International Rectifier
APPLICATION NOTES
PUBLISHED BY INTERNATIONAL RECTIFIER, 233 KANSAS STREET, EL SEGUNDO, CA 90245. (310) 322-3331

AN-989

The HEXFRED™ Ultrafast Diode in Power Switching Circuits

(HEXFRED is a trademark of International Rectifier)

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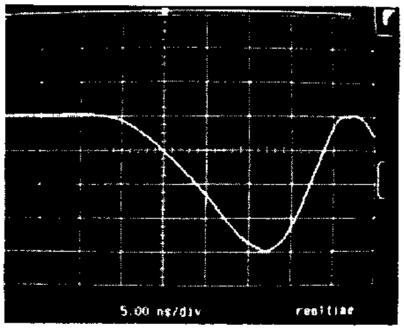
Introduction

This application note describes the benefits of using the International Rectifier 600 volt, 15 amp, ultra-fast recovery epitaxial diode (FRED) in power switching circuits. This device, the first from a broad product family covering a wide range of current and voltage ratings, is based on the new HEXFRED technology developed by International Rectifier. Diodes produced using this technology exhibit extremely fast reverse recovery times (t_{rr}), very low values of reverse recovery current (I_{RRM}), unusually "soft" recovery characteristics, and guaranteed avalanche (see Figures 1a and 1b).

The essentials of reverse recovery are covered, followed by laboratory measurements taken from an IGBT chopper circuit. Finally, guidelines are provided for calculating power losses in ultra-fast rectifiers.



I_F = 1A
diF/dt = 200A/µs
T_J = 25°C
V_R = 30V
t_{rr} = 19ns
I_{RRM} = 3A
Q_{rr} = 28.5nC
di(rec)M/dt = 570A/µs

Figure 1(a). Oscilloscope display of recovery characteristic for the HFA15TB60 HEXFRED

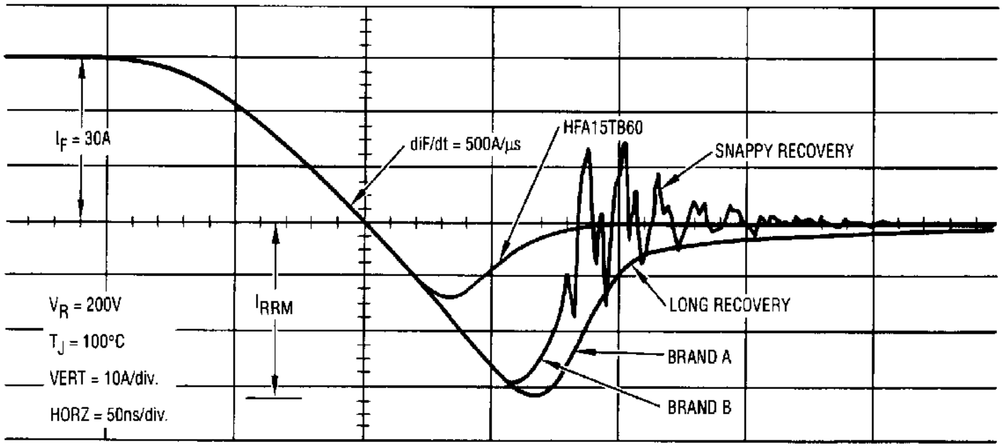


Figure 1(b). Typical t_{rr} comparison results of the HFA15TB60 HEXFRED and conventional FREDs

HEXFRED Technology

HEXFRED stands for HEXagonal Ultra-Fast Recovery Epitaxial Diode. The HEXFRED technology incorporates special high voltage epitaxial silicon, a hexagonal cellular structure, planar design, and a proprietary minority carrier lifetime control process. The result is a startling improvement in recovery characteristics when compared to conventional ultrafast diodes.

HEXFREDs are pin-for-pin compatible with conventional diodes and can therefore be used as direct replacements with no design modifications. However, the designer can achieve the greatest cost benefits and efficiency improvements by taking full advantage of both the low reverse recovery current which will cause the power switches to run at much lower temperatures, and the ultra-soft recovery which will result in lower RFI, EMI, and reduction or elimination of snubber components.

Diode Recovery Characteristics

In any power conversion equipment there are usually more diodes than transistors. They are typically labeled as "catch diodes," "flyback diodes," "freewheeling diodes," and "clamp diodes." A detailed knowledge of how "fast" and how "soft" the diode recovery should be is necessary to properly design an efficient switching circuit. By properly choosing the optimum diode the designer can significantly reduce losses in the power switch, the diode, and many other circuit elements. Additionally, the optimum diode will reduce voltage spikes, RFI and EMI caused by snappy diodes allowing for the reduction or even the elimination of snubber circuits.

The Cause of Recovery Losses

All PN junction diodes, when conducting forward current will store charge in the form of excess minority carriers. Minority carrier injection is the mechanism for conductivity modulation which results in lowering the forward voltage drop (V_F), and in this sense it is beneficial. However, when the circuit commutates the diode, the stored charge must be completely extracted or neutralized before the diode is said to be "off." The time it takes for this to occur is defined as reverse recovery time (t_{rr}). The recovery time is composed of two distinct intervals, t_a and t_b as shown in Figure 2. More will be said about t_a and t_b later.

A diode conducting forward current (I_F) has a corresponding forward voltage drop (V_F) and an amount of stored charge (Q_O) which is proportional to I_F. When the diode current commutates, a portion of the internal stored charge is quickly neutralized via internal recombination. The remaining stored charge (Q_{rr}) is reduced by continued recombination and by reverse current (I_{RR}) circulating through the diode and associated circuit elements.

When the power switch commutates the diode, forward current (I_F) decreases at a rate (diF/dt) determined by the circuit inductance and the applied voltage. When the diode current decreases to zero, Q_{rr} causes reverse current (I_{RR}) to flow until it is fully depleted. It is this unwanted and unavoidable reverse current that causes increased power dissipation in the power switch (IGBT, MOSFET, etc).

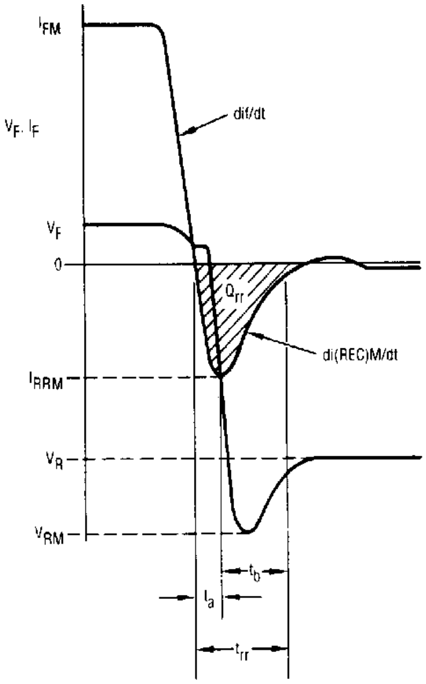


Figure 2. Diode current and voltage waveform definitions

t_{rr}

The total time required to deplete the stored charge is defined as t_{rr} where $t_{rr} = t_a + t_b$. The t_{rr} of a device is generally used as the measure of its switching speed and will determine it's suitability for a given application. The t_{rr} specifications on power diodes given at one amp are for comparison purposes only. International Rectifier HEXFREDs are specified with both typical and maximum t_{rr} at rated current and two times rated current, as well as at 25°C and 125°C. See Figures 3 and 4.

t_a

The time required for the diode reverse current (I_{RR}) to increase (shown in Figure 2) from zero to its peak (I_{RRM}) negative value is defined as "t_a." During this portion of t_{rr}, the voltage drop across the diode is still positive; however, it is less than the value of V_f during forward conduction. The current flowing during t_a can be significant, especially in conventional diodes. Thus, due to the low voltage across the diode, power dissipation in the diode during t_a is minimal. However, power dissipation in the switch may be very high because it carries the full diode reverse current while it supports the full voltage of the circuit. In short, a diode with lower reverse current will allow the power switch to operate at a lower temperature. In some designs, this savings may result in using a smaller, lower cost IGBT or MOSFET switch.

t_b

The time required for t_{rr} to fall from its peak value (I_{RRM}) to zero (shown in Figure 2) is defined as "t_b." During this time the voltage across the diode goes from a small positive value to the full applied reverse voltage. Because there is simultaneous reverse current flow through the diode and high voltage across it during t_b, there will be significant power dissipation in the diode. Intuitively one would reason that to minimize the power loss during t_b one should use the diode with the shortest t_b. However, as will be shown, the actual shape of the t_b curve is more critical than the absolute value of t_b.

Q_{rr}

The total reverse recovered charge (Q_{rr}) is defined as the area under the current-time curve during t_{rr}. This charge represents the energy that must be dissipated in the power switching side of the circuit. International Rectifier HEXFRED data sheets provide typical and maximum values for Q_{rr} at worst case operating conditions (see Figures 5 and 6).

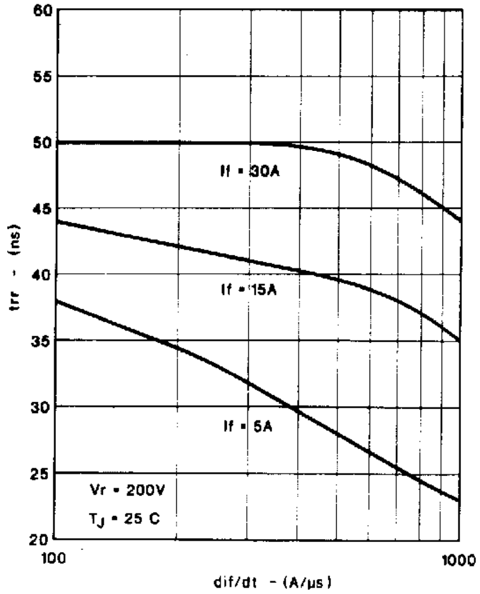


Figure 3. Typical Reverse Recovery Time vs. dif/dt

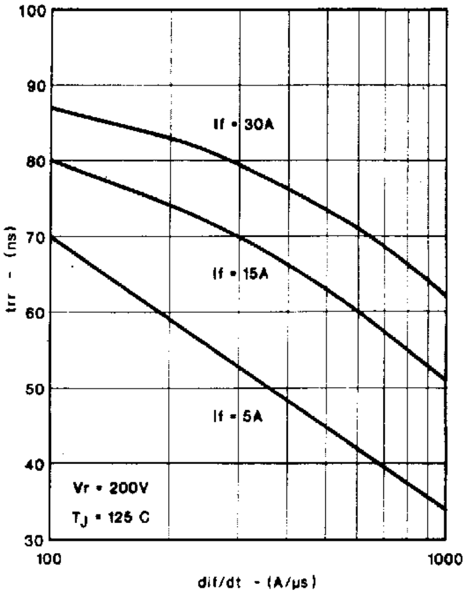


Figure 4. Typical Reverse Recovery Time vs. dif/dt

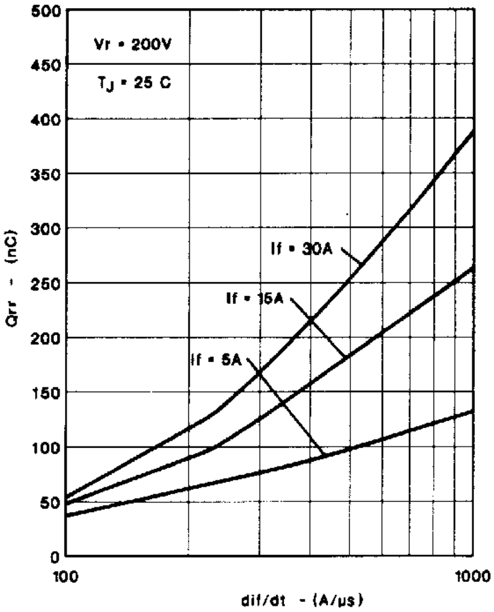


Figure 5. Typical Stored Charge vs. dif/dt

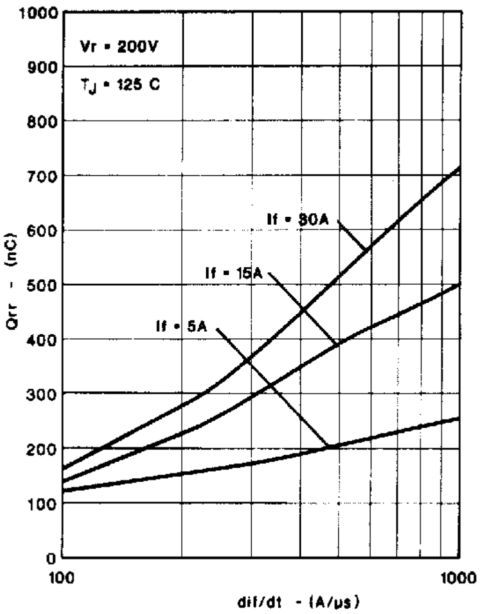


Figure 6. Typical Stored Charge vs. dif/dt

Softness, di(rec)M/dt, and t_b/t_a

When specifying *softness*, semiconductor manufacturers generally use either the ratio of t_b/t_a (softness factor) or the peak slope of t_b. The latter called di(rec)M/dt is the more useful in predicting the magnitude of the voltage spikes that will be generated by the FRED device.

Using the ratio of t_b/t_a as the softness factor can be misleading. Ultra-fast recovery epitaxial diodes with the same softness ratio may cause different values of RFI and over-voltage spikes. Figure 7 shows the waveforms of three FRED devices all with the same ratio of t_b/t_a. Notice that each FRED has a different softness and a different di(rec)M/dt. This clearly illustrates that t_b/t_a used as a softness factor is misleading. Further more, armed with the knowledge of di(rec)M/dt and the inductance of the circuit one can predict the magnitude of the voltage spike:

$$V_{RM} = V_R + L \bullet \mathrm{di(rec)M/dt}$$

Where L is the total circuit inductance.

Care should be taken since the voltage spike resulting from a snappy recovery may exceed the voltage rating of the power switch.

International Rectifier specifies its HEXFRED typical values of di(rec)M/dt at the same test conditions as t_{rr} as shown in Figures 8 and 9.

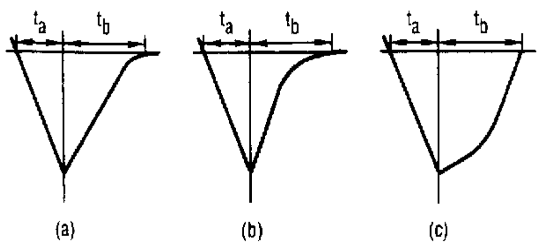


Figure 7. Different diode di(rec)M/dt rates for same softness factor

The HEXFRED vs. Conventional Diodes in a Chopper Circuit

The 15 Amp, 600 Volt TO-220 HEXFRED, part number HFA15TB60, was compared to conventional diodes from two manufacturers. All diodes were rated at 600V and 12 to 15 amps. All were packaged in the industry standard TO-220 plastic case.

Two comparisons were performed. One was simply to measure the devices' dynamic performance in an IGBT chopper circuit (Figure 10) in order to establish a baseline. Table 1 reflects this data.

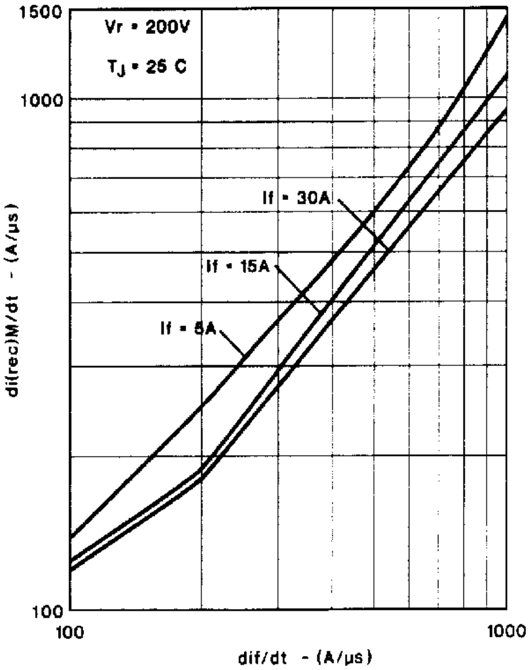


Figure 8. Typical di(rec)M/dt vs. dif/dt

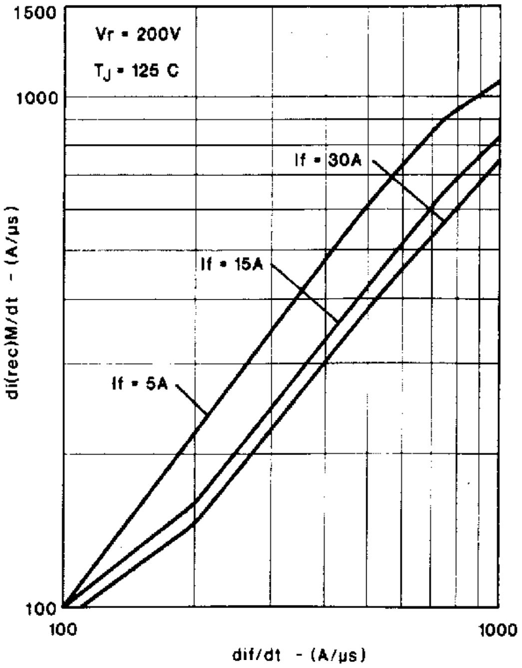


Figure 9. Typical di(rec)M/dt vs. dif/dt

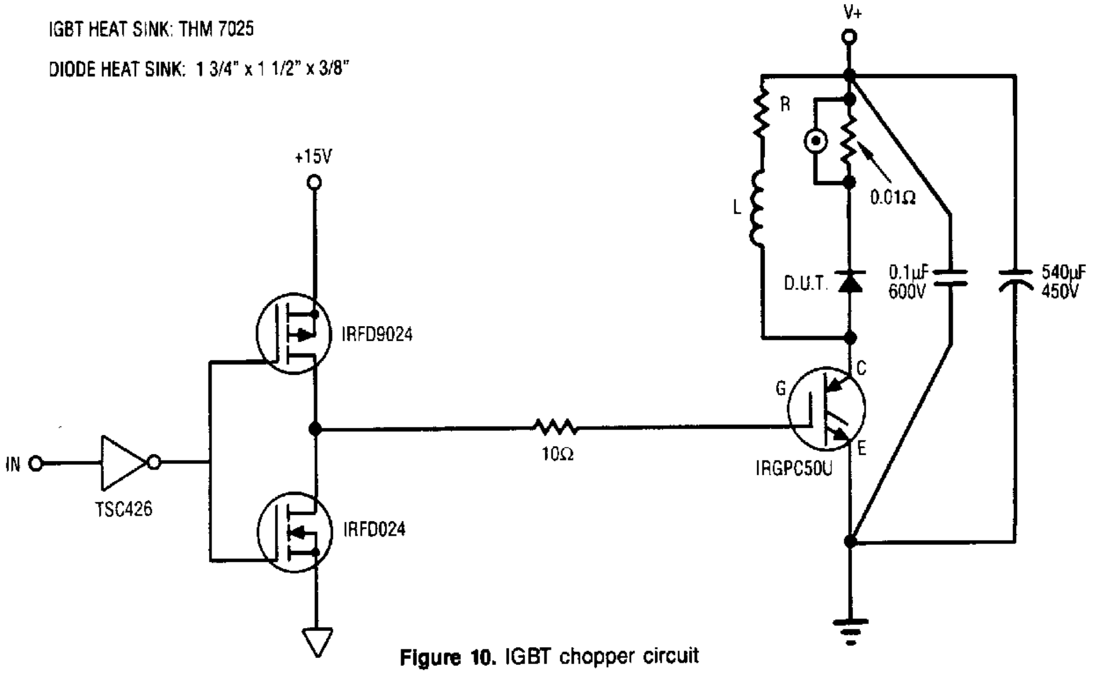


Figure 10. IGBT chopper circuit

Table 1. Baseline Comparisons

FRED Devices	t_{rr} (nsec)	Softness di(rec)M/dt (A/µs)	I_{RRM} (Amp)	t_{rr} (nsec)	Softness di(rec)M/dt (A/µs)	I_{RRM} (Amp)
	@ 25°C	@ 25°C	@ 25°C	@ 125°C	@ 125°C	@125°C
HFA15TB60	65	645	27	75	825	27
Brand A	105	1400	54	140	1480	69
Brand B	85	2210	48	120	2300	61

Conditions:

$V_R = 400V$ $L = 100\mu H$

$I_F = 20$ Amps $R = 0\Omega$

diF/dt = 1200A/µs

T_j = as shown on table

The most significant difference between these ultrafast diodes are:

1) The HEXFRED has less than 1/2 of the reverse recovery current when compared to conventional ultrafast diodes rated at similar voltage and forward current.

2) t_{rr} on the conventional diodes increased by as much as 41% with temperature. The HEXFRED increased only 15%.

3) HEXFRED softness (di(rec)M/dt) was twice as soft as the diode from Brand B, and three times as soft as Brand A which is a very popular but snappy diode.

The second comparison was to measure power losses via case temperature, in the same circuit.

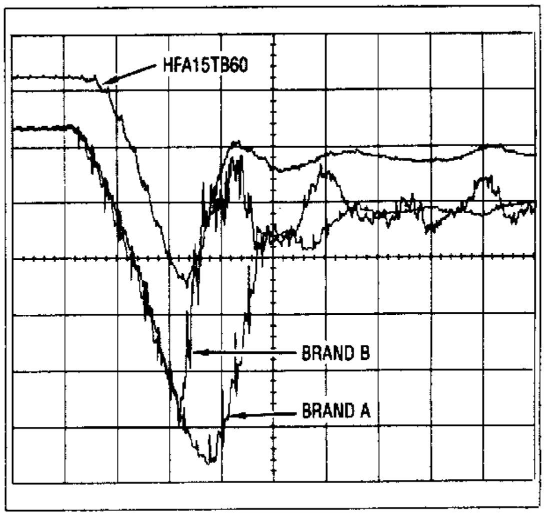


Figure 11. Oscillogram of diode current waveforms in IGBT chopper circuit at 10 kHz. (Traces are offset for clarity)

Each diode was mounted with the same screw on the same aluminum heatsink 1.75" x 1.5" x 0.375". The IRGPC50U was used in every test as the IGBT switch. The IGBT was mounted on a standard heatsink (THM 7025). Both heatsinks were standing in free air in the vertical position.

Case temperature was measured separately for the diode and the transistor. Each thermocouple was attached to the identical location on the heatsink.

Results of the chopper circuit test at switching frequency 10 kHz, are shown in Table 2. An oscillogram of the current waveforms for all three devices is shown in Figure 11.

Table 2. Switching Frequency @ 10 kHz

FRED Devices	Softness di(rec)M/dt (A/µs)	Diode I_{RRM} (Amp)	Diode T_C (°C)	IGBT T_C (°C)
HFA15TB60	998	15	65	37.5
Brand A	1405	23	78.5	41.5
Brand B	2210	38	67	48

Test conditions for each ultra-fast recovery diode test were maintained unchanged as follows:

Load current 6 Amp dc, transistor duty cycle 50%;
Load inductance 8000µH, V_R = 200V.
R = 15Ω, diF/dt = 650A/µs

In this case, the most noticeable difference is not so much in the temperature of the diode but in the temperature of the IGBT. This is attributed to the low reverse recovery current of the HFA15TB60 HEXFRED.

Finally, the operating frequency of the circuit was increased from 10 kHz to 20 kHz. In this test the HEXFRED caused the IGBT to run from 10% to 28% cooler. Even more noticeable was the amount of noise generated by Brand B (see Figure 12). No snubber was used.

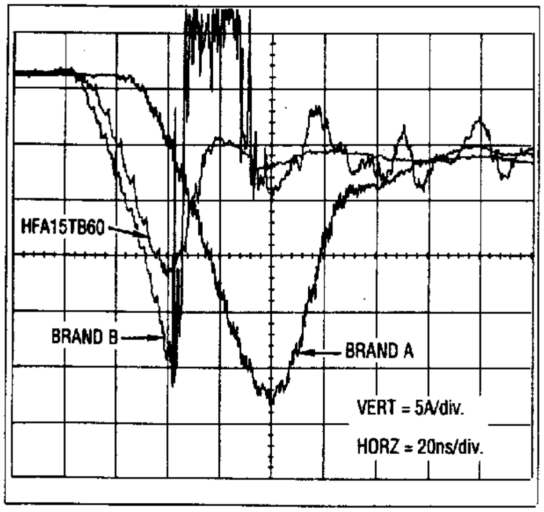


Figure 12. Oscillogram of diode current waveforms in IGBT chopper circuit at 20 kHz. (Traces are offset for clarity)

Table 3. Switching Frequency @ 20 kHz

FRED Devices	Softness di(rec)M/dt (A/µs)	Diode I_{RRM} (Amp)	Diode T_C (°C)	IGBT T_C (°C)
HFA15TB60	998	15	66.5	64.3
Brand A	1405	23	81.5	71.5
Brand B	2210	38	67	81

At 20 kHz, the difference becomes even more noticeable. Snappy Brand B caused the IGBT to run 16.7°C hotter.

Calculating Losses in Switching Circuit

From the foregoing discussion and product comparison it is evident that the diode in a switching circuit will play a major role in the overall performance of the circuit. Modern switching circuits, operating at high frequency are very sensitive to switching losses in the IGBT, MOSFET, etc. switch and in the associated diode(s).

Conduction and off-state losses in the diode are generally easy to predict using straight forward calculations. These losses, although significant, usually do not cause any surprises and they do not have any undue influence on the associated power switch.

This is not the case with diode switching losses as they usually have a major influence on the power dissipation and junction temperature levels of both the diode and the power switch.

Total power losses due to the diode can be calculated as:

$$P_R = P_{con} + P_{off} + P_{sw} \tag{1}$$

Where:

P_{con} = conduction loss $\quad P_{con} = V_F I_F \frac{t_{on}}{T}$ **(2)**

P_{off} = off-state loss $\quad P_{off} = V_R \bullet I_R \bullet \frac{t_{off}}{T}$ **(3)**

P_{sw} = switching power loss due to reverse recovery $\quad P_{sw} = E_{rr} \bullet f$ **(4)**

E_{rr} = switching energy loss due to reverse recovery

f = operating frequency

P_{con} and P_{off} are calculated using data sheet values and circuit operating parameters;

CIRCUIT PARAMETERS	DATA SHEET VALUES
t_{on} = diode on-time	V_F @ I_F @ T_j
t_{off} = diode off-time	I_R @ V_R @ T_j
T = switching period	
V_r = applied voltage	
I_f = forward current	

A more accurate estimation of P_{con} can be made if the exact current wave shape and the diode junction temperature are known (Ref. 1 & 2).

Switching losses, P_{sw}, are more difficult to determine since their calculation requires a good understanding of the diode dynamic recovery characteristics. In a typical half-bridge or buck regulator the total charge associated with diode recovery represents energy that will be dissipated among various components of the circuit and can be expressed as:

$$E_{rr} = \int_0^{t_{rr}} I(t) \bullet V(t)\, dt \tag{5}$$

Assuming linear V and I transition (Ref. 1 & 2), a practical diode with finite t_a, t_b and I_{RRM} will cause switching energy dissipation in the transistor, and is calculated as:

$$E_t = V_R \left(\frac{I_{RRM}}{2} t_a + \frac{I_{RRM}}{4} t_b \right) \qquad \textbf{(6)}$$

Energy dissipated in the diode is calculated as:

$$E_d = \frac{V_r \, I_{RRM} \, t_b}{4} \qquad \textbf{(7)}$$

Total switching losses due to diode reverse recovery are:

$$E_{SW} = (E_t + E_d) \qquad \textbf{(8)}$$

DETERMINING t_a, t_b, t_{rr} and I_{RRM}:

In order to use equations 6 and 7 it is necessary to first determine the values for reverse recovery parameters t_a, t_b, t_{rr} and I_{RRM} at the applicable operating conditions. The HEXFRED data sheet contains the appropriate dynamic performance curves that are used for this purpose. The procedure used here is adequate for a good first order approximation.

1. Ascertain that the operating conditions in question are not the same as those specified in the data sheet for t_{rr} 1, 2 or 3.

2. Use data sheet typical characteristic curves for t_{rr} and I_{RRM} to determine values that correspond to the operating conditions in question. For conditions that are not graphed, use linear interpolation.

3. Use t_{rr} and I_{RRM} calculated values to determine t_a and t_b.

4. Use calculated values of t_a, t_b, t_{rr} and I_{RRM} in equations 6 and 7.

Example:

Determine t_a, t_b, t_{rr} and I_{RRM} for the International Rectifier HFA15TB60 operating at;

$$I_F = 10 \text{ A.,} \quad dif/dt = 800\text{A}/\mu$$
$$V_R = 200\text{V.,} \quad T_j = 125°\text{C}$$

1a. Using t_{rr} vs dif/dt @ 125°C curves of the data sheet and interpolating, determine t_{rr} at $I_f = 10$A and dif/dt = 800A/μs.

$$t_{rr(10)} = t_{rr(5)} + \frac{t_{rr(15)} - t_{rr(5)}}{I_{F(15)} - I_{F(5)}} \left(I_{F(10)} - I_{F(5)} \right)$$

$$t_{rr} = 37 + \frac{55 - 37}{15 - 5} (10 - 5) = 46\text{ns}$$

b. Using I_{rr} vs dif/dt @ 125°C curves of the data sheet and interpolating; determine I_{RRM}.

$$I_{RRM(10)} = I_{RRM(5)} + \frac{I_{RRM(15)} - I_{RRM(5)}}{I_{F(15)} - I_{F(5)}} (I_{F(10)} - I_{F(5)})$$

$$I_{RRM} = 13 + \frac{17 - 13}{15 - 5} (10 - 5) = 15\text{A}$$

2. Determine t_a and t_b.

$$t_a = \frac{I_{RRM}}{\frac{dI_F}{dt}} = \frac{15}{800} = 18.75 \ \eta\text{s} \qquad \textbf{(9)}$$

$$t_b = t_{rr} - t_a = 46 - 18.75 = 27.25\eta\text{s} \qquad \textbf{(10)}$$

3. Substitute values in equations 5 and 6;

Energy loss in transistor;

$$E_t = 200 \left(\frac{15}{2} 18.75 + \frac{15}{4} 27.25 \right) = 48.56 \ \mu\text{J}$$

Energy loss in diode;

$$E_d = \frac{200 \bullet 15 \bullet 27.25}{4} = 20.44 \ \mu\text{J}$$

Total losses due to the diode;

$$E_{SW} = E_d + E_t = 69 \ \mu\text{J}$$

Alternatively;

$$E_{SW} = V_r \times Q_{rr} \qquad \textbf{(11)}$$

In this case, Q_{rr} at $I_f = 10$A would be determined from the data sheet curves for Q_{rr} vs dif/dt @ 125°C using interpolation as before:

$$Q_{rr(10)} = Q_{rr(5)} + \frac{Q_{rr(15)} - Q_{rr(5)}}{I_{F(15)} - I_{F(5)}} \quad I_{F(10)} - I_{F(5)}$$

$$Q_{rr} = 220 + \frac{460 - 220}{15 - 5} (10 - 5) = 340\eta\text{C}$$

Substituting in equation (11):

$$E_{SW} = 200 \bullet 340 \bullet 10^{-9} = 68\mu\text{J}$$

In both cases the result is virtually the same and either method may be used.

Summary

It has been shown that the new HEXFRED technology exhibits unusually low reverse recovery current, very fast t_{rr}, and exceptional softness when compared to conventional ultrafast diodes. This improved device performance translates into increased efficiency and reduced snubbing, as well as reduced RFI and EMI in power conversion circuits.

Test results showed that the major beneficiary of the reduced recovery current and the soft recovery waveform was the MOSFET or IGBT switch which saw significantly reduced operating temperatures, caused simply by replacing the conventional diode with the International Rectifier HEXFRED ultra-fast recovery epitaxial diode.

An example was provided for calculating the total switching loss in both the diode and the switching transistor, in this case an IGBT. ☐

References

(1) International Rectifier Application Note AN-967, "Using HEXFET III in PWM Inverters for Motor Drives and UPS Systems."

(2) International Rectifier Application Note AN-983, "IGBT Characteristics and Applications."

Printed in U.S.A. 0492-M10

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