1 kW Full-Bridge DC-DC Converter

Operation Guide

RD170-OGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION
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1. Introduction

This operation guide describes operation of phase-shifted full-bridge topology which is used for the 1 kW full-bridge DC-DC converter (this power supply). Refer to the Reference Guide for the specifications, operating procedure, and performance of this power supply, and to the Design Guide for the circuit design of this power supply.

2. Phase-Shifted Full-Bridge (PSFB) DC-DC Converter Circuit

Fig. 2.1 shows the phase-shifted full-bridge (PSFB) DC-DC converter circuit. Q₁ to Q₈ in Fig. 2.1 shows MOSFET and DQ₁ to DQ₈ shows MOSFET body diode. In addition, CQ₁ to CQ₈ indicates the parasitic capacitance of MOSFET and LR indicates the leakage inductance of the transformer TR.

![Fig. 2.1 Operation Description Circuit](image-url)
3. Operation Signal and Output Waveform

Fig. 3.1 shows an example of the input gate signal waveform for each MOSFET and the output voltage and current waveforms for the primary and secondary sides. The waveform is only an image, and the dead time for switching between the upper and lower MOSFET is shown longer than the actual value.

The primary Q₁ and Q₂ are switched at -50 % duty and 180 degrees out of phase with each other. Q₃ and Q₄ are also switched similarly. Q₃ and Q₄ switching signals are phase-shifted relative to Q₁ and Q₂ switching signals. This phase shift determines the amount of overlap in the diagonally located MOSFETs and also determines the amount of energy transferred during this overlap period. The secondary side is a circuit that rectifies the energy transmitted from the primary side.

![Diagram of MOSFET waveforms](image)

**Fig. 3.1** Input Signal and Output Voltage, Current Waveform

3.1. Operation Signal and Output Waveform

This section explains the circuit operation in each period of a to h shown in Fig. 3.1.
Period a: Power Transfer to the Secondary Side

[Primary Side] $Q_1$ and $Q_4$ are On

The period during which power is transferred from the primary side to the secondary side through the transformer TR. In this case, the primary winding voltage is the input voltage ($V_{in}$).

Input voltage $V_{in}$ is applied to the primary side of the transformer TR in the negative direction.

[Secondary Side] $Q_5$ and $Q_8$ are On

Voltage $n \times V_{in}$ corresponding to the winding ratio is applied to the secondary winding. The current in the secondary winding flows from the source to drain of $Q_5$, then from $L_o$, and then returns to the secondary winding after flowing from source to drain of $Q_8$. During this period the power is supplied to the secondary side.

![Fig. 3.2 Period a Operation](image)

Period b-1: $C_{Q3}$, $C_{Q4}$ Charge/Discharge

[Primary Side] Only $Q_1$ is On

After $Q_4$ turns off, $C_{Q4}$ is charged in the following way:

$V_{in}$ Positive side $\rightarrow Q_1 \rightarrow n_1$ Winding $\rightarrow L_r \rightarrow C_{Q4} \rightarrow V_{in}$ Negative side

The moment when $Q_4$ turns off, the voltage across $C_{Q4}$ is 0V, thus $Q_4$ turn off becomes ZVS. While $C_{Q4}$ is getting charged, $C_{Q3}$ is discharged in the following way:

$C_{Q3} \rightarrow Q_1 \rightarrow n_1$ Winding $\rightarrow L_r \rightarrow C_{Q3}$

After $C_{Q3}$ and $C_{Q4}$ have been charged/discharged, the unit proceeds to the next operation.

[Secondary Side] $Q_5$ and $Q_8$ are On

Operation of period a continues.

![Fig. 3.3 Period b-1 Operation](image)
Period b-2: $D_{Q3}$ Conduction

[Primary Side] Only $Q_1$ is On

The energy accumulated in $L_r$ continues to flow through the following path even after $C_{Q3}$ and $C_{Q4}$ have been charged/discharged.

$L_r \rightarrow D_{Q3} \rightarrow Q_1 \rightarrow n_1$ Winding $\rightarrow L_r$

In this condition, $Q_3$ turns on and system moves to the next operation. At this time, since $D_{Q3}$ is conducting, the $Q_3$ voltage is approximately 0 V and thus $Q_3$ turn on is ZVS.

[Secondary Side] $Q_5$ and $Q_8$ are On

Operation of period a continues.

Period c: $Q_3$ Conduction (Continuation of current flow through inductor)

[Primary Side] $Q_1$ and $Q_3$ are On

After $Q_3$ turns on, current continues to flow through the following paths because of $L_r$ energy:

$L_r \rightarrow Q_3 \rightarrow Q_1 \rightarrow n_1$ Winding $\rightarrow L_r$

The current of $L_r$ gradually decreases, and the energy accumulated in $L_r$ gradually decreases.

[Secondary Side] $Q_5$, $Q_8$, $Q_6$, and $Q_7$ are On

On secondary side, in addition to $Q_5$ and $Q_8$, $Q_6$ and $Q_7$ are also turned on. Therefore, current flows through following two paths; first is from the source to drain of $Q_8 \rightarrow n_2$ Winding $\rightarrow$ source to drain of $Q_5$, and second is from the drain to source of $Q_7 \rightarrow n_2$ Winding $\rightarrow$ drain to source of $Q_6$.
Period d-1 : C\(_{Q1}\), C\(_{Q2}\) Charge/Discharge

[Primary Side] Only Q\(_3\) is On

Even after Q\(_1\) turns off, current continues to flow through the following paths because of L\(_r\) energy:

\[ L_r \rightarrow Q_3 \rightarrow C_{Q1} \rightarrow n_1 \text{ Winding} \rightarrow L_r \]

While C\(_{Q1}\) is getting charged, C\(_{Q2}\) is discharged in the following way:

\[ L_r \rightarrow Q_3 \rightarrow V_{in} \rightarrow C_{Q2} \rightarrow n_1 \text{ Winding} \rightarrow L_r \]

When charging/discharging of C\(_{Q1}\) and C\(_{Q2}\) is completed, the system moves to next operation.

[Secondary Side] Q\(_5\), Q\(_8\), Q\(_6\), and Q\(_7\) are On

Operation of period c continues.

---

Period d-2 : D\(_{Q2}\) Conduction

[Primary Side] Only Q\(_3\) is On

The energy accumulated in L\(_r\) continues to flow through the following path even after C\(_{Q1}\) and C\(_{Q2}\) have been charged/discharged.

\[ L_r \rightarrow Q_3 \rightarrow V_{in} \rightarrow D_{Q2} \rightarrow n_1 \text{ Winding} \rightarrow L_r \]

In this condition, Q\(_2\) turns on and the system moves to next operation. Because D\(_{Q2}\) is conducting, Q\(_2\) voltage is approximately 0 V and thus Q\(_2\) turn on is ZVS.

[Secondary Side] Q\(_5\), Q\(_8\), Q\(_6\), and Q\(_7\) are On

Operation of period c continues.

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Fig. 3.6  Period d-1 Operation

Fig. 3.7  Period d-2 Operation
**Period d-3 : Q2 Conduction**

**[Primary Side]** Q2 and Q3 are On

After Q2 turns on, current continues to flow through the following paths because of $L_r$ energy:

$L_r \rightarrow Q_3 \rightarrow V_{in} \rightarrow Q_2 \rightarrow n_1 \ Winding \rightarrow L_r$

In $L_r$, the incoming voltage $V_{in}$ is applied in the direction that opposes this current flow, and thus the current of $L_r$ is rapidly reduced, and is immediately inverted, and then the system moves to the next operation.

**[Secondary Side]** Q5, Q8, Q6, and Q7 are On

Operation of period c continues.

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**Fig. 3.8 Period d-3 Operation**

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**Period e : Power Transfer to the Secondary Side**

**[Primary Side]** Q2 and Q3 are On

This is the period during which power is transferred from the primary side to the secondary side through the transformer TR. In this case, the primary winding voltage is the input voltage ($V_{in}$).

**[Secondary Side]** Q6 and Q7 are On

Voltage $n \times V_{in}$ corresponding to the winding ratio is applied to the secondary winding. The current in the secondary winding flows from the source to drain of Q7, then from $L_o$, and then returns to the secondary winding after flowing from the source to drain of Q6. This is the period during which power is supplied to the secondary side.

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**Fig. 3.9 Period e Operation**
Period f-1 : C_{Q3}, C_{Q4} Charge/Discharge

[Primary Side] Only Q2 is On

After Q3 turns off, C_{Q3} is charged in the following way:

Vin Positive side → C_{Q3} → L_r → n_1 Winding → Q2 → Vin Negative side

When Q3 turns off, C_{Q3} voltage is 0V, so Q3 turns off to ZVS.

While C_{Q3} is getting charged, C_{Q4} is discharged in the following way:

C_{Q4} → L_r → n_1 Winding → Q2 → C_{Q4}

After C_{Q3} and C_{Q4} have been charged/discharged, the system moves to the next operation.

[Secondary Side] Q6 and Q7 are On

Operation of period e continues.

Period f-2 : D_{Q4} Conduction

[Primary Side] Only Q2 is On

The energy accumulated in L_r continues to flow through the following path even after C_{Q3} and C_{Q4} have been charged/discharged.

L_r → n_1 Winding → Q2 → D_{Q4} → L_r

In this condition, Q4 turns on and the system moves to the next operation. At this time, since D_{Q4} is conducting, Q4 voltage is approximately 0 V and thus Q4 turn on is ZVS.

[Secondary Side] Q6 and Q7 are On

Operation of period e continues.
Period g : : Q₄ Conduction (Continuation of current flow through inductor)

[Primary Side] Q₂ and Q₄ are On

After Q₄ turns on, the energy accumulated in Lₙ continues to flow through the following path:

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow Q₂ \rightarrow Q₄ \rightarrow Lₙ \]

The current of Lₙ gradually decreases, and the energy accumulated in Lₙ also gradually decreases.

[Secondary Side] Q₅, Q₈, Q₆, and Q₇ are On

On secondary side, in addition to Q₆ and Q₇, Q₅ and Q₈ are also turned on. Therefore, current flows through following two paths; first is from the source to drain of Q₆ \( \rightarrow n₂ \) Winding \( \rightarrow \) source to drain of Q₇, and second is from the drain to source of Q₅ \( \rightarrow n₂ \) Winding \( \rightarrow \) drain to source of Q₈.

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow Q₂ \rightarrow Q₄ \rightarrow Lₙ \]

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow CQ₁ \rightarrow V_{in} \rightarrow Q₄ \rightarrow Lₙ \]

After CQ₁ and CQ₂ have been charged/discharged, the system moves to the next operation.

Period h-1 : C₀₁, C₀₂ Charge/Discharge

[Primary Side] Only Q₄ is On

Even after Q₂ turns off, current continues to flow through the following paths because of Lₙ energy:

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow CQ₂ \rightarrow Q₄ \rightarrow Lₙ \]

While CQ₂ is getting charged, CQ₁ is discharged in the following way:

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow CQ₁ \rightarrow V_{in} \rightarrow Q₄ \rightarrow Lₙ \]

After CQ₁ and CQ₂ have been charged/discharged, the system moves to the next operation.

[Secondary Side] Q₅, Q₈, Q₆, and Q₇ are On

Operation of period g continues.

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow Q₂ \rightarrow Q₄ \rightarrow Lₙ \]

\[ Lₙ \rightarrow n₁ \text{ Winding} \rightarrow CQ₄ \rightarrow Q₈ \rightarrow Lₙ \]
Period h-2: DQ1 Conduction
[Primary Side] Only Q4 is On
The energy accumulated in Lr continues to flow through the following path even after CQ1 and CQ2 have been charged/discharged.

Lr → n1 Winding → DQ1 → Vin → Q4 → Lr
In this condition, Q1 turns on and the system moves to the next operation. Because DQ1 is conducting, Q1 voltage is approximately 0 V and thus Q1 turn on is ZVS.

[Secondary Side] Q5, Q8, Q6, and Q7 are On
Operation of period g continues.

Period h-3: Q1 Conduction
[Primary Side] Q1 and Q4 are On.
After Q1 turns on, current continues to flow through the following paths because of Lr energy:

Lr → n1 Winding → Q1 → Vin → Q4 → Lr
In Lr, the incoming voltage Vin is applied in the direction that opposes this current flow, and thus the current of Lr is rapidly reduced, and is immediately inverted, and then the system moves to the next operation.

[Secondary Side] Q5, Q8, Q6, and Q7 are On
Operation of period g continues.
3.2. Signal Waveform of Actual Operation

Fig. 3.16 shows operation waveforms of the primary side MOSFET Q2 and Q4. Fig. 3.17 shows operation waveforms of the secondary side MOSFET Q6 and Q8. Fig. 3.18 shows gate signal timing of each MOSFET.

![Fig. 3.16 Q2, Q4 Operation Waveforms](image1)

![Fig. 3.17 Q6, Q8 Operation Waveforms](image2)

![Fig. 3.18 Each MOSFET Signal Timing](image3)

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