resonant inductance and magnetizing inductance influence on magnitudes of the transient voltage across MOSFETs in the primary and secondary bridge. Also, the reverse recovery current of body diodes in rectifying bridge side also generates a voltage overshoot with the stray inductance of the circuit. Therefore, the design of bi-directional PSFB should be performed using MOSFET with fast-recovery body diode and the stray inductance of the circuit should be minimized.

2.2 Failure mode in false operation of devices

The main reason for the device false operation in the full-bridge configuration is the reverse recovery current of the body diode. The reverse recovery of body diodes raises serious issues not only in terms of the voltage oscillation in the primary bridge with the overvoltage failure of the MOSFETs, but also the performance of the bi-directional power conversion and transfer from the input source to the output load. Careful consideration in the design of MOSFETs in the bi-directional PSFB converter is therefore required because the false operation of devices according to the reverse recovery current from the body diode can generate a failure mode as shown in Fig. 4. When the false operation of devices is happened, arm short is instantaneously occurred in a single leg of the full-bridge

and short through current flows through the leg, as shown in Fig. 4. As the energy is not transferred to output under the influence of arm short, the output voltage becomes nearly zero. The remained energy cause the current level to be increased in primary side and the growing current stress of MOSFETs in primary full-bridge leads to failure.

Due to the false operation of the MOSFET, the failure mode in the bridge structure has been studied in previous work. However, most studies have focused on the numerical analysis and the empirical results with the statistical method because the factor of the failure mode is formed from the structure and the manufacturing process of the semiconductor device [13-15]. Moreover, the requirement for high efficiency devices has motivated the development of various semiconductor structures of the

(a) Failure effects on the circuit

Ch1: $V_{AB,pri}$ (200V/div) / Ch2: $I_{Lr,pri}$ (10A/div) / Ch3: V_{out} (100V/div)
[Time: 2us/div]

(b) Failure waveforms of primary side

Ch1: $V_{AB,pri}$ (500V/div) / Ch2: $I_{Lr,pri}$ (50A/div) / Ch3: $V_{ds,Sa}$ (100V/div) /
Ch4: $I_{ds,Sa}$ (10A/div) [Time: 1us/div]

(c) Failure waveforms of secondary side

Fig. 4. Failure mode operation due to reverse-recovery of body diode

Fig. 5. Mechanism of dynamic turn-on

device, depending on the manufacturer. For this reason, numerical analysis using the quantified parameters becomes more complex. Thus, the additional design parameters are necessary to avoid the false operation of the MOSFET caused by the reverse recovery characteristic of body diode.

Two main reasons for the false operation of the MOSFET are the dv/dt caused by the stray inductance and the parasitic BJT. The false operation of the MOSFET due to the dv/dt is called dynamic turn-on. When the reverse recovery current of the body diode occurs, the rapid current transition generates a large dv/dt with the stray inductance. The dv/dt is applied across the drain-source of the MOSFET. The applied dv/dt induces the current through the gate capacitance of the MOSFET and the current induces dynamic turn-on as shown in Fig. 5. The generation condition of the dynamic turn-on can be represented by the terms of the minimum turn-on threshold voltage $V_{gs(th)}$, the maximum transient voltage across drain-source $V_{ds,max}$, and the critical charge through gate-drain $Q_{gd,crit}$ as follows:

$$\frac{Q_{gd,crit}}{V_{GS(th)}C_{gs}} < 1 \quad (6)$$

$$\int_0^{V_{ds,max}-V_{th,min}} C_{gd} dV_{gd} = Q_{gd,crit} \quad (7)$$

From (6) and (7), the decrease of the charge applied on the gate-drain can prevent dynamic turn-on. As shown in (7), the C_{gd} is integrated by the variance of the gate-drain voltage from 0 to the difference between the $V_{ds,max}$ and $V_{gs(th)}$ to determine the $Q_{gd,crit}$. Therefore, the small C_{gd} and the high $V_{gs(th)}$ are needed to avoid the dynamic turn-on represented as the critical charge through gate-drain. Additionally, the small C_{gd} reduces the influence of the

Miller effect, so that it can reduce switching time and switching losses when the MOSFET turns on and off. At this time, the increase range of $V_{gs(th)}$ is needed to bigger than the decrease range of C_{gd} , as represented in (6). However, the increase of the $V_{gs(th)}$ links to the increase of the driving power to maintain the channel in on-state. Thus, the ratio between $V_{gs(th)}$ and C_{gd} should be considered to

Fig. 6. Equivalent models of MOSFET and mechanism of its dynamic turn-on

avoid the dynamic turn-on with efficient gate driving in MOSFET.

The other false operation of the MOSFET derives from the turn-on state of the parasitic BJT. In addition, the MOSFET contains a parasitic BJT with a body diode because of its internal semiconductor structure as shown in Fig. 6 [1, 14, 15].

Theoretically, the base and emitter of parasitic BJT are shorted together by the source metal. In practice, however, the small parasitic resistances, determined by the length of the P-body layer, exist in the layer of the semiconductor structure and the resistance works as a base resistor.

When the reverse recovery current is applied to the drain, the current is normally blocked by the body diode. At this time, the displacement current through the coupling capacitor C_{db} to the base of the BJT is large enough to induce a voltage drop in the parasitic resistance of the P-body layer connecting the base and the emitter.

The voltage across the resistance is then worked as the base-emitter voltage V_{BE} of the parasitic BJT and it turns on, temporarily. The large current instantaneously flows from the drain through the P-body layer to the source due to this unwanted turn-on. The current leads to a latch-up so that the BJT maintains the turn-on state, by C_{db} and R_b .

Two false operation mechanisms of the MOSFET trigger the arm short-circuit in one leg of the bridge rectifier structure. According to these phenomena, the MOSFETs break down due to the short through current. The factor in common between mechanisms of both false operations results from the reverse recovery characteristic of the body diode in MOSFET. Therefore, unlike the conventional PSFB converter, the reverse recovery charge Q_{rr} and reverse recovery time t_{rr} , which can be recognized as the reverse recovery characteristic of the body diode, should be considered in the design of the bi-directional PSFB converter.

3. Experimental Comparison for Design MOSFETs of Bi-Directional PSFB

For the design of MOSFETs in the bi-directional PSFB converter, the suitability of the design is evaluated through a parameter analysis and experimental comparison with various devices. The parameters of the MOSFET can be derived from the datasheet given by the manufacturer.

However, as mentioned above, the property of the parasitic BJT and the resistance of the P-body layer are altered according to the manufacturing process and the internal structure.

Hence, the exact measurement of values and the numerical analysis with the equivalent modeling are obscure. Therefore, the effects of the parasitic components are discussed with regard to various MOSFETs through the result of the parameter analysis and the experimental comparison.

Based on the derived design parameters from the analysis of the failure modes mechanism, the suitability of each MOSFET is primarily determined.

The analysis and the comparison of the parameters are performed using the various MOSFETs as shown in Table 1. Before the empirical comparison, the suitability of the MOSFETs in the table is determined, through the criteria which are mentioned design parameters ($V_{GS(th)}$, C_{gd} , Q_{rr} , etc.) with the conventional parameters. MOSFET C, MOSFET E, and MOSFET F are sorted according to the analysis and comparison of the parameters. MOSFET A is also selected as the sample of the worst case.

A laboratory prototype of the bi-directional PSFB converter is built to compare the characteristics and

Table 2. System specifications and parameters of prototype

Parameter		Value [Unit]
Rated Power	P_{max}	1 [kW]
Rated Voltage 1	V_1	380 [V _{dc}]
Maximum Current 1	$I_{1,max}$	2.77 [A]
Rated Voltage 2	V_2	350 [V _{dc}]
Maximum Current 2	$I_{2,max}$	3.00 [A]
Switching Frequency	f_{sw}	100 [kHz]

Fig. 7. Prototype of bi-directional PSFB

suitability of the sorted MOSFETs as shown in Fig. 7. The system specifications and the parameters of the prototype are listed in Table 2. By using this prototype, the experiments of each MOSFET are performed under the same conditions and the results are summarized in Fig. 8.

As shown in Fig. 8, MOSFET C can perform a relatively stable operation due to the superiority of Q_{rr} , t_{rr} , and other parasitic components. MOSFET E generates the increase of the resonant current and the voltage because of the gaps of the parameters compared with MOSFET C.

When a body diode is conducted, the large transient current appears due to the growth of the reverse recovery and parasitic factors in the case of MOSFET F. From the transient, a secondary fault can be incurred by the current stress of devices. In MOSFET A, however, the failure occurs and shorts through the current flow through its main body due to the deficient reverse recovery characteristic.

According to the results of the parameter analysis and experimental comparison, MOSFET C is selected as the final choice for the stable operation of the bi-directional PSFB converter. In the verification, MOSFET A, which causes the failure mode in the system, is also applied on the prototype for comparison as shown in Fig. 9(a). The selected MOSFET C stably operates without the failure mode caused by the voltage spike in the primary side and the false operation of the MOSFETs in the secondary side as shown in Fig. 9(b).

Table 1. System specifications and parameter of prototype

	MOSFET											Body Diode				
	V_{DS}	V_{GS}	$V_{GS(th)}$	I_D	$R_{DS(on)}$	Q_g	C_{oss}	$t_{d(on)}$	t_r	t_f	$t_{d(off)}$	I_S	I_{RRM}	V_{SD}	t_{rr}	Q_{rr}
MOSFET A	650V	20V	3V	53A	70mΩ	170nC	215pF	16ns	12ns	83ns	5ns	46A	52A	0.9V	720ns	19μC
MOSFET B	650V	30V	4V	47A	58mΩ	210nC	160pF	185ns	210ns	75ns	520ns	47A	-	1.4V	590ns	25μC
MOSFET C	600V	20V	3V	52A	72mΩ	165nC	110pF	43ns	38ns	25ns	140ns	52A	-	1.2V	165ns	1.2μC
MOSFET D	600V	20V	2.5V	77A	41mΩ	380nC	187pF	50ns	50ns	85ns	320ns	77A	-	1.2V	590ns	18μC
MOSFET E	600V	25V	3V	51A	60mΩ	190nC	300pF	33ns	68ns	96ns	188ns	51A	24A	1.3V	200ns	1.8μC
MOSFET F	650V	25V	3V	35A	88mΩ	120nC	530pF	30ns	40ns	50ns	120ns	35A	22A	1.3V	190ns	1.6μC

Fig. 8. Experimental comparison of MOSFETs

Fig. 9. Verification of selected MOSFET

4. Conclusion

In this paper, the analysis of the mechanism of failure modes in the bi-directional PSFB converter, composed of MOSFET, was presented with a focus on the basis of the operation of the circuit and parameters with parasitic components of MOSFET. In addition, various MOSFETs have been discussed through the parameter analysis and the experimental comparison according to the transient characteristics and the parasitic components. Through the various comparisons and detailed results, the design criteria of selecting the bi-directional PSFB converter were determined. The result shows that the selected MOSFET has the following parameters: 165 nC of Q_g , 110 pF of C_{oss} , 165 ns of t_{rr} , and 1.2 μ C of Q_{rr} . Each value of the selected

MOSFET is about 10%~90% smaller than the parameters of other MOSFETs, and the effects of the values are shown in the result of the experimental comparison. According to the design procedure of the MOSFET in the bi-directional PSFB converter, following parameters should be considered to ensure stability and reliability:

- C_{oss} : The output parasitic capacitor of MOSFET C_{oss} influences on the ZVS condition as well as the magnitude of the voltage stress on each MOSFET in the bi-directional PSFB converter. Thus, the minimum C_{oss} should be one of the important factor to select the MOSFET.
- Q_{rr} and t_{rr} : The transient voltage caused by the reverse recovery current and the turn-on state of the parasitic BJT is controlled by the reverse-recovery

characteristic of the body diode.

- **Inductance:** The ratio of magnetizing inductance to the resonant inductance (L_m/L_r) maintains sufficiently large and the stray inductance L_σ is minimized to prevent the overvoltage failure of MOSFET with the stable operation.
- **$V_{GS(th)}$ and C_{gd} :** The high $V_{GS(th)}$ and the small C_{gd} are the main factor to avoid the failure mode by dynamic turn-on when the dv/dt is applied across the drain-source of the MOSFET.

Through the result of the analysis, it is expected that the proposed processes can provide a design guideline for a bi-directional PSFB converter.

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