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Numerical Method for Evaluating IGBT Losses

Application Note **January 2000** **AN-7520**

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An analysis is presented describing a numerical algorithm that develops loss prediction techniques for IGBTs operating in switched mode power circuits. A 600W zero-current switching boost PFC (Power Factor Correction) circuit is analyzed as a design example. Predicted losses are validated by test data measured from an operating circuit.

Nomenclature

ΔI_L	Boost inductor peak to peak current.
$Eoff_{300}(I,T_J)$	Turn-off loss energy at 300V as a function of current and junction temperature.
$Eoff_{480}(I,T_J)$	Turn-off loss energy at 480V as a function of current and junction temperature.
$Eoff(V,I,T_J)$	Turn-off loss as a function of peak clamp voltage, IGBT collector current and junction temperature.
f_S	IGBT switching frequency.
$ka(T_J)$, $kb(T_J)$, $kc(T_J)$, $kd(T_J)$	Curve fit vectors for switching loss function $Eoff480(I,T_J)$.
I	IGBT collector current.
IgbtTurnOffLoss $(Vac,Pout,t,T_J)$	Average IGBT turn-off loss at a particular instant in time.
IGBT_TurnOffWatts $(Vac,Pout,T_J)$	Average IGBT turn-off loss as a function of Vac, output power and T_J.
$I_{toff}(Vac,Pout,t)$	Collector current at IGBT turn-off.
L	Boost inductor value.
η	Power supply efficiency.
Pout	Boost regulator output power.
t	Time.
T	Time period per AC mains cycle.
T_J	IGBT junction temperature.
Vac	Input mains RMS voltage.
Vclamp	Maximum IGBT voltage at turn-off.
V_{OFF}	IGBT voltage during off-state period.
$R\theta_{JA}$	IGBT junction to ambient thermal impedance in ^{o}C/watt.
ω	AC mains radian frequency.

Introduction

An analysis is presented describing a numerical algorithm for determining IGBT losses. A math worksheet program such as MathCAD™ may be used for this application. The algorithm flow chart is shown in Figure 1. The required IGBT parametric test data is obtained from basic device test circuits used by semiconductor manufacturers.

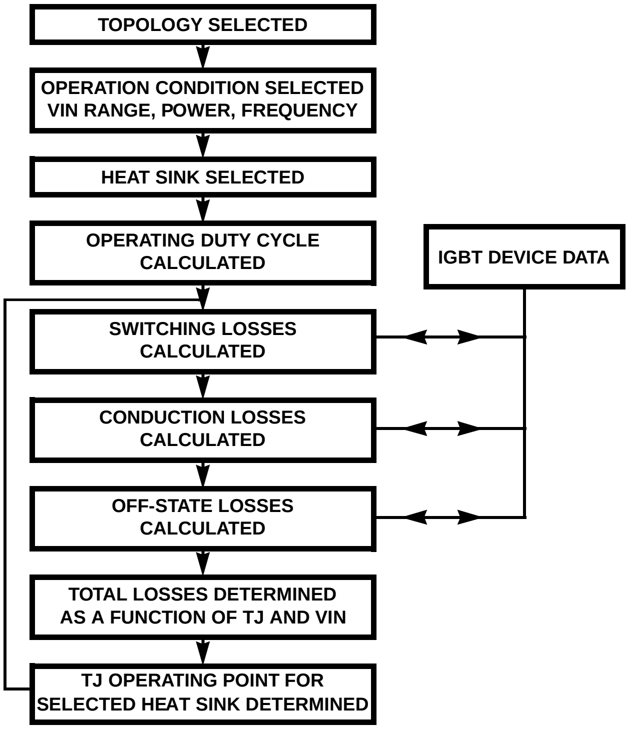
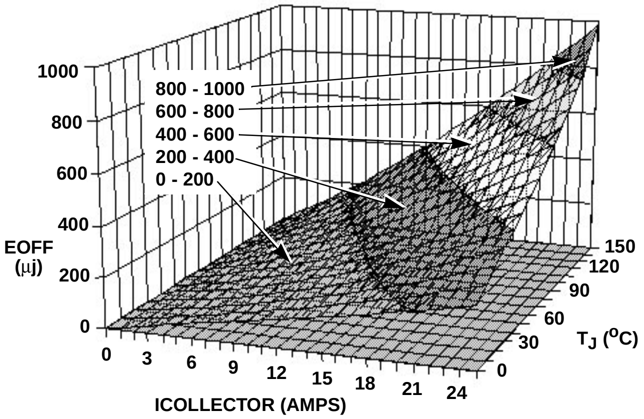


FIGURE 1. LOSS CALCULATION ALGORITHM

Determining switching device losses in power circuits such as active power factor correction (PFC) circuits, AC output UPS systems and solid state AC motor drives that utilize IGBTs as the switching device is extremely complex. The switching device conduction duty cycle and switch current are continually changing as a function of the instantaneous magnitude of the AC mains input or AC output voltage. The problem is further exacerbated by the fact that the IGBT losses are a complex function of turn-off clamp voltage, collector current and junction temperature. The relationship between turn-off energy, collector current and junction temperature is illustrated for a single turn-off clamp voltage of 480V in the surface plot of Figure 2.

Conventional time domain SPICE analysis requires lengthy simulations that generate massive output files. SPICE models representing IGBT switching characteristics may only be run for preset junction temperatures. In addition, IGBT manufacturer data sheets do not provide sufficient information to analyze a device's losses under all switching conditions.



NOTE: Eoff (Vclamp = 480V) HGTG40N60B3

FIGURE 2. TURN-OFF ENERGY AS A FUNCTION OF $I_{COLLECTOR}$ AND $T_{JUNCTION}$

Previous Work

Previous efforts to evaluate transistor operating losses to determine the device junction temperature do not relate the information to the device characteristic in an interactive fashion [2], [3], [4]. IGBT conduction loss is a function of the conducted current and junction temperature. Turn-on and turn-off switching losses are a function of the IGBT collector voltage, current, and junction temperature.

The transistor junction temperature is in turn a function of the combined transistor losses and heatsink temperature.

Methods

In this paper, mathematical models are developed for IGBT turn-off, turn-on, on-state and off-state losses. The models are based on equations developed by curve fitting laboratory test data. The equations describe IGBT losses as a function of junction temperature, collector current and collector clamp voltage. These equations are applied to determine the total losses in transistor Q1 in the continuous mode boost PFC circuit illustrated in Figure 3.

The empirical data used in the curve fit equations was developed utilizing test fixtures that closely represent the PFC circuit operating conditions.

Figure 4 illustrates the basic test circuit used for developing the turn-off losses depicted in Figure 2. The energy loss measurements were made for a single pulse with the device preheated to the specific junction temperature. The energy loss per pulse was recorded as the integral of the total turn-off energy pulse including collector current tailing.

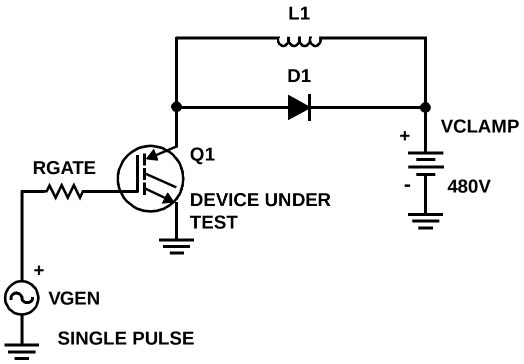


FIGURE 4. IGBT TURN-OFF LOSS TEST CIRCUIT

Turn-Off Switching Loss

Equation 1 expresses the basic form of turn-off losses in an IGBT at a fixed clamp voltage of 480V. This equation evaluates turn-off losses in joules per turn-off cycle as a function of the IGBT collector current and junction temperature. Information obtained from this equation is plotted in Figure 2. Vectors ka(T_J), kb(T_J), kc(T_J), kd(T_J) in Equation 1 are determined by curve fitting the empirical inductive turn-off data. Each of these vectors represents a function that shapes the Eoff equation as a function of junction temperature and collector current.

$$Eoff_{480}(I, T_J) = ka(T_J) \bullet I^3 + kb(T_J) \bullet I^2 + kc(T_J) \bullet I + kd(T_J) \qquad \text{(EQ. 1)}$$

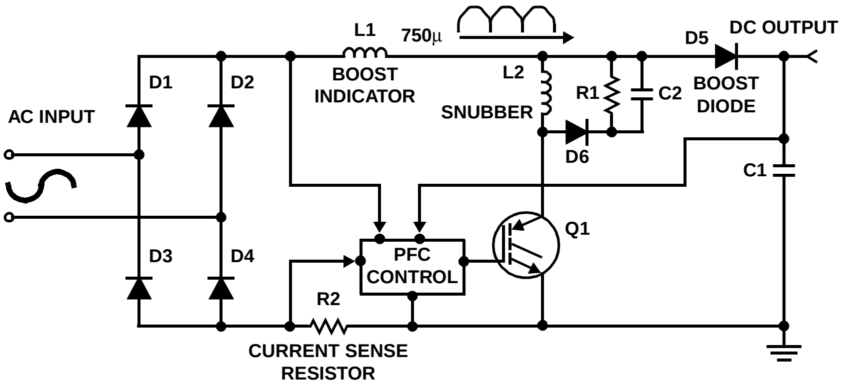


FIGURE 3. BOOST PFC CIRCUIT

The technique used to generate Equation 1 is repeated at a 300V clamp voltage. These two equations are then combined to form Equation 2, which calculates Eoff at intermediate clamp voltages.

$$\mathrm{Eoff}(V, I, T_J) = \left(\begin{array}{c} \mathrm{Eoff}_{300}(I, T_J) + \ldots \\ \dfrac{V-300}{180} \bullet \mathrm{Eoff}_{480}(I, T_J) - \mathrm{Eoff}_{300}(I, T_J) \end{array} \right) \quad \text{(EQ. 2)}$$

This function is then applied in Equation 3 to develop a time varying turn-off loss equation.

$$\begin{array}{l} \mathrm{IGBTTurnOffLoss}(\mathrm{Vac}, \mathrm{Pout}, t, T_J) = \\ f_s \bullet \mathrm{Eoff}(\mathrm{Vclamp}, |I_{toff}(\mathrm{Vac}, \mathrm{Pout}, t)|, T_J) \end{array} \quad \text{(EQ. 3)}$$

The turn-off current I_{toff} in Equation 3 has the form shown in Equation 4. The absolute value of I_{toff} is used in Equation 3 to represent the rectification of the AC input current.

$$I_{toff}(\mathrm{Vac}, \mathrm{Pout}, t) = \frac{\sqrt{2 \bullet \mathrm{Pout}}}{\eta \bullet \mathrm{Vac}} \bullet \sin(\omega \bullet t) + \frac{\Delta I_{L(t)}}{2} \quad \text{(EQ. 4)}$$

Integrating Equation 3 over a quarter cycle of the AC mains calculates the IGBT average turn-off loss as a function of AC mains voltage, output power and junction temperature.

$$\begin{array}{l} \mathrm{IGBT\_TurnOffWatts}\ (\mathrm{Vac}, \mathrm{Pout}, T_J) = \\ \dfrac{4}{T} \bullet \displaystyle\int_0^{\frac{T}{4}} \mathrm{IGBTTurnOffWatts}\ (\mathrm{Vac}, \mathrm{Pout}, t, T_J) \bullet dt \end{array} \quad \text{(EQ. 5)}$$

The IGBT turn-off losses as a function of junction temperature for minimum and maximum mains voltages are plotted in Figure 5. The conditions of Figure 5 are the operation of the boost PFC circuit in Figure 3 with an output load of 600W and a switching frequency of 78kHz. Similar curves may be generated to evaluate the IGBT losses as a function of switching frequency.

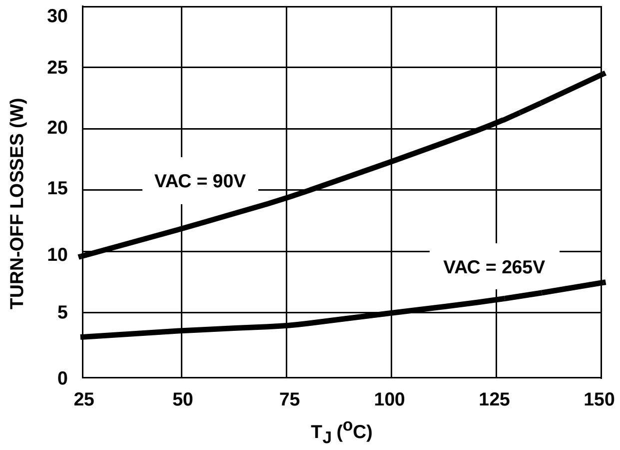


FIGURE 5. IGBT TURN-OFF LOSSES

Turn-On Switching Loss

Q1's turn-on switching losses are determined using similar techniques. It is important to insure that the empirical curve fitting turn-on loss data is representative of the actual circuit operation. In this application the snubber inductor L2 (reference Figure 3) reduces the IGBT turn-on energy loss by permitting the collector voltage to approach its VCE(SAT) value before the peak reverse recovery current occurs in the boost diode D5.

Off-State Loss

The IGBT off-state losses are typically insignificant with respect to turn-on, on-state and turn-off losses. IGBT data sheets provide values for ICES at 25°C and 150°C. These values are for the BVCES voltage condition and do not represent the actual circuit conditions. A meaningful ICES value should be determined for the specific application Voff blocking voltage and operating T_J. The off-state loss Equation 6 is the product of Voff times ICES times the average IGBT off time over a quarter cycle of the AC mains.

$$\begin{array}{l} \mathrm{IGBT\_OffStateLoss}(V_{OFF}, \mathrm{Vac}, I_{CES},) = \\ V_{OFF} \bullet I_{CES} \bullet \dfrac{4}{T} \bullet \displaystyle\int_0^{\frac{T}{4}} [1 - D_{ON}(\mathrm{Vac}, t)] \bullet dt \end{array} \quad \text{(EQ. 6)}$$

Conduction Loss

Equation 10 expresses the basic form of on-state saturation voltage as a function of collector current and junction temperature.

$$\mathrm{Vf}_{IGBT}(I, T_J) = \mathrm{Vf150}(I) + (\mathrm{Vf25}(I) - \mathrm{Vf150}(I)) \bullet \left[\frac{150 - T_J}{125}\right] \quad \text{(EQ. 7)}$$

where

$$\mathrm{Vf25}\ (T_J) = \mathrm{A25} \bullet f(T_J) \quad \text{(EQ. 8)}$$

and

$$\mathrm{Vf150}\ (T_J) = \mathrm{A150} \bullet f(T_J) \quad \text{(EQ. 9)}$$

$$f(x) = \begin{bmatrix} e^{-x} \\ x^{1.4} \\ x \\ 1 \end{bmatrix} \quad \text{(EQ. 10)}$$

Vectors A25 and A150 are determined based on curve fitting IGBT saturation voltages at 25°C and 150°C as a function of current with a 3rd order expression f(x), Equation 10. A general expression for the saturation voltage $\mathrm{Vf}_{IGBT}(I,T_J)$ is then determined by the application of a linear extrapolation between the 25°C and 150°C equations.

The IGBT on-state loss versus time is expressed in Equation 11 as the switching device's forward drop times the boost inductor current times the duty cycle factor.

$$\mathrm{IGBTOnStateWatts}(\mathrm{Vac},\ \mathrm{Pout},\ T_J,\ t) = \qquad \text{(EQ. 11)}$$

$$\left|I_{line}(\mathrm{Vac},\ \mathrm{Pout},\ t)\right| \bullet \mathrm{Vf}_{igbt}\left(\left|I_{line}(\mathrm{Vac},\ \mathrm{Pout},\ t)\right|,\ T_J\right) \bullet D(\mathrm{Vac},\ t)$$

Integrating Equation 11 over a quarter cycle of the AC mains calculates the IGBT average on-state loss as a function of AC mains voltage, output power and junction temperature.

$$\mathrm{IGBTAvgOnStateWatts}(\mathrm{Vac},\ \mathrm{Pout},\ T_J) = \qquad \text{(EQ. 12)}$$

$$\frac{4}{T} \bullet \int_0^{\frac{T}{4}} \mathrm{IGBTOnStateWatts}(\mathrm{Vac},\ \mathrm{Pout},\ T_J,\ t) \bullet dt$$

Total IGBT Losses

Once expressions are developed for all of the loss components, an expression for the total losses may be developed to illustrate the switching device performance.

Figure 6 illustrates one of the calculated results from the loss equations. IGBT total losses are plotted as a function of AC mains input voltage at junction temperatures of 25°C and 120°C. The circuit conditions for Figure 6 are the same as those outlined in Figure 5.

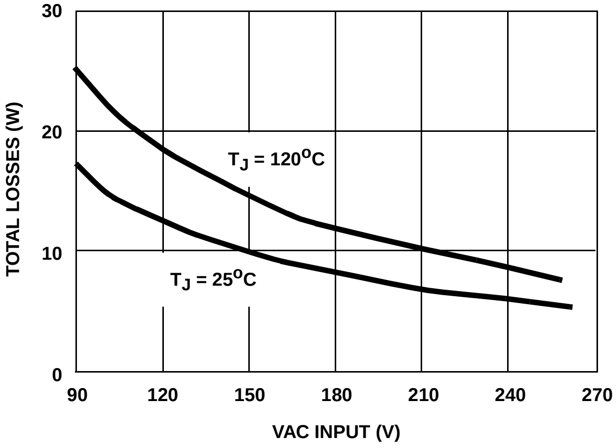


FIGURE 6. TOTAL IGBT LOSSES

Iterative Solution

Once expressions are developed for all of the loss components, an iterative technique is used to determine the IGBT operating temperature as a function of ambient temperature and junction to ambient thermal impedance.

This technique illustrated by Equation 14 determines the operating junction temperature compensating for the change in transistor losses as a function of the junction temperature calculated in the prior iteration. Each iteration of Equation 14 follows the loop illustrated in the lower left of Figure 1. A 15-iteration plot of junction temperature for the conditions of minimum AC mains input, 600W output and a switching frequency of 78kHz is illustrated in Figure 7.

Initializing the junction temperature at T_A

$$T_{J0} = T_{Ambient} \qquad \text{(EQ. 13)}$$

$n = 1 \ldots 15$

The iterative process of Equation 14 is powerful in that it provides a visual illustration of the thermal stability of a design. If the design is near thermal runaway it will be apparent through divergence in Figure 7. This methodology may also be used to test a design's safety margin by increasing the ambient temperature above the anticipated worst case and testing the convergence of the operating junction temperature.

$$T_{Jn} = \qquad \text{(EQ. 14)}$$

$$\mathrm{IGBT\_TotalLosses}(\mathrm{Vac},\ \mathrm{Pout},\ I_{CES},\ T_{J(n-1)} \bullet R_{\theta JA} + T_{Amb}$$

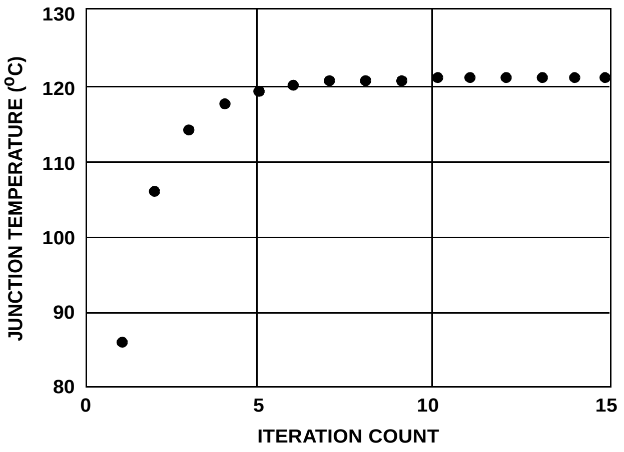


FIGURE 7. ITERATIVE T_J DETERMINATION

Results

A 600W boost PFC circuit Figure 3 was tested using an Fairchild HGTG30N60B3 IGBT as the switching device. For the worst case loss conditions of full load and minimum AC mains input, total IGBT losses were measured to be 23.8W in a 24°C ambient. This measured result compares closely with the 25.2W calculated using the described numerical algorithm. The design approach was further validated by changing the circuit operating frequency from 78kHz to 50kHz, achieving loss correlation to within 3W.

Summary

The techniques described in this paper provide a practical method to accurately predict losses in an IGBT operating in a switched mode power circuit. The predicted losses are itemized such that the designer can make a rapid paper design analysis to predict the performance of one IGBT type versus another. This method also provides an iterative means of determining the maximum junction temperature as a function of the device junction to ambient thermal impedance.

The methodology is flexible and may be applied to other circuit topologies by describing the switching device duty cycle, switch current, off-state voltage and switching frequency as a function of time. The accuracy is limited only by the validity of the data with which the component is curve fit to equations.

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