Analytical Switching Loss Modelling based on Datasheet Parameters for MOSFETs in a Half-Bridge

Journal Article

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Supplement File for journal paper - *Analytical Switching Loss Modeling Based on Datasheet Parameters for MOSFETs in a Half-Bridge*

This supplement document aims to correct some mistakes in the original published journal paper. In addition, some hints are provided for the correct implementation of the proposed analytical switching loss model.

Section 1: Mistakes from the original paper

Mistake 1: equation (15)

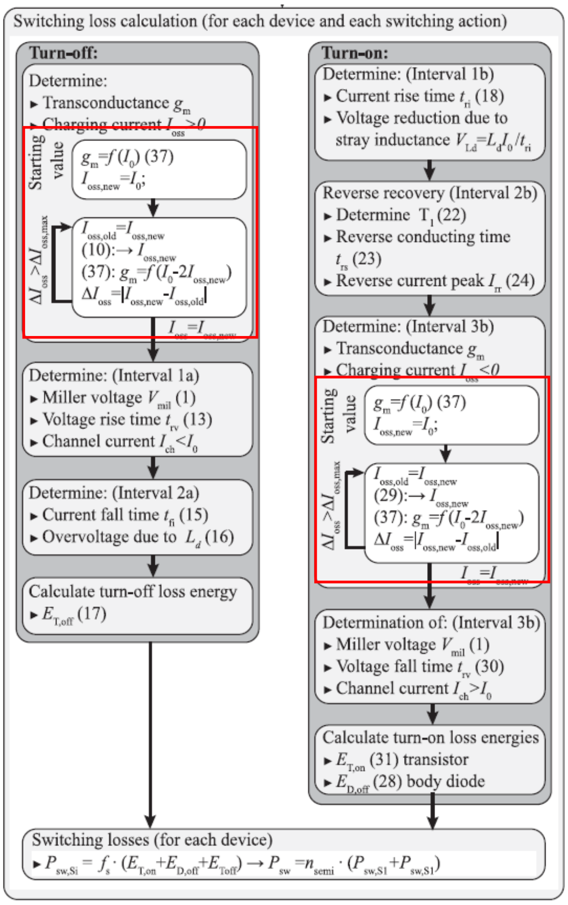
In the paper: $t_{fi} = -\ln(\frac{V_{th}+V_g}{V_{mil}+V_g})(C_{gs}R_g + L_s g_m)$

Correct one: $t_{fi} = -\ln(\frac{V_{th}-V_g}{V_{mil}-V_g})(C_{gs}R_g + L_s g_m)$

Attention: V_g here represents the 0 or negative turn-off gate supply voltage. Similar applies to equation (18), where V_g represents the turn-on gate supply voltage.

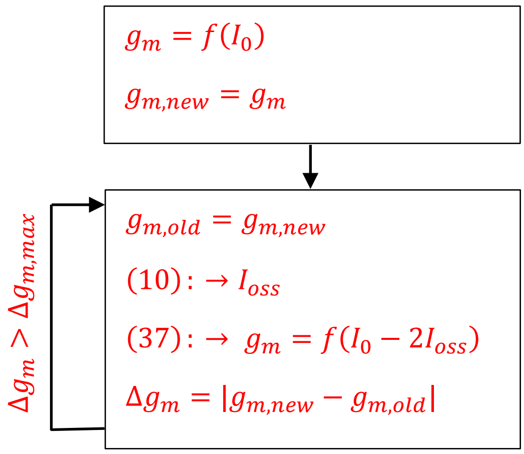
Mistake 2: Fig. 6 Flowchart for calculating the turn-on and turn-off losses of MOSFETs in a half-bridge

In the paper: the red regions are wrong

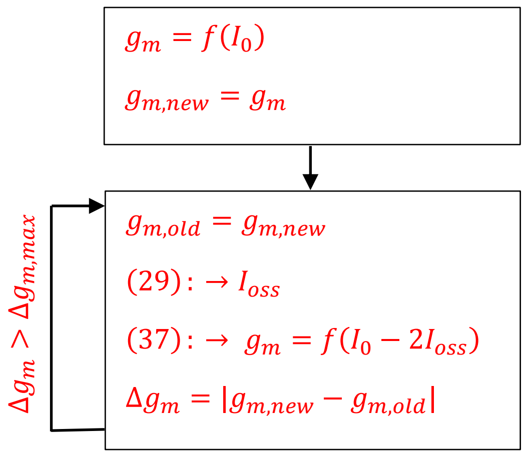


Correct one:

Turn-off:



Turn-on:



Mistake 3: equation (19)

In the paper: $i_{bd}(t) = I_0 - \frac{di_{bd}}{dt}t = \frac{I_0}{t_{ri}}t$

Correct one: $i_{bd}(t) = I_0 - \frac{di_{bd}}{dt}t = I_0 - \frac{I_0}{t_{ri}}t$

Mistake 4: equation (29)

In the paper: $0 = -\frac{2L_s}{Q_{oss}R_g}I_{oss}^2 + \left(\frac{2}{g_m R_g} + \frac{C_{gd}}{C_{gd}+C_{ds}}\right)I_{oss} + \frac{1}{R_g}\left(V_g - V_{th} - \frac{I_0}{g_m}\right)$

Correct one: $0 = \frac{2L_s}{Q_{oss}R_g}I_{oss}^2 + \left(\frac{2}{g_m R_g} + \frac{C_{gd}}{C_{gd}+C_{ds}}\right)I_{oss} + \frac{1}{R_g}\left(V_g - V_{th} - \frac{I_0}{g_m}\right)$ (comment: same to (10))

Mistake 5: equation (41)

In the paper: $\frac{1}{\tau_{rr}} = \frac{1}{\tau_c} - \frac{1}{T_m}$

Correct one: $\frac{1}{T_m} = \frac{1}{\tau_{rr}} - \frac{1}{\tau_c}$

Mistake 6: wrong definition of Q_{oss} in equation (4)

Although Q_{oss} is firstly defined in equation (4) in the paper as the charge value stored in the output capacitance C_{oss} of both switches S_1 and S_2, all of the equations other than equation (4) actually define Q_{oss} as the charge value stored in C_{oss} of only one switch.

In the paper: $E_{par}(V_0) = \int_0^{V_0} v \cdot C_{par}(v)dv = Q_{oss}V_0$

Correct one: $E_{par}(V_0) = \int_0^{V_0} v \cdot C_{par}(v)dv = 2\,Q_{oss}V_0$

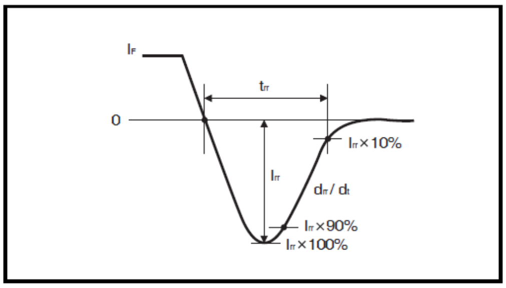
There are several examples to prove that this statement is true. In section II, Turn-off subsection A, Interval 1a, the current required to recharge the parasitic capacitance is defined as $I_{oss} = i_{ds} + i_{gd}$, which represents the current in only one switch. Then in equation (9) and (13), the voltage rise time $t_{rv} = \frac{Q_{oss}}{I_{oss}}$, which is only true if Q_{oss} is defined as the charge value stored in C_{oss} of only one switch.

Section 2: Hints for model implementation

Attention for equation (39):

Equation (39) is derived by assuming $T_2 = +\infty$. However, in some of the device data sheets, e.g. SCH2080KEC (ROHM), the definitions of Q_{rr} related variables are different, as shown below.

Fig.4-2 Reverse Recovery Waveform



In this case, the equation (39) should be: $\tau_{rr} = \frac{Q_{rf}}{0.9 I_{rr}}$ with $T_2 = \ln 10 \cdot \tau_{rr} + T_1$

Attention for two different g_m in Table I:

TABLE I
PARAMETERS FOR THE SiC MOSFET C2M0080120D, 20 A, 600 V

	Turn-off		Turn-on	
Interval 1a/b	g_m	1.02 S	g_m	3.02 S
	I_{oss}	8.33 A	t_{ri}	10.7 ns
	I_{ch}	3.32 A	V_{Ld}	37.35 V
	V_{mil}	7.46 V		
	t_{rv}	10.5 ns		
Interval 2a/b	t_{fi}	3.5 ns	t_{rs}	4.6 ns
			I_{rr}	8.6 A
Interval 3b	-		g_m	4.1 S
	-		I_{oss}	−6.06 A
	-		I_{ch}	32.16 A
	-		V_{mil}	12.16 V
	-		t_{fv}	14.44 ns
Losses (device internal)	$E_{T,off}$	14.1 µJ	$E_{T,on}$	274 µJ
Stored energy	$E_{oss,S1}$	18.9 µJ	$E_{oss,S1}$	18.9 µJ

The first g_m is calculated for interval 1b, which is the current rise interval for turn-on. This value is calculated by $g_m = f(I_0)$, because as shown in Fig. 4 during this interval v_{ds} is assumed to be constant, therefore the channel current $i_{ch} = i_{ds} = I_0$.

The second g_m can be calculated as shown in the flow chart, which is similar to that calculated for turn-off.

It needs to be emphasized that although the nonlinear transfer characteristics have been considered, in the current changing intervals (turn-on: interval 1b, turn-off: interval 2a) g_m is always considered as a constant value, which leads to a linearized current waveform. Therefore, in equation (15) and (18) the g_m is always a constant for one specific operating point.

Attention for equation (27-28):

27: integration from T_1 to $T_1 + t_{fv}$

28: integration from T_1 to $+\infty$

Attention for the DUT: The data sheet of the exemplified device C2M0080120D has been updated by the manufacturer in 2019. The old version (Oct. 2015) is the one used by this paper, which cannot be found online anymore. In addition, the parasitic drain inductance is assumed to be $L_d = 10\text{nH}$, which is not mentioned in the paper.

Example implementation of the reverse recovery related equations (19-25, 38-41):

DUT: C2M0080120D (data sheet: old version (Oct. 2015))

Step I: Find reverse recovery parameters from DUT datasheet

Reverse Diode Characteristics

Symbol	Parameter	Typ.	Max.	Unit	Test Conditions	Note
V_{SD}	Diode Forward Voltage	3.3		V	V_{GS} = - 5 V, I_{SD} = 10 A	Fig. 8, 9, 10
		3.1		V	V_{GS} = - 5 V, I_{SD} = 10 A, T_J = 150 °C	
I_S	Continuous Diode Forward Current		36	A	T_C = 25˚C	Note 1
t_{rr}	Reverse Recover time	32		ns	V_{GS} = - 5 V, I_{SD} = 20 A, V_R = 800 V dif/dt = 2400 A/µs	Note 1
Q_{rr}	Reverse Recovery Charge	192		nC		
I_{rrm}	Peak Reverse Recovery Current	10		A		

Note (1): When using SiC Body Diode the maximum recommended V_{GS} = -5V

Step II: Use only data sheet parameters to calculate three time constants in Fig. 5

$$Q_{rr}^{*} = Q_{rr} - Q_{oss,800V} = 88\text{nC}$$

(38) $Q_{rf} = Q_{rr}^{*} - Q_{rs} = Q_{rr}^{*} - \frac{I_{rrm}^2}{2\times\frac{di_f}{dt}} = 67.17\text{nC}$

(39) $\tau_{rr} = \frac{Q_{rf}}{I_{rrm}} = 6.717\text{ns}$ [attention: assuming $T_2 = +\infty$. $\tau_{rr} = \frac{Q_{rf}}{0.9 I_{rr}}$ with $T_2 = \ln 10 \cdot \tau_{rr} + T_1$]

From the operating point mentioned in the data sheet, T_1 in Fig. 5 can be calculated for this special case: $T_1 = \frac{I_{rrm} + I_{SD}}{\frac{di_f}{dt}} = 12.5\text{ns}$

(40) $I_{rrm} = \frac{di_f}{dt} \cdot (\tau_c - \tau_{rr}) \cdot (1 - e^{-\frac{T_1}{\tau_c}})$

yellow variables are calculated above, can calculate $\tau_c = 13.7\text{ns}$ (from numerical method)

(41) $\frac{1}{T_m} = \frac{1}{\tau_{rr}} - \frac{1}{\tau_c}, T_m = 13.18\text{ns}$

Short summary of step I and step II: use data sheet parameters for a certain operating point to calculate general parameters T_m, τ_c, τ_{rr}

Step III: Find generalized reverse recovery equations for arbitrary operating points

$T_0 = t_{ri}$, which can be obtained by comparing Fig. 5 to Fig. 4 Interval 4b

In (19), now the unknown variables are T_1 and I_{rr}

(22) $q_e(T_1) = 0 = q_m(T_1) + T_m\left(I_0 - \frac{di_{bd}}{dt}T_1\right)$ with $\frac{di_{bd}}{dt} = \frac{I_0}{t_{ri}}$

insert (21) to (22):

$$0 = \frac{di_{bd}}{dt}\tau_c\left(T_0 + \tau_c - T_1 - \tau_c e^{-\frac{T_1}{\tau_c}}\right) + T_m\left(I_0 - \frac{di_{bd}}{dt}T_1\right)$$

Obviously, in this equation the only unknown variable is T_1. As written in the paper, T_1 needs to be found by numerically solving (22).

Finally, after knowing T_1, (23)-(28) can be easily calculated.