

# CALCULATION OF THE LOSSES IN A CHOPPER TOPOLOGY

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## 1. INTRODUCTION

In chopper applications, the components which dissipate power are:

- the input rectifier bridge;
- the free wheeling diode; and
- the power switch.

This paper analyses the losses in the chopper in the fast rectifier (using a STTA806DI as an example) and the IGBT (using a STGP10N50).

The input capacitor has a small value in order to reduce inrush current at start-up, and to reduce input low frequency harmonic currents. The input voltage is 100 Hz full-wave rectified ( see figure 5). The transistor is controlled through a low gate resistance (20Ω) in order to increase turn-off speed. Turn-on is controlled by the transistor emitter inductance.

## 2. CALCULATION OF THE LOSSES IN ONE SWITCHING CYCLE

### 2.1 The fast rectifier

For “free wheeling” operation, we can neglect the turn-on and off state losses:

$$e_{ton} = 0 ; e_{off} = 0 ;$$

The dissipated energy of the device mainly consists of the conduction energy,  $e_{ON}$ , and the turn-off losses energy,  $e_{toff}$  :

$$e_{on} = T_{sw} \cdot ( V_{to} \cdot I_{FAV} + R_d \cdot I_{FRMS}^2 )$$

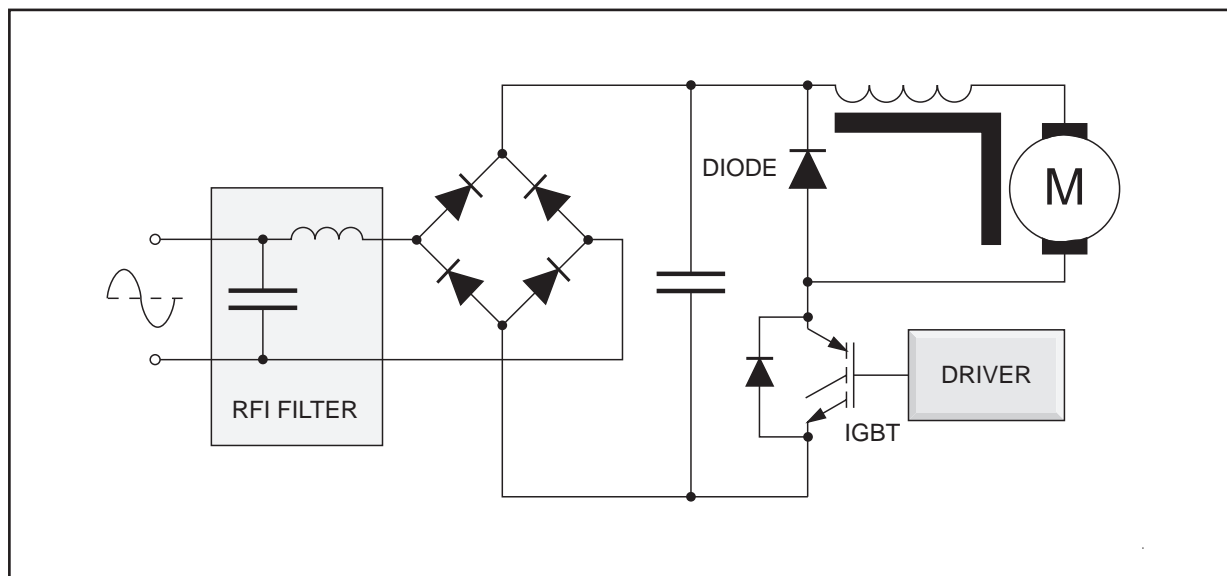
with  $I_{FAV} = \delta' \cdot I_p$  ;  $I_{FRMS} = I_p \cdot \sqrt{\delta'}$  on high inductive load (square waveforms)

$\delta'$  = diode duty cycle (1 - transistor duty cycle)

$$e_{toff} = ( S \cdot V_R \cdot I_{RM}^2 ) / ( 6 \cdot dl_F/dt )$$

with  $dl_F/dt = dl_C/dt$  (controlled by transistor drive)

Figure 1. Basic diagram of a general DC motor control



## APPLICATION NOTE

### 2.2 The IGBT transistor

In motor control applications the switching frequency  $f_{SW}$  of the IGBT transistor is generally less than 20kHz; therefore we neglect its gate energy  $e_G$ . The off state energy  $e_{OFF}$  is also negligible. The dissipated energy is the conduction energy,  $e_{ON}$ , the turn on energy,  $e_{ton}$ , and the turn off energy,  $e_{toff}$  :

$$e_{ON} = T_{SW} \cdot (E_O \cdot I_{CAV} + R_T \cdot I_{CRMS}^2)$$

with  $I_{CAV} = \delta \cdot I_P$ ,  $I_{CRMS} = I_P \cdot \sqrt{\delta}$  on high inductive load (square waveforms)

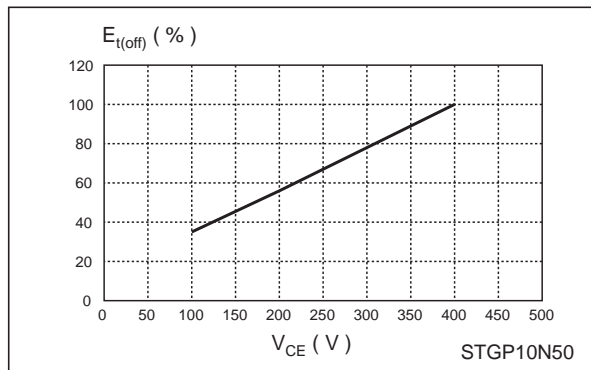
$$e_{ton} = V_{CE} \cdot [(I_{RM} + I_C)^2 / 2 + S \cdot I_{RM} \cdot (2 \cdot I_C + 3 \cdot I_{RM}) / 6] / (dI_C / dt) \\ \approx 1.1 \cdot V_{CE} \cdot (I_{RM} + I_C)^2 / (2 \cdot dI_C / dt)$$

where diode parameters  $I_{RM}$  and  $S$  depend mainly from  $dI_C / dt$  &  $T_{JD}$

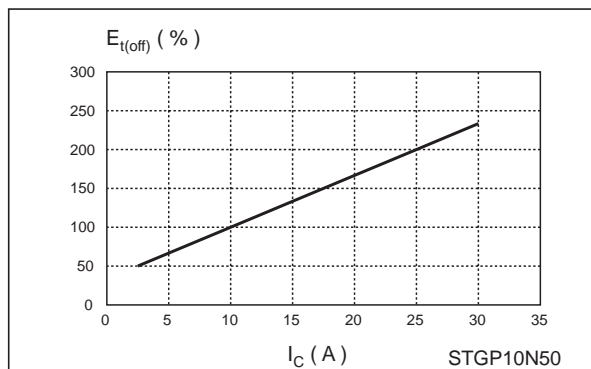
$$e_{toff} \approx V_{CE} \cdot I_T \cdot t_T / 2 + I_C \cdot V_{CE}^2 / (2 \cdot dV_{CE} / dt)$$

The information given by this formula can often be found in the device datasheet. The value for a particular application is obtained using the figures 2., 3. and 4. :  $e_{toff}$  is almost proportional to  $V_{CE}$  and  $I_C$ .

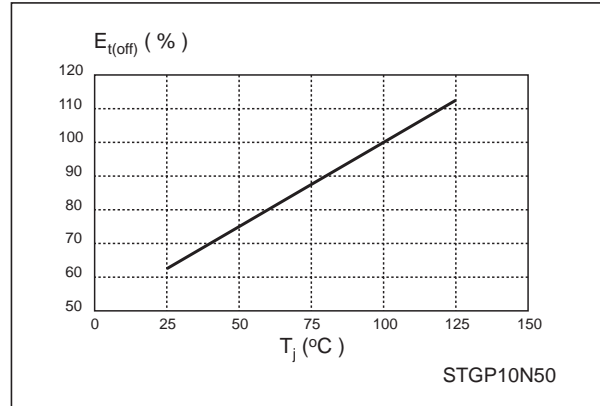
**Figure 2. Turn-off energy  $e_{toff}$  versus applied voltage  $V_{CE}$ .  $R_G=47\Omega$ ,  $I_C = 10A$ ,  $T_J = 100^\circ C$**



**Figure 3. Turn-off energy  $e_{toff}$  versus collector current  $I_C$ .  $R_G=47\Omega$ ,  $V_{CE}=400V$ ,  $T_J=100^\circ C$**



**Figure 4. Turn-off energy  $e_{toff}$  versus junction temperature  $T_J$ .  $R_G=47\Omega$ ,  $I_C=10A$ ,  $V_{CE}=400V$ ,  $V_{GE} = 15V$**



### 3. CALCULATION OF LOSSES IN ONE MAINS HALF CYCLE (10ms)

#### 3.1 An approach to the calculation of the losses

In chopper applications, devices turn on and off the motor current  $I_{mot}$ , while the voltage across them is the direct line voltage  $U_d$ ; these two values define the chopper losses.

In one mains half cycle, the dissipated energy can be calculated by adding the losses of all switching cycles during this time. Modelling  $I_{mot}$  and  $U_d$  simplifies the evaluation.

For switching losses, it can be assumed we suggest that the motor current  $I_{mot}$  is almost constant ( $I_C = I_{AV}$ ), and that the direct voltage  $U_d$  is full wave rectified ( $U_d = 2 \times \sqrt{2} \times U_A / \pi$ ).

$$E_{SW} = \sum_j [e_{SW}(V_{CEj}, I_{Cj})] = \sum_j e_{SW}(U_{dj}, I_{AV})$$

with  $1 \leq j \leq n \approx T / T_{SW}$ , and  $n \geq 50$

$$E_{SW} = 2 \cdot e_{SW}(U_A \cdot \sqrt{2}, I_{AV}) / \pi \quad (A)$$

when  $e_{SW}$  is proportional to  $V_{CE}$  (A)

$$E_{SW} = e_{SW}(U_A \cdot \sqrt{2}, I_{AV}) / 2$$

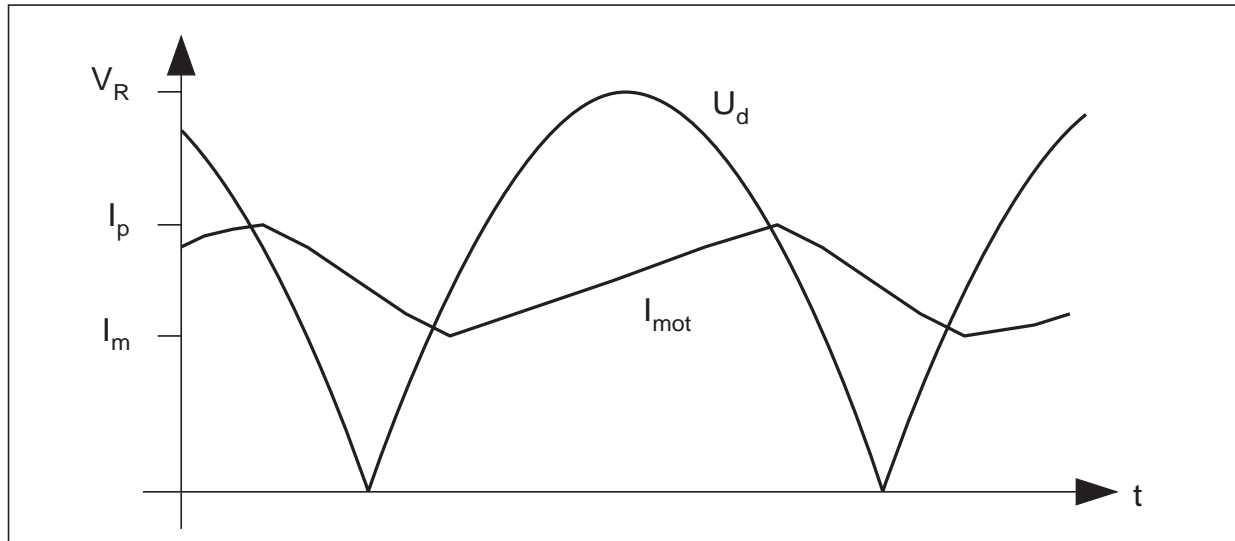
when  $e_{SW}$  is proportional to  $V_{CE}^2$

#### 3.2 Calculation of conduction losses of the IGBT

Conduction losses energy of all switching cycles on one half cycle are added :

$$E_{ON} = \sum_j (e_{ON}) \\ = T_{SW} \cdot [E_O \cdot \delta \cdot \sum_j I_{CP}(j) + R_T \cdot \delta \cdot \sum_j I_{CP}(j)^2] \\ E_{ON} = T \cdot \delta \cdot [E_O \cdot I_{AV} + R_T \cdot I_{RMS}^2]$$

Figure 5. Waveforms of applied mains voltage  $U_d$  and the motor current  $I_{mot}$  (worst case) in a washing machine application)



because  $n \geq 50$  and  $\sum_j I_{CP}(j) \cdot T_{SW} \approx I_{AV} \cdot T$

$$\sum_j I_{CP}(j)^2 \cdot T_{SW} \approx I_{RMS}^2 \cdot T$$

The conduction losses in one half mains cycle are:

$$P_{ON} = \delta \cdot [E_O \cdot I_{AV} + R_T \cdot I_{RMS}^2] \quad (B)$$

### 3.3 Calculation of the switching losses of the IGBT

The switching losses are evaluated as shown with formula (A) :

$$E_{ton} \approx 1.1 \cdot T \cdot f_{SW} \cdot U_A \cdot \sqrt{2} \cdot (I_{AV} + I_{RM})^2 / (\pi \cdot dl_C/dt)$$

$$E_{toff} \approx T \cdot 2 \cdot f_{SW} \cdot e_{toff}(U_A \cdot \sqrt{2}, I_{AV}) / \pi$$

$$P_{SW} \approx (E_{ton} + E_{toff}) / T \quad (C)$$

### 3.4 Calculation of the diode conduction losses

The dissipation in conduction can be calculated in the same way as with the IGBT :

$$P_{ON} = (1 - \delta) \cdot [V_{to} \cdot I_{AV} + R_d \cdot I_{RMS}^2] \quad (D)$$

### 3.5 Calculation of the diode switching losses

$dl_C/dt$  is assumed to be constant, and therefore the diode parameters  $S$  and  $I_{RM}$  become independent of  $V_R$  :

$$P_{SW} \approx E_{toff} / T$$

$$P_{SW} \approx U_A \cdot \sqrt{2} \cdot f_{SW} \cdot S \cdot I_{RM}^2 / (3 \cdot \pi \cdot dl_C/dt) \quad (E)$$

The result is overrated because  $dl_C/dt$  depends on  $U_A$  and  $S$  depends on  $I_{mot}$ , but these are much lower than other chopper losses .

## 4. THERMAL RATING

For a reasonable safety margin, the aim should be to limit the operating junction temperature of the diode and the IGBT to around 125°C.

Generally the diode and the IGBT are considered to be far enough apart on the heat sink for their cooling to be independent of each other. The thermal resistances of the IGBT and the rectifier are calculated separately. The whole heat sink is the result of paralleling the heatsinks required for the two devices.

For each power device thermal cooling is defined as:

$$(P_{SW} + P_{ON}) = (R_{TH} + R_{TH(CT)} + R_{TH(JC)}) \cdot (T_J - T_{AMB}) \quad (F)$$

The heat sink thermal resistance is calculated as:

$$R_{TH(HT)} = R_{TH(D)} \cdot R_{TH(T)} / (R_{TH(D)} + R_{TH(T)}) \quad (G)$$

When the devices are too close for this assumption to be made, mutual thermal impedances should be taken into account.

## 5. CONCLUSION

This note gives some pointers to the design of the cooling system of a chopper converter. The thermal calculation should be confirmed by practical tests to fully validate the cooling rating.

When the power of the system is less than 500W and the switching frequency is round 16kHz, the losses will be mainly generated by the turn off of the IGBT.

## APPLICATION NOTE

### APPENDIX 1. TERMINOLOGY

$e_{ton}$	=	turn on energy	)
$e_{ON}$	=	conduction energy	) for the diode and
$e_{toff}$	=	turn off energy	) the IGBT
$e_{OFF}$	=	OFF state energy	)
$e_G$	=	gate energy	)
$T_{JD}$	=	junction temperature of the diode	)
$S$	=	softness factor of the diode	)
$I_{RM}$	=	reverse recovery of the diode	)
$V_{to}$	=	on state threshold voltage of the diode (@	)
		$T_{JMAX}$ )	
$R_d$	=	dynamic on state resistance of the diode	)
		(@ $T_{JMAX}$ )	
$I_{FAV}$	=	average forward diode current	)
$I_{FRMS}$	=	r.m.s forward diode current	)
$di/dt$	=	rate of removal of diode current at turn off	)
$V_R$	=	reapplied diode voltage ( direct voltage )	)
$\delta^i$	=	diode duty cycle	)
$\delta$	=	transistor duty cycle	)
$T_{SW}$	=	switching period	)
$f_{SW}$	=	switching frequency	)
$I_{CRMS}$	=	R.M.S. collector current	)
$I_{CAV}$	=	average collector current	) of the IGBT
$I_{CP}$	=	peak collector current	)
$di_C/dt$	=	turn on rate of rise of collector current of	)
		the IGBT	
$V_{CE}$	=	turn off reapplied voltage of the transistor	)
$T_{JT}$	=	junction temperature of the transistor	)
$E_O$	=	on state threshold voltage of the IGBT ( @	)
		$T_{JMAX}$ )	
$R_T$	=	dynamic resistance of the IGBT (@ $T_{J(MAX)}$ )	)
$I_T$	=	tail current of the IGBT	)
$t_T$	=	tail current duration	)
$U_A$	=	mains voltage	)
$I_{RMS}$	=	R.M.S. motor current	)
$I_{AV}$	=	average motor current	)
$I_p$	=	peak motor current	)
$T$	=	half period of the mains (10 ms)	)
$P_{ON}$	=	total conduction losses power	) for
$P_{SW}$	=	total switching losses power	) diode
$R_{TH_X}$	=	device heat sink thermal	) (X=F)
		resistance	) or
$R_{TH_{JC}}$	=	junction case thermal	) IGBT
		resistance	) (X=T)
$P_T$	=	total losses power	)
$R_{TH_{HT}}$	=	total heat sink thermal resistance	)
$R_{TH_{CT}}$	=	case contact thermal resistance	)

### APPENDIX 2. CALCULATION OF THE AVERAGE AND RMS VALUES OF COMMON WAVEFORMS

**Sine wave:**  $I_{AV} = \frac{2 \cdot I_p \cdot \delta}{\pi}$

$$I_{RMS} = I_p \cdot \sqrt{\frac{\delta}{2}}$$

**Square wave:**  $I_{AV} = I_p \cdot \delta$

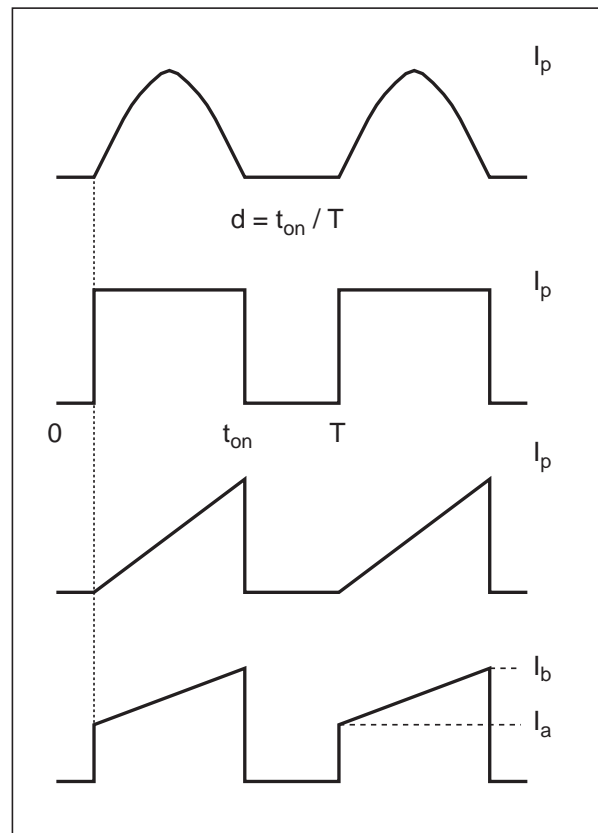
$$I_{RMS} = I_p \cdot \sqrt{\delta}$$

**Triangular wave:**  $I_{AV} = \frac{I_p \cdot \delta}{2}$

$$I_{RMS} = I_p \cdot \sqrt{\frac{\delta}{3}}$$

**Trapezoid:**  $I_{AV} = \delta \cdot \frac{I_a + I_b}{2}$

$$I_{RMS} = \sqrt{\delta \cdot \frac{I_a^2 + I_a \cdot I_b + I_b^2}{3}}$$



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