APPLICATION NOTE

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} :

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

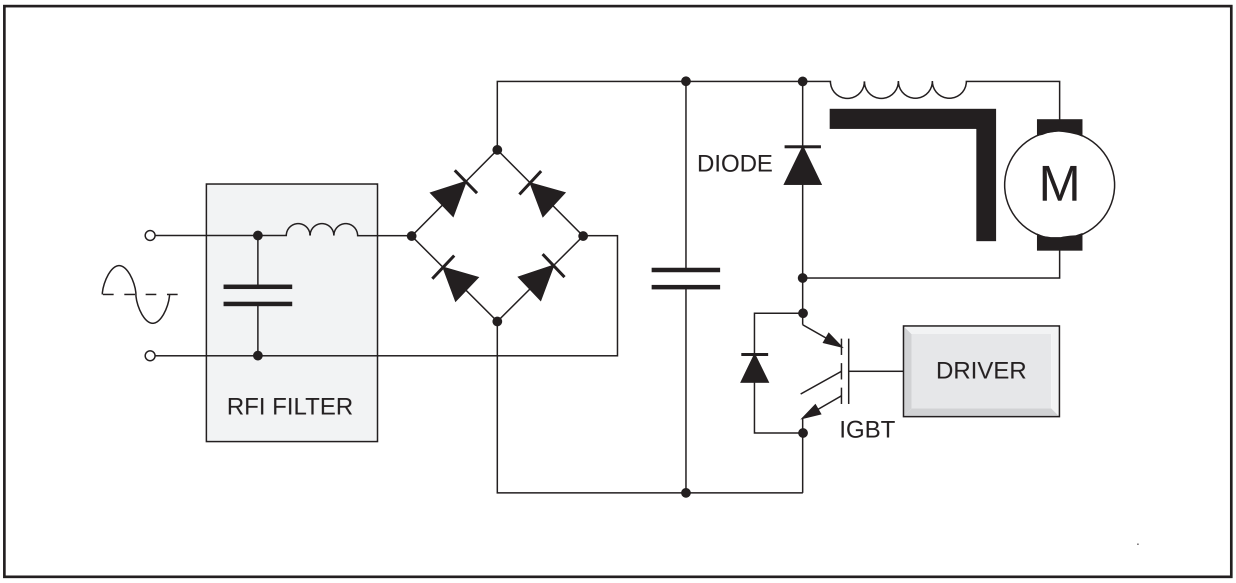
with $I_{FAV} = \delta' . \, I_P$; $I_{FRMS} = I_P . \sqrt{\delta'}$ on high inductive load (square waveforms)

δ' = diode duty cycle (1 - transistor duty cycle)

$$e_{toff} = (S \, . \, V_R \, . \, I_{RM}^2) \, / \, (6 \, . \, dI_F/dt)$$

with $dI_F/dt = dI_C/dt$ (controlled by transistor drive)

Figure 1. Basic diagram of a general DC motor control



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} :

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

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

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

$$\approx 1.1 \,.\, V_{CE} \,.\, (I_{RM} + I_C)^2 \,/\, (\,2 \,.\, dI_C/dt\,)$$

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

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

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=47Ω, I_C = 10A, T_j = 100ºC

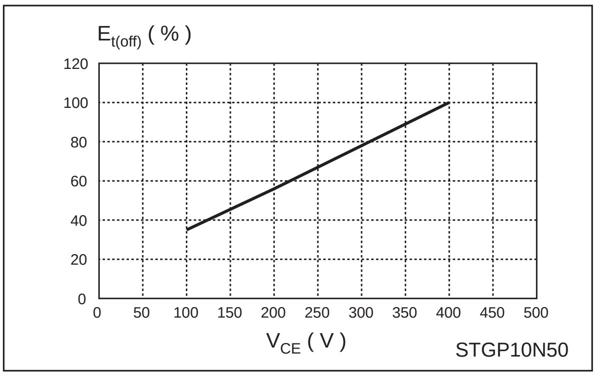


Figure 3. Turn-off energy e_{toff} versus collector current I_C. R_G=47Ω, V_{CE}=400V, T_j=100ºC

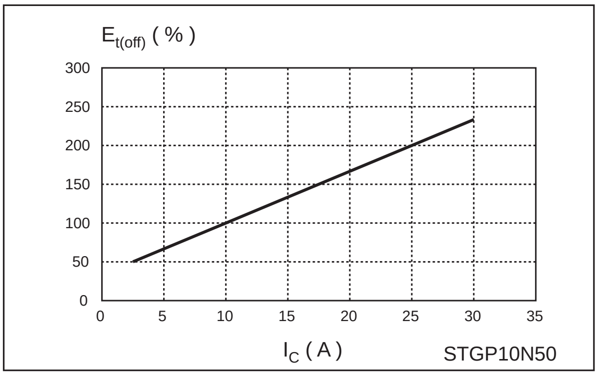
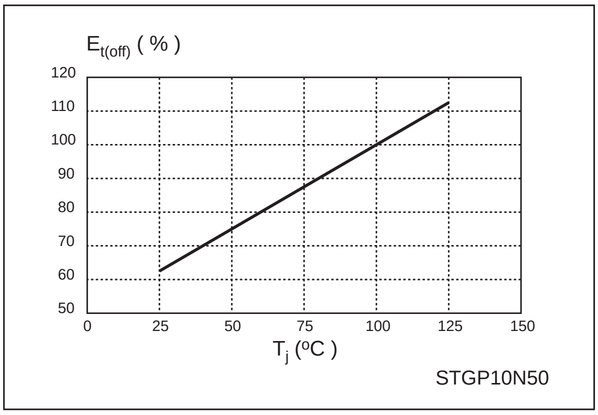


Figure 4. Turn-off energy e_{toff} versus junction temperature T_j. R_G=47Ω, I_C=10A, V_{CE}=400V, V_{GE} = 15V



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 ($U_d = 2 \times \sqrt{2} \times U_A / \pi$).

$$E_{SW} = \textstyle\sum_j \,[\, e_{SW}\,(V_{CE\,j}\,,\, I_{C\,j}\,)] = \sum_j e_{SW}\,(U_{d\,j}\,,\, I_{AV}\,)$$

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

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

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

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

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

3.2 Calculation of conduction losses of the IGBT

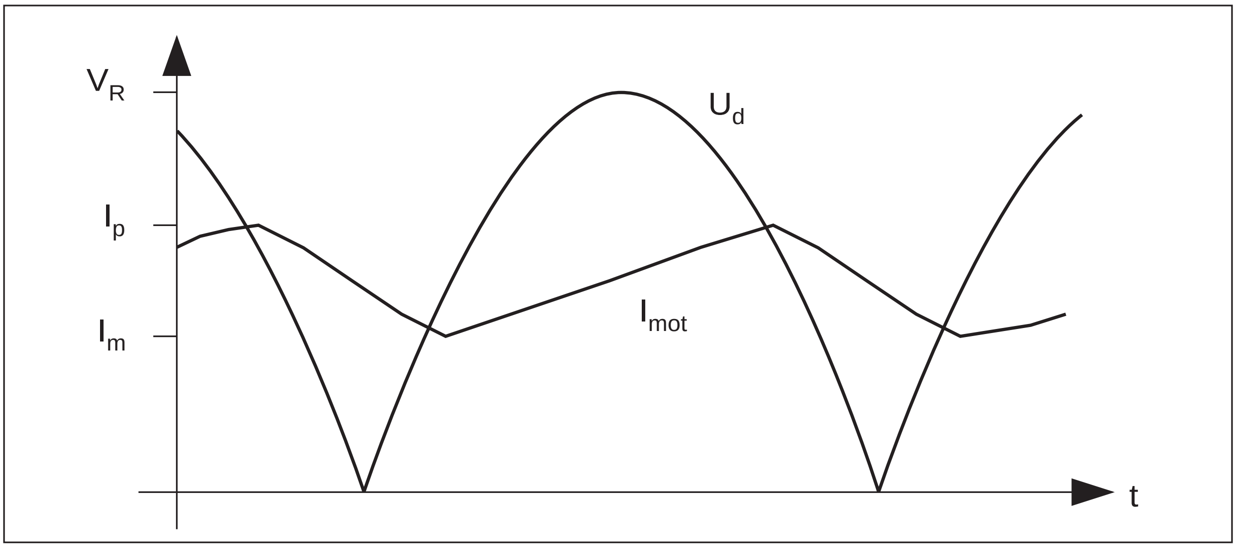
Conduction losses energy of all switching cycles on one half cycle are added :

$$E_{ON} = \textstyle\sum_j \,(\, e_{ON}\,)$$

$$= T_{SW} \,.\, [\, E_O \,.\, \delta \,.\, \textstyle\sum_j I_{CP}\,(j) + R_T \,.\, \delta \,.\, \sum_j I_{CP}\,(j)^2\,]$$

$$E_{ON} = T \,.\, \delta \,.\, [\, E_O \,.\, I_{AV} + R_T \,.\, I_{RMS}{}^2\,]$$

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 $\sum_j I_{CP}(j) \,.\, T_{SW} \approx I_{AV} \,.\, T$

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

The conduction losses in one half mains cycle are:

$$P_{ON} = \delta \,.\, [\, E_O \,.\, I_{AV} + R_T \,.\, I_{RMS}^2 \,] \qquad (\text{B})$$

3.3 Calculation of the switching losses of the IGBT

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

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

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

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

3.4 Calculation of the diode conduction losses

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

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

3.5 Calculation of the diode switching losses

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

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

$$P_{SW} \approx U_A \,.\sqrt{2} \,.\, f_{SW} \,.\, S \,.\, I_{RM}^2 \,/\, (\, 3 \,.\, \pi \,.\, dI_C/dt\,) \qquad (\text{E})$$

The result is overrated because dI_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:

$$(P_{SW} + P_{ON}) = (R_{TH} + R_{TH(CT)} + R_{TH(JC)}) \,.\, (T_J - T_{AMB}) \qquad (\text{F})$$

The heat sink thermal resistance is calculated as:

$$R_{TH(HT)} = R_{TH(D)} \,.\, R_{TH(T)} \,/\, (\, R_{TH(D)} + R_{TH\_T}\,) \qquad (\text{G})$$

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.

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 (@ $T_{J\,MAX}$)
R_d = dynamic on state resistance of the diode (@ $T_{J\,MAX}$)
I_{FAV} = average forward diode current
I_{FRMS} = r.m.s forward diode current
dI_F/dt = rate of removal of diode current at turn off
V_R = reapplied diode voltage (direct voltage)
δ' = diode duty cycle
δ = 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 (@ $T_{J\,MAX}$)
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:

$$I_{AV} = \frac{2 . I_P . \delta}{\pi}$$

$$I_{RMS} = I_P . \sqrt{\frac{\delta}{2}}$$

Square wave:

$$I_{AV} = I_P . \delta$$

$$I_{RMS} = I_P . \sqrt{\delta}$$

Triangular wave:

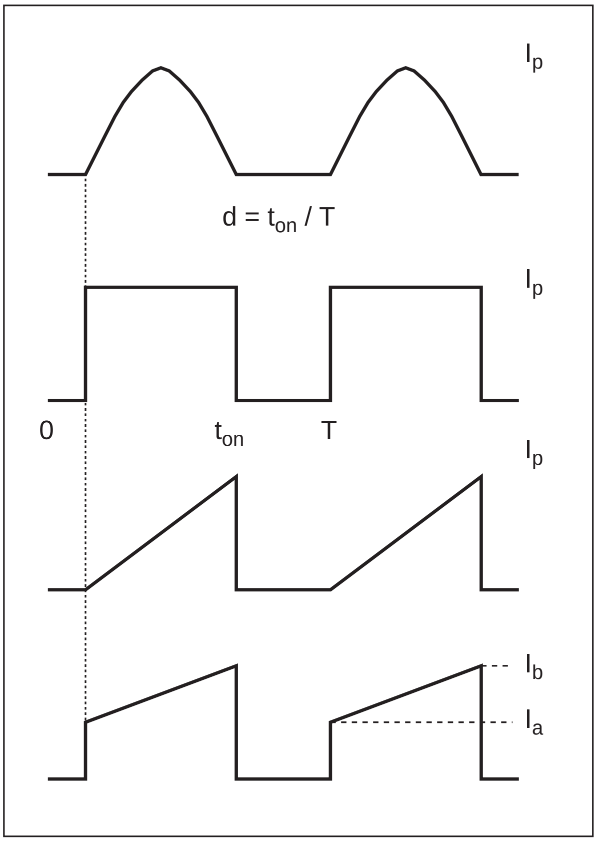
$$I_{AV} = \frac{I_P . \delta}{2}$$

$$I_{RMS} = I_P . \sqrt{\frac{\delta}{3}}$$

Trapezoid:

$$I_{AV} = \delta . \frac{I_a + I_b}{2}$$

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



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