杭州云镓半导体科技有限公司

Hangzhou CloudSemi Technology Co., Ltd

GaN FET Loss Calculation in Boost Converter

GaN Device R&D Team

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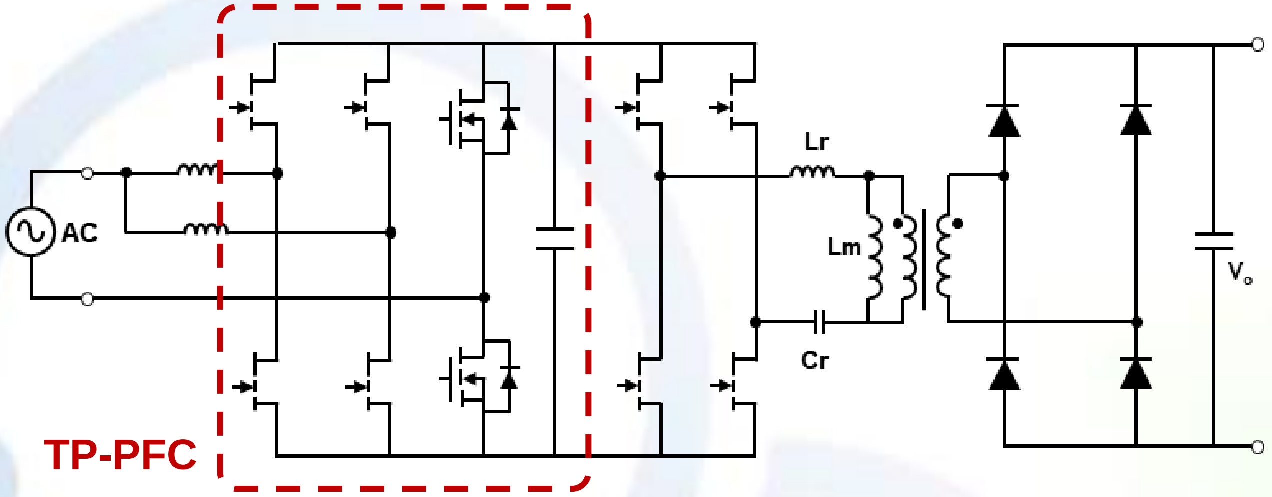
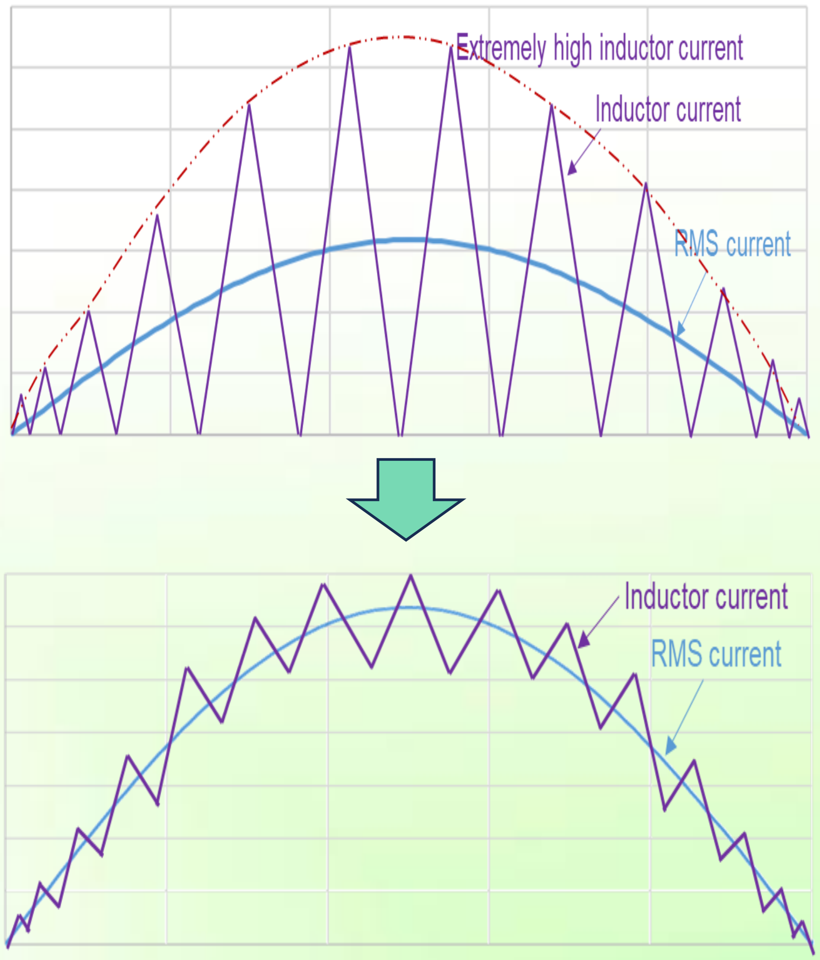
Powering the Dreams!

Zero Qrr enables GaN to work in CCM TP-PFC





Enhancement-mode GaN FET:

Low Qoss → Low Qoss loss

Low Qoss → High switching frequency

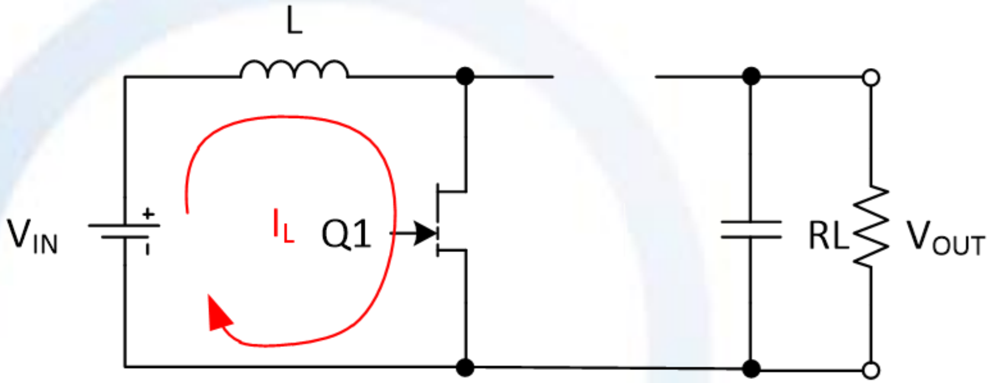
Zero Qrr → No Qrr loss → high efficiency

Zero Qrr enables GaN work in CCM mode, then help reduce system cost

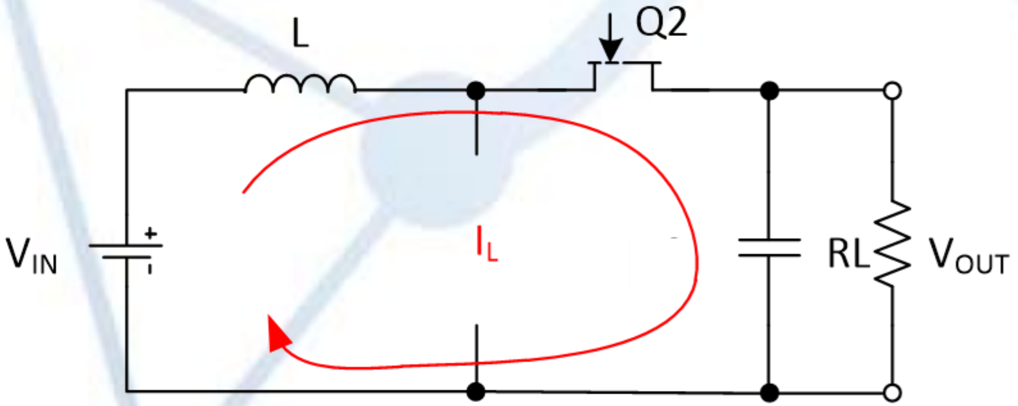
In this slide, GaN FET loss is analyzed using a synchronous boost converter (CCM mode)

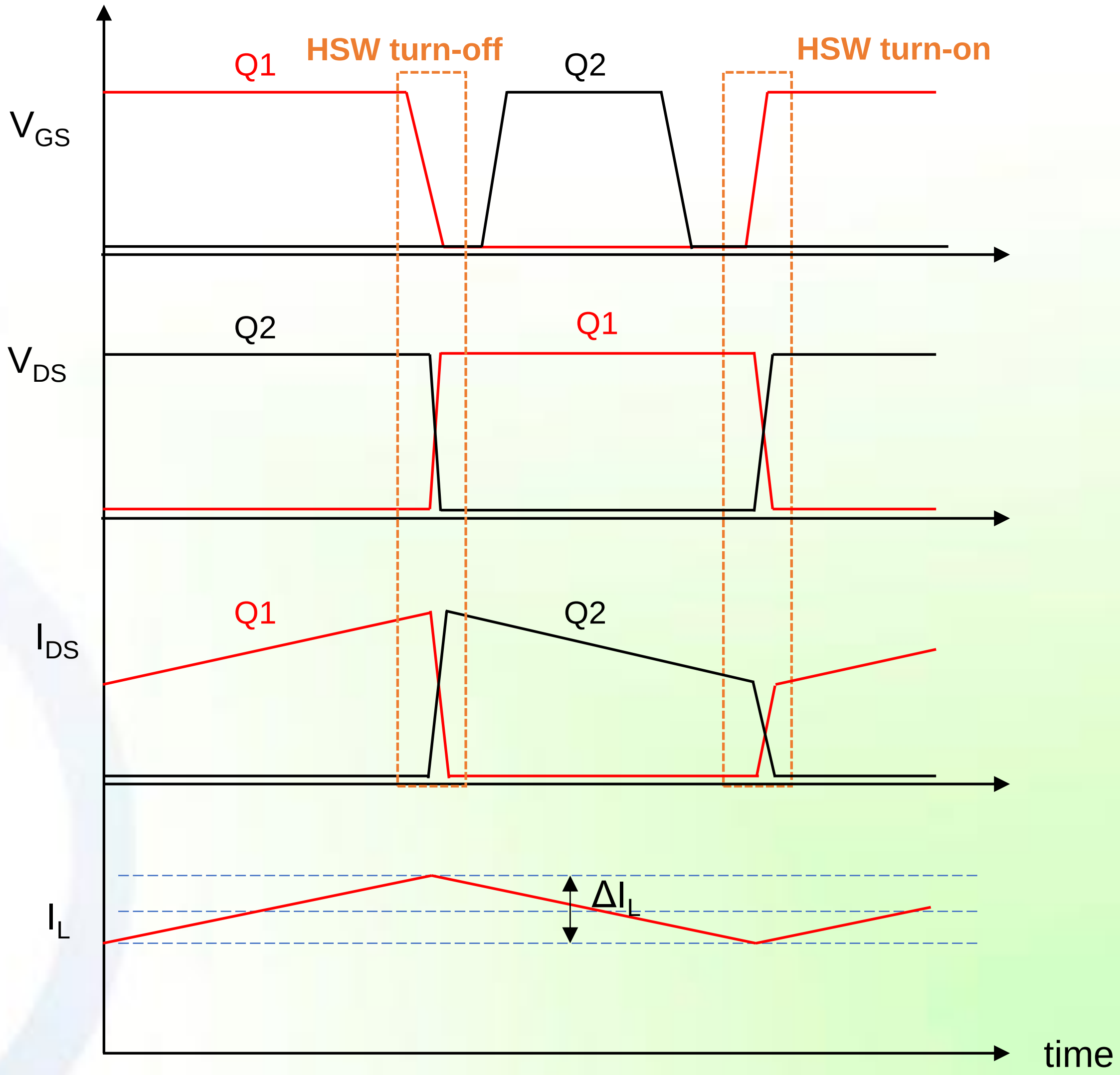
Synchronous CCM boost converter – waveforms

When Q1 turns on

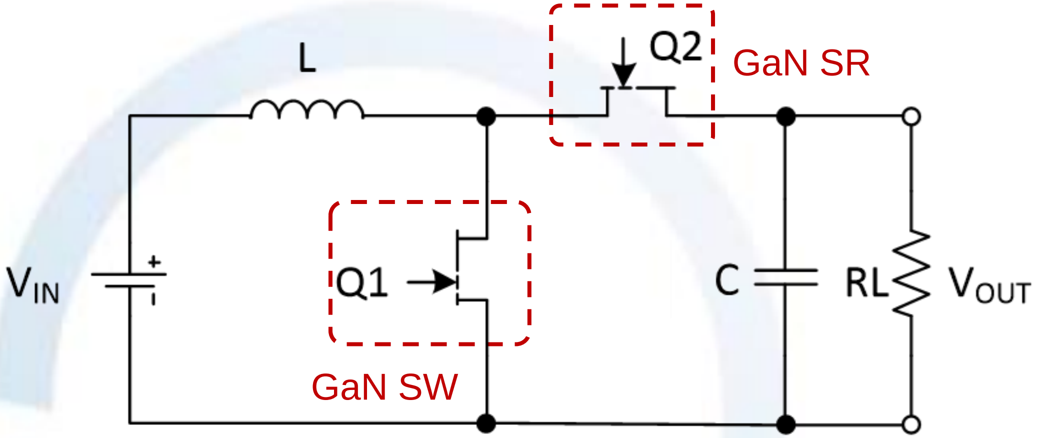


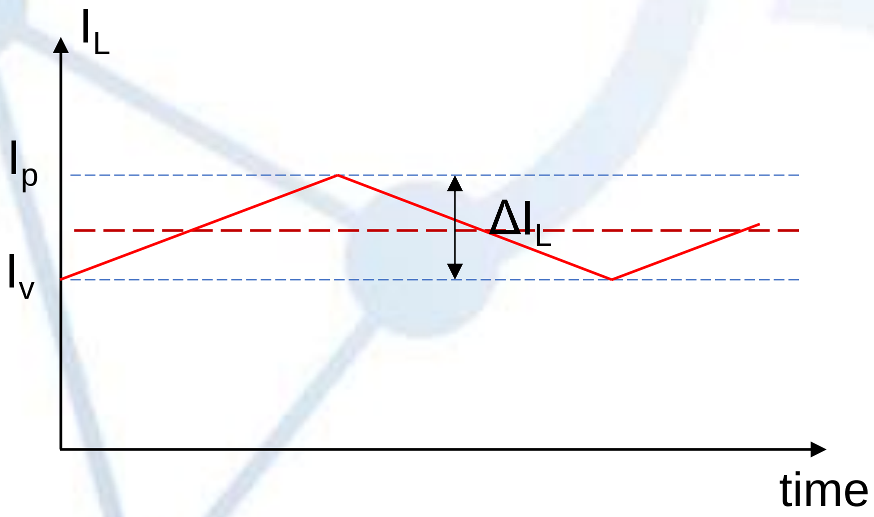
When Q1 turns off





Synchronous CCM boost converter – key equations





When Q1 turns on:

$$\frac{dI_{\mathrm{L}}}{dt} = \frac{V_{\mathrm{IN}}}{L}$$

When Q1 turns off:

$$\frac{dI_{\mathrm{L}}}{dt} = \frac{V_{\mathrm{OUT}} - V_{\mathrm{IN}}}{L}$$

According to *Volt-Second Balance*:

$$V_{\mathrm{OUT}} = V_{\mathrm{IN}} * \frac{1}{1 - D}$$

Output current vs inductor current

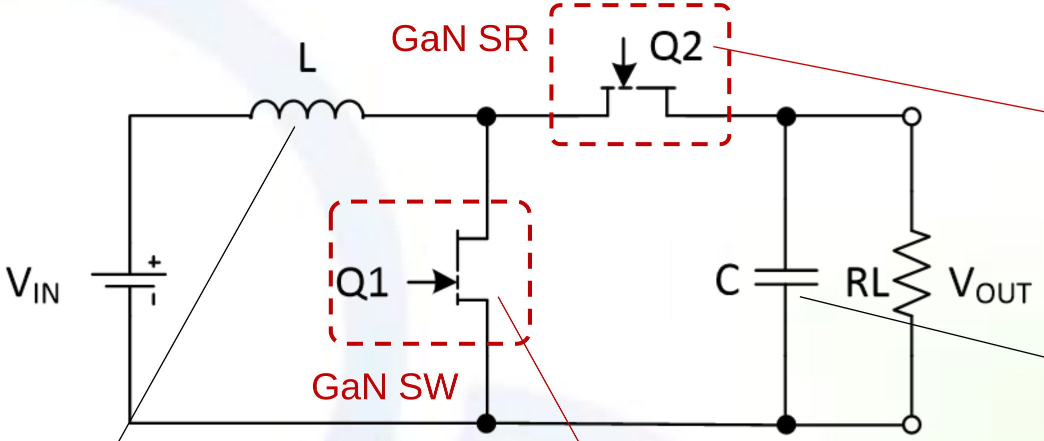
$$I_{\mathrm{O}} = I_{\mathrm{L}} * (1 - D)$$

Ripple current through inductor ΔI_{L}

$$\Delta I_{\mathrm{L}} = \frac{V_{\mathrm{IN}}}{L} * DT = I_{\mathrm{p}} - I_{\mathrm{v}}$$

$$I_L = \frac{1}{2} * (I_{\mathrm{p}} + I_{\mathrm{p}})$$

Loss breakdown of GaN FETs



Deadtime loss: P_{DT}

Conduction loss: P_{CON}

ESR loss

Core loss

DCR loss

ACR loss

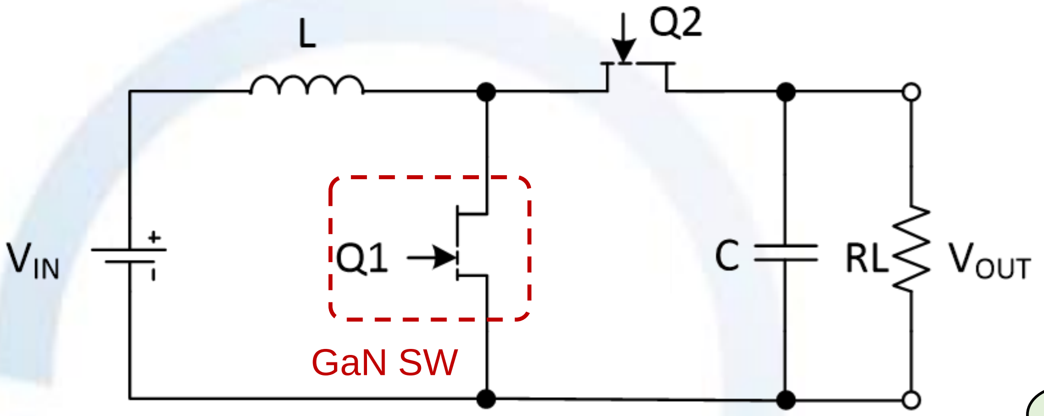
Conduction loss: P_{CON}

HSW I-V overlap loss: $P_{SW,ON} + P_{SW,OFF}$

C_{OSS} loss from SW & SR: P_{CAP}

No Qrr loss

Loss breakdown of GaN FETs: SW conduction loss

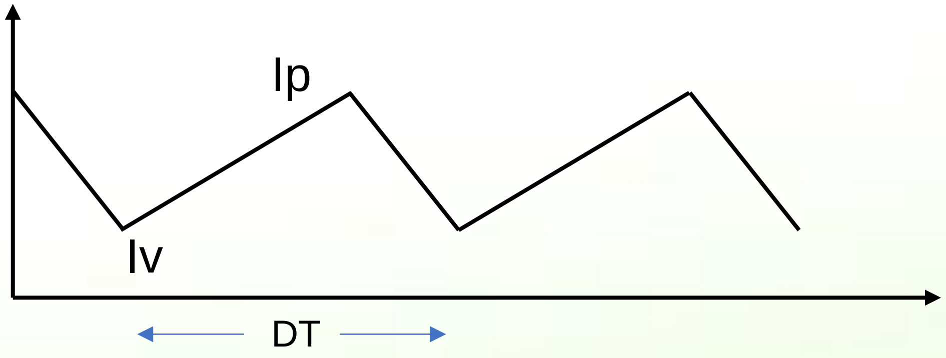


$$Ip = I_L + \frac{\Delta I_L}{2} \qquad Iv = I_L - \frac{\Delta I_L}{2}$$

$$Irms,sw = \sqrt{\frac{Ip^2 + Iv^2 + IpIv}{3} * D}$$

$$\boldsymbol{Pcond,sw = Irms,sw^2 * Rdson = \frac{Ip^2 + Iv^2 + Ip * Iv}{3} * D * Rdson}$$

RMS current derivation



$$\int_0^{DT} i(t)^2\,dt = \int_0^{DT} \left(Iv + \frac{Ip - Iv}{DT}t\right)^2 dt$$

$$= \int_0^{DT} \left(Iv^2 + \frac{(Ip - Iv)^2}{(DT)^2}t^2 + 2\frac{IvIp - Iv^2}{DT}t\right) dt$$

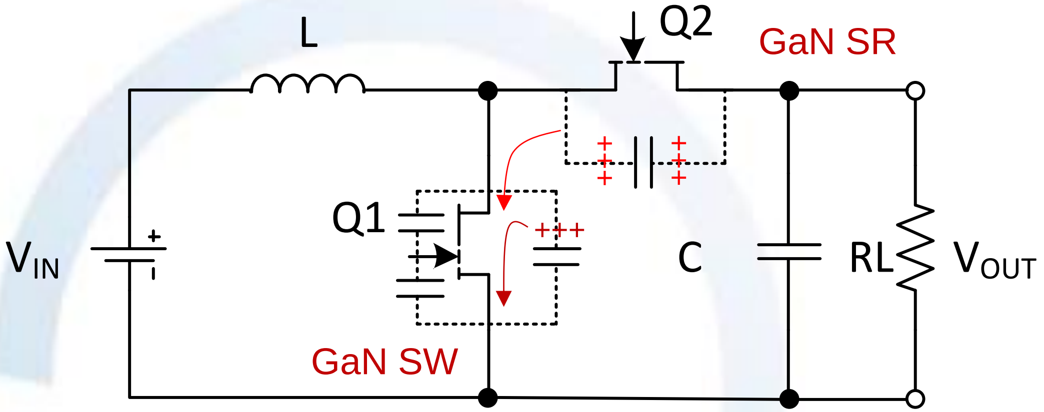
$$= \left(Iv^2 t + \frac{(Ip - Iv)^2}{3(DT)^2}t^3 + \frac{IvIp - Iv^2}{DT}t^2\right)\Big|\frac{DT}{0}$$

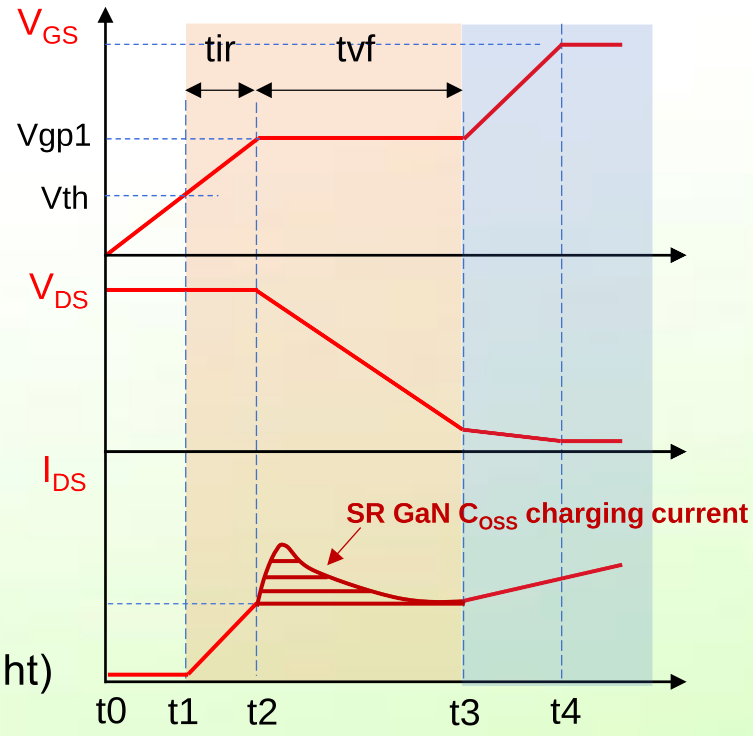
$$= Iv^2 DT + \frac{Ip^2 + Iv^2 - 2IpIv}{3}DT + \left(IvIp - Iv^2\right)DT$$

$$= \frac{Ip^2 + Iv^2 + IpIv}{3}DT$$

$$Irms = \sqrt{\frac{Ip^2 + Iv^2 + IpIv}{3}D}$$

Loss breakdown of GaN FETs: SW+SR C_{OSS} loss





During SW turn-on transient,

C_{OSS} of SW-Q1 is discharged through SW-Q1's channel (Current CANNOT be captured)

C_{OSS} of SR-Q2 is charged through SW-Q1's channel (Current CAN be captured, as in right)

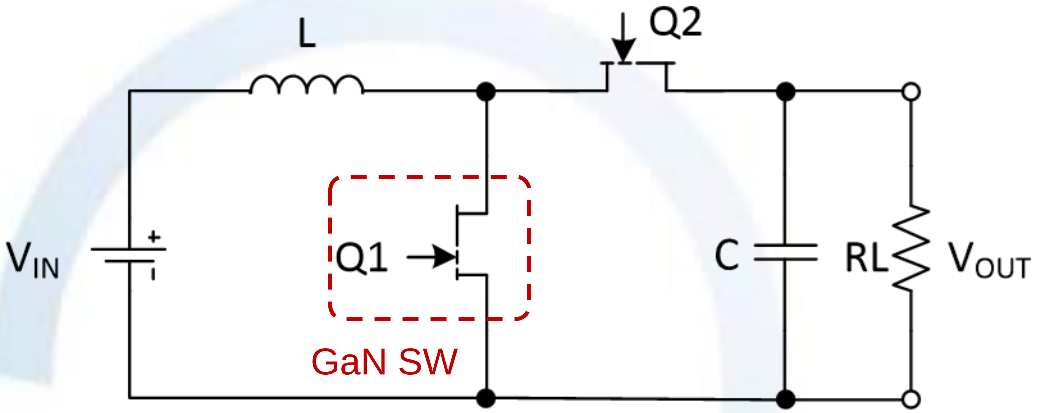
Both two capacitors charge behavior **generates heat on SW-Q1**.

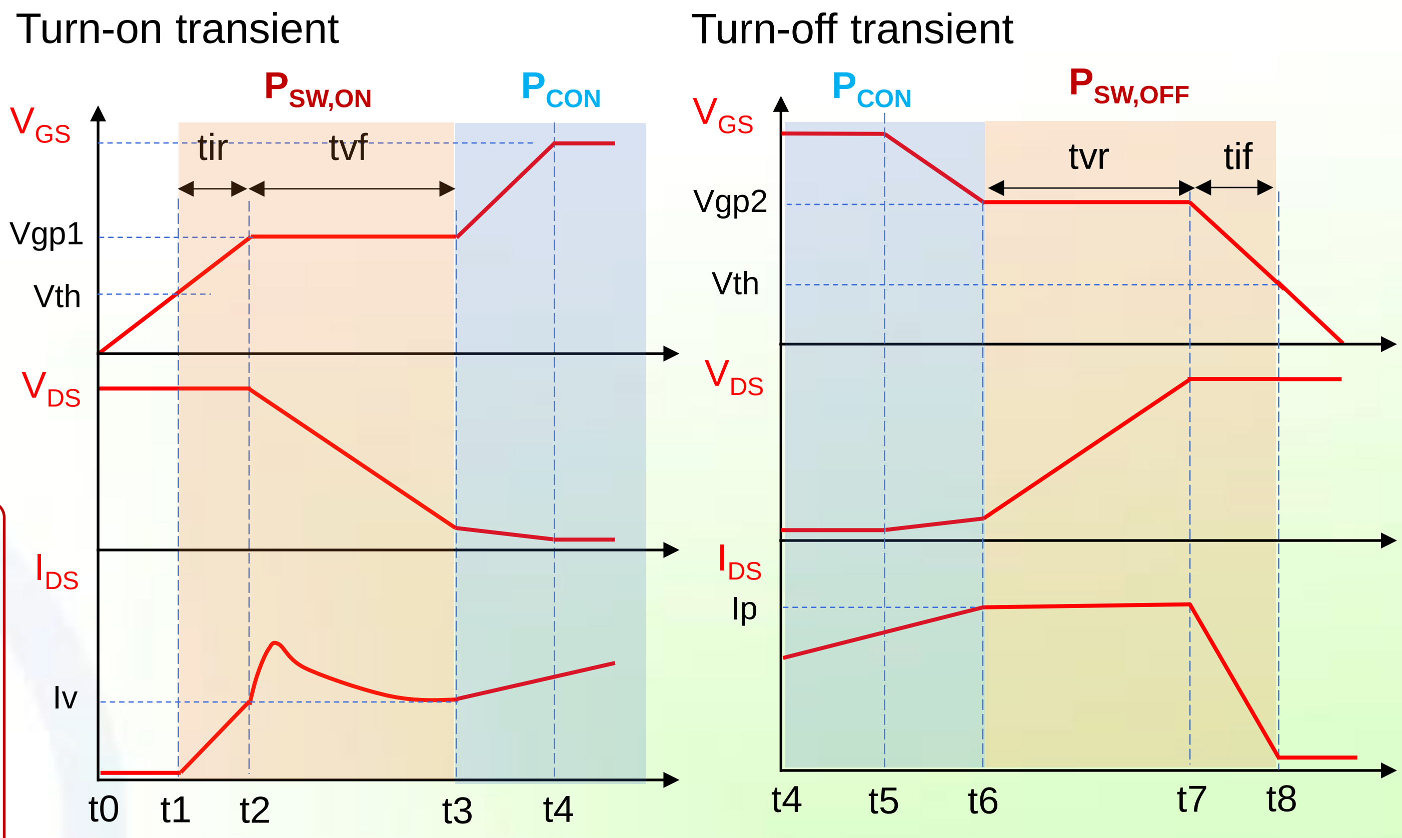
$$Cap\ loss(SW) = \int_0^{V_{bus}} C_{OSS} * Vds\, dV \qquad Cap\ loss(SR) = \int_0^{V_{bus}} C_{OSS} * (V_{bus} - Vds) dV = Vbus * Qoss - \int_0^{V_{bus}} C_{OSS} * Vds\, dV$$

If Q1 and Q2 features the same part, then the C_{OSS} loss on SW-Q1 will be:

Pcap = (Cap_loss_SW + Cap_loss_SR) * fs = V_{bus} * Q_{OSS} * fs

Loss breakdown of GaN FETs: SW I-V overlap loss





Roughly based on right schematic waveforms:

$$P_{SW,ON} \approx \frac{1}{2} * V_{IN} * I_v * t_{on} * f_s$$

$$P_{SW,OFF} \approx \frac{1}{2} * V_{IN} * I_p * t_{off} * f_s$$

$$P_{SW} \approx \frac{1}{2} * V_{IN} * I_v * t_{on} * f_s + \frac{1}{2} * V_{IN} * I_p * t_{off} * f_s$$

$t_{on} \approx t_{ir} + t_{vf}$ $\quad t_{off} \approx t_{vr} + t_{if}$

Turn-on and turn-off time (ton, toff) also can be calculated from capacitance charging & discharging analysis.

Switching time calculation - tir

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During t0~t2

According to equivalent circuit

$$I_g = I_{gs} + I_{gd} = \frac{V_{GS} - V_{gs}}{R_g}$$

$$I_{gs} = C_{gs}\frac{dV_{gs}}{dt}$$

$$I_{gd} = C_{gd}\frac{d(V_{gs} - V_{DS})}{dt} = C_{gd}\frac{d(V_{gs})}{dt}$$

Then

$$I_g = C_{gs}\frac{dV_{gs}}{dt} + C_{gd}\frac{d(V_{gs})}{dt} = (C_{gs} + C_{gd})\frac{d(V_{gs})}{dt}$$

$$\frac{d(V_{gs})}{V_{GS} - V_{gs}} = \frac{dt}{R_g(C_{gs} + C_{gd})}$$

$$-\ln(V_{GS} - V_{gs}) = \frac{t}{R_g(C_{gs} + C_{gd})} + k$$

$$V_{gs} = V_{GS} - ke^{\frac{-t}{R_g(C_{gs}+C_{gd})}}$$

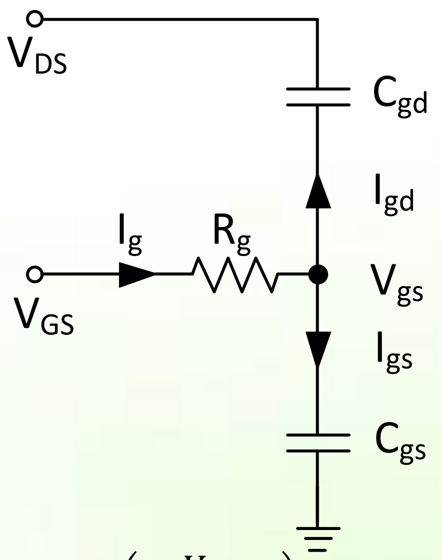
So

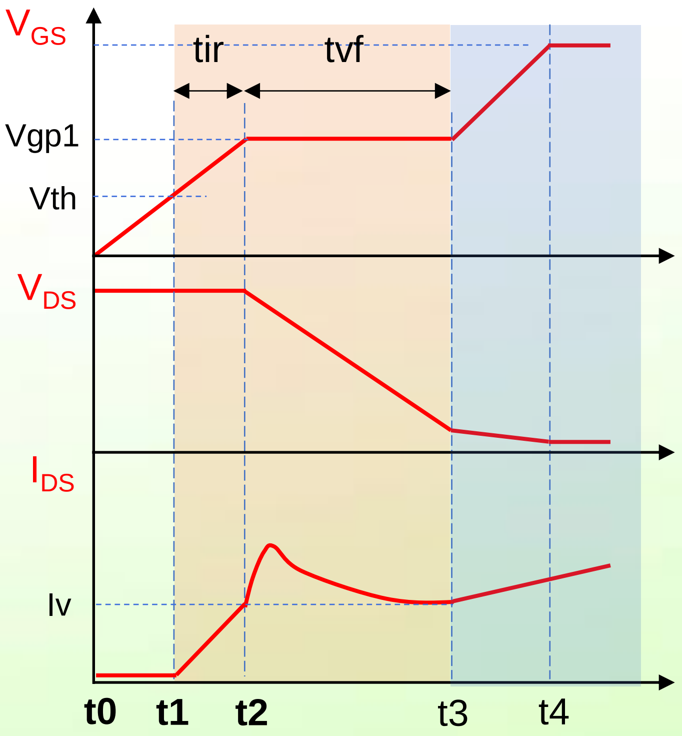
$$V_{gs} = V_{GS} * \left(1 - e^{\frac{-t}{R_g(C_{gs}+C_{gd})}}\right)$$

$$e^{\frac{-t}{R_g C_{iss}}} = 1 - \frac{V_{gs}}{V_{GS}}$$

$$t = R_g C_{iss} * \ln\left(\frac{1}{1 - \frac{V_{gs}}{V_{GS}}}\right) = R_g C_{iss} * \ln\left(\frac{V_{GS}}{V_{GS} - V_{gs}}\right)$$

equivalent circuit





Finally (R_G includes R_g and external resistance R_{gon})

$$t_1 - t_0 = R_G C_{iss} * \ln\left(\frac{V_{GS}}{V_{GS} - V_{TH}}\right)$$

$$t_2 - t_0 = R_G C_{iss} * \ln\left(\frac{V_{GS}}{V_{GS} - V_{gp}}\right)$$

$$t_{ir} = t_2 - t_1 = R_G C_{iss} * \ln\left(\frac{V_{GS} - VTH}{V_{GS} - V_{gp1}}\right)$$

$$V_{gp1} = V_{TH} + \frac{I_v}{g_m}$$

Switching time calculation - tvf

During t2~t3

According to equivalent circuit

$$I_g = I_{gd}$$

$$I_{gd} = C_{gd}\frac{d(V_{ds})}{dt}$$

Then

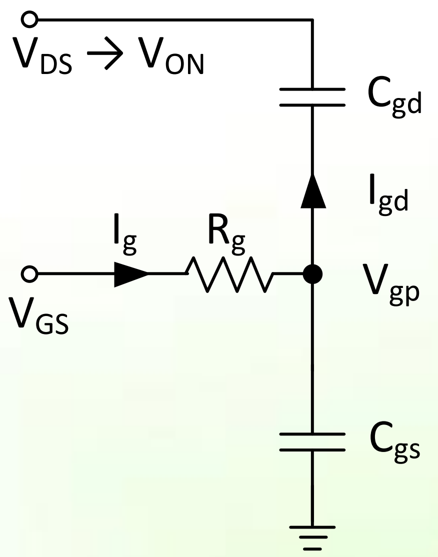
$$\frac{V_{GS} - V_{gs}}{R_g} = C_{gd}\frac{d(V_{ds})}{dt}$$

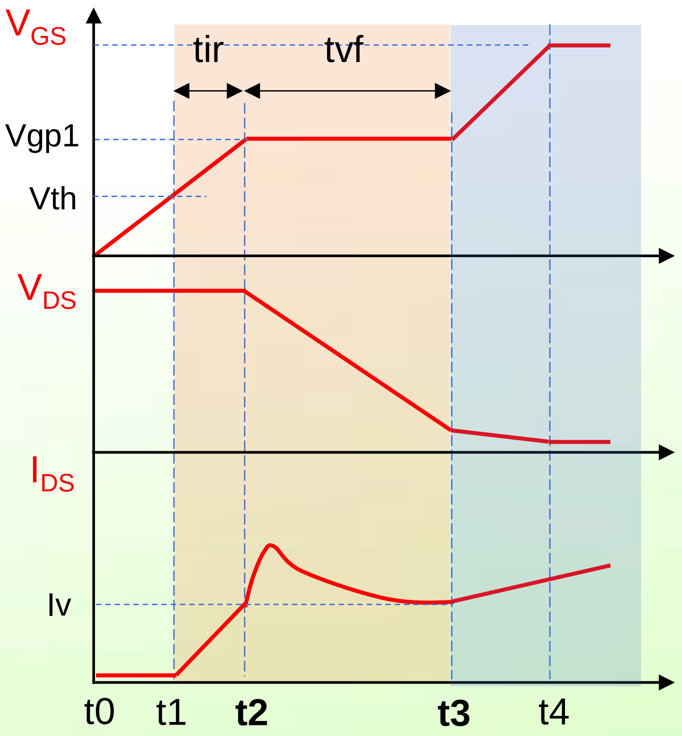
$$dt = R_g C_{gd} * \frac{d(V_{ds})}{(V_{GS} - V_{gs})}$$

Finally (R_G includes R_g and external resistance R_{gon})

$$t_3 - t_2 = R_G C_{gd} * \frac{V_{DS}}{V_{GS} - V_{gp}}$$

equivalent circuit





$$t_{vf} = t_3 - t_2 = R_G C_{gd} * \frac{V_{DS}}{V_{GS} - V_{gp1}}$$

$$t_{vf} = R_G * \frac{Q_{GD}}{V_{DS}} * \frac{V_{DS}}{(V_{GS} - V_{gp1})}$$

$$V_{gp1} = V_{TH} + \frac{I_v}{g_m}$$

Switching time calculation – tvr & tif

Similar to the analysis of turn-on transient

(R_G includes R_g and external resistance R_{goff})

$$t_6 - t_5 = R_G C_{iss} * \ln\left(\frac{V_{GS}}{V_{gp}}\right)$$

$$t_7 - t_6 = R_G C_{gd} \frac{V_{DS}}{V_{gp}}$$

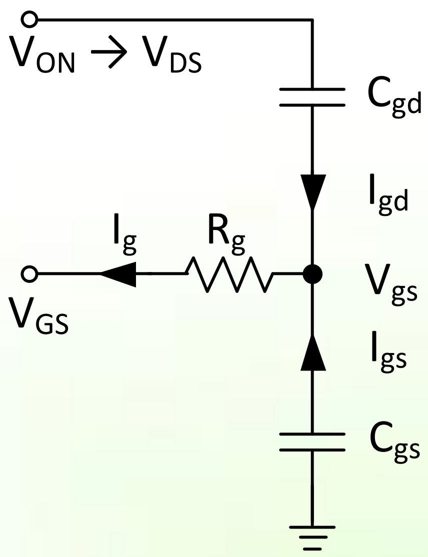
$$t_8 - t_7 = R_G C_{iss} \ln\left(\frac{V_{gp}}{V_{TH}}\right)$$

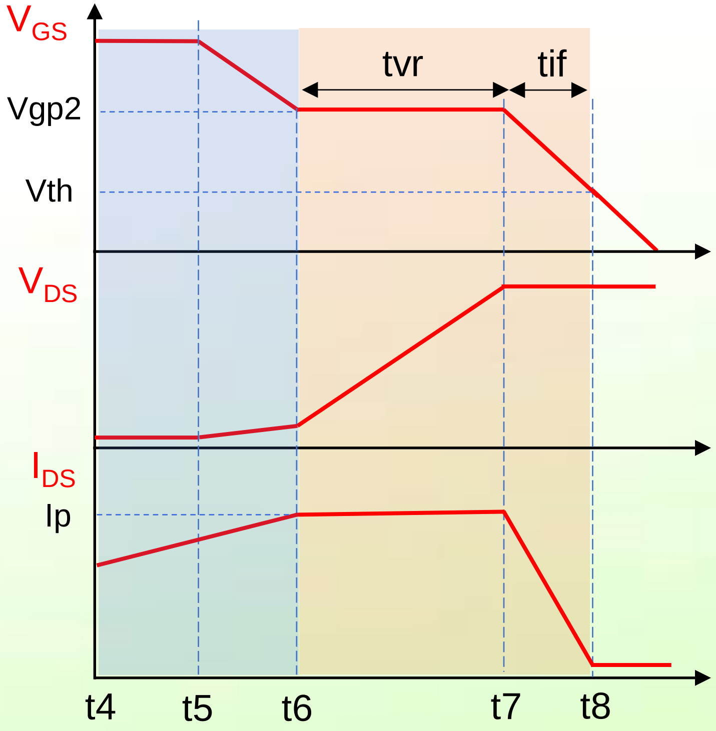
$$t_{vr} = t_7 - t_6 = R_G * \frac{Q_{GD}}{V_{DS}} * \frac{V_{DS}}{V_{gp2}}$$

$$t_{if} = t_8 - t_7 = R_G * C_{iss} * \ln\left(\frac{V_{gp2}}{V_{TH}}\right)$$

$$V_{gp2} = V_{TH} + \frac{I_p}{g_m}$$

equivalent circuit





** Miller plateau V_{gp2} during turn-off transient is not the same as turn-on because of the different switching current.*

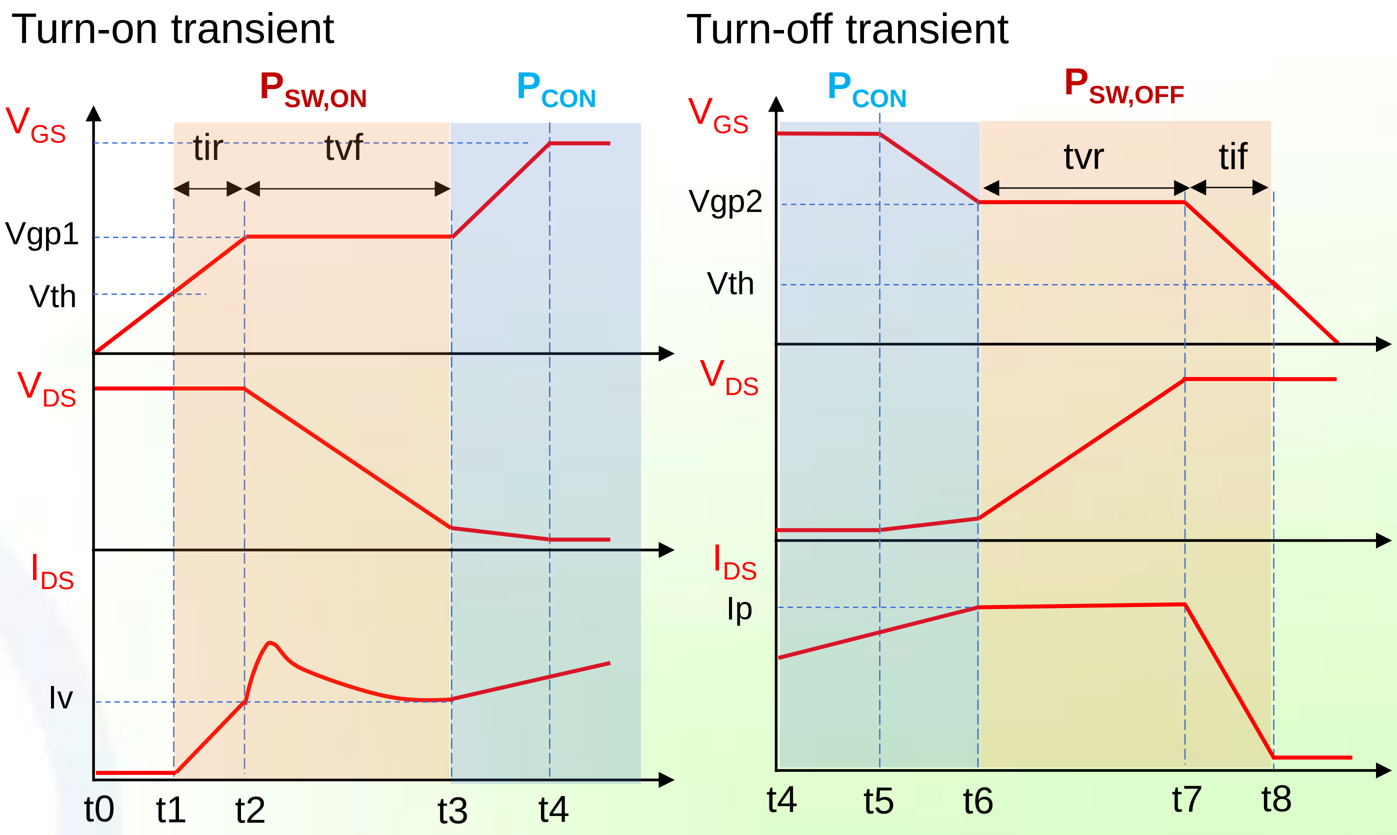
Switching time summary

$$t_{ir} = R_G C_{iss,} * \ln\left(\frac{V_{GS} - V_{TH}}{V_{GS} - V_{gp1}}\right)$$

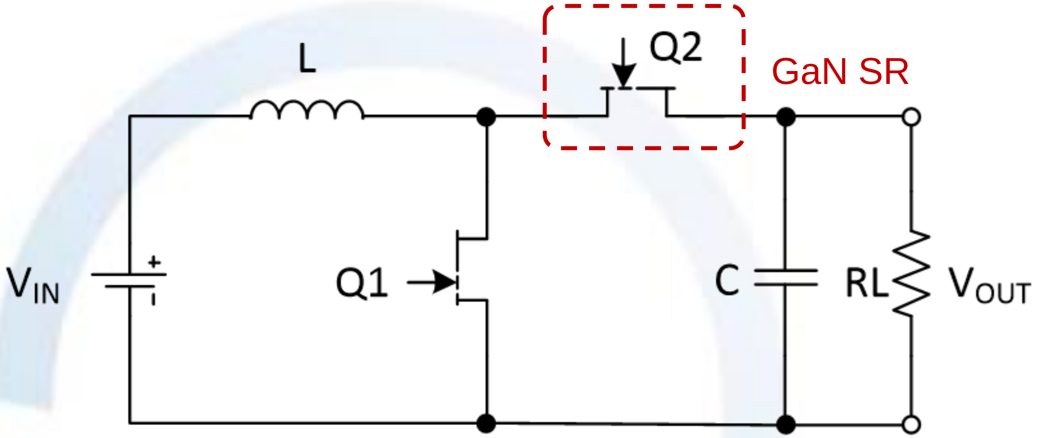
$$t_{vf} = R_G \frac{Q_{GD}}{V_{DS}} * \frac{V_{DS}}{(V_{GS} - V_{gp1})}$$

$$t_{vr} = R_G \frac{Q_{GD}}{V_{DS}} * \frac{V_{DS}}{V_{gp2}}$$

$$t_{if} = R_G C_{iss} * \ln\left(\frac{V_{gp2}}{V_{TH}}\right)$$



Loss breakdown of GaN FETs: SR conduction loss

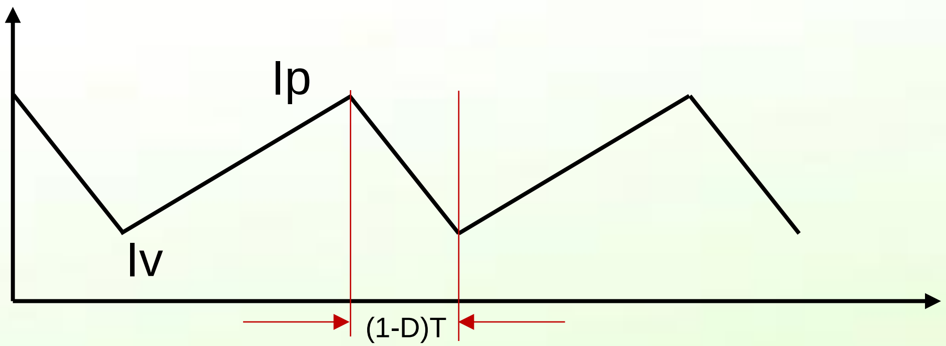


$$Ip = I_L + \frac{\Delta I_L}{2} \qquad Iv = I_L - \frac{\Delta I_L}{2}$$

$$Irms, sr = \sqrt{\frac{Ip^2 + Iv^2 + IpIv}{3} * (1 - D)}$$

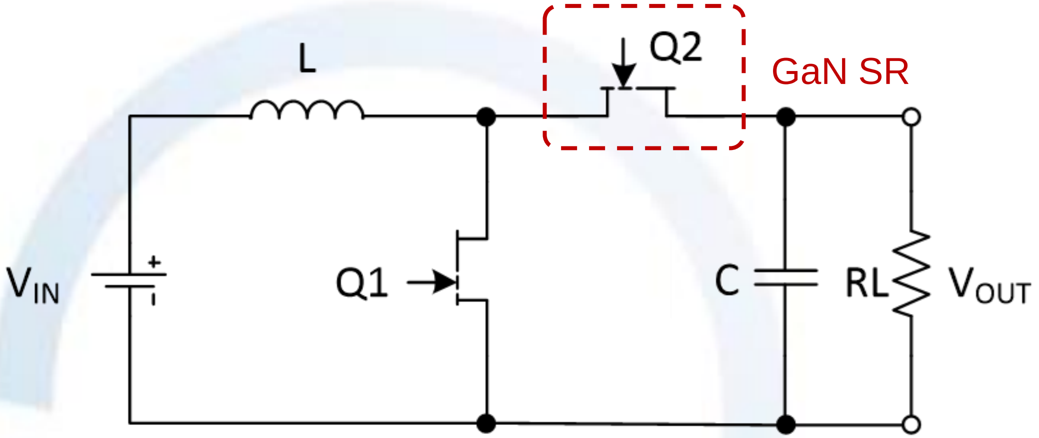
$$\boldsymbol{Pcond, sr = Irms, sr^2 * Rdson = \frac{Ip^2 + Iv^2 + Ip * Iv}{3} * (1 - D) * Rdson}$$

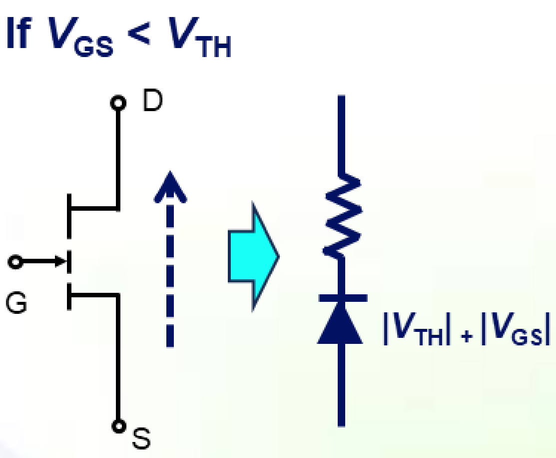
Similar to RMS current derivation of SW

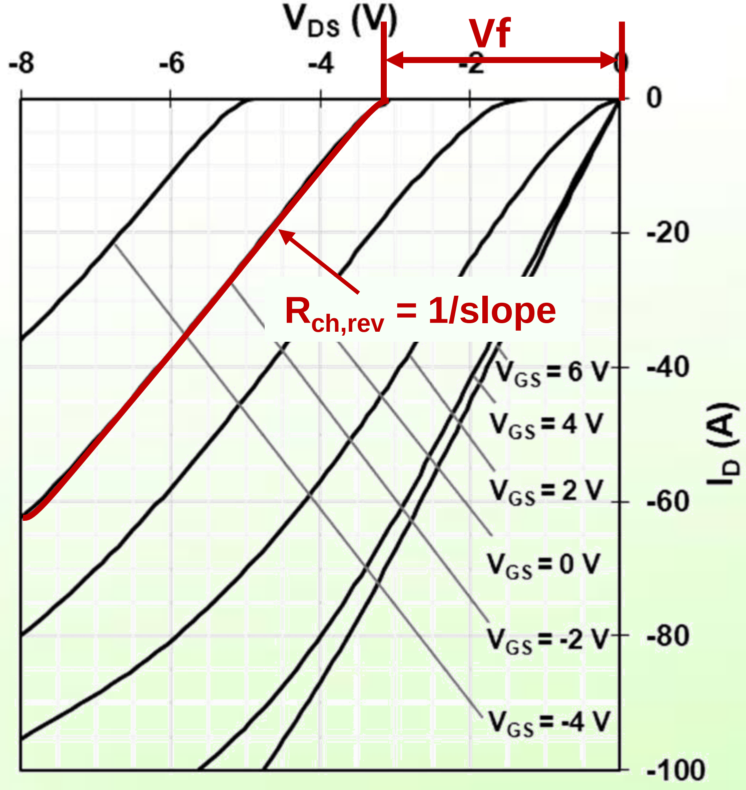


$$Irms, sr = \sqrt{\frac{Ip^2 + Iv^2 + IpIv}{3}(1 - D)}$$

Loss breakdown of GaN FETs: SR deadtime loss







For turn-on and turn-off transient, the load current are different (Ip, Iv). If deadtime is a t_{dt}

- $Vf = |V_{TH}| + |V_{GS,OFF}|$
- $V_{SD} = Vf + I_L * R_{ch,rev}$

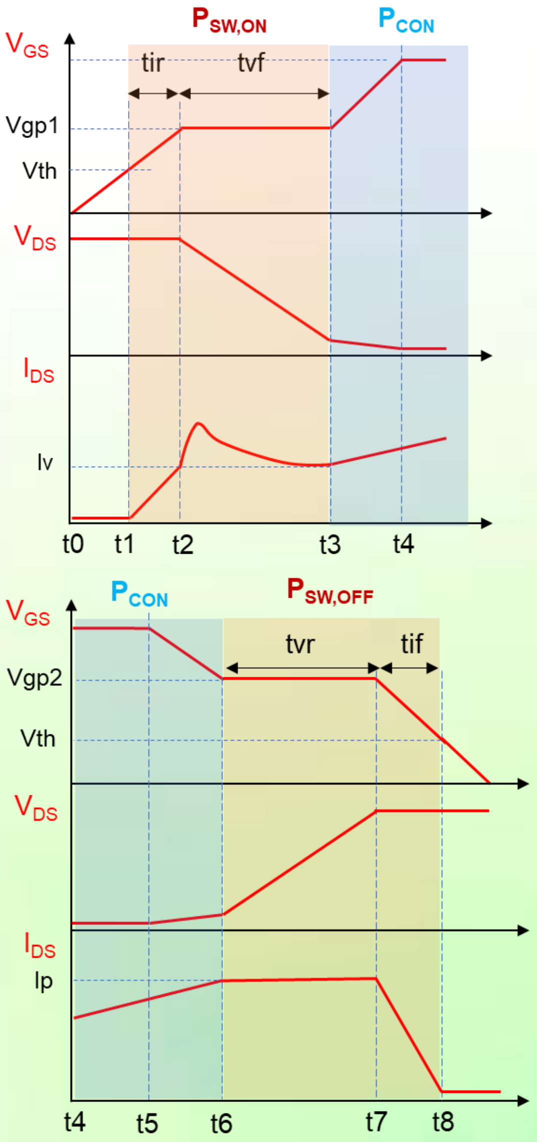
The deadtime loss is:

$$P_{dt} = (Ip * V_{SD\_Ip} * t_{dt} + Iv * V_{SD\_Iv} * t_{dt}) * fs$$

Boost converter loss summary

	Loss type	Equations
SW-Q1	Conduction loss	$Pcond, sw = \frac{Ip^2 + Iv^2 + Ip * Iv}{3} * D * Rdson$
	Switching loss	$P_{SW} \approx \frac{1}{2} * V_{IN} * I_v * t_{on} * f_s + \frac{1}{2} * V_{IN} * I_p * t_{off} * f_s$
	Capacitive loss	$P_{CAP} = Q_{OSS} * Vbus * f_s$
	Gate drive loss	$P_{GATE} = Q_G * V_{GS} * f_s$
SR-Q2	Conduction loss	$Pcond, sr = \frac{Ip^2 + Iv^2 + Ip * Iv}{3} * (1 - D) * Rdson$
	Deadtime loss	$P_{dt} = (Ip * V_{SD\_Ip} * t_{dt} + Iv * V_{SD\_Iv} * t_{dt}) * fs$
	Gate drive loss	$P_{GATE} = (Q_G - Q_{GD}) * V_{GS} * f_s$

** Gate drive loss mainly happens in driver circuit, not in GaN FETs.*



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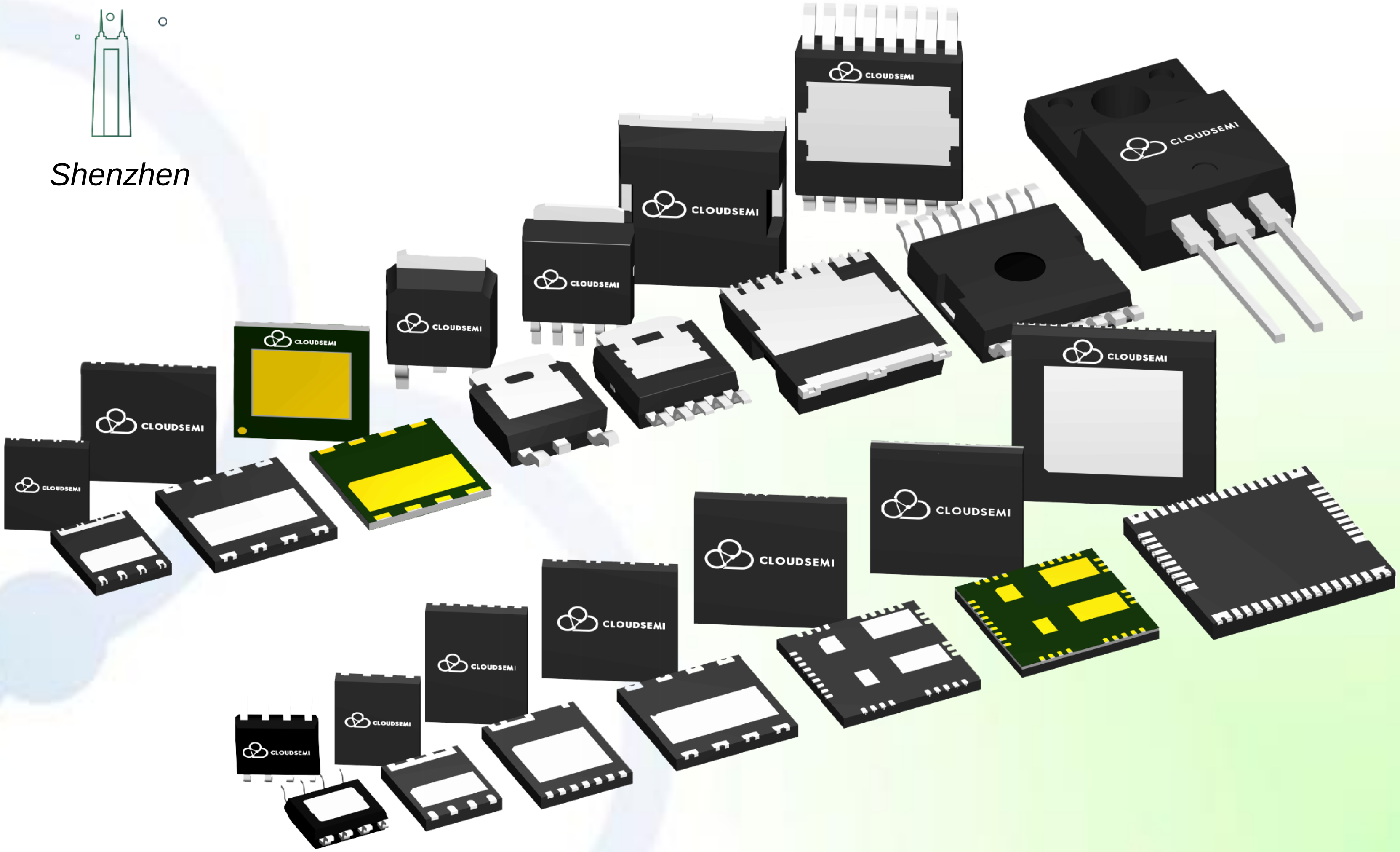

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