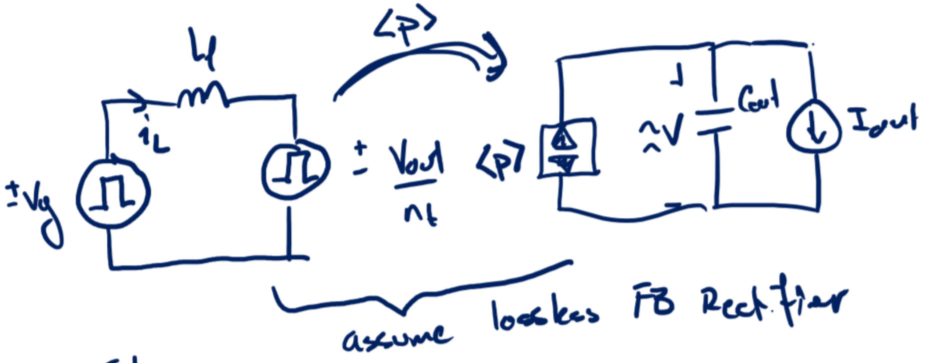
One Approach: Relaxing The Average

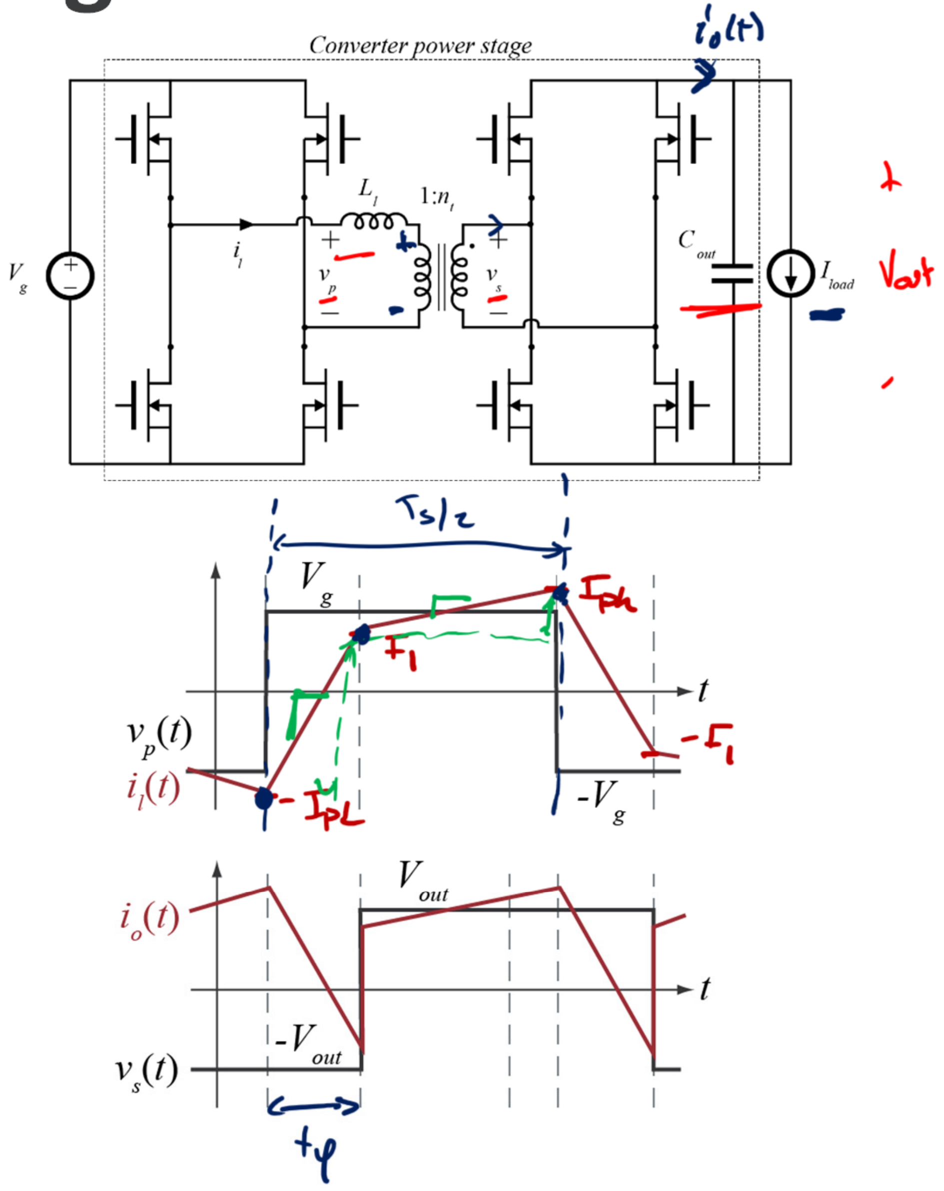


$$\langle p \rangle = \frac{2}{T_s} \int_0^{T_s/2} i_L(t) \cdot \frac{v_s(t)}{n_t}\, dt$$

$$= \frac{2}{T_s} \frac{1}{n_t} \left[(-V_{out}) \frac{-I_{pk} + I_1}{2} (t_\varphi) + \frac{I_1 + I_{pk}}{2} (V_{out}) \left(\frac{T_s}{2} - t_\varphi \right) \right]$$

$$= \frac{V_{out}}{n_t T_s} \left[(I_{pk} - I_1)\, t_\varphi + (I_1 + I_{pk}) \left(\frac{T_s}{2} - t_\varphi \right) \right]$$

$$\begin{cases} I_{pk} - I_1 = \dfrac{V_g - \frac{V_{out}}{n_t}}{L_\ell} \left(\dfrac{T_s}{2} - t_\varphi \right) \\ I_{pk} + I_1 = \dfrac{V_g + \frac{V_{out}}{n_t}}{L_\ell}\, t_\varphi \end{cases}$$



$$\langle p \rangle = \frac{V_{out}}{n_t T_s}\left[\frac{V_g - \frac{V_{out}}{n_t}}{L_\ell} t_\varphi \left(\frac{T_s}{2} - t_\varphi\right) + \frac{V_g + \frac{V_{out}}{n_t}}{L_\ell}\left(\frac{T_s}{2} - t_\varphi\right) t_\varphi \right]$$

$$\langle p \rangle = \frac{V_{out}}{n_t T_s L_\ell} t_\varphi \left(\frac{T_s}{2} - t_\varphi\right)\left[2 V_g \right]$$

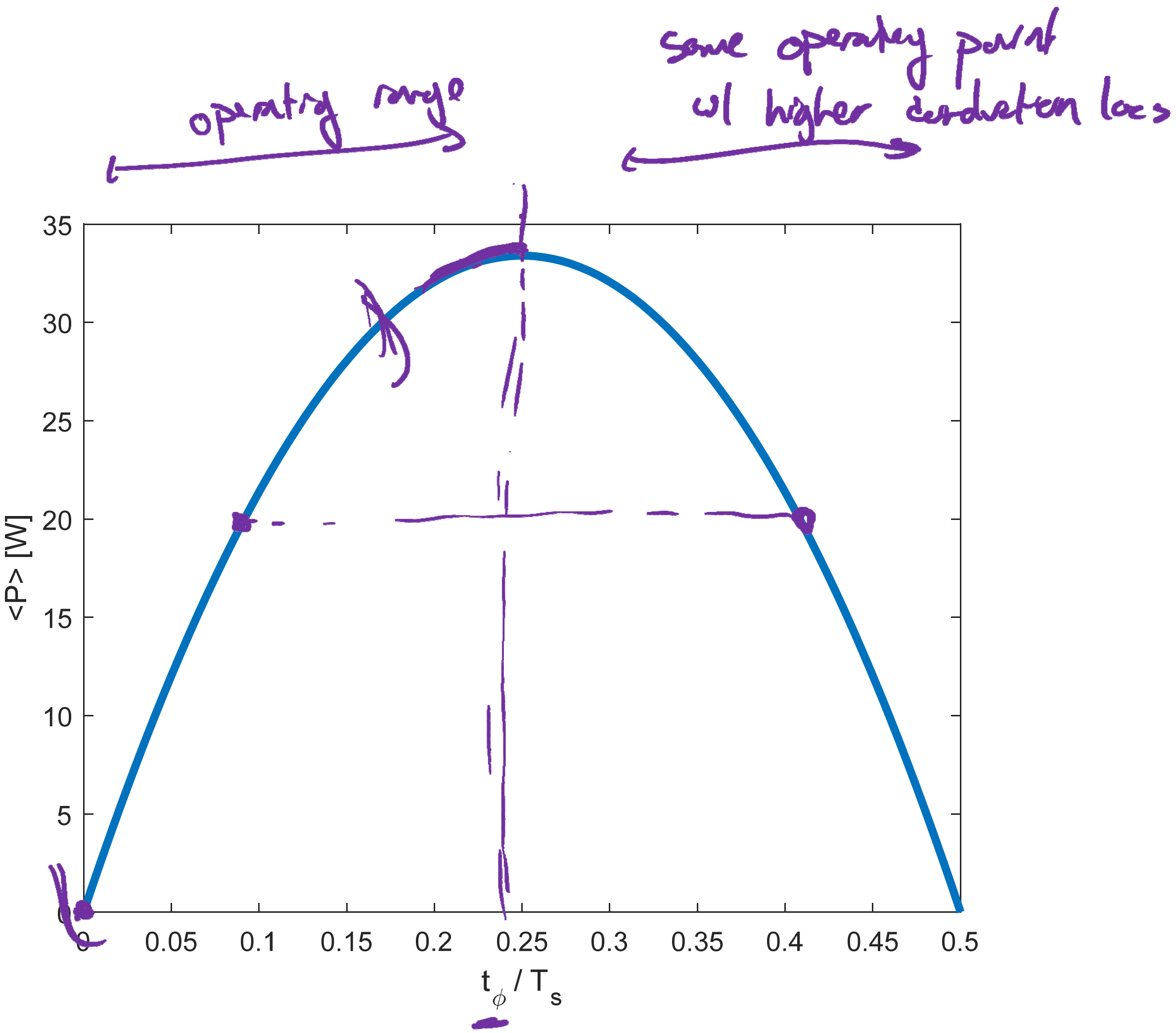
$$\langle p \rangle = \frac{V_{out} V_g}{n_t T_s L_\ell}\left(T_s t_\varphi - 2 t_\varphi^2\right)$$

$$\boxed{\langle i_o \rangle = \frac{\langle p \rangle}{V_{out}} = \frac{V_g}{n_t T_s L_\ell}\left(T_s t_\varphi - 2 t_\varphi^2\right)}$$

← $\langle i_o \rangle$ is independent of V_{out}

output looks like a current source

Output Power

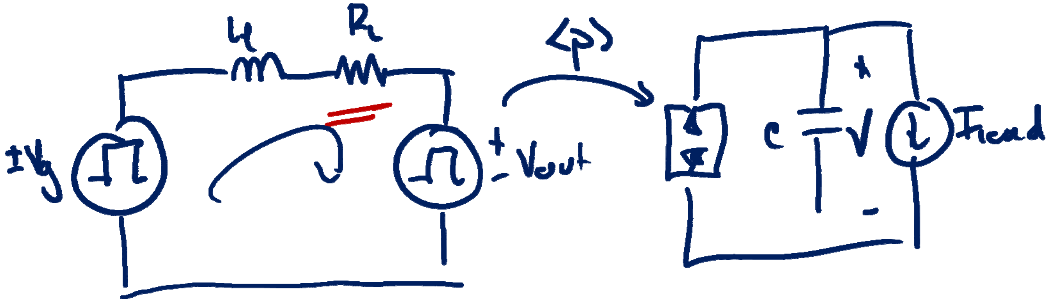


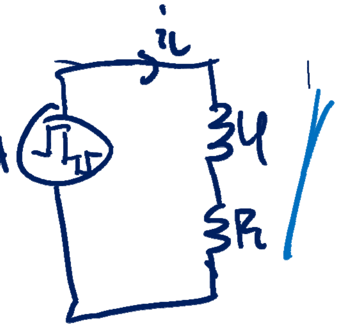
Including R_L

common in power electronics design

"high-η" approximation

Neglect all losses, solve converter, then calculate losses using your solution





$$v_x = \pm V_g - \pm V_{out}$$

$$v_x = L\frac{di_L}{dt} + i_L R_L$$

$$i_L(t) = \frac{v_x}{R_L} + C e^{-\frac{R_L}{L}t}$$

$$= f(v_x, I_{L0}, t)$$

for $i_L(t=0) = I_{L0}$

$$C = I_{L0} - \frac{v_x}{R_L}$$

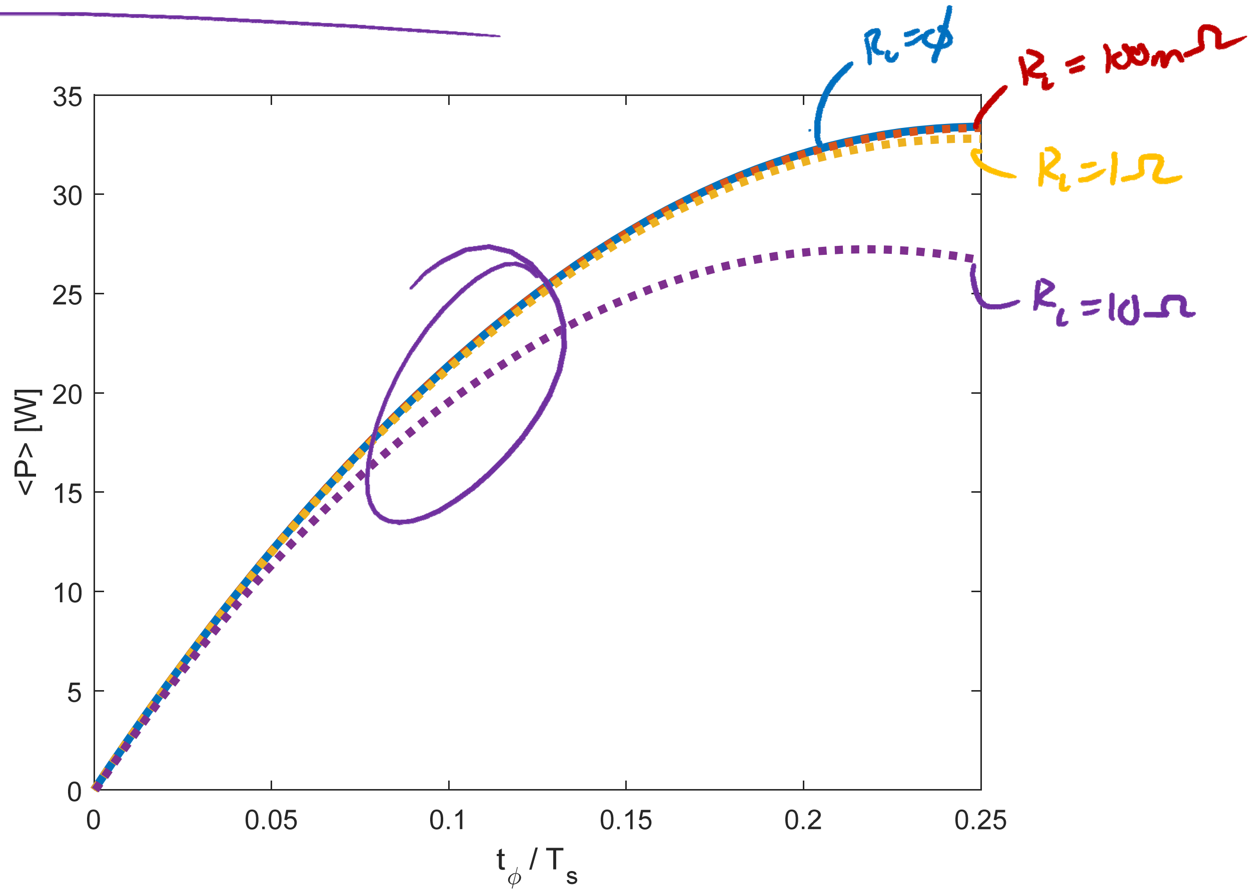
$$I_{pk} = f\left(V_g + \frac{V_{out}}{n_t}, I_1, \frac{T_s}{2} - t_\varphi\right)$$

$$I_1 = f\left(V_g - \frac{V_{out}}{n_t}, -I_{pk}, t_\varphi\right)$$

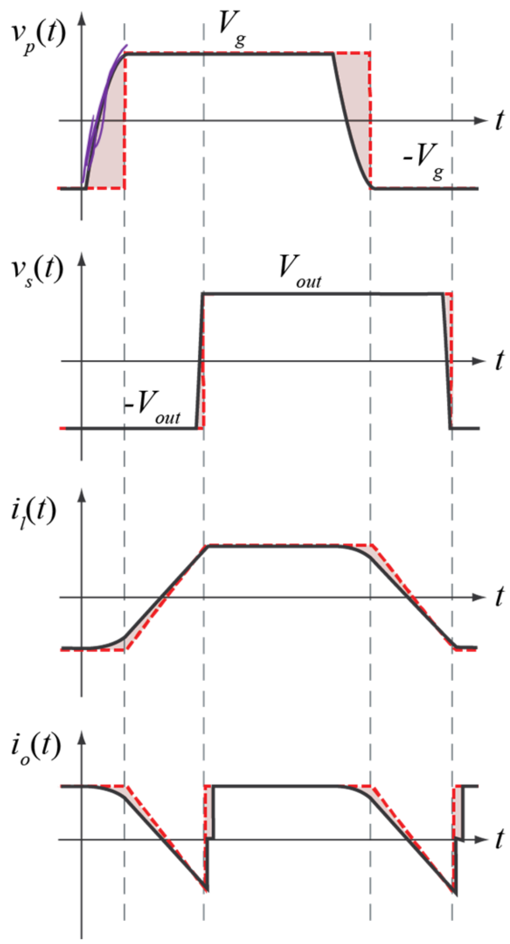
$$\langle p \rangle = \frac{2}{T_s}\left[\int_0^{t_\varphi} \left(-\frac{V_{out}}{n_t}\right) f\left(V_g + \frac{V_{out}}{n_t}, -I_{pk}, \tau\right) d\tau + \int_0^{\frac{T_s}{2} - t_\varphi} \frac{V_{out}}{n_t} f\left(V_g - \frac{V_{out}}{n_t}, I_1, \tau\right) d\tau\right]$$

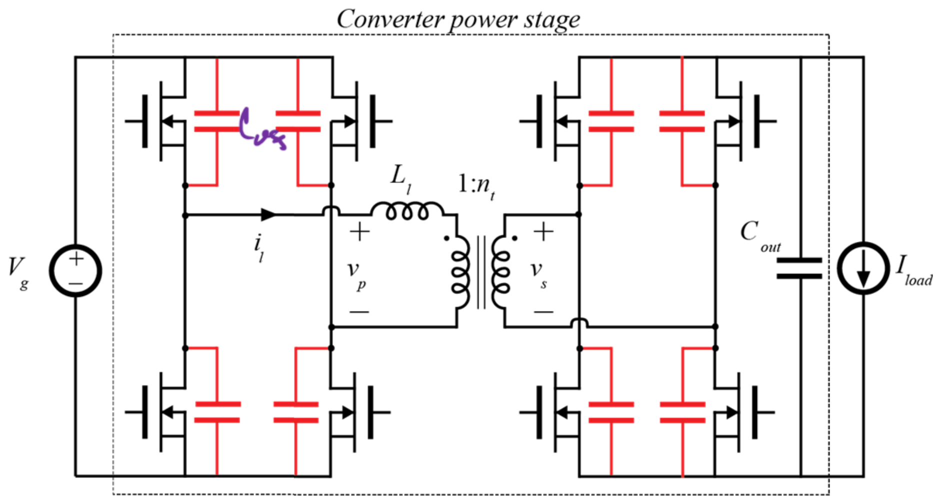
Including Losses

$$\langle P\rangle = \frac{nV}{R_L^2 T_s}\left(\frac{4L_l\left(\left(1+e^{\frac{R_L Ts}{2L_l}} - 2e^{\frac{R_L(-2t_\varphi+T_s)}{2L_l}}\right)V_g + \left(-1+e^{\frac{R_L Ts}{2L_l}}\right)nV\right)}{1+e^{\frac{R_L T_s}{2L_l}}} + R_L\left(-4t_\varphi Vg + T_s(V_g - nV)\right)\right)$$



DAB Operated at High Frequency





- At high switching frequency, resonant ZVS transitions become significant

State Plane Solution

Covered in ECE581

works for one resonance in any subinterval & a lossless converter

$$\alpha = \sin^{-1}\frac{2}{J_p}$$

$$\beta = \frac{1}{2}\left(J_2 + J_1\right)$$

$$\delta = n_t \sin^{-1}\frac{2n_t^2}{\frac{R_0'}{R_0}J_p}\sqrt{\frac{C_s}{C_p}}$$

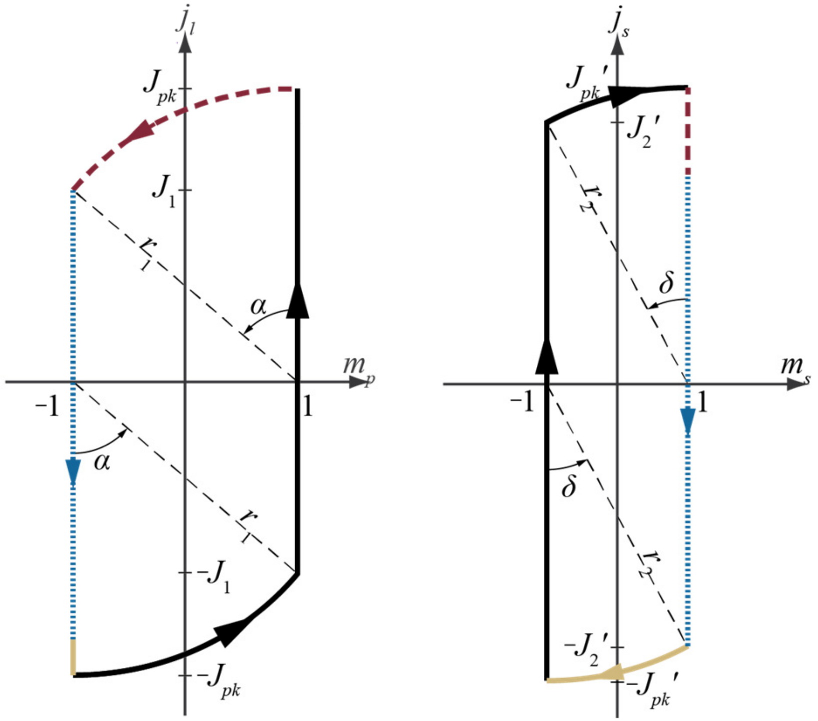
$$\zeta = \frac{F}{\pi} - \alpha - \beta - \delta$$

$$J_1 = \sqrt{J_p^2 - 4}$$

$$J_2 = \frac{R_0}{R_0'}\sqrt{\left(J_p\frac{R_0'}{R_0}\right)^2 - \left(2n_t\right)^2}$$

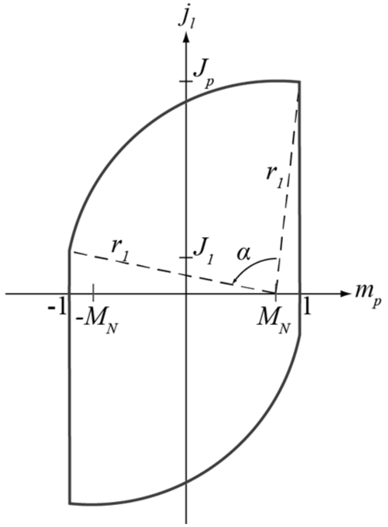
$$J = \frac{F}{\pi}\left[2 + \frac{1}{4}\left(J_1^2 - J_2^2\right) + J_p\left(\frac{\pi}{F} - \alpha - \beta - \delta\right)\right]$$

Primary | Secondary



Different Operating Modes

Mode I



$$J_1 = \sqrt{{J_p}^2 - 4M_N}$$

$$\alpha = \cos^{-1}\left(1 - \frac{(J_p - J_1)^2 + 4}{2{J_p}^2 + 2(1 - M_n)^2}\right)$$

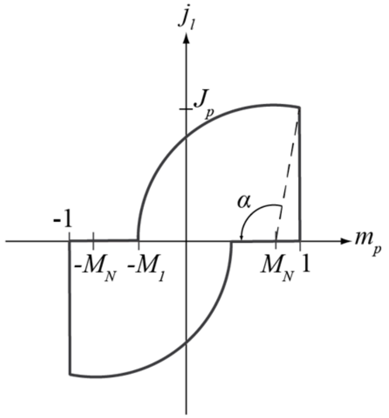
$$\beta = \frac{J_1 + J_2}{1 + M_N}$$

$$\zeta = \frac{J_p - J_2}{1 - M_N}$$

$$\frac{\pi}{F} = \alpha + \beta + \delta$$

$$J = \frac{\langle i_o \rangle}{I_{base}} = \frac{F}{n_t \pi}\left(2 + \frac{J_p + J_2}{2}\zeta + \frac{J_1 - J_2}{2}\beta\ .\right)$$

Mode II



$$M_1 = \sqrt{{J_p}^2 + (1 - M_N)^2} - M_N$$

$$\alpha = \cos^{-1}\left(1 - \frac{{J_p}^2 + (1 + M_1)^2}{2(M_1 - M_n)^2}\right)$$

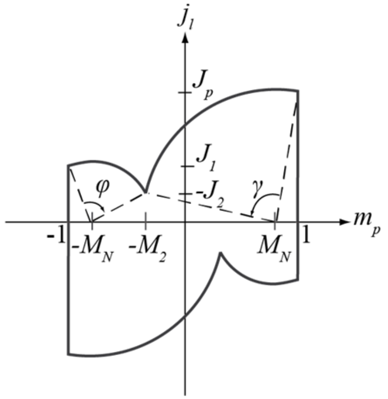
$$J = \frac{\langle i_o \rangle}{I_{base}} = \frac{F}{n_t \pi}\left(1 + M_1 + \frac{J_p + J_2}{2}\zeta - \frac{J_2}{2}\beta\right)$$

$$\beta = \frac{J_1 + J_2}{1 + M_N}$$

$$\zeta = \frac{J_p - J_2}{1 - M_N}$$

$$\frac{\pi}{F} = \alpha + \beta + \delta$$

Mode III



$$\gamma = \cos^{-1}\left(1 - \frac{(J_p + J_2)^2 + (1 + M_2)^2}{2(1 - M_n)^2 + 2{J_p}^2}\right)$$

$$\phi = \cos^{-1}\left(1 - \frac{(J_1 + J_2)^2 + (1 - M_2)^2}{2(M_n - M_2)^2 + 2{J_2}^2}\right)$$

$${J_2}^2 = (1 - M_N)^2 + {J_p}^2 - (M_2 + M_N)^2$$

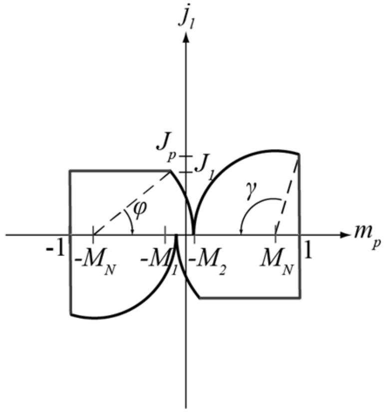
$${J_1}^2 = -(1 - M_N)^2 + {J_2}^2 + (M_N - M_2)^2$$

$$\zeta = \frac{J_p + J_1}{1 - M_N}$$

$$\frac{\pi}{F} = \gamma + \phi + \zeta = \alpha + \zeta$$

$$J = \frac{\langle i_o \rangle}{I_{base}} = \frac{F}{n_t \pi}\left(2M_2 + \frac{J_p - J_1}{2}\zeta\right)$$

Mode IV



$$\phi = \cos^{-1}\left(1 - \frac{{J_1}^2 + (M_1 - M_2)^2}{2(M_n - M_2)^2}\right)$$

$$J = \frac{\langle i_o \rangle}{I_{base}} = \frac{F}{n_t \pi}\left(2M_2 + 1 - M_1 + \frac{J_p - J_1}{2}\zeta\right)$$

$${J_2}^2 = (1 - M_N)^2 + {J_p}^2 - (M_2 + M_N)^2$$

$${J_1}^2 = -(1 - M_N)^2 + {J_2}^2 + (M_N - M_2)^2$$

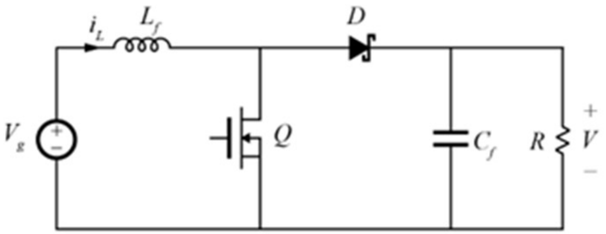
$$\zeta = \frac{J_p + J_1}{1 - M_N}$$

$$\frac{\pi}{F} = \gamma + \phi + \zeta = \alpha + \zeta$$

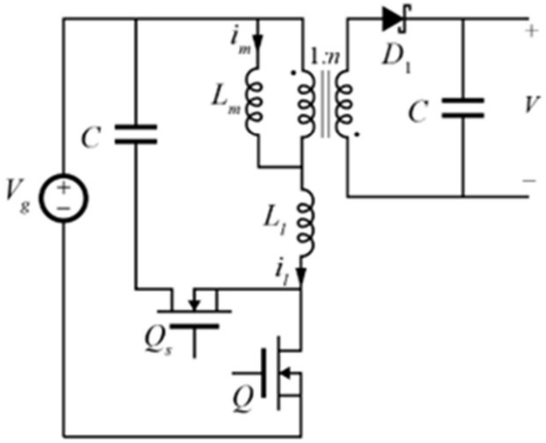
D Costinett, D. Maksimovic, and R Zane, “Design and Control for High Efficiency in High Step-Down Dual Active Bridge Converters Operating at High Switching Frequency,” *Trans. On Pwr. Elec*. 2013

Different Topologies

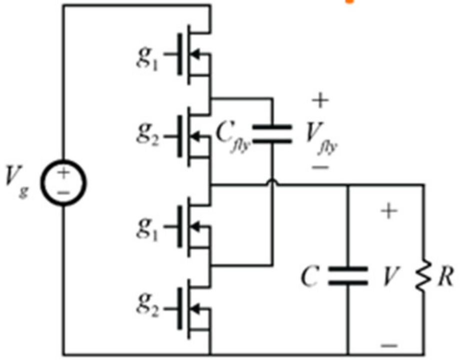
PWM



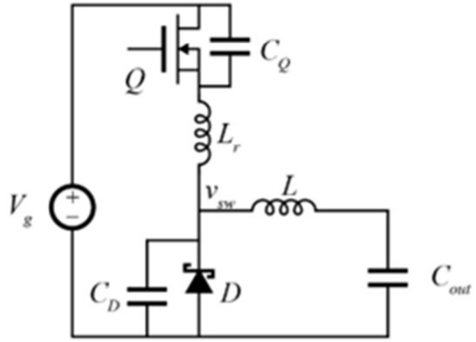
Quasi-Resonant



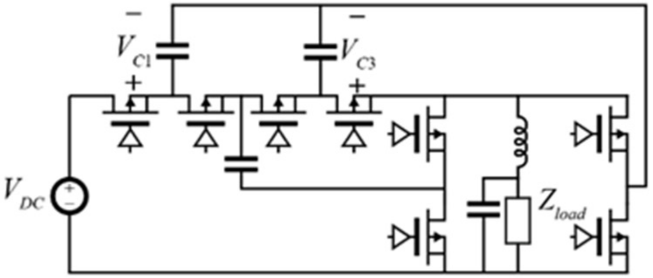
Switched-Capacitor



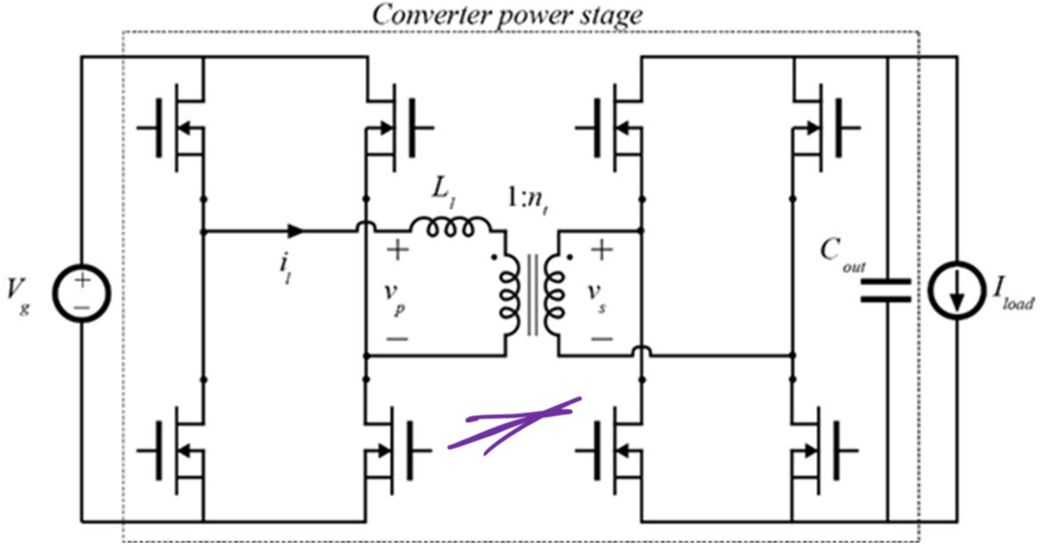
Multi-Resonant



Hybrid Switched-Capacitor



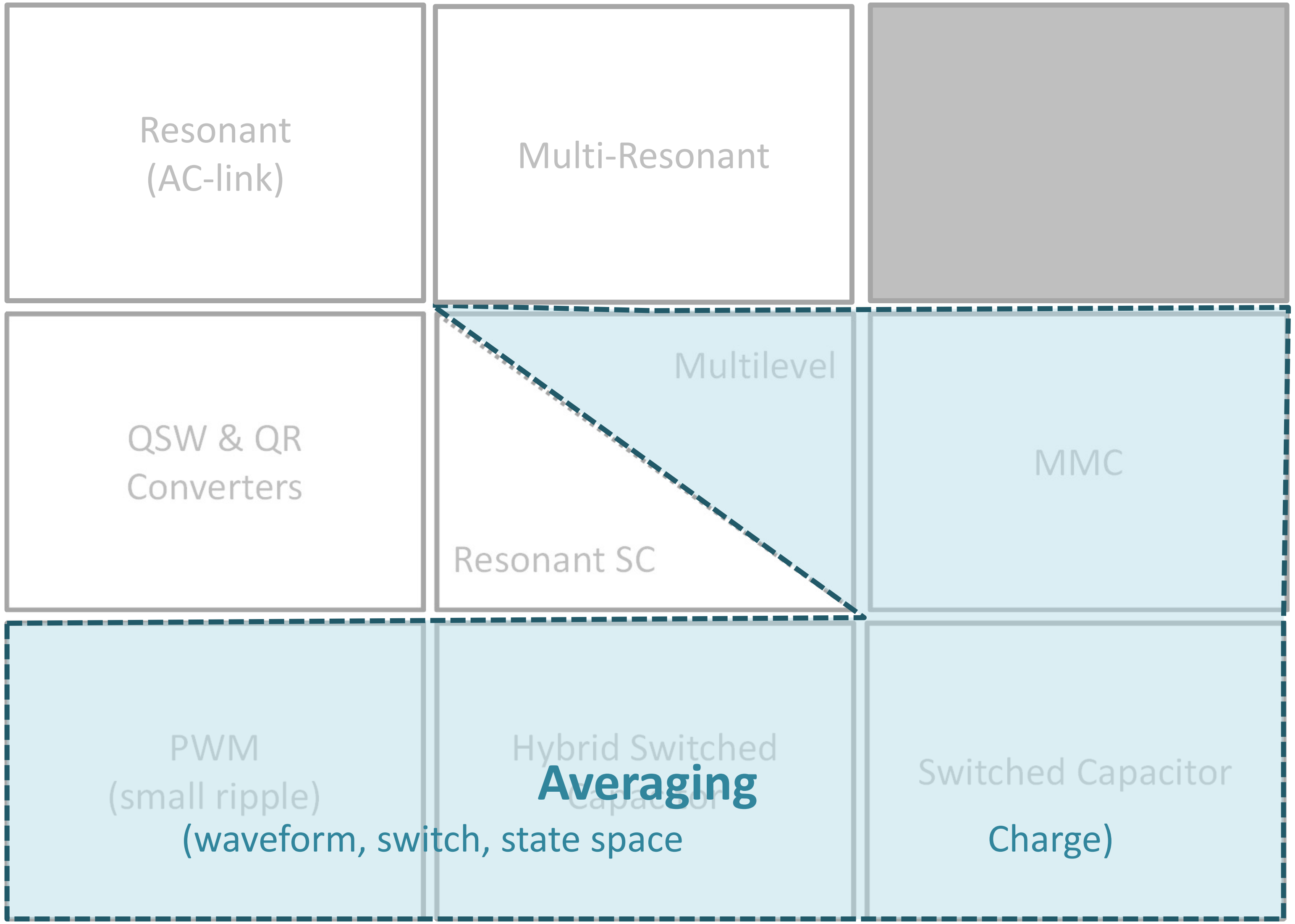
AC-Link



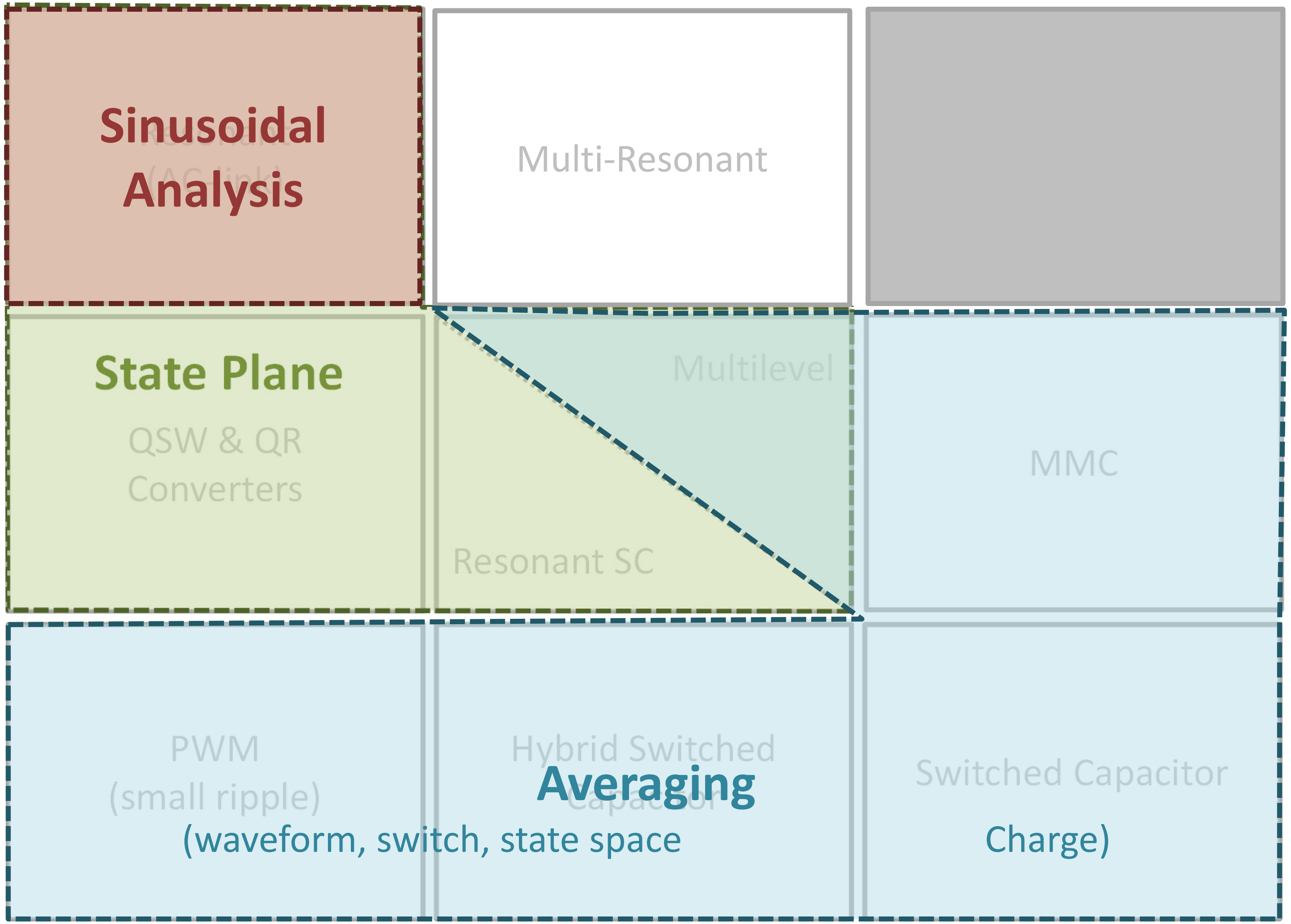
Converter Analysis

Resonant (AC-link)	Multi-Resonant	Z-source, matrix, others
QSW & QR Converters	Multilevel / Resonant SC	MMC
PWM (small ripple)	Hybrid Switched Capacitor	Switched Capacitor

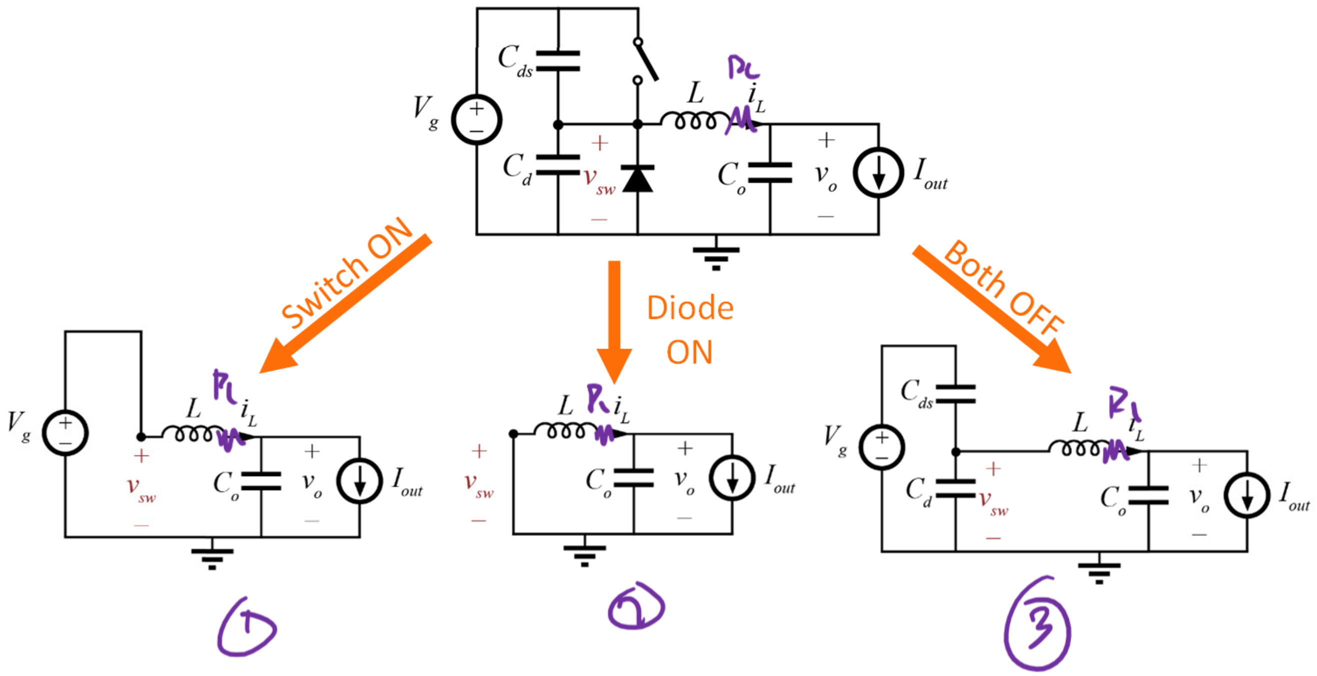
Converter Analysis



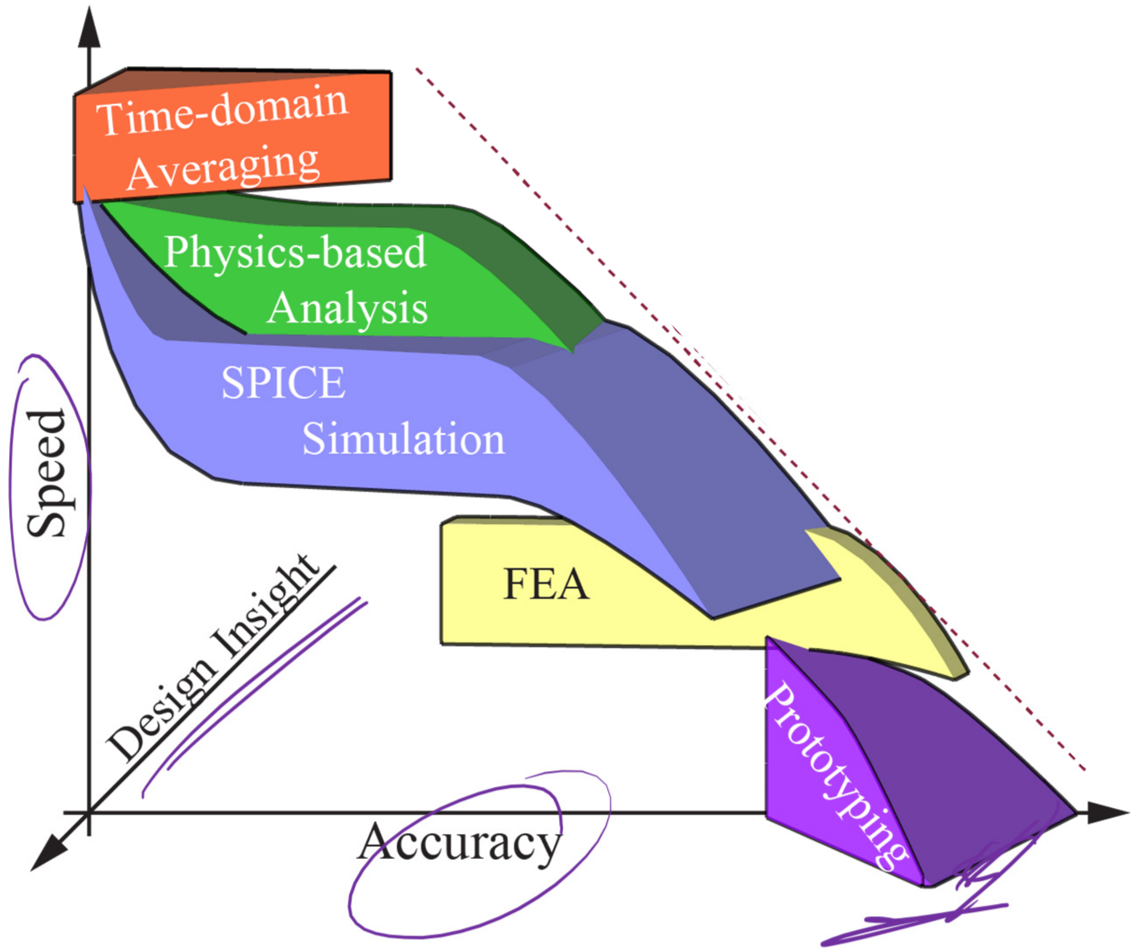
Converter Analysis



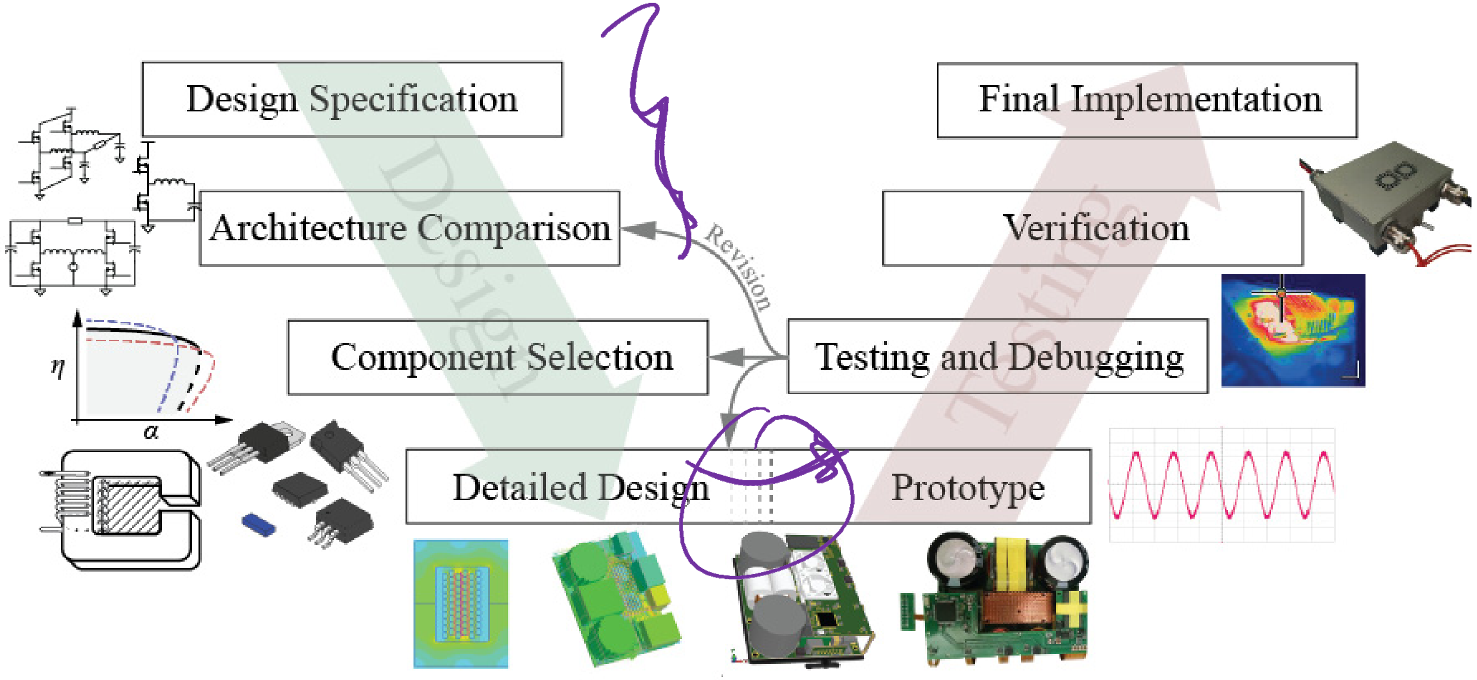
High-level View



Purposes Of Analysis



The Design "V"


Design Specification
Architecture Comparison
Component Selection
Detailed Design
Final Implementation
Verification
Testing and Debugging
Prototype
Design
Testing
Revision
η
α