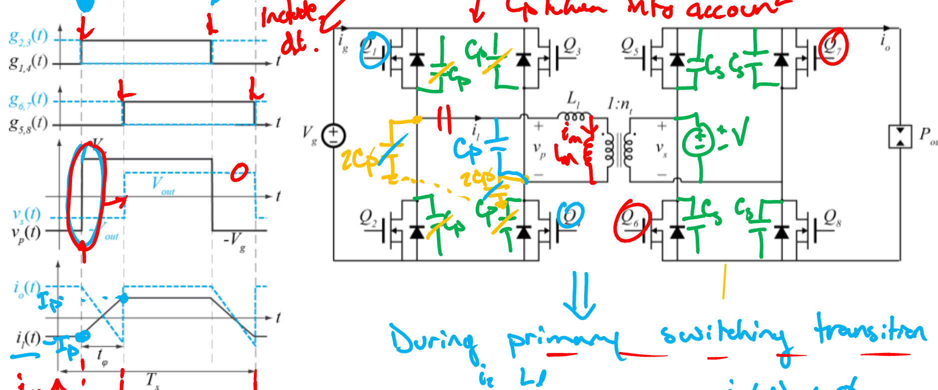
Switching Behavior

neglecting deadtime

Include dt.

C_p taken into account



During primary switching transition

$i_p(\phi) < \phi$

$v_p: -V_g \to V_g$ (increasing)

→ possible to obtain ZVS (on all 8 devices)

State Plane Analysis of DAB Converter

I. $\alpha = \sin^{-1}\left(\frac{2}{J_p}\right)$, $J_p = \sqrt{4 + J_1^2}$

II. $\frac{(I_2+I_1)}{t_2 \omega_0} = \frac{2V_g}{L_l \omega_0}$

$\frac{(J_2+J_1)}{\beta} = \frac{2V_g}{4 \cdot \sqrt{L_l C_p}} = \frac{2V_g}{R_0}$

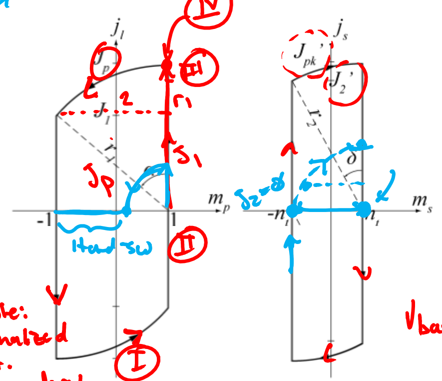
$J_2 + J_1 = 2\beta$

III. $\delta' = \sin^{-1}\left(\frac{2n_t}{J_{pk}'}\right)$, $J_{pk}' = \sqrt{(2n_t)^2 + J_2'^2}$

note: normalized wrt. secondary

ZVS: $J_p > 2$ Primary

ZVS: χ Secondary



$V_{base} = V_g$

$I_{base} = V_g \sqrt{\frac{C_p}{L_l}}$ $\quad I_{base}' = V_g \sqrt{\frac{C_s}{n_t^2 L_l}}$

IV. → χ

$T_s \cdot \frac{1}{2} = \frac{\alpha}{\omega_0} + \frac{\beta}{\omega_0} + \frac{\delta}{\omega_0} + \frac{\chi}{\omega_0}$ → $\frac{\pi}{F} = \alpha + \beta + \delta + \chi$

Averaging Step

$$n_t\langle i_{out}\rangle = \frac{2}{T_s}\int_0^{T_s/2} n_t i_{out}(t)\,dt = \frac{2}{T_s}\left[q_1 + q_2 + q_3 + q_4\right] \quad (q_3 \to \phi)$$

$$\frac{1}{I_{base}}\cdot n_t\langle i_{out}\rangle = \frac{2}{T_s}\left[2C_pV_g + t_2\frac{I_1-I_2}{2} + \phi + t_4 I_p\right]\cdot\frac{1}{I_{base}}$$

$$J \equiv n_t\frac{\langle i_{out}\rangle}{I_{base}} = \frac{2}{T_s}\left[2C_pV_g\frac{R_0}{V_g} + t_2\frac{J_1-J_2}{2} + t_4 J_p\right]$$

$$J = 2f_s\left[\frac{2}{\omega_0} + t_2\frac{J_1-J_2}{2} + t_4 J_p\right]\cdot\frac{\omega_0}{\omega_0}$$

$$J = \frac{2f_s}{2\pi f_0}\left[2 + \beta\frac{J_1-J_2}{2} + \delta J_p\right]$$

$$J = \frac{F}{\pi}\left[2 + \frac{\beta}{2}(J_1-J_2) + \delta J_p\right]$$

Output Plane

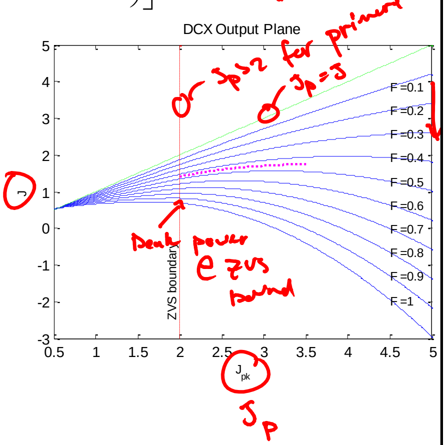
$$J = \frac{n\langle i_{out}\rangle}{I_{base}} = \frac{F}{\pi}\left[2 + \frac{1}{4}\left(J_1^{\ 2} - J_2^{\ 2}\right) + J_p\left(\frac{\pi}{F} - \alpha - \beta - \delta\right)\right]$$

$F = \frac{f_s}{f_0}$

$F \to 1 \quad f_0 = f_s$ ✓

$F \to 0 \quad f_0 \gg f_s$ ✓

ZVS is very fast wrt T_s



Selection of Tank Inductance

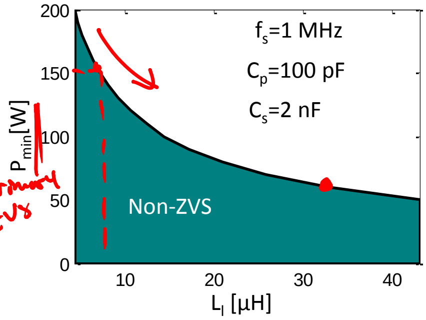
- State plane analysis gives equation of the form:

$$P_{out} = f(L_l, C_p, C_s, , f_s, J_p)$$

- If we select some minimum power P_{min} for ZVS design to place ZVS boundary ($J_p = 2$), at P_{min}

$$P_{min} = f(L_l, \text{devices}, f_s)$$

- From resulting equation, L_l determined from converter devices, application requirements, and placement of ZVS boundary
- Now select devices for minimum loss in converter



Selecting MOSFETs for DAB

150 V FETS

Device Variant	Type	r_{on} [mΩ]	C_{oss} [pF]	Q_g [nC]
EPC1012	GaN	70	80	1.9
EPC1010	GaN	18	310	7.5
FDMS2672	MOS	64	95	30
IPD320N	MOS	35	135	12.0
IRFS4020	MOS	85	91	18.0

12V FETS

Device Variant	Type	r_{on} [mΩ]	C_{oss} [pF]	Q_g [nC]
EPC1014	GaN	12.0	150	3.0
EPC1015	GaN	3.2	575	11.6
CSD16325Q5C	MOS	1.7	2190	18.0
STD60N3LH5	MOS	8.8	265	8.8
CSD16411Q3	MOS	12.0	330	2.9

- Representative sample of HV and LV devices, including Si and GaN devices
- Above P_{min}, all devices have no switching loss, so efficiency only depends on conduction losses

$$P_{cond} = P_{cond,p} + P_{cond,s} = 2r_{on,p}i_{g,rms}^2 + 2r_{on,s}i_{out,rms}^2$$

Selecting MOSFETs for DAB

150 V FETS

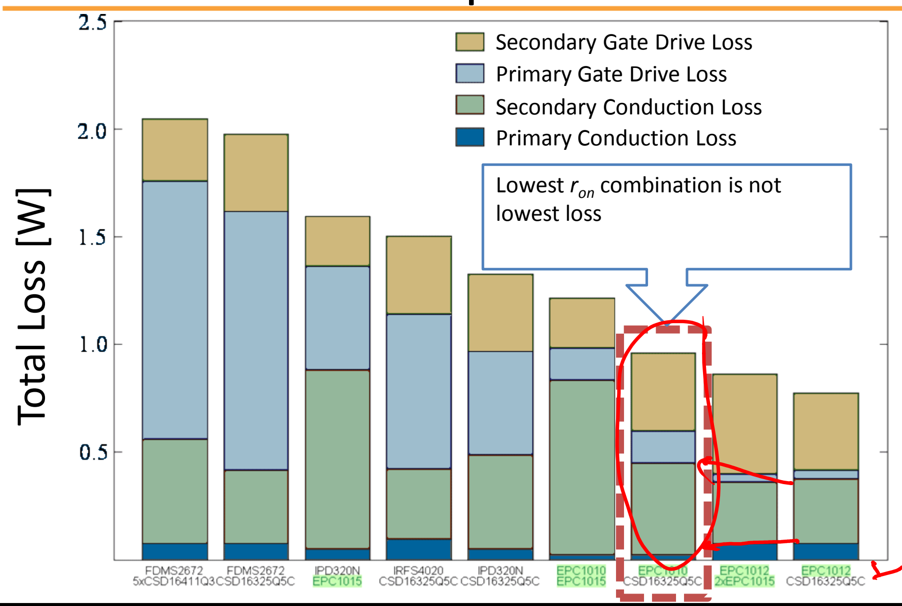
Device Variant	Type	r_{on} [mΩ]	C_p [pF]	Q_g [nC]
EPC1012	GaN	70	87	1.9
EPC1010	GaN	18	353	7.5
FDMS2672	MOS	64	177	30
IPD320N	MOS	35	379	12.0
IRFS4020	MOS	85	140	18.0

12V FETS

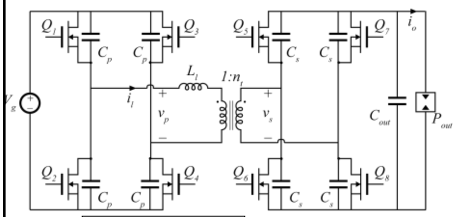
Device Variant	Type	r_{on} [mΩ]	C_s [pF]	Q_g [nC]
EPC1014	GaN	12.0	241	3.0
EPC1015	GaN	3.2	1000	11.6
CSD16325Q5C	MOS	1.7	3200	18.0
STD60N3LH5	MOS	8.8	713	8.8
CSD16411Q3	MOS	12.0	486	2.9

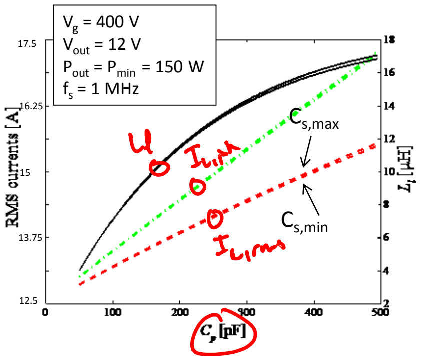
- Representative sample of HV and LV devices, including Si and GaN devices
- Above P_{min}, all devices have no switching loss, so efficiency only depends on conduction losses
- Initial conclusion is to select lowest r_{on} devices
- Can solve analytical loss model from state plane analysis

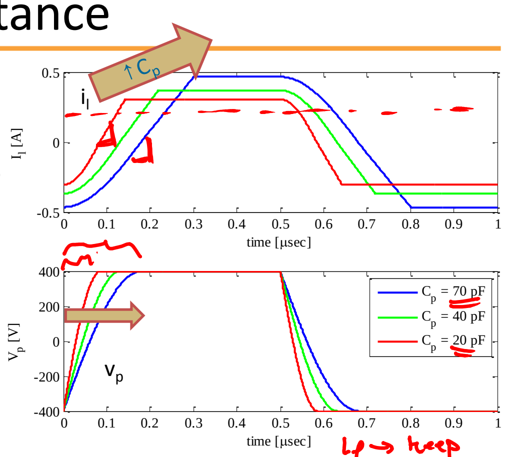
Device Loss Comparison: 150-12 V



Effects of primary-side device capacitance







- Higher RMS currents lead to greater conduction losses
- RMS currents strongly dependant on C_p

Lp → keep the same Pmin

Low current primary → Cp strongly influences RMS i's
High current sec → Cs does not

Selecting MOSFETs for DAB

150 V FETS

Device Variant	Type	r_{on} [mΩ]	C_p [pF]	Q_g [nC]
EPC1012	GaN	70	87	1.9
EPC1010	GaN	18	353	7.5
FDMS2672	MOS	64	177	30
IPD320N	MOS	35	379	12.0
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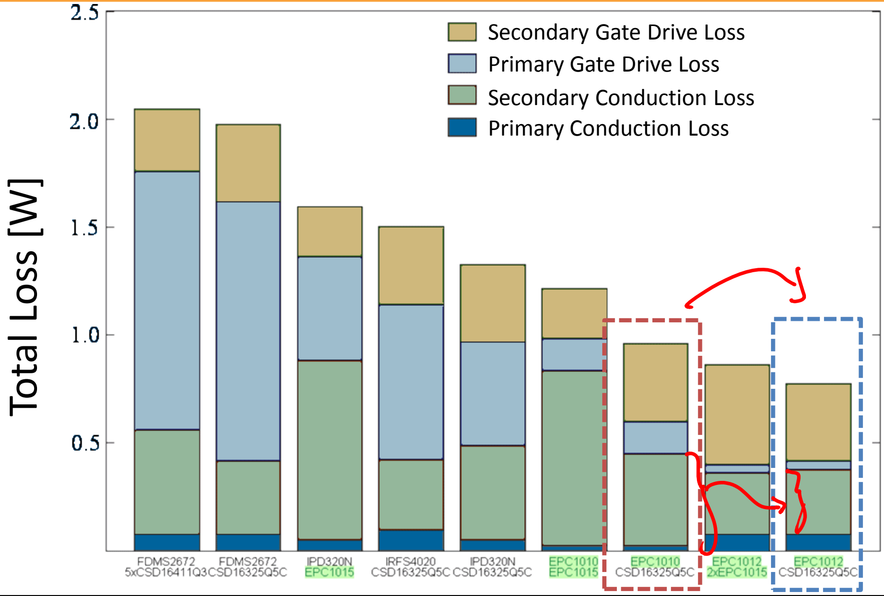
12V FETS

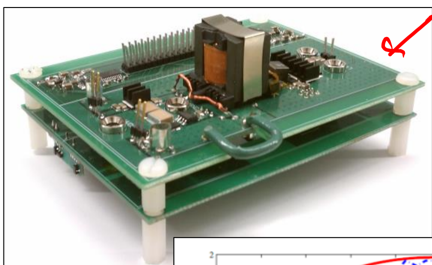
Device Variant	Type	r_{on} [mΩ]	C_s [pF]	Q_g [nC]
EPC1014	GaN	12.0	241	3.0
EPC1015	GaN	3.2	1000	11.6
CSD16325Q5C	MOS	1.7	3200	18.0
STD60N3LH5	MOS	8.8	713	8.8
CSD16411Q3	MOS	12.0	486	2.9

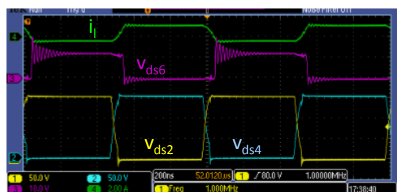
- Analysis predicts that optimal selection consists of lowest C_p primary device and lowest r_{on} secondary device

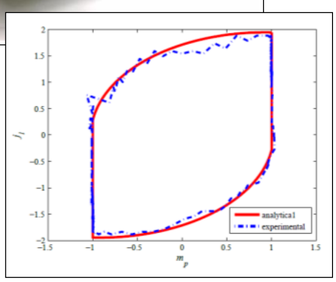
Device Loss Comparison: 150-12 V

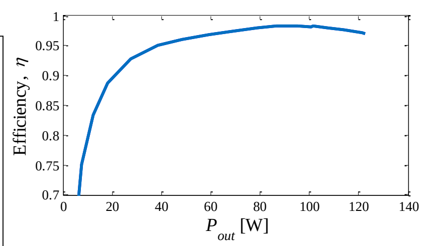


DAB: Experimental Results







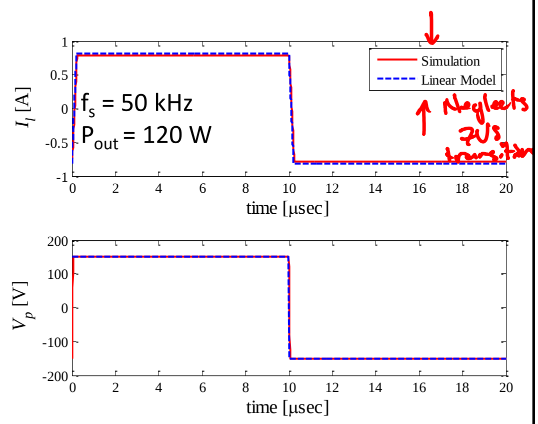


D. Costinett, H. Nguyen, R. Zane, and D. Maksimovic, "GaN-FET based dual active bridge DC-DC converter," in Proc. Appl. Power Electron. Conf. (APEC), march 2011, pp. 1425 –1432.

D. Costinett, D. Maksimovic, and R. Zane, "Design and control for high efficiency in high step-down dual active bridge converters operating at high switching frequency," IEEE Trans. Power Electron., vol. PP, no. 99, p. 1, 2012.

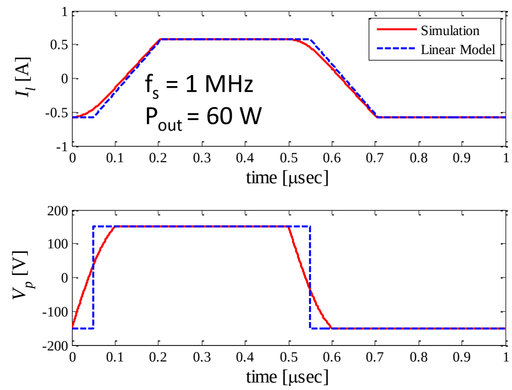
Linear Model Comparison to Simulation

- At high output power and low switching frequency, square wave model of DAB converter accurately predicts behavior of full circuit simulation



High Frequency, Low Power Operation

- At low output power and high switching frequency, square wave model is poor fit to circuit behavior
- Effect of switching transitions need to be considered



Application Example: Automotive

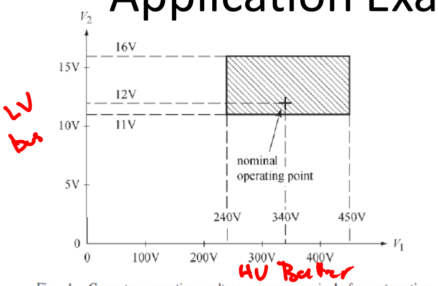
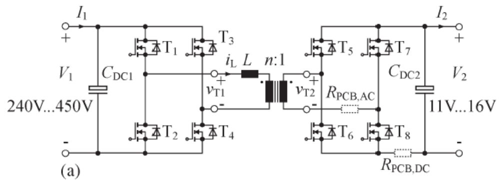


Fig. 1. Converter operating voltage ranges required for automotive application.



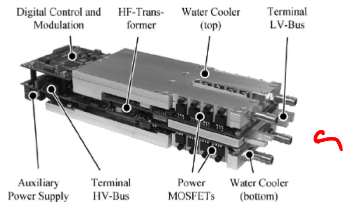


Fig. 3. Automotive DAB converter (273 × 90 × 53 mm).

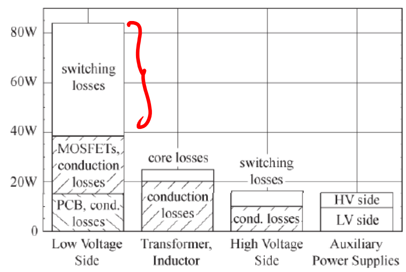


Fig. 13. Calculated distribution of the power losses for operation at $V_1 =$ 340 V, $V_2 = 12$ V, and $P_2 = 2$ kW.

*F. Krismer, J.W.Kolar, "Accurate Power Loss Model Derivation of a High-Current Dual Active Bridge Converter for an Automotive Application, IEEE Trans. On Industrial Electronics, March 2010

Efficiency Results

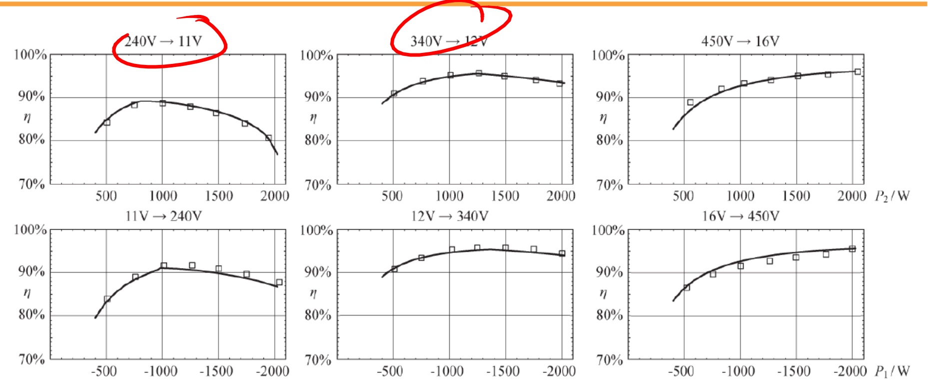


Fig. 12. (Solid lines) Predicted efficiencies and (□) measured efficiencies for different operating conditions. The efficiencies are calculated with the improved DAB loss model which includes all methods discussed in Section IV.

Alternate Modulation Schemes