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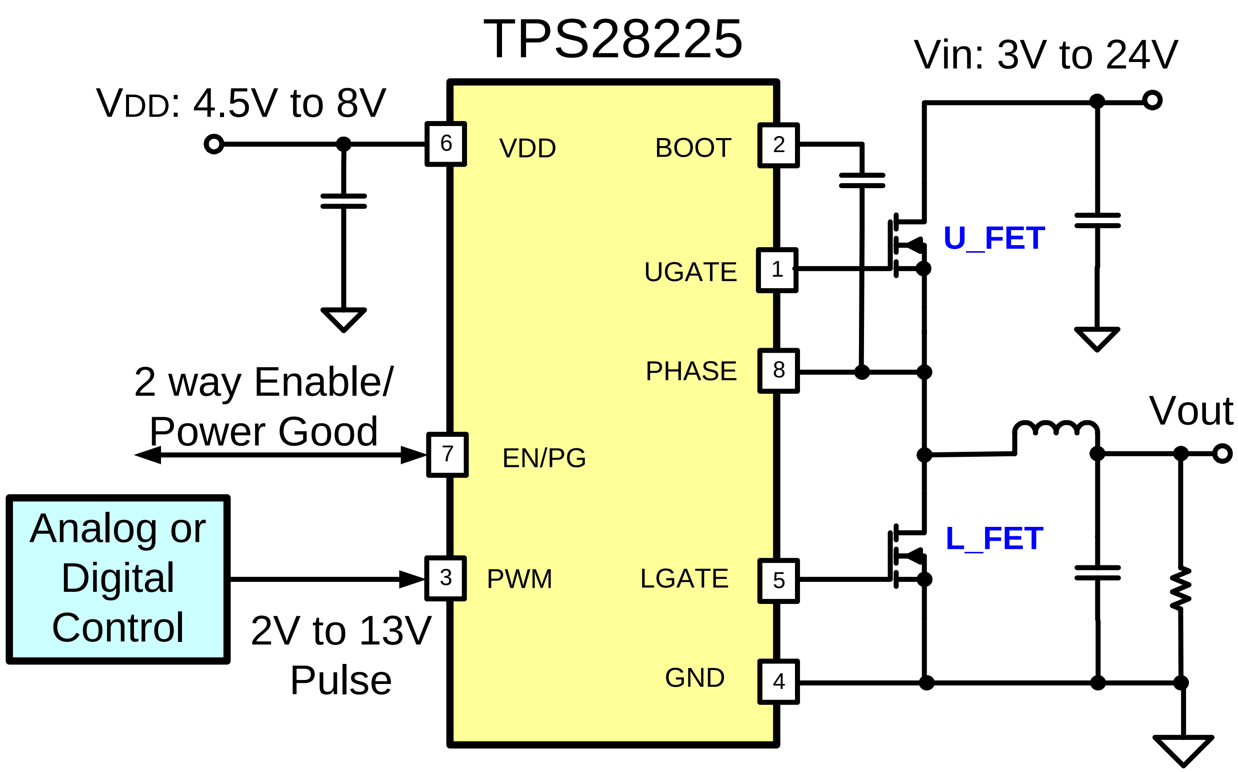
# EFFICIENCY AND POWER LOSSES CALCULATION of SYNCHRONOUS BUCK CONVERTER

Supplemental MathCad file to the paper
"What MOSFET Driver Can Do to Boost the Performance of VRM Design"
presented at Power Electronics Technology Exhibition & Conference, October 25, 2006, Long Beach, California



## One Phase of Synchronous Buck Converter used as an Example in this File



## Control FET (U_FET): HAT2168N: Parameters taken from Data Sheet

$gU := \frac{0.5 \cdot V}{35 \cdot A}$ $gU = 0.014 \frac{V}{A}$ $\frac{1}{gU} = 70\,S$ **- Forward Transconductnace**

$VthU := 2.0 \cdot V$ **- Threshold Voltage**

$Qgs1t := 2.5 \cdot ncoul$ **- Charge from 0 to Vth**

$Qgs2t := 2.5 \cdot ncoul$ **- Charge from Vth to Vmiller**

$Qgst := Qgs1t + Qgs2t$

$Qgst = 5\,ncoul$

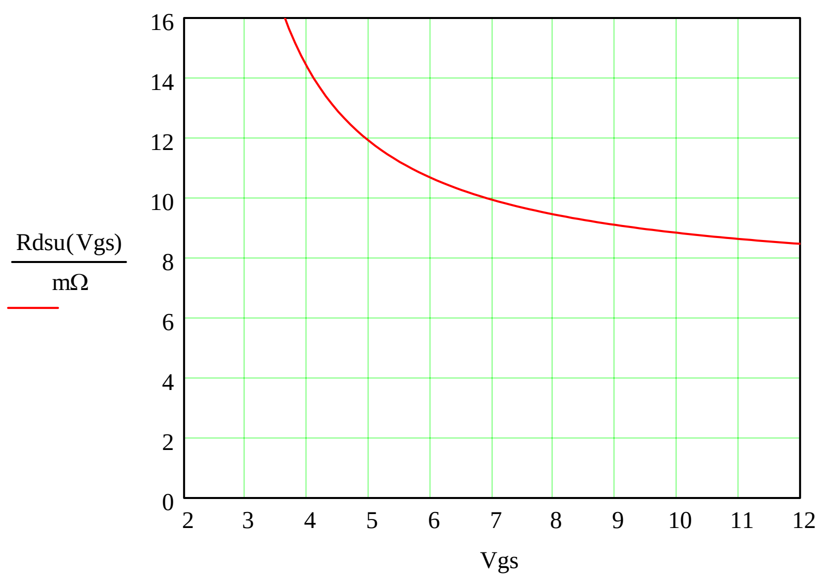
$Qgdt := 2.4 \cdot ncoul$

$Vgs := 2.3 \cdot V, 2.4 \cdot V .. 12 \cdot V$

$Qtt(Vgs) := Qgst + Qgdt + \frac{27 \cdot ncoul}{10 \cdot V} \cdot (Vgs - 0.4 \cdot V - 3 \cdot V)$ **- Charge at Vgs**

$Qtt(4.5 \cdot V) = 10.37\,ncoul$ $Qtt(5 \cdot V) = 11.72\,ncoul$ $Qtt(7 \cdot V) = 17.12\,ncoul$ $Qtt(10 \cdot V) = 25.22\,ncoul$ $Qtt(12 \cdot V) = 30.62\,ncoul$

$Rdsu(Vgs) := \left[ 5 \cdot m\Omega + \frac{10.5 \cdot V \cdot m\Omega}{(Vgs - VthU)} \right] \cdot 1.4$ **- Rdson at 125 C**



## Synchronous FET (L_FET): HAT2166N: Parameters taken from Data Sheet

$gL := \frac{0.5 \cdot V}{35 \cdot A}$ $gL = 0.014 \frac{V}{A}$ $\frac{1}{gL} = 70\,S$ **- Forward Transconductnace**

$VthL := 2.2 \cdot V$

$Qgs1b := 6 \cdot ncoul$

$Qgs2b := 6 \cdot ncoul$

$Qgsb := Qgs1b + Qgs2b$

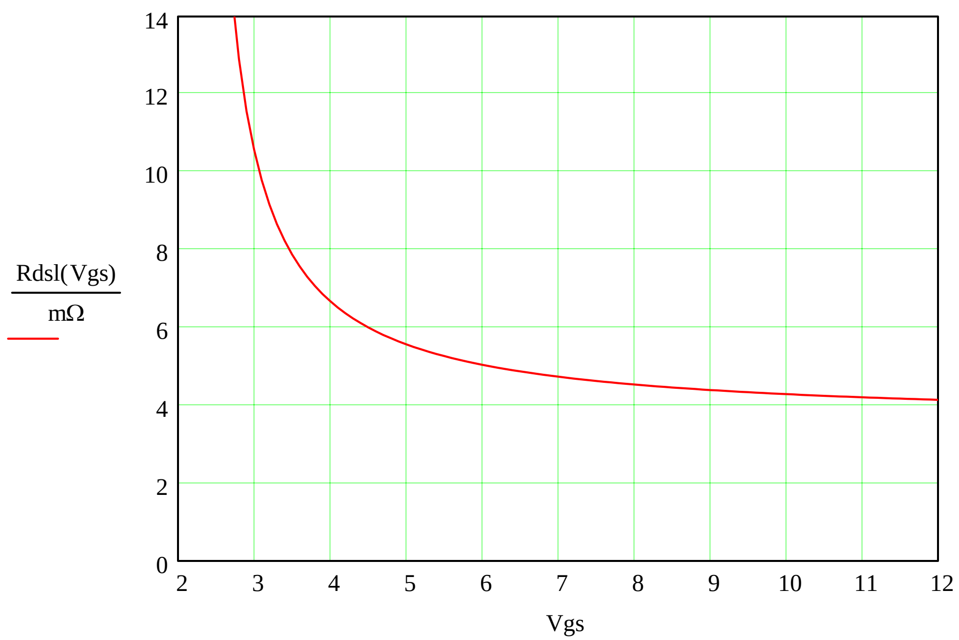
$Qgsb = 12\,ncoul$

$Qgdb := 5.9 \cdot ncoul$

$Qtb(Vgs) := Qgsb + Qgdb + \frac{30 \cdot ncoul}{4 \cdot V} \cdot (Vgs - 3.2 \cdot V)$ **- Charge at Vgs**

$Qtb(4.5 \cdot V) = 27.65\,ncoul$ $Qtb(5 \cdot V) = 31.4\,ncoul$ $Qtb(7 \cdot V) = 46.4\,ncoul$ $Qtb(10 \cdot V) = 68.9\,ncoul$ $Qtb(12 \cdot V) = 83.9\,ncoul$

$Rdsl(Vgs) := \left[2.55 \cdot m\Omega + \frac{4 \cdot V \cdot m\Omega}{(Vgs - VthL)}\right] \cdot 1.4$ **- Rdson at 125 C**



# EFFICIENCY AND POWER LOSSES BUDGET

## INPUT DATA

$Vs := 12 \cdot V$ $Vo := 1.3 \cdot V$ $Iomax := 32.5 \cdot A$ $fs := 400 \cdot kHz$ $Ts := \frac{1}{fs}$ $Nph := 4$ **number of phases**

$Vgs := 7 \cdot V$ $Lo := 0.12 \cdot \mu H$ $Ri := 0.36 \cdot m\Omega$ **- Output Inductor** $Rpcb := 0 \cdot m\Omega$

$Nu := 1$ **- number of top FETs** $Nl := 2$ **- number of low FETs**

$RdsU(Vgs) := \frac{Rdsu(Vgs)}{Nu}$ $RdsU(5 \cdot V) = 11.9\, m\Omega$ $RdsU(7 \cdot V) = 9.94\, m\Omega$ $RdsU(12 \cdot V) = 8.47\, m\Omega$ $RdsU\_25(Vgs) := \frac{Rdsu(Vgs)}{1.4}$

**- Rdson at 125 C** **- Rdson at 25 C**

$RdsL(Vgs) := \frac{Rdsl(Vgs)}{Nl}$ $RdsL(5 \cdot V) = 2.785\, m\Omega$ $RdsL(7 \cdot V) = 2.368\, m\Omega$ $RdsL(12 \cdot V) = 2.071\, m\Omega$ $RdsL\_25(Vgs) := \frac{Rdsl(Vgs)}{1.4}$

## STATIC POWER LOSSES PER PHASE

$Io := 0 \cdot A, 1 \cdot A .. Iomax$

$Kt(Io) := 1 + 0.4 \cdot \frac{Io}{Iomax}$

$0.57 \cdot 120 \cdot 13 = 889.2$

$$D(Vs, Io, Vgs) := \frac{Vo + Io \cdot \left(RdsL(Vgs) \cdot \frac{Kt(Io)}{1.4} + Ri \cdot Kt(Io)\right)}{Vs - Io \cdot (RdsU(Vgs) - RdsL(Vgs)) \cdot \frac{Kt(Io)}{1.4}}$$

$D(Vs, Iomax, Vgs) = 0.119$

$$\delta Io(Vs, Io, Vgs) := \frac{[Vs - Io \cdot (RdsU(Vgs) + Ri) - Vo] \cdot D(Vs, Io, Vgs)}{Lo \cdot fs}$$

$\delta Io(Vs, 40 \cdot A, Vgs) = 26.109\, A$ **- inductor ripple current**

$$IQ1rms(Vs, Io, Vgs) := \left[D(Vs, Io, Vgs) \cdot \left(Io^2 + \frac{1}{12} \cdot \delta Io(Vs, Io, Vgs)^2\right)\right]^{0.5}$$ **- high-side FET RMS current**

$$PQ1(Vs, Io, Vgs) := IQ1rms(Vs, Io, Vgs)^2 \cdot RdsU(Vgs) \cdot \frac{Kt(Io)}{1.4}$$ **- high-side FET static losses**

$$IQ2rms(Vs, Io, Vgs) := \left[(1 - D(Vs, Io, Vgs)) \cdot \left(Io^2 + \frac{1}{12} \cdot \delta Io(Vs, Io, Vgs)^2\right)\right]^{0.5}$$ **- low-side FET RMS current**

$$PQ2(Vs, Io, Vgs) := IQ2rms(Vs, Io, Vgs)^2 \cdot RdsL(Vgs) \cdot \frac{Kt(Io)}{1.4}$$ **- low-side FET static losses**

$$IQ1p(Vs, Io, Vgs) := Io + \frac{\delta Io(Vs, Io, Vgs)}{2}$$ **- high-side FET peak current**

$$IQ1m(Vs, Io, Vgs) := Io - \frac{\delta Io(Vs, Io, Vgs)}{2}$$ **- high-side FET minimum current**

$$Iirms(Vs, Io, Vgs) := \left(Io^2 + \frac{1}{12} \cdot \delta Io(Vs, Io, Vgs)^2\right)^{0.5}$$ **- inductor RMS current**

$$Iirms(Vs, Iomax, Vgs) = 33.33\ A$$

$$ICorms(Vs, Io, Vgs) := \frac{1}{2 \cdot \sqrt{3}} \cdot \delta Io(Vs, Io, Vgs)$$ **- output capacitor RMS current (for 1-phase buck)**

$$ICorms(Vs, Iomax, Vgs) = 7.39\ A \qquad ICorms(Vs, 0 \cdot A, Vgs) = 6.971\ A$$

$$ICinrms(Vs, Io, Vgs) := \left[D(Vs, Io, Vgs) \cdot (1 - D(Vs, Io, Vgs)) \cdot Io^2 + \frac{D(Vs, Io, Vgs)}{12} \cdot \delta Io(Vs, Io, Vgs)^2\right]^{0.5}$$ **input capacitor RMS current**

$$PLo(Vs, Io, Vgs) := Iirms(Vs, Io, Vgs)^2 \cdot Ri \cdot Kt(Io)$$ **- output inductor power losses**

$$Ppcb(Vs, Io, Vgs) := Iirms(Vs, Io, Vgs)^2 \cdot Rpcb \cdot Kt(Io)$$ **- PCB traces power losses**

$$Iin(Vs, Io, Vgs) := Io \cdot D(Vs, Io, Vgs)$$ **- input current**

$$PQ(Vs, Io, Vgs) := PQ1(Vs, Io, Vgs) + PQ2(Vs, Io, Vgs)$$ **- conduction losses in FETs**

**Total Conduction Power Losses**

$$Ploss(Vs, Io, Vgs) := PQ1(Vs, Io, Vgs) + PQ2(Vs, Io, Vgs) + PLo(Vs, Io, Vgs) + Ppcb(Vs, Io, Vgs)$$

$$PQ1(Vs, Iomax, Vgs) = 1.309\ W \qquad PQ1(Vs, 0 \cdot A, Vgs) = 0.037\ W$$

$$PQ2(Vs, Iomax, Vgs) = 2.319\ W \qquad PQ2(Vs, 0 \cdot A, Vgs) = 0.073\ W$$

## Conduction losses per FET

$$PQ11(Vs, Io, Vgs) := \frac{1}{Nu} \cdot PQ1(Vs, Io, Vgs)$$

$$PQ11(Vs, Iomax, Vgs) = 1.309\ W$$

$$PQ21(Vs, Io, Vgs) := \frac{1}{Nl} \cdot PQ2(Vs, Io, Vgs)$$

$$PQ21(Vs, Iomax, Vgs) = 1.16\ W$$

$PLo(Vs, Iomax, Vgs) = 0.56\ W$ **- inductor conduction losses**

$Ppcb(Vs, Iomax, Vgs) = 0\ W$ **- PCB conduction losses**

$Ploss(Vs, Iomax, Vgs) = 4.188\ W$ **- Total Conduction Power Losses**

## DYNAMIC POWER LOSSES

$RgU := 0.5 \cdot ohm$ **- internal gate resistor of FET**

$RgeU := 0 \cdot ohm$ **- external gate resistor**

$Rdp := 1 \cdot ohm$ **- source output resistor of driver**

$Rdn := 1 \cdot ohm$ **- sink output resistor of driver**

$$IgU1(Vs, Io, Vgs, Rdp) := \frac{Vgs - 0.4 \cdot V - \left(VthU + \frac{gU}{Nu} \cdot IQ1m(Vs, Io, Vgs)\right)}{\frac{RgU}{Nu} + RgeU + Rdp}$$

**- source gate current of high-side FET**

$IgU1(Vs, Iomax, 5 \cdot V, Rdp) = 1.547\ A$ $IgU1(Vs, Iomax, 7 \cdot V, Rdp) = 2.879\ A$ $IgU1(Vs, Iomax, 12 \cdot V, 1.8 \cdot ohm) = 4.051\ A$

$$IgU2(Vs, Io, Vgs, Rdn) := \frac{VthU + \frac{gU}{Nu} \cdot IQ1p(Vs, Io, Vgs)}{\frac{RgU}{Nu} + RgeU + Rdn}$$

**- sink gate current of high-side FET**

$IgU2(Vs, Iomax, 5 \cdot V, Rdp) = 1.766\ A$ $IgU2(Vs, Iomax, 7 \cdot V, Rdp) = 1.765\ A$ $IgU2(Vs, Iomax, 12 \cdot V, 1.0 \cdot ohm) = 1.764\ A$

**- high-side FET switching losses**

$$Pswt(Vs, Io, Vgs, Rdp, Rdn) := IQ1m(Vs, Io, Vgs) \cdot Vs \cdot \frac{fs}{2} \cdot Nu \cdot \frac{Qgs2t + Qgdt}{IgU1(Vs, Io, Vgs, Rdp)} + IQ1p(Vs, Io, Vgs) \cdot Vs \cdot \frac{fs}{2} \cdot Nu \cdot \frac{Qgs2t + Qgdt}{IgU2(Vs, Io, Vgs, Rdn)}$$

$Pswt(Vs, Iomax, Vgs, Rdp, Rdn) = 0.382\ W$

$Pswt(Vs, Iomax, Vgs, Rup, Rdn) = 0.382\ W$

$Pswbd(Vgs) := 0.5 \cdot Qtt(Vgs) \cdot (Vgs - 0.4 \cdot V) \cdot fs \cdot Nu$ **- losses in bootstrap diode**

$Pswbd(Vgs) = 0.023\ W$

$Pswdt(Vgs) := Qtt(Vgs) \cdot (Vgs - 0.4 \cdot V) \cdot fs \cdot Nu$

$Pswdt(Vgs) = 0.045\ W$ **- high-side FET drive losses**

$Pswdb(Vgs) := Qtb(Vgs) \cdot Vgs \cdot fs \cdot Nl$

$Pswdb(Vgs) = 0.26\ W$ **- low-side FET driver losses**

$Idd(Vgs) := \frac{Vgs}{7 \cdot V} \cdot 3 \cdot mA$ $Pbias(Vgs) := Vgs \cdot Idd(Vgs)$

$Pswdr(Vgs) := Pswdt(Vgs) + Pswdb(Vgs) + Pbias(Vgs)$ $Pswdr(Vgs) = 0.326\ W$ **- drive power losses without bootstrap diode**

$Pswd(Vgs) := Pswdt(Vgs) + Pswdb(Vgs) + Pswbd(Vgs) + Pbias(Vgs)$

$Pswd(Vgs) = 0.349\ W$ **- drive power losses**

$Idr(Vgs) := \frac{Pswd(Vgs)}{Vgs}$

$Pldo(Vgs) := (Vs - Vgs) \cdot Idr(Vgs)$ **- LDO power losses**

**Driver input current**

| | | | |
|---|---|---|---|
| $Idr(5 \cdot V) = 33.732\ mA$ | $Nph \cdot Idr(5 \cdot V) = 134.929\ mA$ | $Pswd(5 \cdot V) = 0.169\ W$ | $Pswdr(5 \cdot V) = 0.158\ W$ |
| $Idr(6 \cdot V) = 41.767\ mA$ | $Nph \cdot Idr(6 \cdot V) = 167.067\ mA$ | $Pswd(6 \cdot V) = 0.251\ W$ | $Pswdr(6 \cdot V) = 0.234\ W$ |
| $Idr(7 \cdot V) = 49.805\ mA$ | $Nph \cdot Idr(7 \cdot V) = 199.22\ mA$ | $Pswd(7 \cdot V) = 0.349\ W$ | $Pswdr(7 \cdot V) = 0.326\ W$ |
| $Idr(8 \cdot V) = 57.846\ mA$ | $Nph \cdot Idr(8 \cdot V) = 231.384\ mA$ | $Pswd(8 \cdot V) = 0.463\ W$ | $Pswdr(8 \cdot V) = 0.433\ W$ |
| $Idr(12 \cdot V) = 90.022\ mA$ | $Nph \cdot Idr(12 \cdot V) = 360.09\ mA$ | $Pswd(12 \cdot V) = 1.08\ W$ | $Pswdr(12 \cdot V) = 1.009\ W$ |

$(Vs - 6 \cdot V) \cdot Nph \cdot Idr(6 \cdot V) = 1.002\ W$

$(Vs - 7 \cdot V) \cdot Nph \cdot Idr(7 \cdot V) = 0.996\ W$ - overall LDO power losses

$(Vs - 8 \cdot V) \cdot Nph \cdot Idr(8 \cdot V) = 0.926\ W$

$Nph \cdot Pswd(5 \cdot V) = 0.675\ W$

$Nph \cdot Pswd(6 \cdot V) = 1.002\ W$

$Nph \cdot Pswd(7 \cdot V) = 1.395\ W$ - overall drive losses without LDO

$Nph \cdot Pswd(8 \cdot V) = 1.851\ W$

$Nph \cdot Pswd(12 \cdot V) = 4.321\ W$

**Diode losses:** **HAT2166N at 125C**

$Tdt := 20 \cdot nS$ $Rdi := 0.006 \cdot ohm$ $Vf := 0.5 \cdot V$

$$Pd(Vs, Io, Vgs) := IQ1m(Vs, Io, Vgs) \cdot \left(Vf + \frac{Rdi}{Nl} \cdot IQ1m(Vs, Io, Vgs)\right) \cdot \frac{Tdt}{Ts} + IQ1p(Vs, Io, Vgs) \cdot \left(Vf + \frac{Rdi}{Nl} \cdot IQ1p(Vs, Io, Vgs)\right) \cdot \frac{Tdt}{Ts}$$

$Pd(Vs, Iomax, Vgs) = 0.319\ W$ $Pd(Vs, 0 \cdot A, Vgs) = 6.998 \times 10^{-3}\ W$

**Diode recovery losses (HAT2166N for If = 45A, dI/dt=100A/us. Trr = 37ns):**

$Qrr(Vs, Io, Vgs) := 46 \cdot ncoul$

$$PQ1rr(Vs, Io, Vgs) := if\left(IQ1m(Vs, Io, Vgs) < 0, 0 \cdot W, fs \cdot Qrr(Vs, Io, Vgs) \cdot \frac{IQ1m(Vs, Io, Vgs)}{45 \cdot A} \cdot Vs\right)$$

$PQ1rr(Vs, Iomax, Vgs) = 0.097\ W$ $PQ1rr(Vs, 0 \cdot A, Vgs) = 0\ W$

**Total switching losses proportional to current**

$$PswIo(Vs, Io, Vgs, Rdp, Rdn) := Pd(Vs, Io, Vgs) + PQ1rr(Vs, Io, Vgs) + Pswt(Vs, Io, Vgs, Rdp, Rdn)$$

$PswIo(Vs, Iomax, Vgs, Rdp, Rdn) = 0.798\ W$ $PswIo(Vs, 0 \cdot A, Vgs, Rdp, Rdn) = 0.06\ W$

**Coss related losses:** $Cossu10 := 400 \cdot pF$ $Cossl10 := 1000 \cdot pF$

$Cossu(Vs) := Cossu10 \cdot \frac{\sqrt{10 \cdot V}}{\sqrt{Vs}}$ $Cossl(Vs) := Cossl10 \cdot \frac{\sqrt{10 \cdot V}}{\sqrt{Vs}}$

$Crssu10 := 130 \cdot pF$ $Crssl10 := 330 \cdot pF$

$Crssu(Vs) := Crssu10 \cdot \frac{\sqrt{10 \cdot V}}{\sqrt{Vs}}$ $Crssl(Vs) := Crssl10 \cdot \frac{\sqrt{10 \cdot V}}{\sqrt{Vs}}$

$$Possint(Vs) := fs \cdot \frac{2}{3} \cdot [\,(Cossu(Vs) + Crssu(Vs)) \cdot Nu + (Cossl(Vs) + Crssl(Vs)) \cdot Nl\,] \cdot Vs^2$$

$$Poss(Vs, Io) := if\left[Io < \frac{1}{2} \cdot \frac{Vo \cdot (Vs - Vo)}{Vs \cdot Lo \cdot fs}, \frac{Io \cdot 2 \cdot (Vs \cdot Lo \cdot fs)}{Vo \cdot (Vs - Vo)} \cdot (Possint(Vs)), Possint(Vs)\right]$$

$$Poss(Vs, Iomax) = 0.112\,W$$

**Snubber losses:**

$$Csn := 2000 \cdot pF$$

$$Psn(Vs) := Csn \cdot Vs^2 \cdot fs$$

$$Psn(Vs) = 0.115\,W$$

$$Pswconst(Vs, Io, Vgs) := Poss(Vs, Io) + Psn(Vs) + Pswd(Vgs)$$ **-total constant switching losses without LDO but with bootstrap diode**

$$Pswtt(Vs, Io, Vgs, Rdp, Rdn) := Pswt(Vs, Io, Vgs, Rdp, Rdn) + PQ1rr(Vs, Io, Vgs) + Poss(Vs, Io)$$ **-upper FET switching losses**

$$Psw(Vs, Io, Vgs, Rdp, Rdn) := Pswtt(Vs, Io, Vgs, Rdp, Rdn) + Pd(Vs, Io, Vgs) + Psn(Vs) + Pswd(Vgs)$$ **-total switching losses**

$$Psw(Vs, Iomax, Vgs, Rdp, Rdn) = 1.373\,W \qquad Pswtt(Vs, Iomax, Vgs, Rdp, Rdn) = 0.591\,W \qquad Pswt(Vs, Iomax, Vgs, Rdp, Rdn) = 0.382\,W$$

$$Pufet(Vs, Io, Vgs, Rdp, Rdn) := PQ1(Vs, Io, Vgs) + Pswt(Vs, Io, Vgs, Rdp, Rdn) + PQ1rr(Vs, Io, Vgs) + Poss(Vs, Io)$$ **-total upper FET losses**

$$Pufet(Vs, Iomax, Vgs, Rdp, Rdn) = 1.9\,W$$

$$Pu(Vs, Io, Vgs, Rdp, Rdn) := \frac{1}{Nu} \cdot Pufet(Vs, Io, Vgs, Rdp, Rdn) \qquad Pu(Vs, Iomax, Vgs, Rdp, Rdn) = 1.9\,W$$ **Upper FET power losses (per one FET):**

$$Plfet(Vs, Io, Vgs) := (PQ2(Vs, Io, Vgs) + Pd(Vs, Io, Vgs))$$ **-total lower FET losses**

$$Plfet(Vs, Iomax, Vgs) = 2.638\,W$$

$$Pl(Vs, Io, Vgs) := \frac{1}{Nl} \cdot Plfet(Vs, Io, Vgs) \qquad Pl(Vs, Iomax, Vgs) = 1.319\,W$$ **Lower FET power losses (per one FET):**

$Pfet(Vs, Io, Vgs, Rdp, Rdn) := Pufet(Vs, Io, Vgs, Rdp, Rdn) + Plfet(Vs, Io, Vgs)$ **-overall FET losses**

$Pp(Vs, Io, Vgs, Rdp, Rdn) := Psw(Vs, Io, Vgs, Rdp, Rdn) + Ploss(Vs, Io, Vgs)$ **-total power losses per phase without LDO and input inductor**

$Pp(Vs, Iomax, Vgs, Rdp, Rdn) = 5.561\ W$

**Input Inductor:**

**Not present** $Riin := 0.0 \cdot m\Omega$ $Riin = 0\ m\Omega$

$$Iin(Vs, Io, Rdp, Rdn) := \frac{Nph \cdot (Vo \cdot Io + Pp(Vs, Io, Vgs, Rdp, Rdn))}{Vs}$$ $Iin(Vs, Iomax, Rdp, Rdn) = 15.937\ A$

$Piin(Vs, Io, Rdp, Rdn) := Iin(Vs, Io, Rdp, Rdn)^2 \cdot Riin \cdot Kt(Io)$ $Piin(Vs, Iomax, Rdp, Rdn) = 0\ W$

$Ppl(Vs, Io, Vgs, Rdp, Rdn) := Pp(Vs, Io, Vgs, Rdp, Rdn) + Piin(Vs, Io, Rdp, Rdn)$ **-total power losses**

$Ppl2(Vs, Io, Vgs, Rdp, Rdn) := Ppl(Vs, Io, Vgs, Rdp, Rdn) + (Vs - Vgs) \cdot Idr(Vgs)$ **- counts losses in LDO**

$Ppl(Vs, Iomax, Vgs, Rdp, Rdn) = 5.561\ W$ **- total power losses**

$Ppl(Vs, Iomax, 5 \cdot V, Rdp, Rdn) = 6.136\ W$ $Nph \cdot [(Ppl(Vs, Iomax, 4.5 \cdot V, Rdp, Rdn)) - (Ppl(Vs, Iomax, 7 \cdot V, Rdp, Rdn))] = 3.744\ W$

$Ppl(Vs, Iomax, 7 \cdot V, Rdp, Rdn) = 5.561\ W$ $Nph \cdot [(Ppl(Vs, Iomax, 5 \cdot V, Rdp, Rdn)) - (Ppl(Vs, Iomax, 7 \cdot V, Rdp, Rdn))] = 2.302\ W$

$Ppl(Vs, Iomax, 12 \cdot V, Rdp, Rdn) = 5.754\ W$

$Nph \cdot [(Ppl(Vs, 0 \cdot A, 12 \cdot V, Rdp, Rdn)) - (Ppl(Vs, 0 \cdot A, 7 \cdot V, Rdp, Rdn))] = 2.959\ W$

$Vgs := 2.6 \cdot V, 2.7 \cdot V .. 12 \cdot V$

$Imph(Io) := Nph \cdot Io$

$$Eff(Vs, Io, Vgs, Rdp, Rdn) := \frac{Io \cdot Vo \cdot 100}{Io \cdot Vo + Ppl(Vs, Io, Vgs, Rdp, Rdn)}$$ $$Eff2(Vs, Io, Vgs, Rdp, Rdn) := \frac{Io \cdot Vo \cdot 100}{Io \cdot Vo + Ppl2(Vs, Io, Vgs, Rdp, Rdn)}$$

$Eff(12 \cdot V, 32.5 \cdot A, 7 \cdot V, 1 \cdot ohm, 1 \cdot ohm) = 88.369$

$Io := 32.5 \cdot A$ $Itot := Nph \cdot Io$

## Power Losses Summary

$Vs = 12\,V$ $Vo = 1.3\,V$ $Io = 32.5\,A$ $Nph = 4$ $Itot = 130\,A$ $fs = 400\,kHz$ $Nu = 1$ **HAT2168N** $Nl = 2$ **HAT2166N**

$Lo = 0.12\,\mu H$ $Ri = 0.36\,m\Omega$ **Inductor at 25C**

$Rpcb = 0\,m\Omega$ **PCB and traces at 25C**

## Power Losses per Phase

### Conduction Losses

| | | | |
|---|---|---|---|
| $\delta Io(Vs, Io, 5\cdot V) = 25.799\,A$ | $\delta Io(Vs, Io, 7\cdot V) = 25.599\,A$ | $\delta Io(Vs, Io, 12\cdot V) = 25.456\,A$ | **P-P Inductor current** |
| $PLo(Vs, Io, 5\cdot V) = 0.56\,W$ | $PLo(Vs, Io, 7\cdot V) = 0.56\,W$ | $PLo(Vs, Io, 12\cdot V) = 0.56\,W$ | **Inductor losses** |
| $Ppcb(Vs, Io, 5\cdot V) = 0\,W$ | $Ppcb(Vs, Io, 7\cdot V) = 0\,W$ | $Ppcb(Vs, Io, 12\cdot V) = 0\,W$ | **- PCB traces power losses** |
| $PQ1(Vs, Io, 5\cdot V) = 1.59\,W$ | $PQ1(Vs, Io, 7\cdot V) = 1.309\,W$ | $PQ1(Vs, Io, 12\cdot V) = 1.103\,W$ | **-Conduction losses for U_FET** |
| $PQ2(Vs, Io, 5\cdot V) = 2.724\,W$ | $PQ2(Vs, Io, 7\cdot V) = 2.319\,W$ | $PQ2(Vs, Io, 12\cdot V) = 2.029\,W$ | **-Conduction losses for L_FET** |
| $PQ(Vs, Io, 5\cdot V) = 4.314\,W$ | $PQ(Vs, Io, 7\cdot V) = 3.628\,W$ | $PQ(Vs, Io, 12\cdot V) = 3.133\,W$ | **-Cond. losses for FETs** |
| $Ploss(Vs, Io, 5\cdot V) = 4.875\,W$ | $Ploss(Vs, Io, 7\cdot V) = 4.188\,W$ | $Ploss(Vs, Io, 12\cdot V) = 3.692\,W$ | **-total conduction losses** |

### Switching losses proportional to current

| | | | |
|---|---|---|---|
| $IgU1(Vs, Io, 5\cdot V, 1\cdot ohm) = 1.547\,A$ | $IgU1(Vs, Io, 7\cdot V, 1\cdot ohm) = 2.879\,A$ | $IgU1(Vs, Io, 12\cdot V, 1.8\cdot ohm) = 4.051\,A$ | |
| $IgU2(Vs, Io, 5\cdot V, 1\cdot ohm) = 1.766\,A$ | $IgU2(Vs, Io, 7\cdot V, 1\cdot ohm) = 1.765\,A$ | $IgU2(Vs, Io, 12\cdot V, 1.0\cdot ohm) = 1.764\,A$ | |
| $Pswt(Vs, Io, 5\cdot V, 1\cdot ohm, 1\cdot ohm) = 0.451\,W$ | $Pswt(Vs, Io, 7\cdot V, 1\cdot ohm, 1\cdot ohm) = 0.382\,W$ | $Pswt(Vs, Io, 12\cdot V, 1.8\cdot ohm, 1\cdot ohm) = 0.359\,W$ | **-U_FET** |
| $Pd(Vs, Io, 5\cdot V) = 0.319\,W$ | $Pd(Vs, Io, 7\cdot V) = 0.319\,W$ | $Pd(Vs, Io, 12\cdot V) = 0.318\,W$ | **-L_FET_Body_Diode** |
| $PQ1rr(Vs, Io, 5\cdot V) = 0.096\,W$ | $PQ1rr(Vs, Io, 7\cdot V) = 0.097\,W$ | $PQ1rr(Vs, Io, 12\cdot V) = 0.097\,W$ | **-U_FET_Diode_Recov** |
| $PswIo(Vs, Io, 5\cdot V, 1\cdot ohm, 1\cdot ohm) = 0.866\,W$ | $PswIo(Vs, Io, 7\cdot V, 1\cdot ohm, 1\cdot ohm) = 0.798\,W$ | $PswIo(Vs, Io, 12\cdot V, 1.8\cdot ohm, 1\cdot ohm) = 0.774\,W$ | |

**-total proportional to current switching losses**

## Constant switching losses

| | | | |
|---|---|---|---|
| Poss(Vs, Io) = 0.112 W | Poss(Vs, Io) = 0.112 W | Poss(Vs, Io) = 0.112 W | -U_FET |
| Psn(Vs) = 0.115 W | Psn(Vs) = 0.115 W | Psn(Vs) = 0.115 W | -snubber |
| Pswbd(5 · V) = 0.011 W | Pswbd(7 · V) = 0.023 W | Pswbd(12 · V) = 0.071 W | -bootstrap diode |
| Pswdt(5 · V) = 0.022 W | Pswdt(7 · V) = 0.045 W | Pswdt(12 · V) = 0.142 W | - high-side FET drive losses |
| Pswdb(5 · V) = 0.126 W | Pswdb(7 · V) = 0.26 W | Pswdb(12 · V) = 0.805 W | - low-side FET drive losses |
| Pbias(5 · V) = 0.011 W | Pbias(7 · V) = 0.021 W | Pbias(12 · V) = 0.062 W | - drive bias losses |
| Pswdr(5 · V) = 0.158 W | Pswdr(7 · V) = 0.326 W | Pswdr(12 · V) = 1.009 W | - drive losses without bootstrap diode |
| Pswd(5 · V) = 0.169 W | Pswd(7 · V) = 0.349 W | Pswd(12 · V) = 1.08 W | - drive losses with bootstrap diode |
| Idr(5 · V) = 33.732 mA | Idr(7 · V) = 49.805 mA | Idr(12 · V) = 90.022 mA | -driver input current |
| | Pldo(7 · V) = 0.249 W | -LDO losses if necessary | |
| Pswconst(Vs, Io, 5 · V) = 0.396 W | Pswconst(Vs, Io, 7 · V) = 0.576 W | Pswconst(Vs, Io, 12 · V) = 1.307 W | -total const switching losses without LDO |

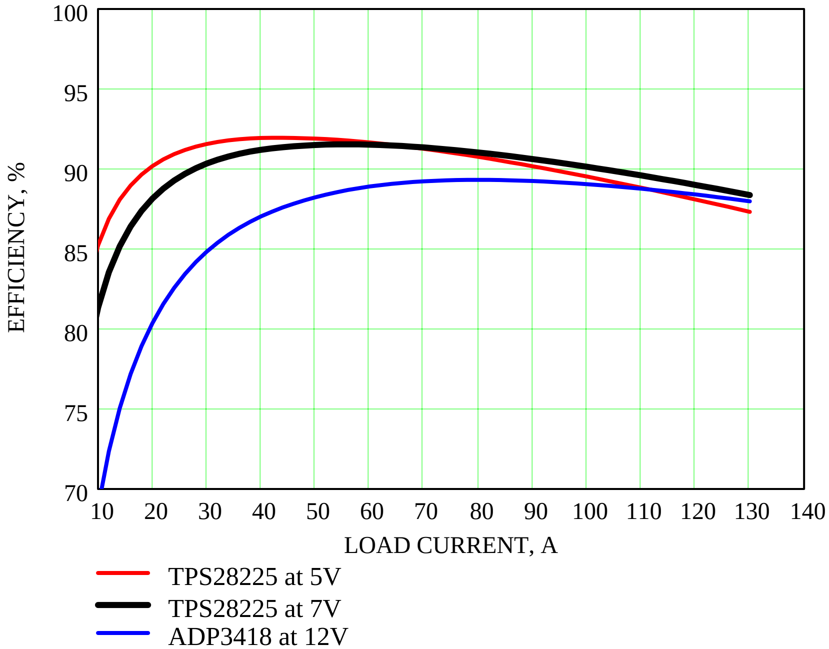
## Total switching losses without LDO

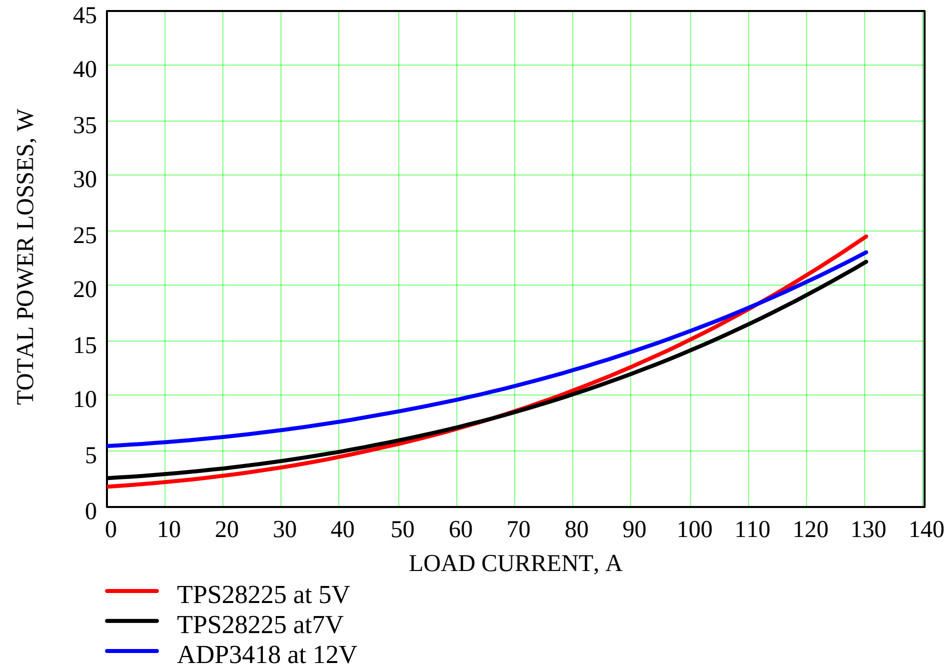
| | | | |
|---|---|---|---|
| Pswtt(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 0.659 W | Pswtt(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 0.591 W | Pswtt(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 0.568 W | -U_FET switching losses |
| Psw(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 1.262 W | Psw(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 1.373 W | Psw(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 2.082 W | - total switching losses |

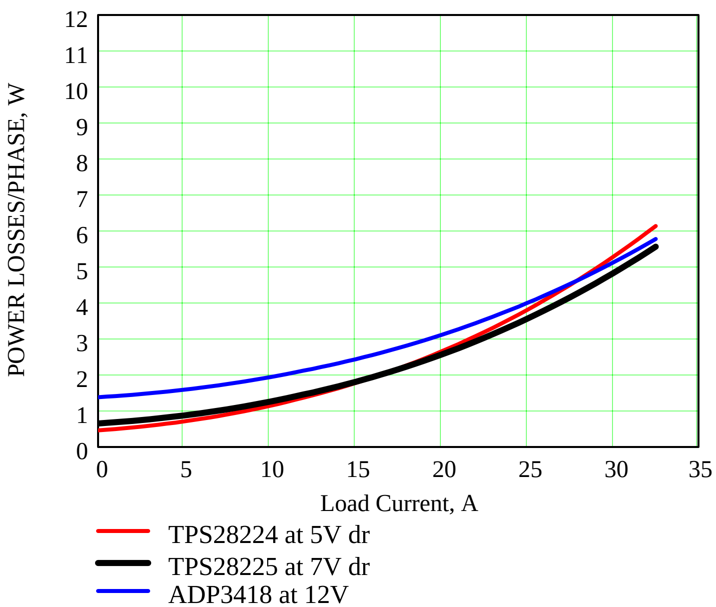
## Total losses

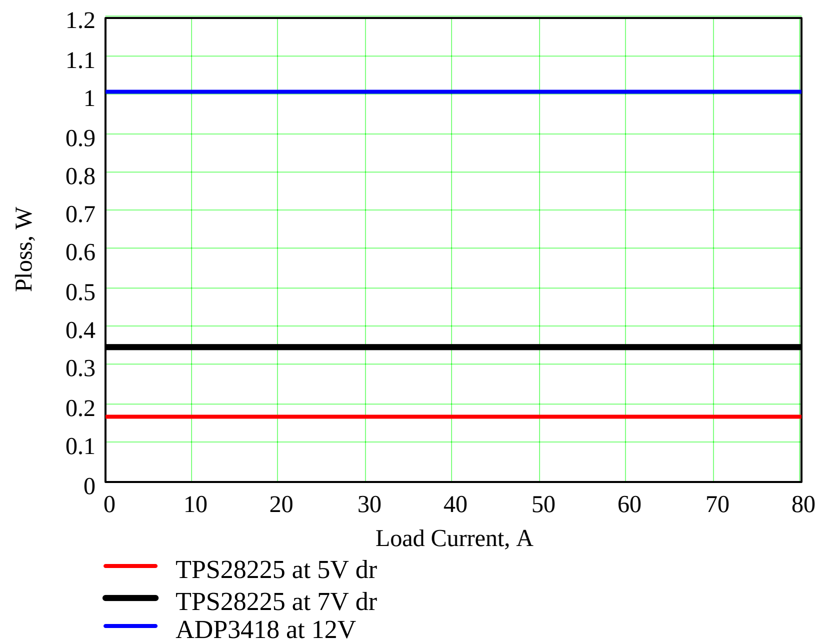
| | | | |
|---|---|---|---|
| Pufet(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 2.25 W | Pufet(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 1.9 W | Pufet(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 1.671 W | -total U_FET losses |
| Pu(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 2.25 W | Pu(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 1.9 W | Pu(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 1.671 W | -total U_FET losses (per one FET) |
| Plfet(Vs, Io, 5 · V) = 3.043 W | Plfet(Vs, Io, 7 · V) = 2.638 W | Plfet(Vs, Io, 12 · V) = 2.348 W | -total L_FET losses |
| Pl(Vs, Io, 5 · V) = 1.521 W | Pl(Vs, Io, 7 · V) = 1.319 W | Pl(Vs, Io, 12 · V) = 1.174 W | -total L_FET losses (per one FET) |
| Pfet(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 5.292 W | Pfet(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 4.537 W | Pfet(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 4.019 W | -total FET losses |
| Ppl(Vs, Io, 5 · V, 1 · ohm, 1 · ohm) = 6.136 W | Ppl(Vs, Io, 7 · V, 1 · ohm, 1 · ohm) = 5.561 W | Ppl(Vs, Io, 12 · V, 1.8 · ohm, 1 · ohm) = 5.774 W | -total losses without LDO |

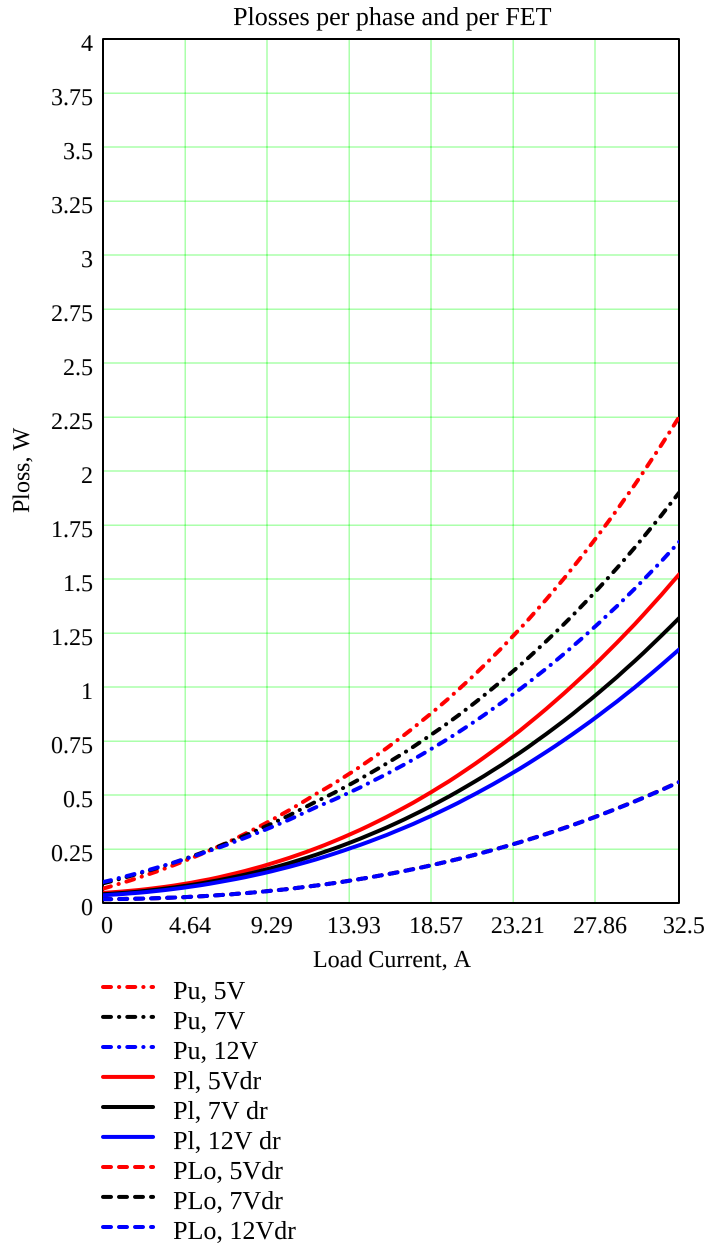
Io := 0 · A, 0.5 · A .. Iomax


EFFICIENCY, %
100
95
90
85
80
75
70
10 20 30 40 50 60 70 80 90 100 110 120 130 140
LOAD CURRENT, A
TPS28225 at 5V
TPS28225 at 7V
ADP3418 at 12V


TOTAL POWER LOSSES, W
45
40
35
30
25
20
15
10
5
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
LOAD CURRENT, A
TPS28225 at 5V
TPS28225 at7V
ADP3418 at 12V


POWER LOSSES/PHASE, W
12
11
10
9
8
7
6
5
4
3
2
1
0
0 5 10 15 20 25 30 35
Load Current, A
TPS28224 at 5V dr
TPS28225 at 7V dr
ADP3418 at 12V


Ploss, W
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 10 20 30 40 50 60 70 80
Load Current, A
TPS28225 at 5V dr
TPS28225 at 7V dr
ADP3418 at 12V




Qtt(5 · V) = 11.72 ncoul Qtt(7 · V) = 17.12 ncoul Qtt(12 · V) = 30.62 ncoul

Qtb(5 · V) = 31.4 ncoul Qtb(7 · V) = 46.4 ncoul Qtb(12 · V) = 83.9 ncoul

**- Overall Rdson at 125 C**

RdsU(5 · V) = 11.9 mΩ RdsU(7 · V) = 9.94 mΩ RdsU(12 · V) = 8.47 mΩ

RdsL(5 · V) = 2.785 mΩ RdsL(7 · V) = 2.368 mΩ RdsL(12 · V) = 2.071 mΩ

**- Rdson of each FET at 25 C**

RdsU_25(4.5 · V) = 9.2 mΩ RdsU_25(7 · V) = 7.1 mΩ RdsU_25(10 · V) = 6.313 mΩ

RdsL_25(4.5 · V) = 4.289 mΩ RdsL_25(7 · V) = 3.383 mΩ RdsL_25(10 · V) = 3.063 mΩ

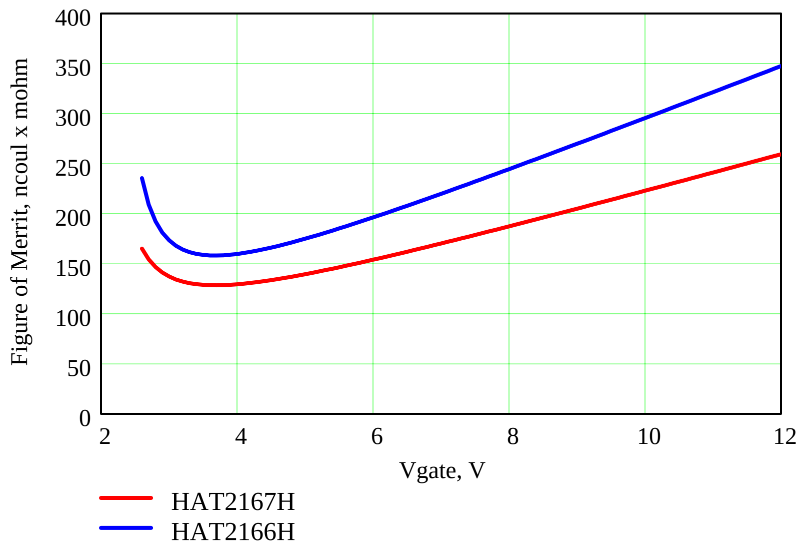
**- Rdson at 25 C from DS**

**HAT2168N**

**HAT2166N**

FMu(Vgs) := Rdsu(Vgs) · Qtt(Vgs) FMu(7 · V) = 170.173 ncoul · mΩ

FMl(Vgs) := Rdsl(Vgs) · Qtb(Vgs) FMl(7 · V) = 219.781 ncoul · mΩ



$fs := 100 \cdot kHz, 150 \cdot kHz .. 1000 \cdot kHz$

$Vgs := 12 \cdot V$

$Pswbd(Vgs, fs) := 0.5 \cdot Qtt(Vgs) \cdot (Vgs - 0.4 \cdot V) \cdot fs \cdot Nu$ **- losses in bootstrap diode**

$Pswbd(Vgs, 250 \cdot kHz) = 0.044\,W$

$Pswdt(Vgs, fs) := Qtt(Vgs) \cdot (Vgs - 0.4 \cdot V) \cdot fs \cdot Nu$

$Pswdt(Vgs, 250 \cdot kHz) = 0.089\,W$

**- high-side FET drive losses**

$Pswdb(Vgs, fs) := Qtb(Vgs) \cdot Vgs \cdot fs \cdot Nl$

$Pswdb(Vgs, 250 \cdot kHz) = 0.503\,W$

**- low-side FET driver losses**

$Idd(Vgs) := \frac{Vgs}{7 \cdot V} \cdot 3 \cdot mA$ $Pbias(Vgs) := Vgs \cdot Idd(Vgs)$

$Pswdr(Vgs, fs) := Pswdt(Vgs, fs) + Pswdb(Vgs, fs) + Pbias(Vgs)$ $Pswdr(Vgs, 250 \cdot kHz) = 0.654\,W$

$Pswd(Vgs, fs) := Pswdt(Vgs, fs) + Pswdb(Vgs, fs) + Pswbd(Vgs, fs) + Pbias(Vgs)$

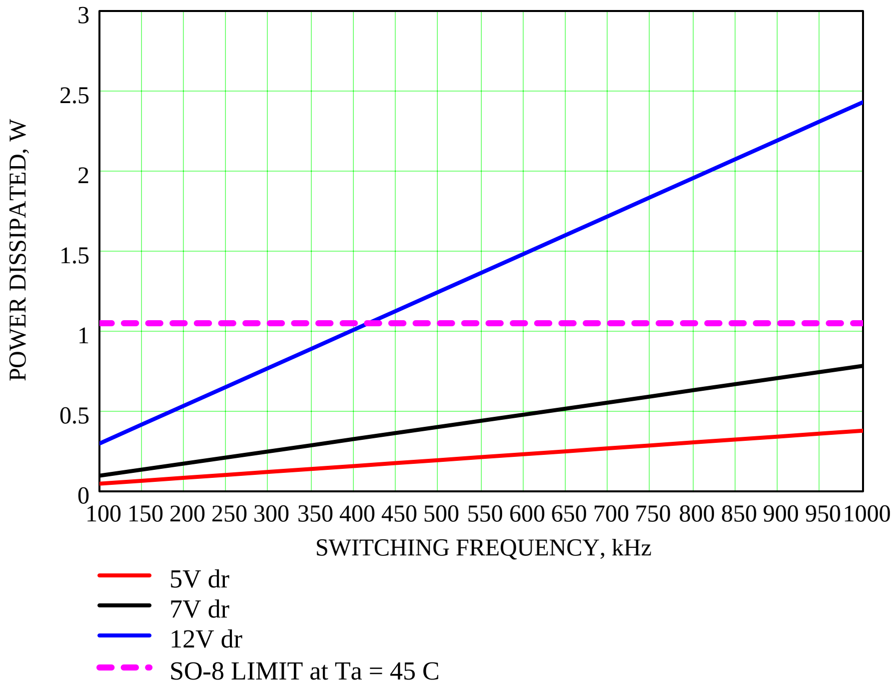
$Pswd(Vgs, 250 \cdot kHz) = 0.698\,W$ **- drive power losses**

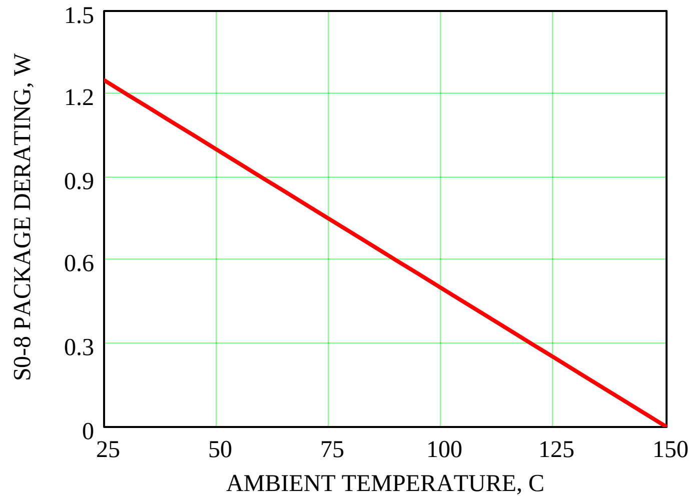
## Derating Power for SO-8

Ta := 25, 30 .. 150

Pdiss(Ta) := 1.25W − 0.01 · W · (Ta − 25)

Pdiss(45) = 1.05 W



**UNIT DEFINITIONS** **MKS (SI) unit system**

## Base units

$m \equiv 1L$ $kg \equiv 1M$ $sec \equiv 1T$ $coul \equiv 1Q$

## Derived units: Electrical

$cm \equiv 10^{-2} \cdot m$ $\mu S \equiv 10^{-6} \cdot sec$ $nS \equiv 10^{-9} \cdot sec$ $mS \equiv 10^{-3} \cdot sec$

$newton \equiv kg \cdot \frac{m}{sec^2}$ $joule \equiv newton \cdot m$ $\mu J \equiv 10^{-6} \cdot joule$ $W \equiv \frac{joule}{sec}$

$A \equiv \frac{coul}{sec}$ $V \equiv \frac{W}{A}$ $ohm \equiv \frac{V}{A}$ $weber \equiv V \cdot sec$

$siemence \equiv \frac{1}{ohm}$ $farad \equiv \frac{coul}{V}$ $oersted \equiv \frac{1000}{4 \cdot \pi} \cdot \frac{A}{m}$

$H \equiv \frac{weber}{A}$ $T \equiv \frac{weber}{m^2}$ $gauss \equiv 10^{-4} \cdot T$ $MHz \equiv \frac{10^6}{sec}$

$nH \equiv 10^{-9} \cdot H$ $\mu H \equiv 10^{-6} \cdot H$ $pF \equiv 10^{-12} \cdot farad$ $ncoul \equiv 10^{-9} \cdot coul$

$m\Omega \equiv 10^{-3} \cdot ohm$ $nF \equiv 10^{-9} \cdot farad$ $mA \equiv 10^{-3} \cdot A$ $S \equiv \frac{A}{V}$ $\mu F \equiv 10^{-6} \cdot farad$