Errata/Notes for *Switched Inductor Power IC Design*

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Sec. 1.1.3: Conductors like metal conduct charge easily because valence electrons are so weakly bound to their home sites that they are practically free and available for conduction. Ions in aqueous solutions of salts behave like these valence electrons, so they are also conductors.

Sec. 1.1.4.C: Since intrinsic molecules also scatter with temperature, molecular resistance rises with temperature. So mobility increases with the thermal energy of valence electrons in impurity atoms until the molecular resistance of the lattice overcomes this energy. This inflection temperature, where the effects balance and past which mobility falls, climbs with higher doping concentration.

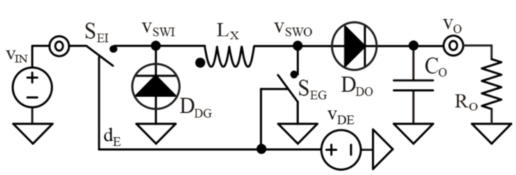
Ex. 3.3: ...t_E, t_D, and i_L's variation when...$i_{L(AVG)}$ is 25 mA, t_{SW} is 1 μs, and...

$$i_{L(AVG)} = 25\ \text{mA} < \frac{\Delta i_L}{2} = \frac{66\text{m}}{2} = 33\ \text{mA}$$

Sec. 3.2.6: Body terminals should connect to source/drain terminals so the body diodes that remain block undesired current conduction. These connections should therefore short the body diodes that would otherwise conduct undesired currents.

Ex. 3.4: $R_{SER} < ... = 1.2\ \Omega ... R_{CH} < ... = 500\ \text{m}\Omega ... t_{SW} < 10\%(0.25)t_{LC} = ... f_{SW} > 620$ kHz

Ex. 3.5–3.6: Circuit simulated with SPICE code:



Eq. 3.34: $v_{SWI(AVG)} = v_{IN}d_E'...$

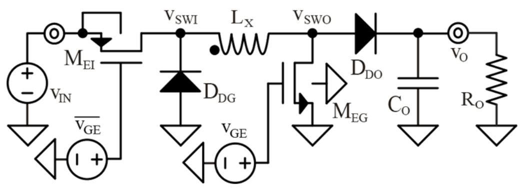
Eq. 3.35: $v_{SWO(AVG)} = (0)d_E'...$

Eq. 3.36: $$\frac{d_E'}{d_D'} = \frac{v_D}{v_E} = \frac{v_O + v_{DG} + v_{DO}}{v_{IN}} = ...$$

Eq. 3.37: $$d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DG} + v_{DO}}{v_{IN} + v_O + v_{DG} + v_{DO}} > d_E$$

Ex. 3.7: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DG} + v_{DO}}{v_{IN} + v_O + v_{DG} + v_{DO}} = ...$

Circuit simulated with SPICE code:



Eq. 3.39: $v_{SWI(AVG)} = v_{IN} d_E''...$

Eq. 3.40: $v_{SWO(AVG)} = (0) d_E''...$

Eq. 3.41: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O}{v_{IN} + v_O}...$

Ex. 3.8: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O}{v_{IN} + v_O}...$

Eq. 3.47: $v_O = v_{SWI(AVG)} = v_{IN} d_E'...$

Eq. 3.48: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DG}}{(v_{IN} - v_O) + (v_O + v_{DG})} = \frac{v_O + v_{DG}}{v_{IN} + v_{DG}} > d_E$

Ex. 3.10: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DG}}{v_{IN} + v_{DG}} = ...$

Eq. 3.50: $v_O = v_{SWI(AVG)} = v_{IN} d_E''...$

Eq. 3.51: $d_E'' = \frac{v_D}{v_E + v_D} = \frac{v_O}{v_{IN}} + ...$

Ex. 3.11: $d_E'' = \frac{v_D}{v_E + v_D} = \frac{v_O}{v_{IN}} + ...$

Eq. 3.58: $v_{IN} = v_{SWO(AVG)} = (0) d_E'...$

Eq. 3.59: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DO} - v_{IN}}{v_{IN} + (v_O + v_{DO} - v_{IN})} = ...$

Ex. 3.13: $d_E' = \frac{v_D}{v_E + v_D} = \frac{v_O + v_{DO} - v_{IN}}{v_{IN} + (v_O + v_{DO} - v_{IN})} = ...$

Eq. 3.61: $v_{IN} = v_{SWO(AVG)} = (0) d_E''...$

Eq. 3.62: $d_E'' = \frac{v_D}{v_E + v_D} = \frac{v_O - v_{IN}}{v_O} + ...$

Ex. 3.14: $d_E'' = \frac{v_D}{v_E + v_D} = \frac{v_O - v_{IN}}{v_O} + ...$

Eq. 4.2: $\sigma_R \equiv ...$

Eq. 4.10: $i_{L(PK)} = \sqrt{2 d_E \left(\frac{v_E}{L_X}\right) t_{SW} i_{L(AVG)}} = \sqrt{2\left(\frac{v_D \parallel v_E}{L_X}\right) t_{SW} \left(\frac{i_{O(AVG)}}{d_O}\right)}$

Ex. 4.1–4.2, 4.5: Results are approximations because R_L and R_E are unaccounted non-idealities in d_E – d_E should be higher. Approximations are not bad because v_R is a small fraction of v_E and v_D.

Sec. 4.3.2.C: In steady state, i_O supplies a static or regulated load, so i_O is $i_{O(AVG)}$ and Δi_O is zero.

Fig. 4.20: Static i_O is $i_{O(AVG)}$.

Ex. 4.5: $\sigma_{RC} = \frac{P_{RC}}{(i_O / d_O) d_{IN} v_{IN}} = \frac{13m}{(250m/50\%)(1)(2)} = 1.3\%$

Eq. 4.25: $P_{RC(DO)} = ... = {i_O}^2 R_C \left[1 - d_D\left(\frac{t_C}{t_{SW}}\right)\right] + \left[\left(\frac{i_{L(PK)}}{2} - i_O\right)^2 + \left(\frac{0.5 i_{L(PK)}}{\sqrt{3}}\right)^2\right] R_C d_D \left(\frac{t_C}{t_{SW}}\right)$

Ex. 4.6: $P_{RC(DO)} = {i_O}^2 R_C \left[1 - d_D\left(\frac{t_C}{t_{SW}}\right)\right] + \left[\left(\frac{i_{L(PK)}}{2} - i_O\right)^2 + \left(\frac{0.5 i_{L(PK)}}{\sqrt{3}}\right)^2\right] R_C d_D \left(\frac{t_C}{t_{SW}}\right) = ...$

Ex. 4.7, 4.9, 4.14: …ideal synchronous boost…

Ex. 4.8: …ideal synchronous buck…

$$t_C = \left(\frac{i_{L(PK)}}{d_E}\right)\left(\frac{L_X}{v_E}\right) \approx 450 \text{ ns}$$

Re-calculate d_E:$i_{L(PK)}$:t_C and iterate until values match:

→ $d_E = 52\%$, $i_{L(PK)} = 46$ mA, $t_C = 440$ ns

$$P_{DT} \approx i_{L(PK)} v_{DG} \left(\frac{t_{DT}}{t_{SW}}\right) = (46m)(700m)\left(\frac{50n}{1\mu}\right) = 1.6 \text{ mW}$$

$$\sigma_{DT} = \frac{P_{DT}}{d_{IN}\left(i_{O(AVG)}/d_O\right) v_{IN}} = \frac{1.6m}{(52\%)(10m/1)(4)} = 7.7\%$$

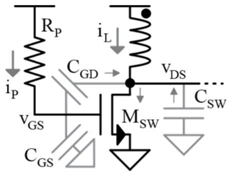
Fig. 4.22: 

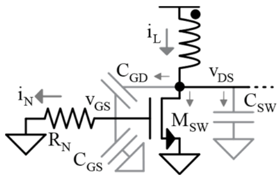
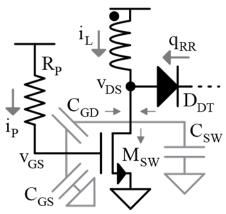
Fig. 4.23: 

Fig. 4.24: 

Eq. 4.37–4.42: When i_P isn't negligible, i_P raises i_{DS} & the $v_{TH(C)}$ that sets $t_{I(C)}$.

Eq. 4.42: $t_{I(C)} \approx t_{TH(C)} - t_{T0} = ...$

Ex. 4.9: SPICE: …id(Meg) often includes C_{GD}'s and D_{DB}'s currents.

Eq. 4.45, 4.47: When i_N isn't negligible, i_N reduces i_{DS} & the $v_{TH(O)}$ that sets $t_{I(O)}$.

Eq. 4.47: $t_{I(O)} \approx t_{T0} - t_{TH(O)} = ...$

Ex. 4.14: SPICE: vdo do 0 dc=1 pulse 0 1 565n 1n 1n 385n 1u

Eq. 4.66: $q_G \approx (C_{GS} + C_{GB} + C_{GD})v_{DD} + C_{GD(SAT)}\Delta v_{SW}$

Ex. 4.18: …ideal synchronous buck–boost…

$$d_{IN} = d_E = \frac{v_O}{v_{IN} + v_O} + ...$$

$d_O = d_D = 1 – d_E = 1 – 68\% = 32\%$

$$\Delta i_L = ... = \left(\frac{v_{IN}}{L_X}\right) d_E t_{SW} = \left(\frac{2}{10\mu}\right)(68\%)(1\mu) = 140 \text{ mA}$$

$\Delta v_{SWI} = v_{DG} = 400$ mV

$q_G \approx ... = \{(210p)(400m) + [2(210p) + 1.3n](2)\}W_{CH} = (3.5n)W_{CH}$

P_G, W_{DG}, R_{DG}, P_{MOS}, & σ_{MOS} with new q_G

$\approx$ (7.0m)W_{CH}, 110 mm, 5.4 mΩ, 1.5 mW, 0.14%

Eq. 5.55: $A_{G-} \equiv \left.\frac{i_G}{v_{IN}}\right|_{v_O=0} \equiv \left.\frac{i_{G0} - i_B}{v_{IN}}\right|_{v_O=0} = A_{G0} - \frac{1}{Z_B} = A_{G0}\left(1 - \frac{sC_B}{A_{G0}}\right) = A_{G0}\left(1 - \frac{s}{2\pi z_{C-}}\right)$

Eq. 5.64: $\ldots \frac{1}{2\pi R_C C_O} \equiv f_C \ldots$

Ex. 5.9: $f_C = \frac{1}{2\pi R_C C_O} \ldots = 3.2$ MHz

$f_{CP} < z_L < f_{LC} < f_C \quad \therefore \quad \ldots < z_C = f_C$

Ex. 5.10: …f_C = 3.2 MHz…from previous example

$f_{LC} < z_L < f_C \quad \therefore \quad \ldots < z_C = f_C$

Ex. 5.11: …f_C = 3.2 MHz…from previous example

or $Q_{LC} = \frac{f_{LC}}{f_{CP}} = 2\pi\left(R_C + R_{LD}\right)C_O f_{LC} = 2\pi(75m + R_{LD})(5\mu)(22k) \le 1$

$\therefore \quad R_{LD} \le 1.4\ \Omega$

$\ldots < z_C = f_C$

Ex. 5.12: $f_C = \frac{1}{2\pi R_C C_O} \ldots = 3.2$ kHz

$z_L < f_{CP} < f_C < f_{LC} \ldots$

Ex. 5.13: …f_C = 3.2 MHz…from previous example

$f_{CP} < f_L < f_{LC} < f_C \quad \therefore \quad \ldots < z_C = f_C$

$$A_{G(LC)} \approx \frac{1}{R_L + \left(R_C \parallel R_{LD}\right)} = \frac{1}{50m + (10m \parallel 100)} = \ldots$$

$$A_{V(LC)} = A_{G(LC)}\left(\frac{1}{2\pi f_{LC} C_O} \parallel R_{LD}\right) = (17)\left(\frac{1}{2\pi(22k)(5k)} \parallel 100\right) = \ldots$$

Ex. 5.14: …f_C = 3.2 MHz…from previous example

$\ldots < z_C = f_C$

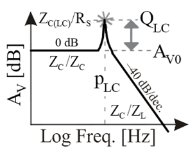
Ex. 5.15: $$Q_{LC} = \frac{f_{LC}}{f_{CP}} = 2\pi\left(R_C + R_{LD}\right)C_O f_{LC} = 2\pi(10m + R_{LD})(5\mu)(22k) \le 1$$

or $$Q_{LC} = \frac{f_{LP}}{f_{LC}} = \frac{R_L + R_{LD}}{2\pi L_X f_{LC}} = \frac{50m + R_{LD}}{2\pi(10\mu)(22k)} \le 1$$

Ex. 5.16: $$f_C = \frac{1}{2\pi R_C C_O} \ldots = 3.2\text{ kHz}$$

$\ldots f_{CS} < z_C = f_C < f_{LC} \ldots$

Fig. 5.27:



Eq. 5.90: $$i_l' \equiv \ldots = d_e' A_L = d_e'\left(\frac{\partial i_L}{\partial d_E}\right)\Bigg|_{v_o=0} = \ldots$$

Eq. 5.98: k_d is the small-signal fraction of T_E, T_C, and $I_{L(PK)}$.

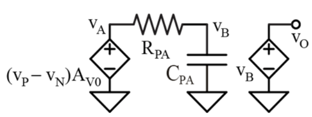
Eq. 5.100: $$P_{RO} = \ldots \equiv \frac{E_{LX}}{T_{SW}} = \ldots$$

Eq. 5.109: $$A_{VO} \equiv \ldots = \left(\frac{V_E + V_D}{D_O}\right)\left(\frac{1 - s/2\pi z_{DO}}{1 + s/2\pi p_{SW}}\right)\left\{\frac{(Z_C + R_C) \parallel R_{LD}}{Z_{LO} + R_{LO} + \left[(Z_C + R_C) \parallel R_{LD}\right]}\right\}$$

Eq. 5.115: $A_{VO} \equiv \ldots = \ldots = A_{LI} \ldots \approx \ldots$

Ex. 5.19: $A_{VO0} = A_{LI}(R_{DO} \parallel R_{LD}) \approx \ldots$

Sec. 6.2.1: SPICE Model for Op Amp's A_{V0} and p_A:

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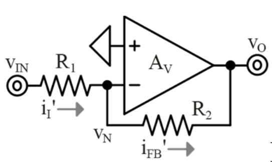
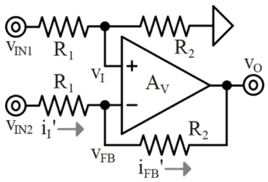
* AV = 1 kV/V, pA = 42 kHz
eav0 vo 0 vp vn 1000
rpa va vb 1
cpa vb 0 3.791u
eavo vo 0 vb 0 1
```

Fig. 6.16:



Note: i_I' carries i_I.

Fig. 6.19: 

Note: i_I' carries i_I.

Eq. 6.59: $|A_\beta| \ldots \leq |A_F| \ldots$

Eq. 6.60: $|A_F| \ldots \leq |A_\beta| \ldots$

Eq. 6.75: $\ldots \leq |A_{F0}| \ldots$

Eq. 6.80: The PWM is usually the culprit that imposes $p_{PWM} \approx p_{SW}$, so $A_{PWM} \equiv \ldots \approx \frac{1/v_{EO(PP)}}{1+s/2\pi p_{SW}}$

Eq. 6.81: $$A_{SL(CCM)} \equiv \frac{v_o}{d_e'} \approx \left(\frac{V_E+V_D}{D_O}\right)\left(\frac{R_{LD}}{R_{LO}+R_{LD}}\right)\left\{\frac{(1+s/2\pi z_C)(1-s/2\pi z_{DO})}{\left[(s/2\pi p_{LC})^2+s/2\pi p_{LC}Q_{LC}+1\right]}\right\}$$

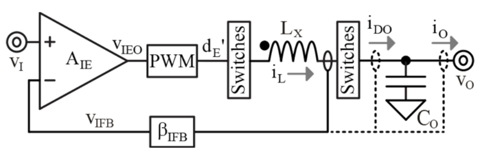
Ex. 6.8: $C_O = 5\ \mu F$

Sec. 6.4.4: Current-mode loops usually regulate i_L (instead of i_{DO}) to exclude the effects of z_{DO}, which would otherwise compromise the stability of the current loop.

Eq. 6.87: $$A_{LG} \equiv \frac{v_{FB}}{v_E} = \ldots = \ldots \approx \frac{A_E A_{G0} D_O R_{LD} \beta_{FB}(1-s/2\pi z_{DO})(1+s/2\pi z_C)}{(1+s/2\pi p_G)(1+s/2\pi p_{SW})(1+s/2\pi p_{CP})}$$

Eq. 6.90: $$A_{SL(DCM)} \equiv \frac{v_o}{d_e'} \approx \left(\frac{I_{L(PK)}}{D_E}\right)(R_{DO} \parallel R_{LD})\left(\frac{1+s/2\pi z_C}{1+s/2\pi p_{CS}}\right)$$

Eq. 6.93: In general, $i_{L/DO/O} = \ldots$

Fig. 6.43: 

Eq. 6.94: A_{IL} excludes p_{SW} (which the PWM usually imposes on A_{LG}):

$$A_{IL(CCM)} \equiv \frac{i_l}{d_e'} = \ldots = \ldots = \ldots \approx \left[\frac{V_E+V_D}{D_O{}^2(R_{LO}+R_{LD})}\right]\left[\frac{1+s/2\pi z_{CP}}{(s/2\pi p_{LC})^2+s/(2\pi p_{LC}Q_{LC})+1}\right]$$

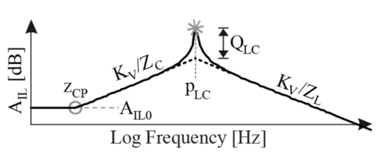
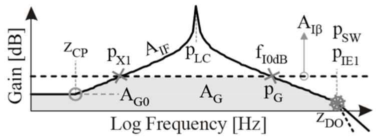
Fig. 6.44: 

Fig. 6.45:



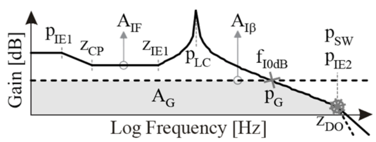
Note: A_{IF} includes z_{DO}.

Eq. 6.98: $|A_{IF}| \ldots \geq |A_{I\beta}| \ldots$

Ex. 6.17: $A_{G0} = \ldots \approx \ldots = 370$ mA/V $= \ldots$

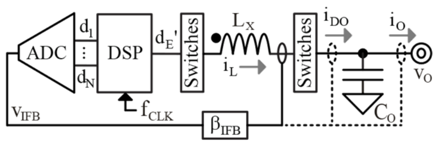
Eq. 6.100: $|A_{IF}| \ldots \leq |A_{I\beta}| \ldots$

Fig. 6.46:



Note: A_{IF} includes z_{DO}.

Fig. 6.49:

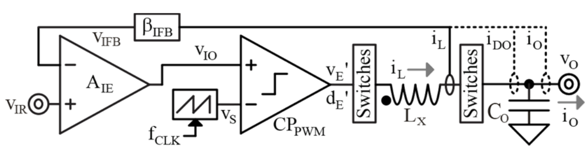


Eq. 7.6: $K_{VO} \equiv \ldots = \Delta v_{ID}\left(\frac{A_{V0}}{V_{OH} - V_{OL}}\right) \geq 1$

Ex. 7.1: SPICE: vs … pulse 200m 500m 0 999n 1n 0n 1u

Sec. 7.1.1.D: β_{FBI} should be β_{IFB}.

Fig. 7.9:

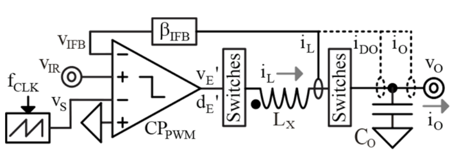


Ex. 7.2: SPICE: vs … pulse 200m 500m 0 999n 1n 0n 1u

Sec. 7.1.2.C: β_{FBI} should be β_{IFB}.

Ex. 7.4: $v_{O(AVG)} = \ldots = \ldots = 1.80\ V \pm 31$ mV

Fig. 7.20:



Ex. 7.8: $v_{IOS} = \ldots = \ldots = 335$ mV

$v_{VOS} \approx \ldots = \ldots = 635 \pm 200$ mV

$v_{FB(AVG)} \approx \ldots = \ldots = 565 \pm 200$ mV

$$\beta_{FB} \equiv \frac{\overline{v_{FB(AVG)}}}{v_{O(AVG)}} = \frac{565m}{1.8} = 31.4\%$$

$$v_{O(AVG)} = \frac{v_{FB(AVG)}}{\beta_{FB}} = \frac{565m}{31.4\%} = 1.80 \text{ V} \pm 640 \text{ mV}$$

Ex. 7.10: **Note**: v_O is 1.80 V…

SPICE: vs … pulse 200m 500m 0 999n 1n 0n 1u

Eq. 7.56: $v_{VOS} \equiv v_R - v_{FB(AVG)} = \ldots$

Eq. 7.80: Δv_O is also the ripple $i_{C(AC)}$'s average produces when $i_{C(AC)}$ is positive. Since i_L ripples across Δi_L in CCM and $i_{L(AC)}$ is positive across half of t_{SW}, $i_{C(AC)}$ peaks with $0.5\Delta i_L$ and averages half of that across $0.5t_{SW}$. So Δv_O is effectively the ripple $\Delta i_L/4$ produces across $t_{SW}/2$:

$$\Delta v_O = \left(\frac{0.5\Delta i_L}{2}\right)\left(\frac{t_{SW}}{2}\right)\left(\frac{1}{C_O}\right) = \frac{\Delta i_L}{8 f_{SW} C_O}$$

Sec. 8.1.1.C: $\beta_{IFB(MF)}$ is greater than R_L when sL_X overcomes R_L before C_F shorts with respect to R_F.

Sec. 8.2.2: p_{FB} should be p_{FBX}.

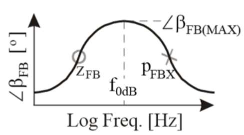


Fig. 8.10:

Sec. 8.3.3.D: t_P is usually much lower than t_{SW}, so minimizing t_P is usually not as critical as minimizing power. And since P_{ST} is usually much lower than P_G and t_P is less sensitive to N, reducing and limiting N to three or five is not uncommon.

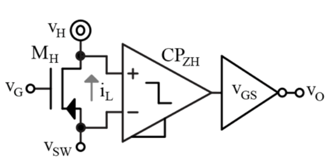
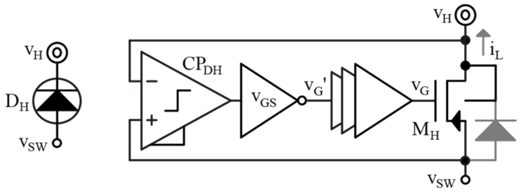


Fig. 8.33:

Fig. 8.36:



Appendix: **Note on MOSFET Model**: … C_{GS} currents. Drain and source currents also include drain– and source–body diode currents.