IGBT

Loss Calculation

About this document

This document will discuss the basics of the loss calculation that included the conduction loss and the switching loss for Insulated Gate Bipolar Transistors (IGBT) and Fast Recovery Diode (FRD).

Target Device

IGBT & FRD

Contents

1. Introduction

1.1 Overview

This application note will introduce the fundamentals of calculating power losses in Insulated Gate Bipolar Transistor (IGBT) and their complementary Fast Recovery Diode (FRD), with a focus on the two main types of losses: conduction and switching.

IGBT combine the high input impedance of a MOSFET with the high current and voltage capabilities of a BJT, making them well-suited for applications such as inverters, motor drives, and power converters. Their ability to handle high power with fast switching makes them a preferred choice in power electronics.

To enhance their performance in high-speed switching circuits, IGBT are often paired with FRD, specially designed diodes that have short reverse recovery times. These FRD help manage rapid changes in current flow, reducing switching losses and improving overall efficiency.

Accurate loss calculations are crucial for effective IGBT and FRD design, as they affect the thermal management, reliability, and overall efficiency of the system. This application note will cover both conduction and switching losses, which are the main contributors to power dissipation in IGBT and FRD components.

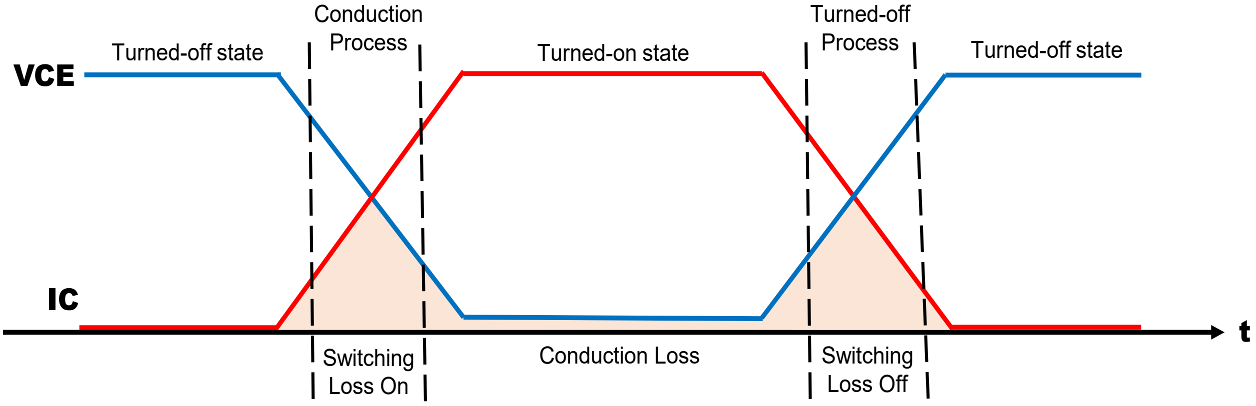


Figure 1-1 Power Loss of IGBT

2. IGBT Conduction Loss & Switching Loss

This section provides an in-depth look at conduction and switching losses specific to IGBTs, including formulas and explanations.

2.1 IGBT Conduction Loss

Conduction loss occurs when the IGBT is in its "on" state and allows current to flow. This loss depends on the on-state voltage and the current flowing through the device.

The conduction loss $P_{cond,\ IGBT}$ for an IGBT is calculated as:

$$P_{cond,\ IGBT} = V_{CE0} \times I_{avg}$$

- P_{cond} : *Conduction loss in IGBT*
- V_{CE0} : *Collector-emitter saturation voltage of the IGBT.*
- I_{avg} : *Average load current flowing through the IGBT(Depends on Application load current)*

For the example, if V_{CE0} = 2V and I_{avg} = 10A:

$$P_{cond,\ IGBT} = 2\text{V X } 10\text{A} = 20\text{W}$$

2.2 IGBT Switching Loss

Switching loss occurs when the IGBT transitions between its "on" and "off" states. During these transitions, the overlap of voltage and current causes energy dissipation.

The switching loss $P_{sw,\ IGBT}$ per cycle is:

$$P_{sw,\ IGBT} = f \times (E_{on} + E_{off})$$

- P_{sw} : *Switching loss in IGBT*
- f : *The switching frequency.*
- E_{on} & E_{off} : *The energy losses during turn-on and turn-off transitions, respectively.*

For example, if f = 10kHz, E_{on} = 0.5mJ and E_{off} = 0.4mJ:

$$P_{sw,\ IGBT} = 10000 \times (0.5 + 0.4)\ \text{mJ} = 9\text{W}$$

3. FRD Conduction Loss & Switching Loss

This section covers the loss calculations for FRDs, including conduction and switching losses.

3.1 FRD Conduction Loss

FRD conduction loss occurs when the diode is forward-biased, allowing current to flow with a small forward voltage drop.

The conduction loss $P_{cond,\ FRD}$ for an FRD is calculated as:

$$P_{cond,\ FRD} = V_F \times I_{avg}$$

- P_{cond} *: Conduction loss in FRD*
- V_F *: The forward voltage drops of the diode.*
- I_{avg} *: Average load current flowing through the FRD when conducting*

For example, if V_F = 1.2V and I_{avg} =10A:

$$P_{cond,\ FRD} = 1.2\text{V} \times 10\text{A} = 12\text{W}$$

3.2 FRD Switching Loss

Switching losses in FRDs occur due to the reverse recovery time when the diode transitions from conducting to blocking states. This loss is significant in high-frequency applications where switching speed is crucial.

The switching loss $P_{sw,\ FRD}$ per cycle is:

$$P_{sw,\ FRD} = f \times E_{rr}$$

- P_{sw} *: Switching loss in IGBT*
- F *: The switching frequency.*
- E_{rr} *: The reverse recovery energy, which depends on factors like reverse recovery time and current.*

For example, if f = 10kHz and E_{rr} =0.3mJ:

$$P_{sw,\ FRD} = 10000 \times 0.3\text{mJ} = 3\text{W}$$

4. Total Power Loss

Total power loss in electronic devices, such as IGBTs and FRDs, refer to the sum of conduction and switching losses that occur during operation. These losses directly impact the efficiency and thermal performance of power electronics systems.

By applying the example values from the previous chapter, we can calculate the total power losses (P_{total}) for the IGBT and FRD.

$$P_{total} = P_{cond} + P_{sw}$$

- $P_{total,\ IGBT}$ = 20W + 9W = 29W
- $P_{total,\ RFD}$ = 12W + 3W = 15W

Thus, the combined total power loss for the IGBT and FRD is:

$$P_{total} = 29\text{W} + 15\text{W} = 44\text{W}$$

This value highlights the importance of considering both conduction and switching losses to optimize the performance of power electronic systems.

5. Case study for Loss Calculation in Inverter Operation

In this section, we will use a Renesas product (RBN75H125S1FP4) as an example to calculate the IGBT losses for an inverter motor.

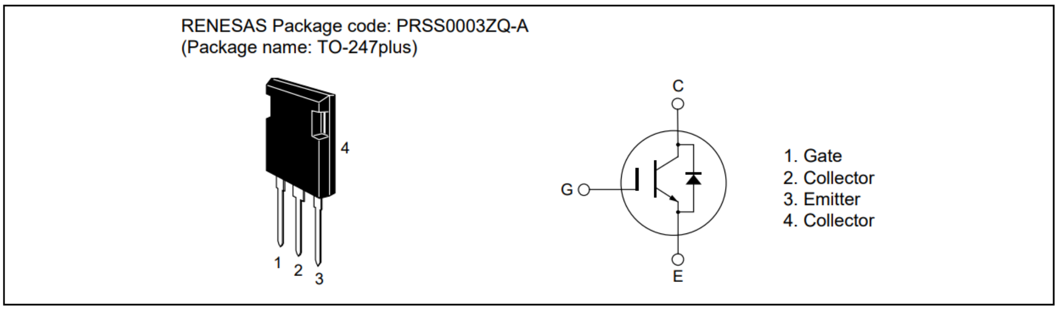
RBN75H125S1FP4 Key Features

- Trench gate and thin wafer technology (G8H series)
- High speed switching
- Short circuit withstands time (10 µs min.)
- Built in fast recovery diode in one package
- Low collector to emitter saturation voltage VCE(sat) = 1.8 V typ. (at IC = 75 A, VGE = 15 V, Ta = 25°C)

Key Performance

Type	V_{CES}	I_C	$V_{CE(sat)}$, T_C = 25°C	I_F	t_{SC}	T_j
RBN75H125S1FP4-A0	1250 V	75 A	1.8 V	50 A	10 µs	175 °C

Outline



Below Figure 5-1 shows an inverter phase basic circuit diagram.

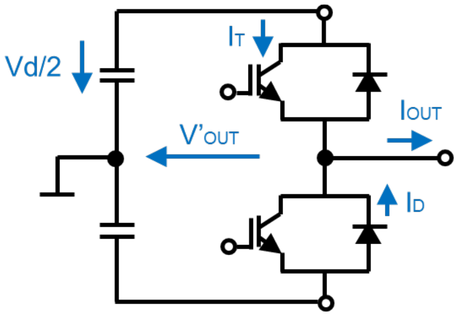


Figure 5-1 Inverter basic circuit diagram

Below Figure 5-2 shows the ideal case characteristic of an inverter phase for a sinusoidal pulse width modulation (PWM).

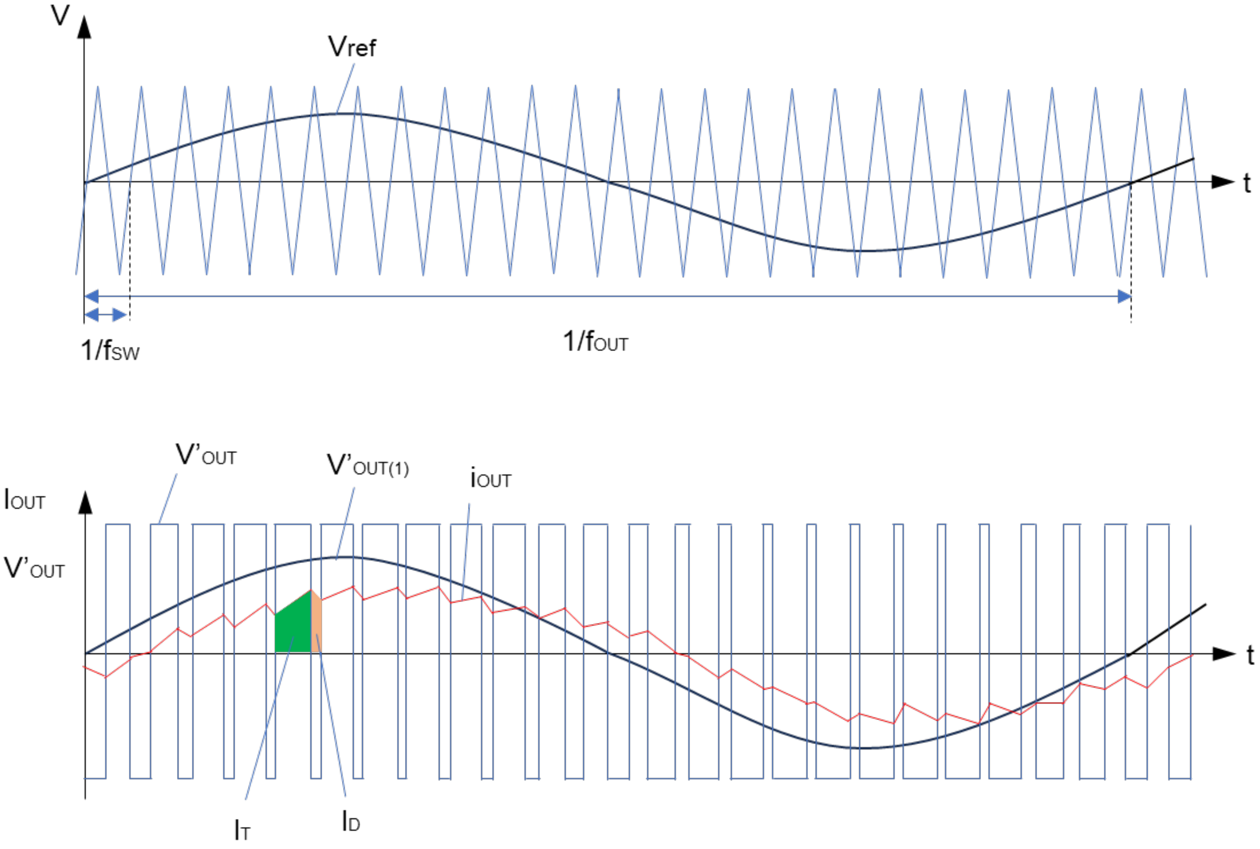


Figure 5-2 PWM, output voltages and currents

Assuming the parameter values available in Table 5-1 below will be used for the loss calculation below.

Table 5-1 Parameter value for loss calculation

V_{CC} = 813V	$I1$ = 13A	f_{sw} = 10,000Hz	E_{on} = 0.021J	rCE = 0.022Ω
V_{ref} = 600V	I_{ref} = 75A	m = 0.85	E_{off} = 0.006J	rF = 0.03 Ω
V_{CE0} & V_{F0} = 1V	I_{out} = $I1$ / √2	$\cos\varphi$ = 0.8	E_{rr} = 0.001176J	

Besides the condition from inverter application, there are parameters which need to be calculated from products datasheet. The datasheet contains parameter graphs that can be used to determine the resistance values **(*rCE* and *rF*)** and the Switching Energy losses **(**E_{on} and E_{off}**)** to be used in the formula.

The rCE, value can be calculated from datasheet graph in Figure 5-3 as below:

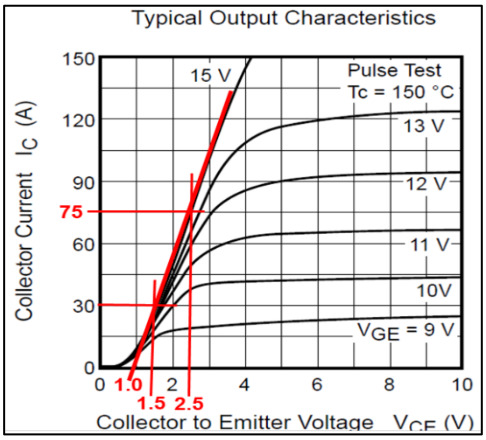


Figure 5-3

$$\boldsymbol{rCE} = \frac{(2.5-1.5)}{(75-30)} = 0.022$$

The rF, value can be calculated from datasheet graph in Figure 5-4 as below:

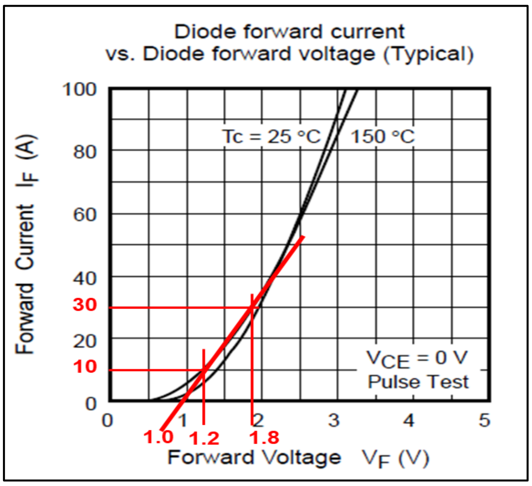


Figure 5-4

$$\boldsymbol{rF} = \frac{(1.8-1.2)}{(30-10)} = 0.03$$

For both E_{on} and E_{off}: it’s can be calculated from datasheet graph in Figure 5-5 as below:

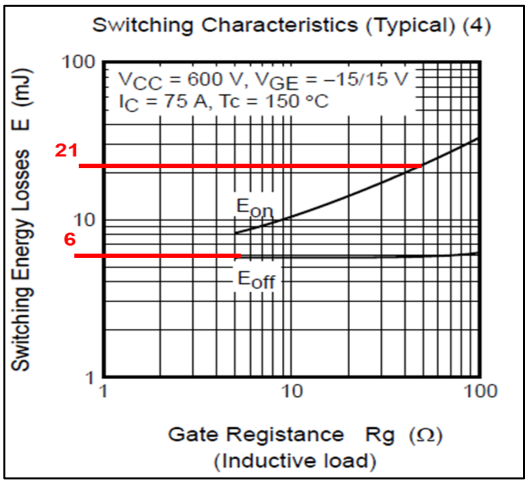


Figure 5-5

As final, the IGBT equation for conduction loss $P_{cond,\,IGBT}$ and switching loss $P_{sw,\,IGBT}$ are calculated as below:

$$
\begin{aligned}
Pcond, IGBT &= \left(\frac{1}{2\pi} + \frac{m \times cos\varphi}{8}\right) \times VCE0 \times I1 + \left(\frac{1}{8} + \frac{m \times cos\varphi}{3\pi}\right) \times rCE \times I1^2 \\
&= \left(\frac{1}{2\pi} + \frac{0.85 \times 0.8}{8}\right) \times 1.0 \times 13 + \left(\frac{1}{8} + \frac{0.85 \times 0.8}{3\pi}\right) \times 0.022 \times 13^2 \\
&= 3.9W
\end{aligned}
$$

$$
\begin{aligned}
Psw, IGBT &= fsw \times (Eon + Eoff) \times \frac{\sqrt{2}}{\pi} \times \frac{Iout}{Iref} \times \left(\frac{Vcc}{Vref}\right)^{Kv} \times \left(1 + TCEsw \times (Tj - Tref)\right) \\
&= 10{,}000 \times (0.021 + 0.006) \times \frac{\sqrt{2}}{\pi} \times \frac{9.2}{75} \times \left(\frac{813}{600}\right)^{1.3} \times \left(1 + 0.003 \times (72 - 150)\right) \\
&= 16.9W
\end{aligned}
$$

$$Ptotal, IGBT = 3.9 + 16.9 = 20.8W$$

Where,

$I1$: Amplitude of the inverter output current

VCE0(Tj): Temperature-dependent threshold voltage of the on-state characteristic

rCE (Tj): Temperature-dependent bulk resistance of the on-state characteristic

Iref, Vref, Tref: Reference values of the switching loss measurements taken from the datasheet

Kv: Exponents for the voltage dependency of switching losses ~1.3...1.4

TCEsw: Temperature coefficients of the switching losses ~ 0.003 1/K.

The FRD equation for conduction loss $P_{cond,\,FRD}$ and switching loss $P_{sw,\,FRD}$ are calculated as below:

$$
\begin{aligned}
Pcond, FRD &= \left(\frac{1}{2\pi} + \frac{m \times cos\varphi}{8}\right) \times VF0 \times I1 + \left(\frac{1}{8} + \frac{m \times cos\varphi}{3\pi}\right) \times rF \times I1^2 \\
&= \left(\frac{1}{2\pi} + \frac{0.85 \times 0.8}{8}\right) \times 1.0 \times 13 + \left(\frac{1}{8} + \frac{0.85 \times 0.8}{3\pi}\right) \times 0.03 \times 13^2 \\
&= 1.2W
\end{aligned}
$$

$$\boldsymbol{Psw, FRD = fsw \times Err \times \left(\frac{\sqrt{2}}{\pi} \times \frac{I1}{Iref}\right)^{Ki} \times \left(\frac{Vcc}{Vref}\right)^{Kv} \times \left(1 + TCErr \times (Tj - Tref)\right)}$$

$$\boldsymbol{= 10{,}000 \times 0.001176 \times \left(\frac{\sqrt{2}}{\pi} \times \frac{13}{75}\right)^{0.6} \times \left(\frac{813}{600}\right)^{0.6} \times \left(1 + 0.006 \times (72 - 25)\right)}$$

$$\boldsymbol{= \ 2.8W}$$

$$\boldsymbol{Ptotal, FRD = 1.2W + 2.8W = 4W}$$

Where,

VF0(Tj): Temperature-dependent threshold voltage of the on-state characteristic

rF(Tj): Temperature-dependent bulk resistance of the on-state characteristic

Kv: Exponents for the voltage dependency of switching losses ~0.6

Ki: Exponents for the current dependency of switching losses ~0.6

TCErr: Temperature coefficients of the switching losses ~ 0.006 1/K.

Thus, the combined total power loss for the IGBT and FRD is:

$$\boldsymbol{Ptotal = 20.8W + 4W = 24.8W}$$

6. Considerations for Loss Calculations

Temperature Effects:

Both the on-state voltage drops and switching losses vary with temperature, which can significantly impact total loss. Managing temperature variations is essential in IGBT and FRD design.

Load Variability:

Variations in load current and switching frequency can affect losses, making it essential to select components optimized for specific operating conditions.

Thermal Management:

Minimizing and managing heat generated from conduction and switching losses improves device reliability and efficiency, underscoring the importance of proper cooling solutions.

7. Conclusion

In conclusion, calculating the conduction and switching losses in IGBTs and FRDs is essential for efficient power system design. Understanding these losses allows engineers to optimize device selection, improve thermal management, and enhance overall system performance. Accurate loss calculations ensure that IGBT and FRD applications in power electronics systems achieve maximum efficiency and reliability under varying operating conditions.

Revision History

Rev.	Date	Description	
		Page	Summary
1.00	Dec.12.2024	-	First edition

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