How to Estimate Motor Driver Power Dissipation

MPS Jackson Gao

Half-Bridge Power Losses: 1st Order Estimation

MOSFET Turn-On Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{RISE}}{T_{PWM}}$$

MOSFET Turn-Off Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{FALL}}{T_{PWM}}$$

$$t_{RISE} = t_{FALL} \text{ (VDS transition)}$$

MOSFET Switching Losses

$$P_{SW} = V_{IN}^{2} \times I_{MOTOR} \times f_{PWM} \times \frac{1}{SR}$$

Where I_{MOTOR} is assumed to have a very low ripple

MOSFET Conduction Losses

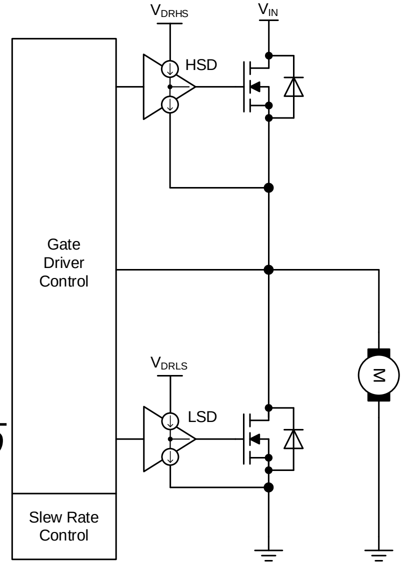
$$P_{COND} = R_{DS(ON)} \times I^2_{(RMS)} \qquad I_{RMS} = I_{MOTOR} \times \sqrt{D}$$

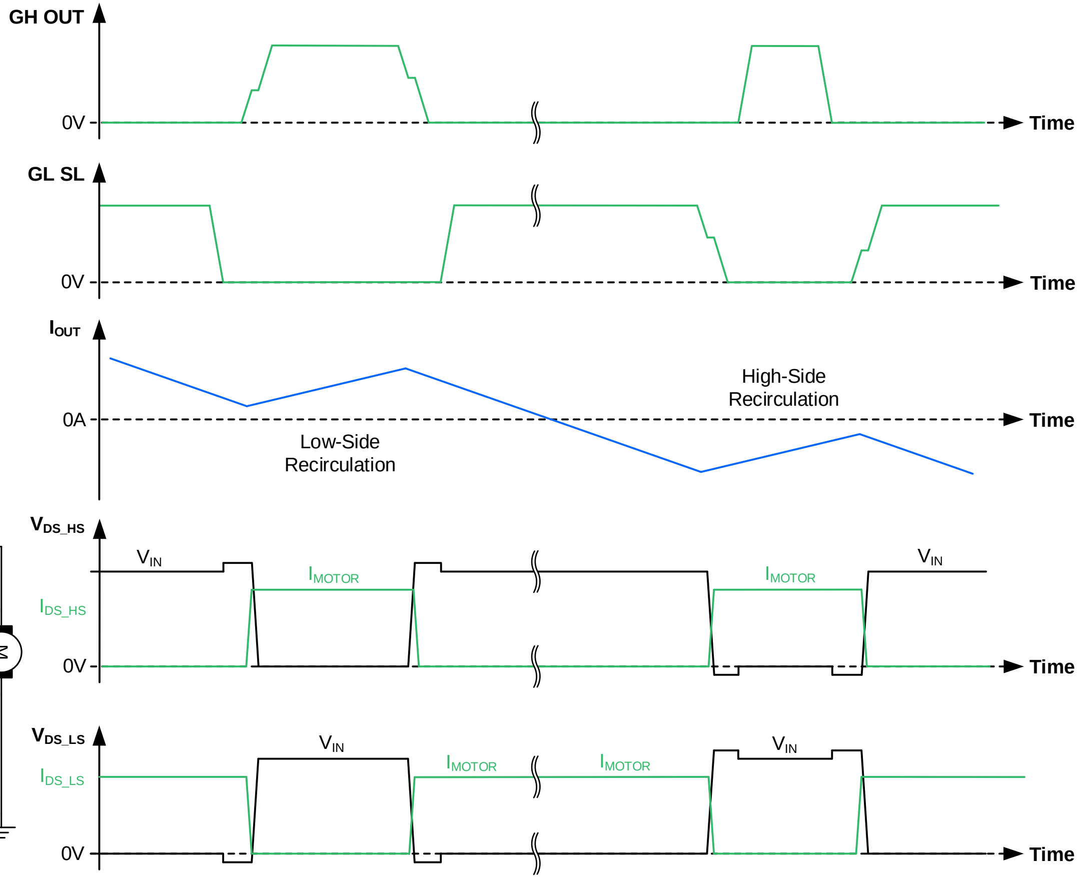
$$P_{COND} = R_{DS\,(ON)} \times I^2_{MOTOR} \times D$$

MOSFET Back-Gate Diode Losses

$$P_{BG} = 2 \times V_F \times I_{MOTOR} \times t_{BG\_TIME} \times f_{PWM}$$

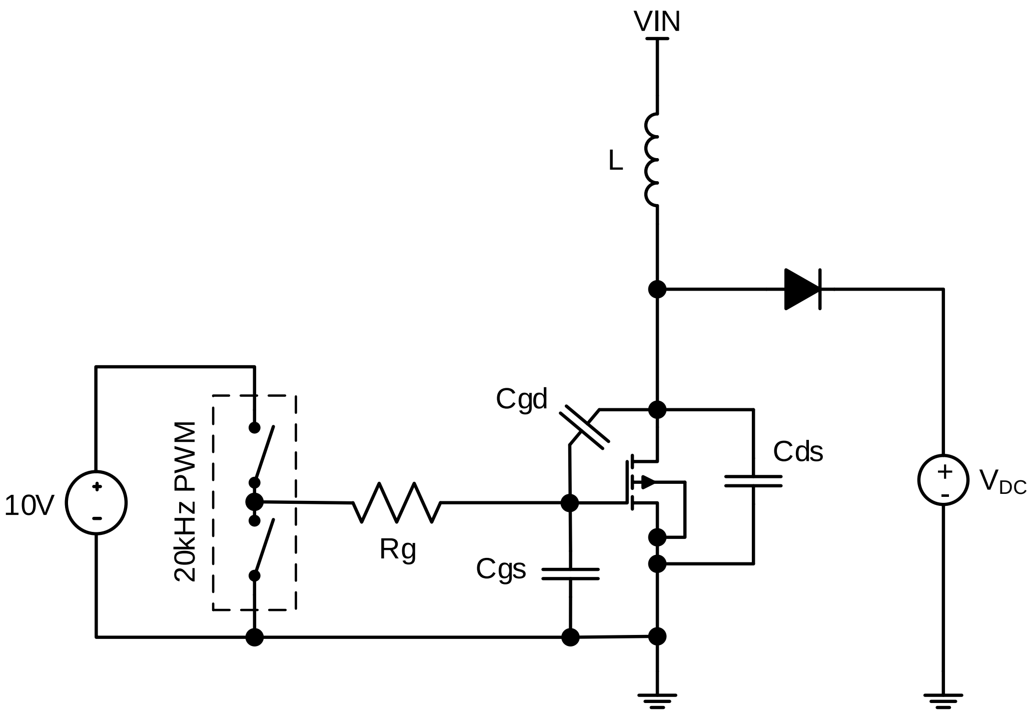
Where the I_{DS} transition is assumed to be negligible

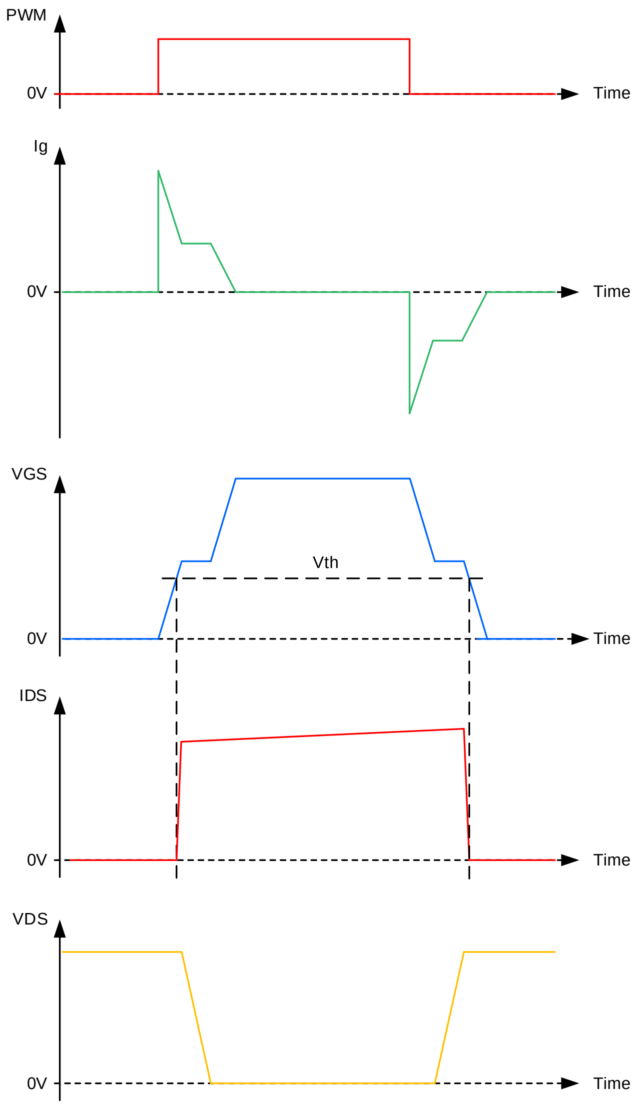




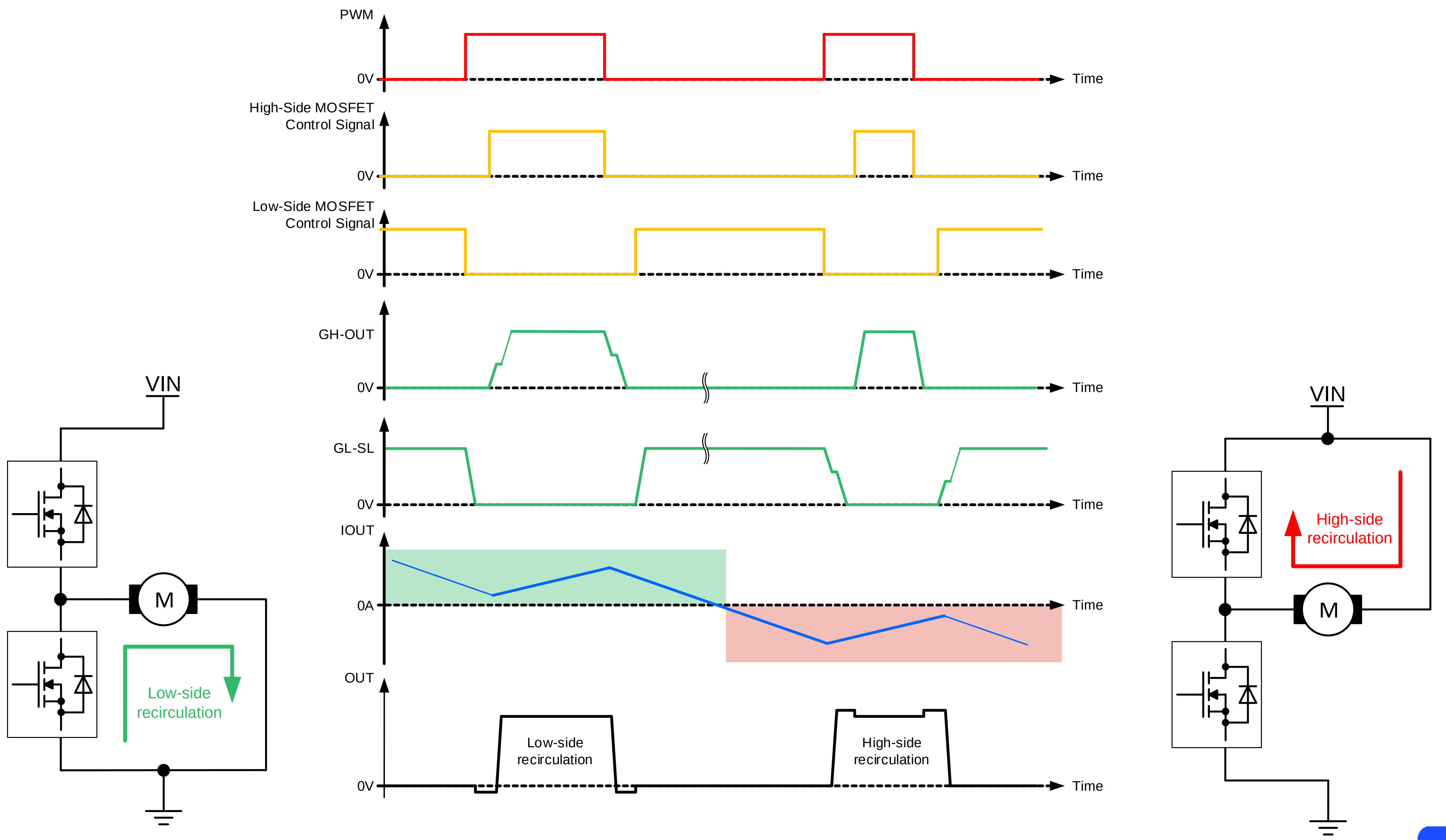
Understanding MOSFET Basic Switching (Inductive Load)

Input Capacitance	C_{iss}	V_{DS} = 15 V, V_{GS} = 0 V, f = 1 Mhz		5861		pF
Output Capacitance	C_{oss}			224		
Reverse Transfer Capacitance	C_{rss}			185		





Half-Bridge Switching Waveforms



Half-Bridge Power Losses: 1st Order Estimation

MOSFET Turn-On Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{RISE}}{T_{PWM}}$$

MOSFET Turn-Off Losses

$$P_D = \frac{V_{IN}}{2} \times I_{MOTOR} \times \frac{t_{FALL}}{T_{PWM}}$$

$t_{RISE} = t_{FALL}$ (VDS transition)

MOSFET Switching Losses

$$P_{SW} = V_{IN}^2 \times I_{MOTOR} \times f_{PWM} \times \frac{1}{SR}$$

Where I_{MOTOR} is assumed to have a very low ripple

MOSFET Conduction Losses

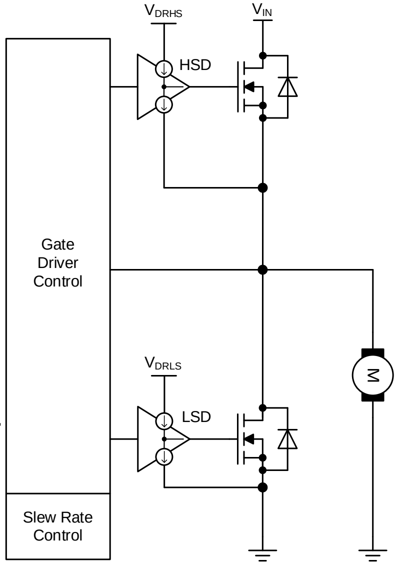
$$P_{COND} = R_{DS(ON)} \times I^2{}_{(RMS)} \qquad I_{RMS} = I_{MOTOR} \times \sqrt{D}$$

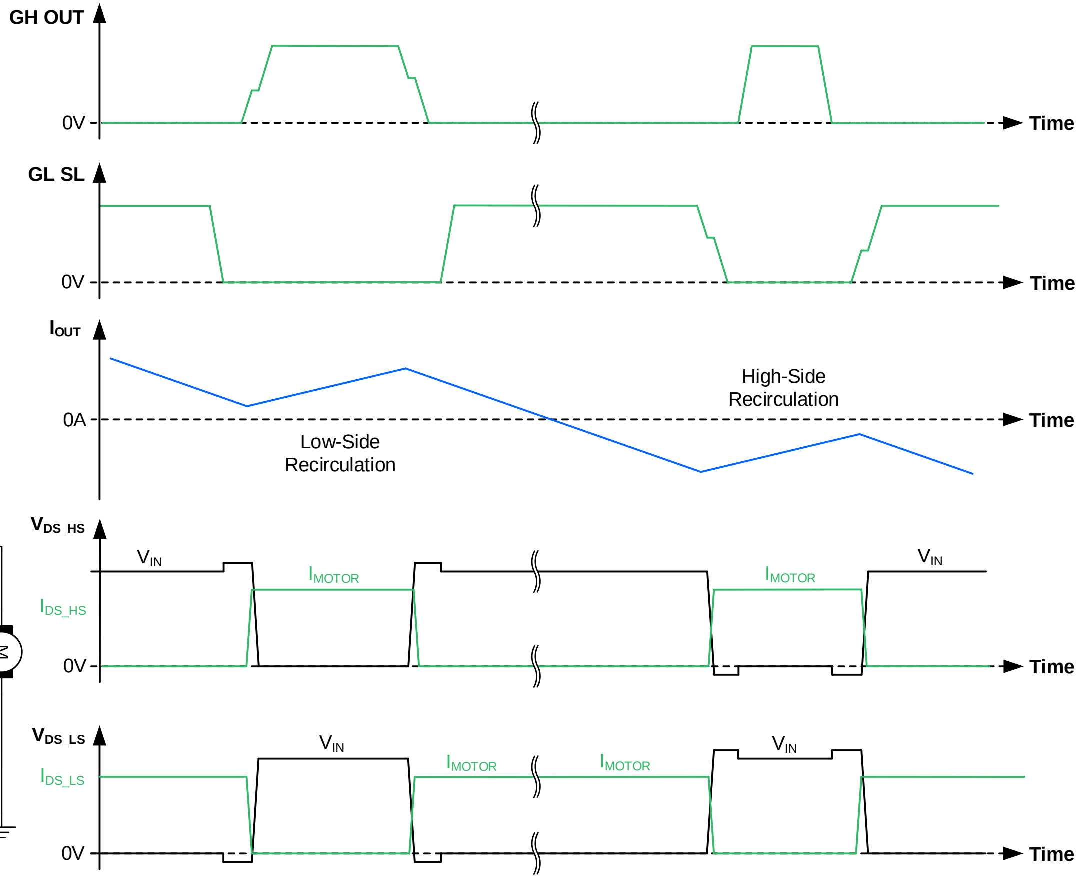
$$P_{COND} = R_{DS\,(ON)} \times I^2{}_{MOTOR} \times D$$

MOSFET Back-Gate Diode Losses

$$P_{BG} = 2 \times V_F \times I_{MOTOR} \times t_{BG\_TIME} \times f_{PWM}$$

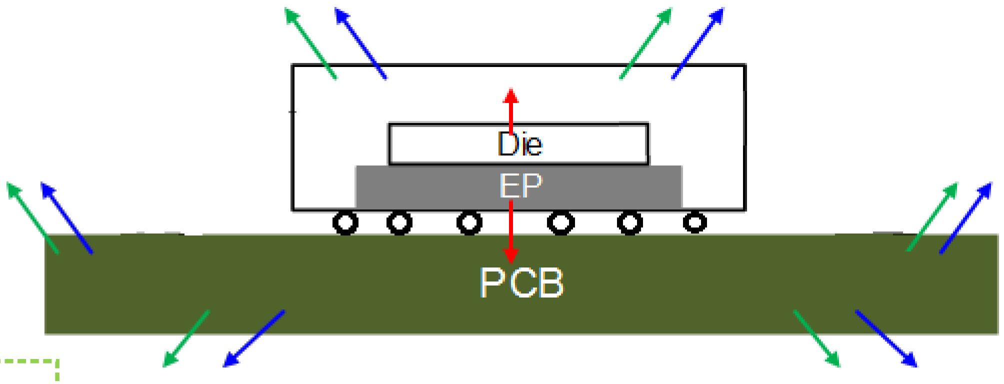
Where the I_{DS} transition is assumed to be negligible

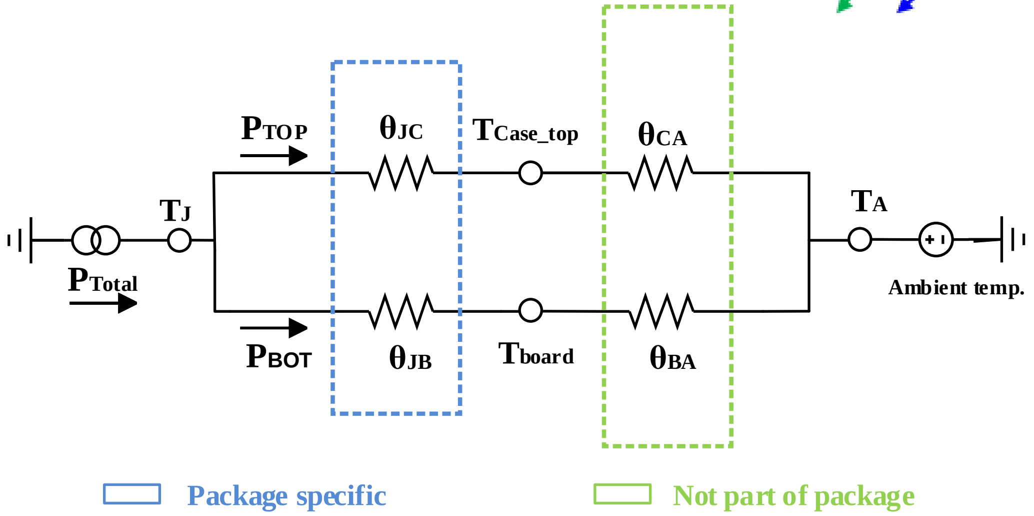




Steady State Thermal Modeling

Heat Transfer Paths





$$R_{Jx} \text{ or } \theta_{Jx} = \frac{T_J - T_x}{P_{Jx}}$$

$$\Psi_{Jx} = \frac{T_J - T_x}{P_{total}}$$

$$\theta_{JA} \quad \Psi_{JT} \quad \Psi_{JB}$$

θ_{jx}=junction-to-x thermal resistance

T_j=junction temperature

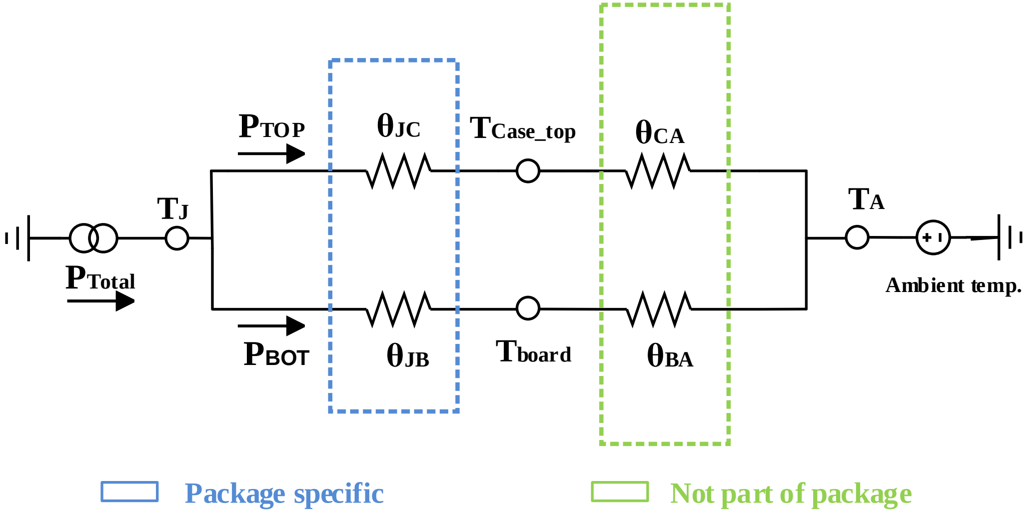
T_x=the specific point temperature

P_{jx}=the power loss of heat flow through x

P_{total}=the total power

For natural convection heat transfer,
>90% of the heat is dissipated by the board and not from the package surfaces

How To Use Thermal Resistance Parameters



Thermal Metrics (4)

θ_{JA} (junction-to-ambient)…………………44.3°C/W
θ_{JC_TOP} (junction-to-case top)…………..37.5°C/W
θ_{JC_BOTTOM} (junction-to-case bottom)…..2.6°C/W
θ_{JB} (junction-to-board)……………………5.3°C/W
Ψ_{JT} (junction-to-top)……………………...1.1°C/W
Ψ_{JB} (junction-to-board)…………………...5.1°C/W

Notes:

- Ψ_{JB}: Characteristic thermal resistance allowing system designers to calculate the device's junction temperature based on a board temperature measurement. The Ψ_{JB} metric should be close to θ_{JB}, as the PCB dissipates most of the heat of the device.

$$T_J = \boldsymbol{T_{PCB}} + (\Psi_{JB} \times P_D)$$

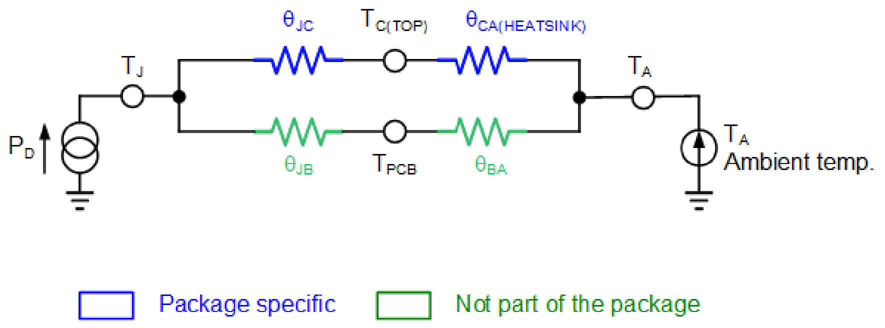
- Ψ_{JT}: Characteristic thermal resistance reflecting the temperature difference between the die (junction) and the top of the package. Ψ_{JT} is not a true thermal resistance, as the heat flowing from the die to the top of the package is unknown (but assumed to be the total power of the device). This assumption is clearly not valid, but when calculated this way, Ψ_{JT} becomes a very useful number as its characteristics are much like the application environment of the IC package.

$$\Psi_{JT} = \frac{T_J - T_C}{P_D}$$

$$T_J = \boldsymbol{T_{case}} + (\Psi_{JT} \times P_D)$$

Pulsed Operation

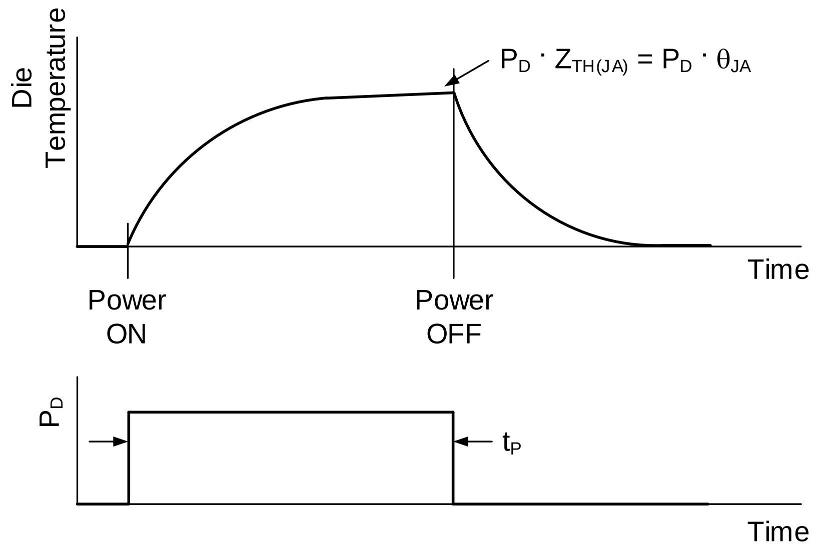
Under pulsed load operation, higher peak power dissipation can be tolerable. The critical junction temperature is not reached instantaneously, even when excessive power is being dissipated in the device.



θ_{JB}: Thermal impedance from the die to the board. θ_{JB} includes some of the board characteristics and their coupling with the package.

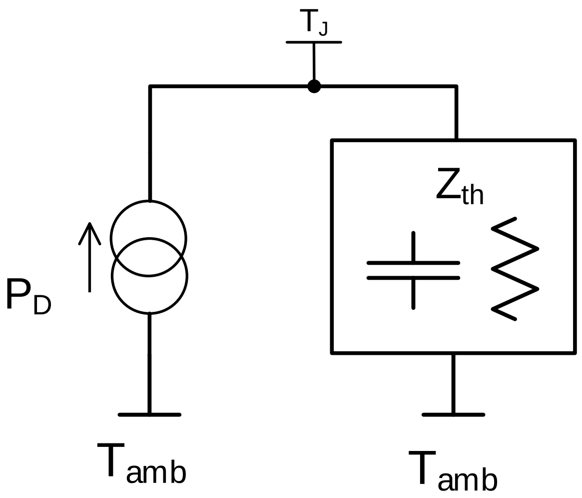
Thermal capacitance (C_{TH}) is a measure of the capability to accumulate heat and it depends on the specific heat capacity (c), volume (V), and density (ρ):

$$C_{TH} = c \cdot \rho \cdot V$$ expressed in J/K



Transient Thermal Modeling

Any $Z_{th}(s)$ impedance can be synthesized in a passive network using the Cauer or Foster algorithm. For thermal models, RC networks result quite handy and representative of the reality.



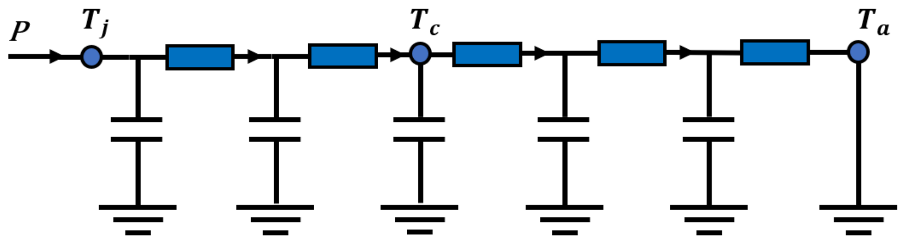
$$Z_{th}(s) = \frac{N_{th}(s)}{D_{th}(s)}$$

RC network extraction from $Z_{th}(s)$:
Cauer or Foster representation

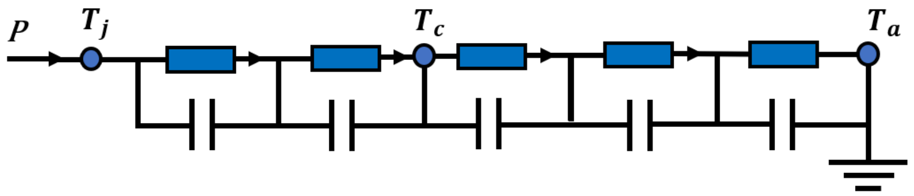
$$Z_{th}(t) = \sum_{i=1}^{n} r_i \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

$$\tau_i = r_i\, c_i$$

Cauer

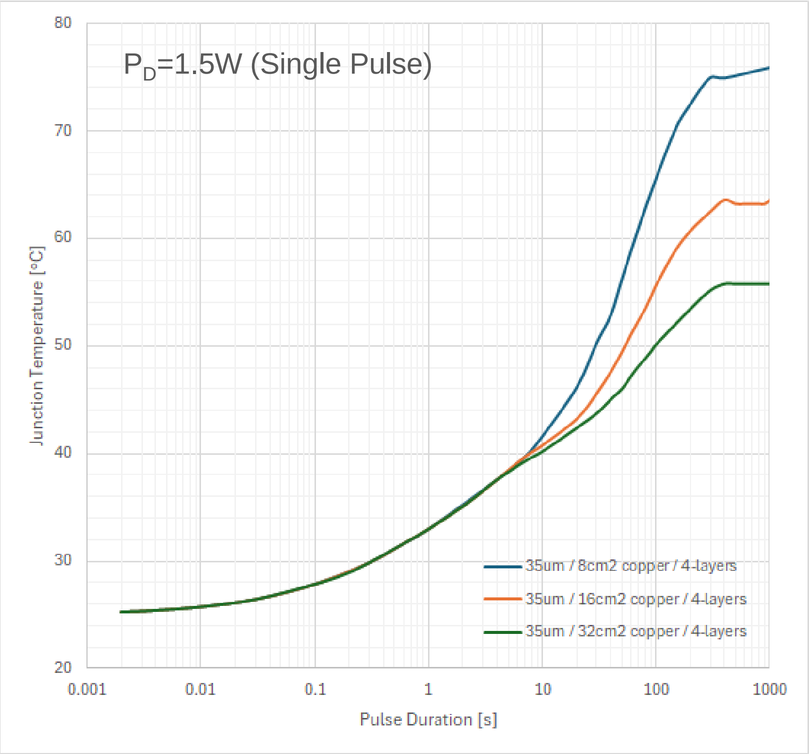


Foster



Transient Thermal Modeling(Cont'd)

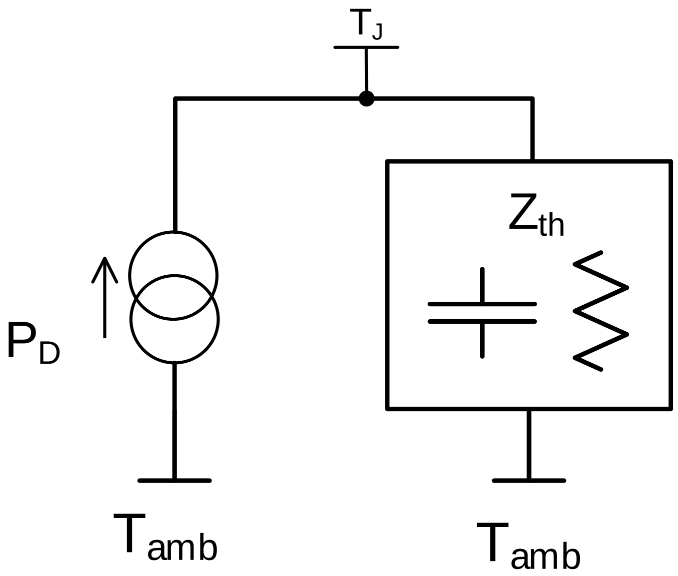
Transient Measurements



$$T_J(t) = TJ(0) + f(t)$$

$T_J(t)$ can be found using curve fitting techniques

Model



$$T_J(t) = \underbrace{Tamb}_{T(0)} + \underbrace{PD(t) * Zth(t)}_{f(t)}$$

$$\downarrow \mathcal{L}$$

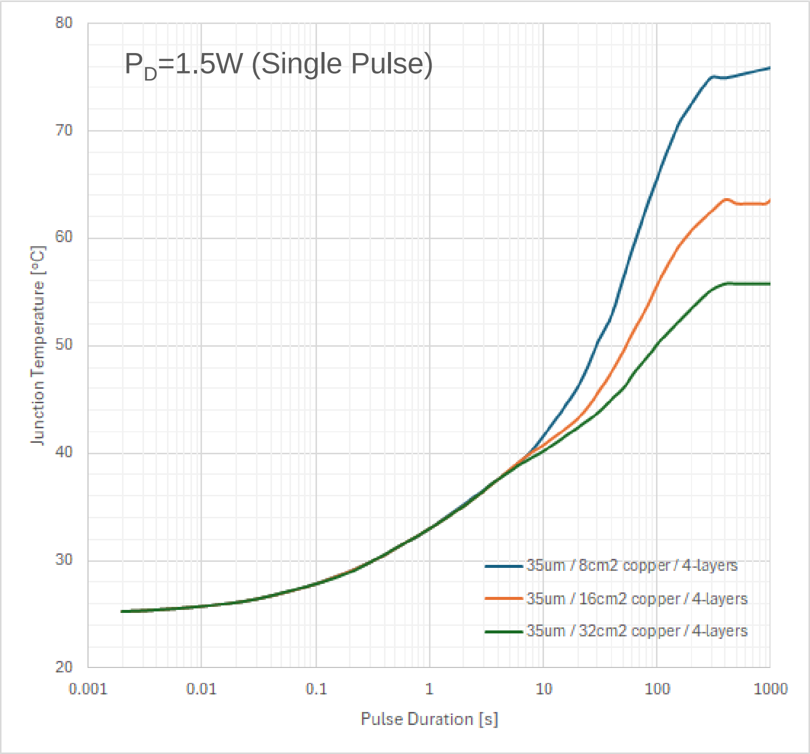
$$\mathcal{L}\{T_J(t) - TJ\ (0)\} = PD(s)\, Zth(s)$$

$$Z_{th}(s) = \frac{\mathcal{L}\{T_J(t) - TJ(0)\}}{P_D(s)}$$

To know Zth(s) one needs:
-T_J(t) time response (i.e. to step or impulse power dissipation stimuli)
-resting condition T_J(0) (temp. when no power dissipation is applied)
-stimuli function (i.e. step or impulse and its amplitude)

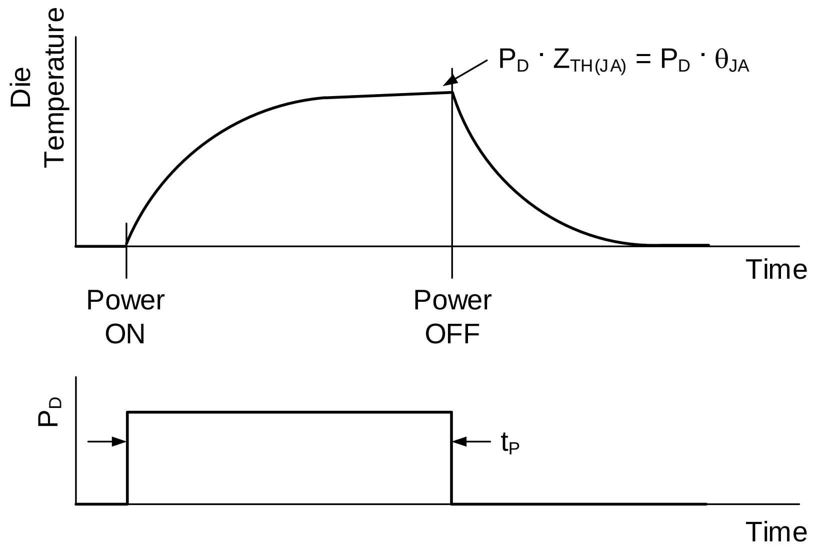
How to use Zth to calculate the Tj

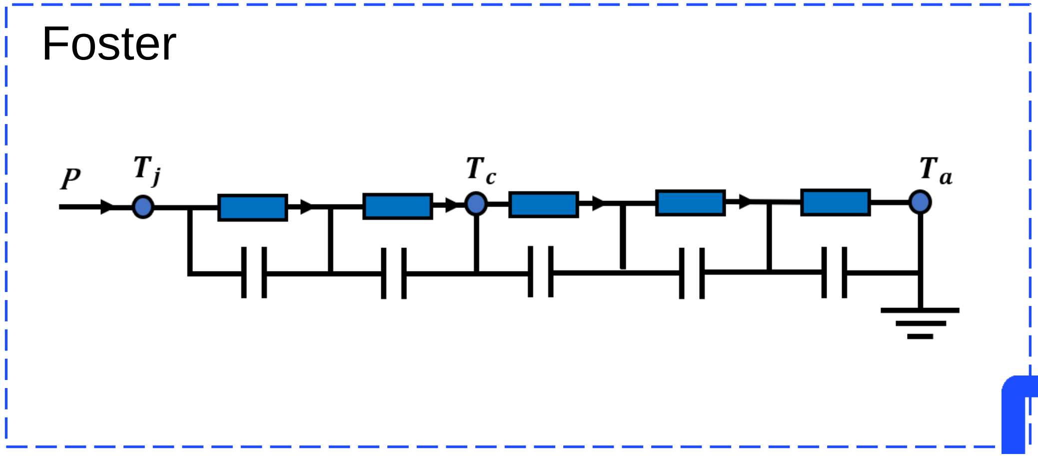
Zth Curve



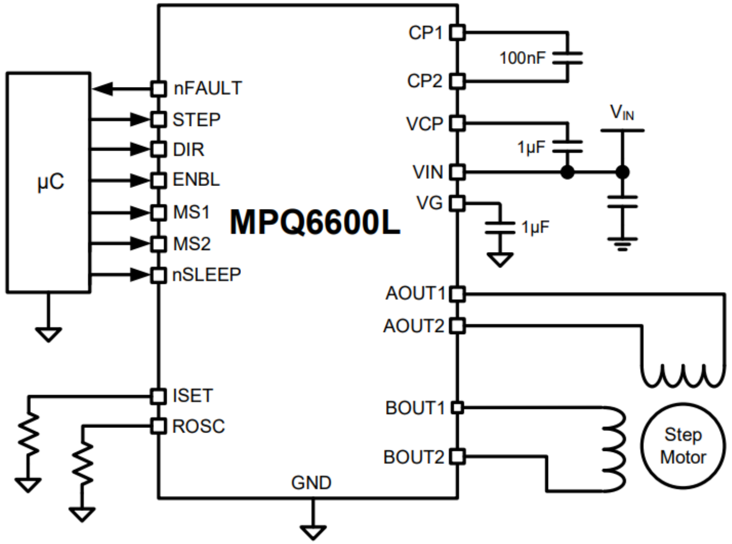
Transient calculation related

$$T_J = P_D \times Z_{th}$$





How to use Zth to calculate the Tj (Cont'd)



$$Z_{th}(t) = \sum_{i=1}^{n} r_i \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

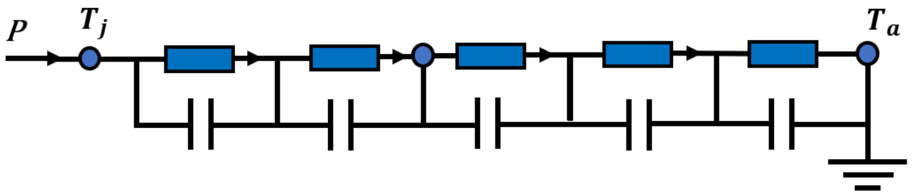
$$\tau_i = r_i \, c_i$$

Background

1. Based on EVQ6600L-R-00A

2. Assumed that even heat is spread on each FETs

Foster

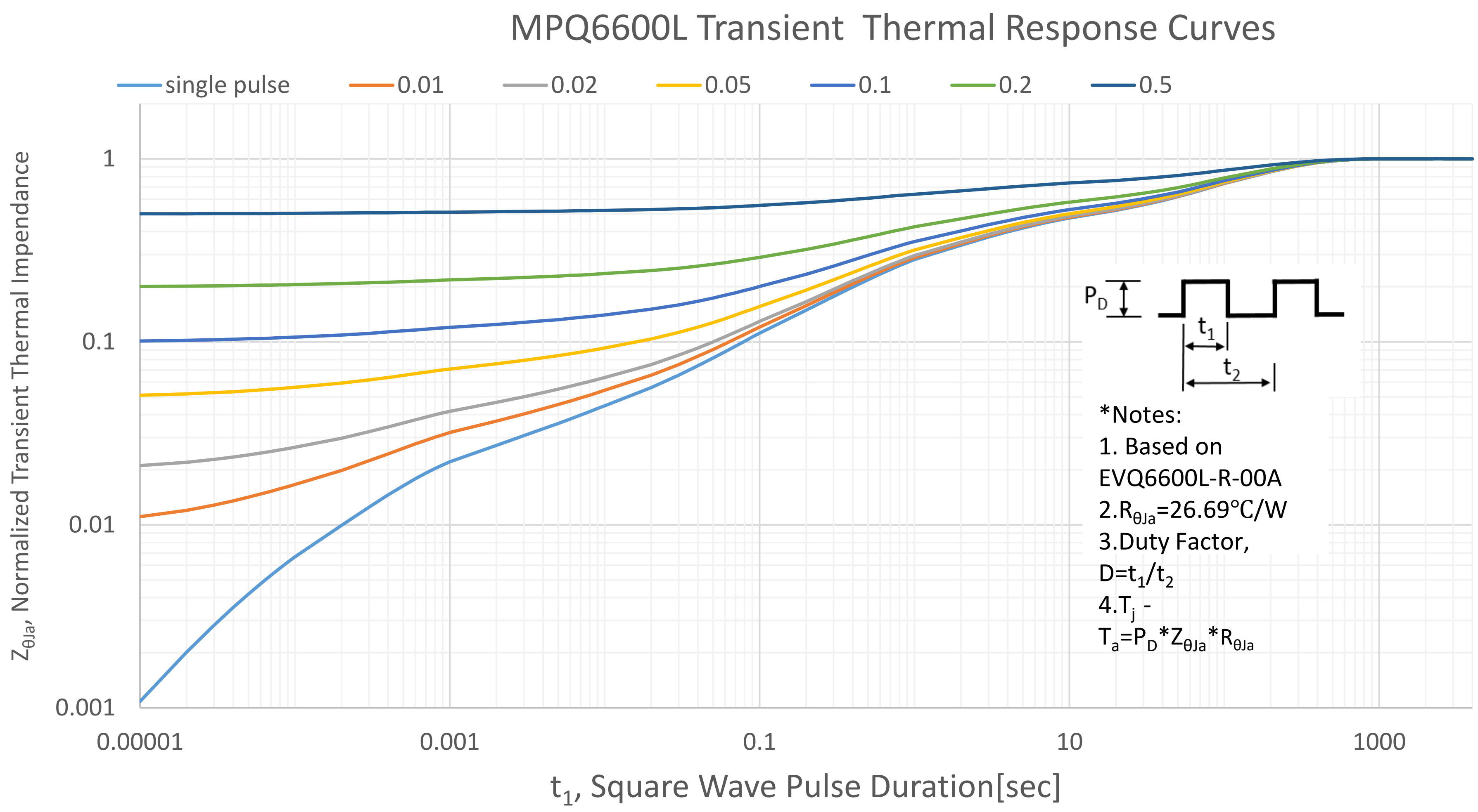


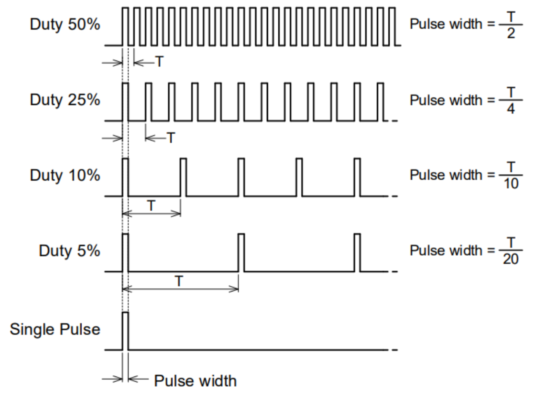
Cth1 /F	6.348760E-01	Rth1 /Ω	1.46521000E-03
Cth2 /F	6.158431E+00	Rth2 /Ω	1.27947204E-01
Cth3 /F	8.166576E+00	Rth3 /Ω	1.93982226E+01
Cth4 /F	1.740248E+00	Rth4 /Ω	3.27211250E-02
Cth5 /F	5.968462E+00	Rth5 /Ω	2.27979106E+01
Cth6 /F	3.840516E+00	Rth6 /Ω	1.78817714E+00
Cth7 /F	1.405920E-01	Rth7 /Ω	4.43541000E-04

How to use Zth to calculate the Tj (Cont'd)

```
import matplotlib.pyplot as plt
from math import e
import numpy as np


R_th = [6.34876e-1,6.158431e+0,8.166576e+0,1.740248e+0,5.968462e+0,3.840516e+0,1.40592e-1]
C_th = [1.46521e-3,1.27947204e-1,1.939822263e+1,3.2721125e-2,2.279791058e+1,1.788177141e+0,4.43541e-4]

assert len(R_th) == len(C_th)

th = len(R_th)
#x = np.arange(0,1,0.0001,dtype =  float)
x = np.logspace(-6, 0, num=7, base=10)  # 对数域
y= np.sum([R_th[i] * (1-e**(-1*x/(R_th[i]*C_th[i]))) for i in range(th)],axis=0)    # Foster模型的热阻抗曲线方程
plt.figure(figsize=(25,9))
plt.yscale("log")  # 对数坐标
plt.xscale("log")  # 对数坐标
plt.xlim(1E-6,1)
plt.ylim(1E-3,1)
# 开启刻度线网格
plt.grid(which='major',axis='both',linewidth=0.75,linestyle='-',color='orange')
plt.grid(which='minor',axis='both',linewidth=0.25,linestyle='-',color='orange')
plt.plot(x,y)
plt.show()
```

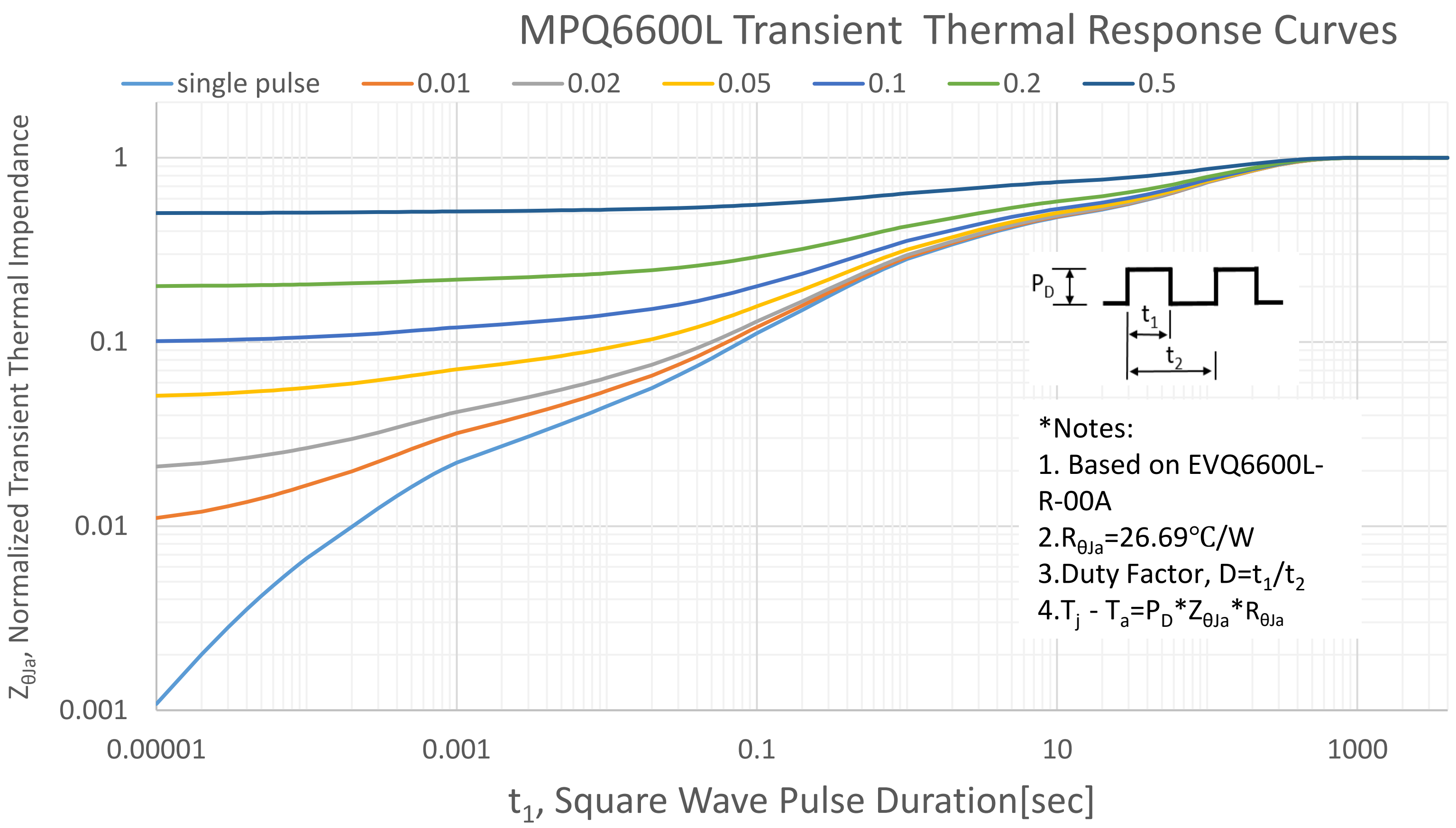
How to use Zth to calculate the Tj (Cont'd)





1. The X-axis is Pulse width, representing the time power is applied to the device.
2. The Y-axis is the value of the transient thermal resistance.
3. The Y curve set is transient thermal resistance data.
4. The differences among the curves in the curve cluster are due to the varying duty cycles of the applied pulse power. Figure 2 shows the waveforms of pulse width and duty cycle used during measurement.

How to use Zth to calculate the Tj (Cont'd)



How to use it?

Step 1. Observe the power pulse width and duty cycle applied to the power devices and record the values.

Step 2. Read the transient thermal resistance values from the chart.

Step 3. Calculate the power loss of IC

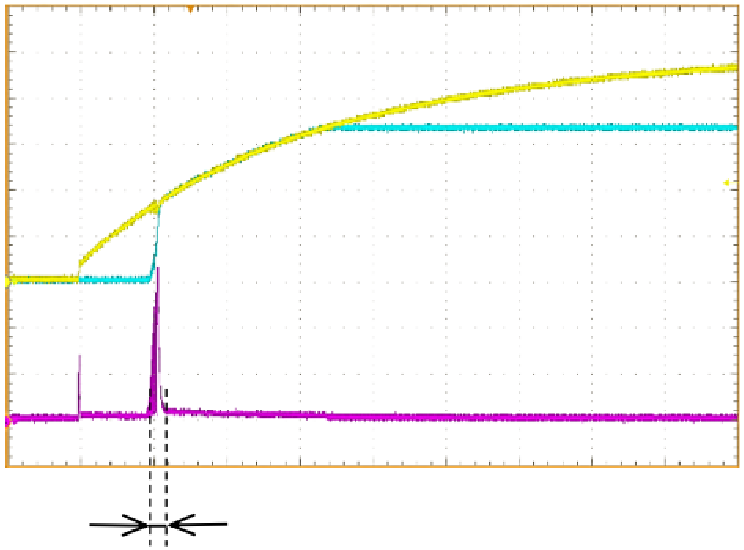
Step 4. Calculate the junction temperature by the formula.

$T_J = T_A + Z_{TH} \times P$ [°C]

Example one---Single Pulse

Background

During the circuit startup, phenomena such as surge currents may often occur, which happen only for a short time. Therefore, the [Single Pulse] curve is used to estimate the junction temperature.

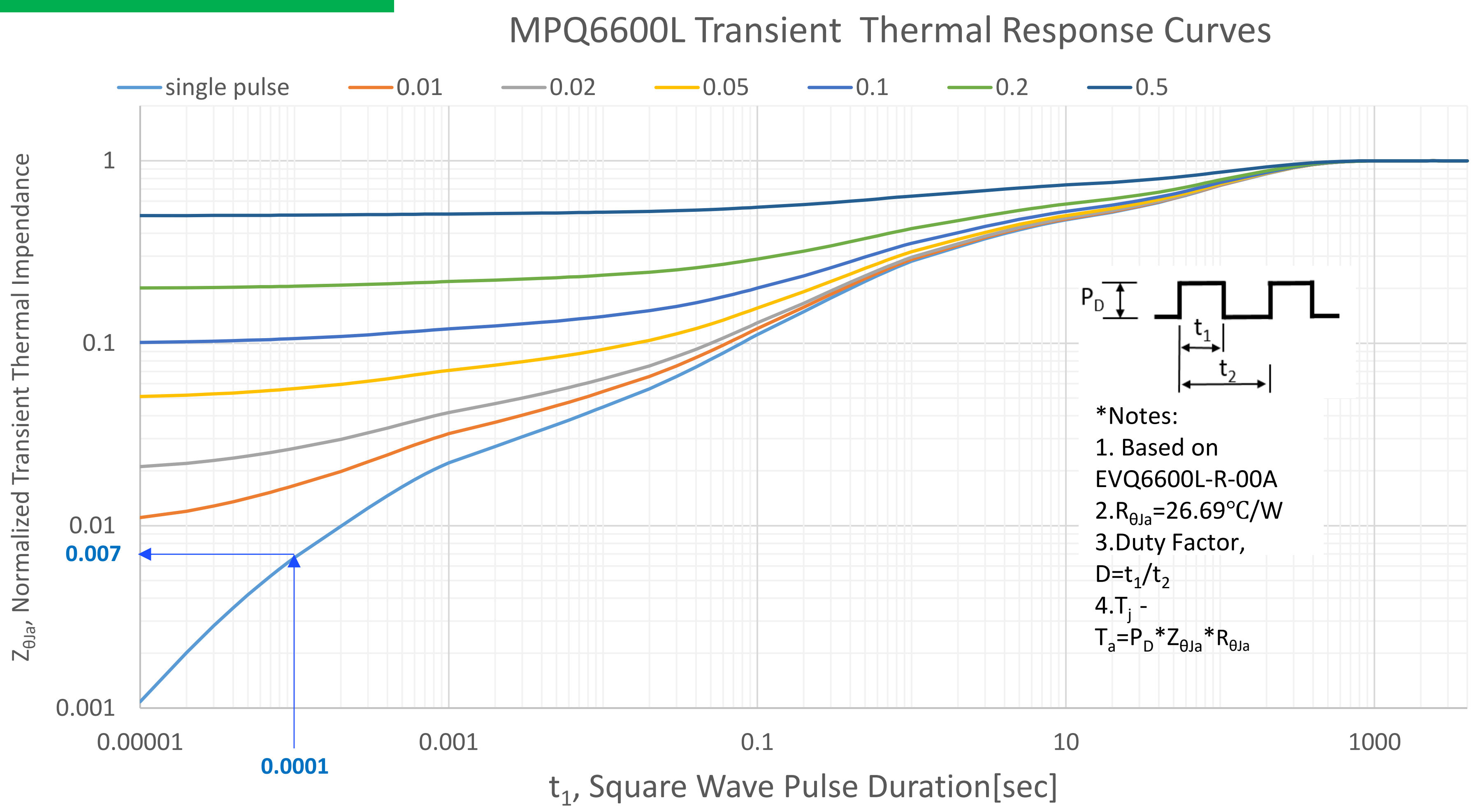


Setp1

Pulse width is measured about **0.1ms**.

Example one. (Cont'd)

Setp2: Find the Zth



Example one. (Cont'd)

Setp3: The calculation

Calculate the junction temperature by the formula.

$$T_J = T_A + Z_{TH} \times P \; [°C]$$

T_A: The ambient temperature → **60°C**

Z_{TH}: the transient resistance from junction to ambient → (0.07*26.69=**1.8683**) °C/W

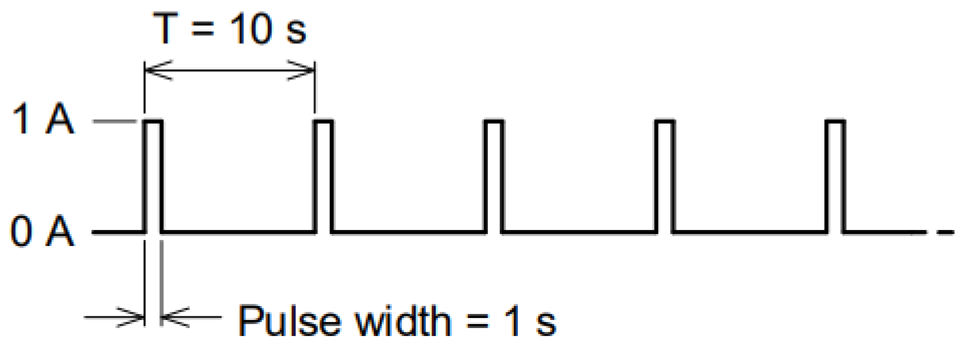
P: Power loss → **10W**

T_J = **60** + **1.8683** * **10=78.683** °

Example Two---Duty xx%

Background

During the circuit is working under on-off mode, use the Duty curve to do the calculation of junction temperature

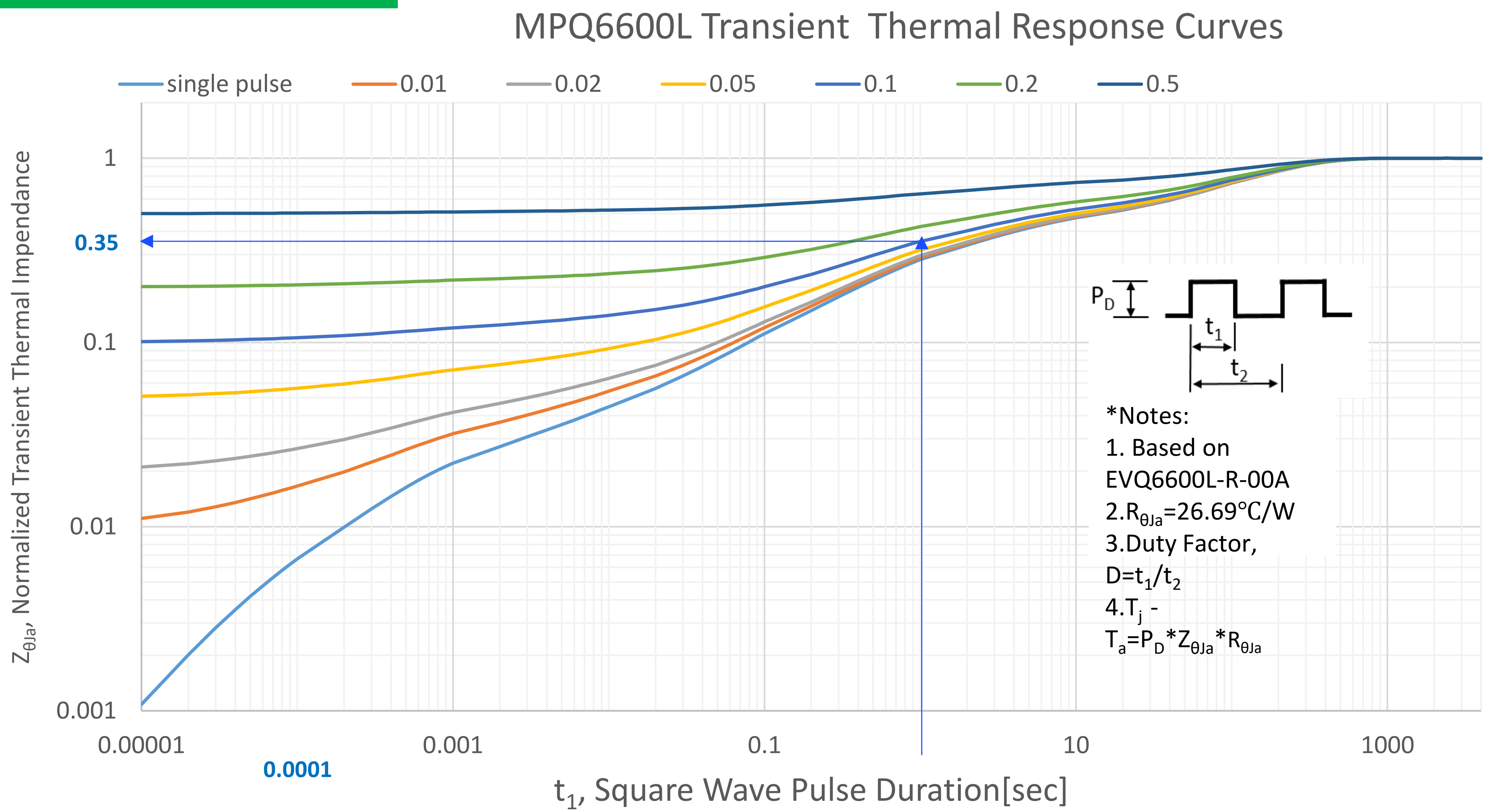


Setp1

Pulse width is measured about **1s, 10%Duty.**

Example two. (Cont'd)

Setp2: Find the Zth



Example two. (Cont'd)

Setp3: The calculation

Calculate the junction temperature by the formula.

$$T_J = T_A + Z_{TH} \times P\ [℃]$$

T_A: The ambient temperature → **50°C**

Z_{TH}: the transient resistance from junction to ambient → (0.35*26.69=**9.3415**) °/W

P: Power loss → **2W**

T_J = **50** + **9.3415** * **2=68.683** °

Conclusion

- Power loss calculation: Switching loss and Conduction loss
- Cgd, Cgs
- How to use thermal Resistance Parameters
- Pulsed operation, Cauer, Foster, Zth
- How to use Zth?

Thank you for watching