ΒΑΣΙΚΕΣ ΕΞΙΣΩΣΕΙΣ ΗΛΕΚΤΡΟΝΙΚΗΣ ΙΙΙ

Μάρτιος 2013

Τρανζίστορ N-MOS

$$i_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(v_{GS}-V_t)^2\left(1+\frac{v_{DS}}{V_A}\right)$$

$$= \frac{1}{2}\mu_n C_{ox}\frac{W}{L}v_{OV}^2\left(1+\frac{v_{DS}}{V_A}\right)$$

$$k_n' = \mu_n C_{ox}$$

$$g_m = (\mu_n C_{ox})\left(\frac{W}{L}\right)V_{OV} \qquad g_m = 2I_D/|V_{OV}|$$

$$r_o = |V_A|/I_D = V_A' L/I_D$$

$$r_{in}=\infty \quad (\text{στο συνεχές})$$

$$\omega_T = g_m/(C_{gs}+C_{gd})$$

$$C_{ov} = WL_{ov}C_{ox}$$

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1+\frac{V_{SB}}{V_0}}} \qquad C_{db} = \frac{C_{db0}}{\sqrt{1+\frac{V_{DB}}{V_0}}}$$

Τριοδική (ωμική):

$$C_{gs} = C_{gd} = \frac{1}{2}WL\,C_{ox}$$

Κορεσμού:

$$\left.\begin{aligned} C_{gs} &= \tfrac{2}{3}WL\,C_{ox} \\ C_{gd} &= 0 \end{aligned}\right\}$$

Αποκοπής:

$$\left.\begin{aligned} C_{gs} &= C_{gd} = 0 \\ C_{gb} &= WL\,C_{ox} \end{aligned}\right\}$$

Διπολικό τρανζίστορ (BJT) ($r_x \equiv r_{bb'}$, $r_\pi \equiv r_{b'e}$ $r_e \equiv r_d$)

V_A: Τάση Early, V_T= kT/q:Θερμική Τάση (~25mV για T=290°K)

$$i_C = I_S e^{v_{BE}/V_T}\left(1+\frac{v_{CE}}{V_A}\right) \qquad r_e = \frac{\alpha}{g_m} \qquad r_\pi = \frac{\beta}{g_m}$$

$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{V_T}{I_E} = \alpha\left(\frac{V_T}{I_C}\right) \qquad r_\pi = \frac{V_T}{I_B} = \beta\left(\frac{V_T}{I_C}\right) \qquad r_o = \frac{|V_A|}{I_C}$$

$$g_m = \frac{\alpha}{r_e} \qquad r_\pi = (\beta+1)r_e \qquad g_m + \frac{1}{r_\pi} = \frac{1}{r_e}$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{\beta+1} \qquad \beta+1 = \frac{1}{1-\alpha}$$

$$C_\pi + C_\mu = \frac{g_m}{2\pi f_T} \qquad C_\pi = C_{de}+C_{je} \qquad C_{de} = \tau_F g_m \qquad C_{je} \cong 2C_{je0}$$

$$C_\mu = C_{jc0}\Big/\left(1+\frac{V_{CB}}{V_{0c}}\right)^m, \quad m = 0.3\text{–}0.5$$

$$\omega_\beta = \frac{1}{(C_\pi + C_\mu)r_\pi}$$

$$\omega_T = \beta_0\omega_\beta$$

Διαφορικός ενισχυτής με MOS

$$v_{CM\max} = V_t + V_{DD} - \frac{I}{2}R_D$$

$$v_{CM\min} = -V_{SS} + V_{CS} + V_t + V_{OV}$$

$$i_{D1} = \frac{I}{2} + \left(\frac{I}{V_{OV}}\right)\left(\frac{v_{id}}{2}\right)\sqrt{1-\left(\frac{v_{id}/2}{V_{OV}}\right)^2}$$

$$i_{D2} = \frac{I}{2} - \left(\frac{I}{V_{OV}}\right)\left(\frac{v_{id}}{2}\right)\sqrt{1-\left(\frac{v_{id}/2}{V_{OV}}\right)^2}$$

$$i_d = \left(\frac{I}{V_{OV}}\right)\left(\frac{v_{id}}{2}\right) \qquad -\sqrt{2}V_{OV} \le v_{id} \le \sqrt{2}V_{OV}$$

Διαφορική έξοδος:

$$A_d \equiv \frac{v_{o2}-v_{o1}}{v_{id}} = g_m R_D \qquad \text{CMRR} = \infty$$

$$v_o = v_{o2} - v_{o1} = g_m(R_D \,\|\, r_o)v_{id}$$

Διαφορικός ενισχυτής με BJT

$$i_{E1} = \frac{I}{1+e^{-v_{id}/V_T}}$$

$$i_{E2} = \frac{I}{1+e^{v_{id}/V_T}}$$

Διαφορική έξοδος:

$$A_d = \frac{v_{c1}-v_{c2}}{v_d} = -g_m R_C \qquad A_d = -g_m(R_C \,\|\, r_o)$$

$$A_d = -\frac{\alpha(2R_C)}{2r_e+2R_e} \simeq -\frac{R_C}{r_e+R_e}$$

$$R_{id} = (\beta+1)(2r_e+2R_e) \qquad \text{CMRR} = \infty$$

$$R_{icm} \simeq (\beta+1)\left(R_{EE} \,\|\, \frac{r_o}{2}\right)$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = (2g_m R_{EE})\Big/\left(\frac{\Delta R_C}{R_C}\right)$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = (2g_m R_{SS})\Big/\left(\frac{\Delta R_D}{R_D}\right)$$

$$\text{CMRR} \equiv \left|\frac{A_d}{A_{cm}}\right| = (2g_m R_{SS})\Big/\left(\frac{\Delta g_m}{g_m}\right)$$

Απλή έξοδος:

$$|A_d| = \frac{1}{2} g_m R_D \qquad |A_{cm}| = \frac{R_D}{2R_{SS}}$$

$$\text{CMRR} \equiv \left|\frac{A_d}{A_{cm}}\right| = g_m R_{SS}$$

Τάση εκτροπής εισόδου:

$$V_{OS} = \sqrt{\left(\frac{V_{OV}}{2}\,\frac{\Delta R_D}{R_D}\right)^2 + \left(\frac{V_{OV}}{2}\,\frac{\Delta(W/L)}{W/L}\right)^2 + (\Delta V_t)^2}$$

Με ενεργό φορτίο:

$$R_o \equiv \frac{v_x}{i_x} = r_{o2} \| r_{o4}$$

$$A_d \equiv \frac{v_o}{v_{id}} = G_m R_o = g_m(r_{o2} \| r_{o4})$$

$$A_{cm} \equiv \frac{v_o}{v_{icm}} = -\frac{1}{2R_{SS}}\frac{r_{o4}}{1 + g_{m3} r_{o3}}$$

$$\text{CMRR} = (g_m r_o)(g_m R_{SS})$$

Απλή έξοδος:

$$A_d = \frac{v_{c1}}{v_d} = -\frac{1}{2} g_m R_C \qquad A_{cm} = -\frac{\alpha R_C}{2R_{EE}}$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| \simeq g_m R_{EE}$$

Τάση εκτροπής εισόδου:

$$V_{OS} = V_T\sqrt{\left(\frac{\Delta R_C}{R_C}\right)^2 + \left(\frac{\Delta I_S}{I_S}\right)^2}$$

Ρεύμα εκτροπής εισόδου:

$I_{OS} = I_B\left(\dfrac{\Delta\beta}{\beta}\right)$, **όπου:** $I_B \equiv \dfrac{I_{B1} + I_{B2}}{2} = \dfrac{I}{2(\beta + 1)}$

Με ενεργό φορτίο:

$$R_o \equiv \frac{v_x}{i_x} = r_{o2} \| r_{o4}$$

$$A_d \equiv \frac{v_o}{v_{id}} = G_m R_o = g_m(r_{o2} \| r_{o4})$$

$$A_{cm} \cong -\frac{r_{o4}}{\beta_3 R_{EE}} \qquad \text{CMRR} = \tfrac{1}{2}\beta_3 g_m R_{EE}$$

$$V_{OS} = -\frac{\alpha I/\beta_P}{\alpha I/2V_T} = -\frac{2V_T}{\beta_P}$$

Απόκριση στις χαμηλές συχνότητες

Κοινής πηγής:

$$A_M \equiv \frac{V_o}{V_{\text{sig}}} = -\frac{R_G}{R_G + R_{\text{sig}}} g_m(r_o \| R_D \| R_L)$$

$$\omega_{P1} = \omega_0 = \frac{1}{C_{C1}(R_G + R_{\text{sig}})}$$

$$\omega_{P2} = \frac{g_m}{C_S}$$

$$\omega_{P3} = \frac{1}{C_{C2}(R_D + R_L)}$$

Κοινού εκπομπού:

$$A_M = \frac{V_o}{V_{\text{sig}}} = -\frac{(R_B \| r_\pi)}{(R_B \| r_\pi) + R_{\text{sig}}} g_m(r_o \| R_C \| R_L)$$

$$\omega_{P1} = \frac{1}{C_{C1}[(R_B \| r_\pi) + R_{\text{sig}}]}$$

$$\omega_{P2} = \frac{1}{C_E\left[r_e + \dfrac{R_B \| R_{\text{sig}}}{\beta + 1}\right]}$$

$$\omega_{P3} = \frac{1}{C_{C2}(R_C + R_L)}$$

Απόκριση στις υψηλές συχνότητες

Κοινής πηγής:

$$f_H = \frac{\omega_H}{2\pi} = \frac{1}{2\pi C_{\text{in}} R'_{\text{sig}}} \qquad R'_L = r_o /\!/ R_D /\!/ R_L$$

$$C_{\text{in}} = C_{gs} + C_{eq} = C_{gs} + C_{gd}(1 + g_m R'_L)$$

Κοινής πηγής με ενεργό φορτίο:

$$A_M = -g_m R'_L \qquad f_H = \frac{1}{2\pi C_{\text{in}} R_{\text{sig}}}$$

Κοινού εκπομπού:

$$f_H = \frac{\omega_0}{2\pi} = \frac{1}{2\pi C_{\text{in}} R'_{\text{sig}}}$$

$$R'_{\text{sig}} = r_\pi /\!/ [r_x + (R_B /\!/ R_{\text{sig}})] \qquad R'_L = r_o /\!/ R_C /\!/ R_L$$

$$C_{\text{in}} = C_\pi + C_\mu(1 + g_m R'_L)$$

$$\tau_H = C_{gs}R_{\text{sig}} + C_{gd}[R_{\text{sig}}(1+g_mR_L') + R_L'] + C_LR_L'$$

$$f_H \cong \frac{1}{2\pi\tau_H} \qquad \omega_Z = g_m/C_{gd}$$

$$\omega_{P1} \cong \frac{1}{[C_{gs}+C_{gd}(1+g_mR_L')]R_{\text{sig}} + (C_L+C_{gd})R_L'}$$

$$\omega_{P2} = \frac{[C_{gs}+C_{gd}(1+g_mR_L')]R_{\text{sig}} + (C_L+C_{gs})R_L'}{[(C_L+C_{gd})C_{gs}+C_LC_{gd}]R_L'R_{\text{sig}}}$$

$$f_H \cong \frac{1}{2\pi C_{gd}R_{gd}} \qquad |A_M|f_H = \frac{1}{2\pi C_{gd}R_{\text{sig}}}$$

Κοινής πύλης με ενεργό φορτίο:

$$f_{P1} = \frac{1}{2\pi C_{gs}\left(R_s \parallel \dfrac{1}{g_m+g_{mb}}\right)}$$

$$f_{P2} = \frac{1}{2\pi(C_{gd}+C_L)R_L}$$

$$f_H = \frac{1}{2\pi[C_{gs}R_{gs}+(C_{gd}+C_L)R_{gd}]}$$

Κοινής εκροής με ενεργό φορτίο:

$$\omega_Z = \frac{g_m}{C_{gs}}$$

$$f_H = \frac{1}{2\pi\tau_H} = 1/2\pi(C_{gd}R_{\text{sig}} + C_{gs}R_{gs} + C_LR_{C_L})$$

Κοινού εκπομπού με ενεργό φορτίο:

$$A_M = -\frac{r_\pi}{R_{\text{sig}}+r_x+r_\pi}(g_mR_L')$$

$$f_H \cong \frac{1}{2\pi C_{\text{in}}R_{\text{sig}}'}$$

$$\tau_H = C_\pi R_{\text{sig}}' + C_\mu[(1+g_mR_L')R_{\text{sig}}' + R_L'] + C_LR_L'$$

$$f_H \cong \frac{1}{2\pi\tau_H} \qquad f_Z = \frac{1}{2\pi}\frac{g_m}{C_\mu}$$

$$f_{P1} \cong \frac{1}{2\pi}\frac{1}{[C_\pi + C_\mu(1+g_mR_L')]R_{\text{sig}}' + (C_L+C_\mu)R_L'}$$

$$f_{P2} \cong \frac{1}{2\pi}\frac{[C_\pi + C_\mu(1+g_mR_L')]R_{\text{sig}}' + (C_L+C_\mu)R_L'}{[C_\pi(C_L+C_\mu)+C_LC_\mu]R_{\text{sig}}'R_L'}$$

Κοινού συλλέκτη με ενεργό φορτίο:

$$\omega_Z = \frac{1}{C_\pi r_e}$$

$$f_H = 1/2\pi[C_\mu R_\mu + C_\pi R_\pi]$$

$$R_\mu = R_{\text{sig}}' \parallel [r_\pi + (\beta+1)R_L']$$

$$R_\pi = \frac{R_{\text{sig}}'+R_L'}{1+\dfrac{R_{\text{sig}}'}{r_\pi}+\dfrac{R_L'}{r_e}}$$

$$R_L' = R_L \parallel r_o \qquad R_{\text{sig}}' = R_{\text{sig}} + r_x$$

Πολυβάθμιοι ενισχυτές

$$A_u = e_{out}/V_S = A_1A_2 \ldots\ldots A_n \quad \frac{R_{in1}}{R_{in1}+R_S}\;\frac{R_{in2}}{R_{in2}+R_{out1}}\;\ldots\ldots\;\frac{R_L}{R_L+R_{outn}}$$

Με n **<u>όμοιες</u>** βαθμίδες: $\omega_{nL} = \dfrac{\omega_o}{\sqrt{2^{1/n}-1}}$. Με n βαθμίδες με f_{Lj}, $j = 1,\ldots,n$: $f_{nL} \approx 1.1\sqrt{f_{L1}^2 + f_{L2}^2 + \ldots + f_{Ln}^2}$

Με n **<u>όμοιες</u>** βαθμίδες: $\omega_{nH} = \omega_o\sqrt{2^{1/n}-1}$. Με n βαθμίδες με f_{Hj}, $j = 1,\ldots,n$: $f_{nH} \approx \dfrac{1}{1.1\sqrt{\dfrac{1}{f_{H1}^2}+\dfrac{1}{f_{H2}^2}+\ldots+\dfrac{1}{f_{Hn}^2}}}$

Ζεύγος κοινού συλλέκτη – κοινής βάσης:

$$\frac{V_o}{V_{\text{sig}}} = \frac{1}{2}\left(\frac{R_{\text{in}}}{R_{\text{in}}+R_{\text{sig}}}\right)(g_m R_L) \qquad R_{\text{in}} = 2r_\pi$$

$$f_{P1} = \frac{1}{2\pi\left(\frac{C_\pi}{2}+C_\mu\right)(R_{\text{sig}} \| 2r_\pi)} \qquad f_{P2} = \frac{1}{2\pi C_\mu R_L} \qquad f_H \cong 1\Big/\sqrt{\frac{1}{f_{P1}^2}+\frac{1}{f_{P2}^2}}$$

Ζεύγος κοινής πηγής – κοινής πύλης (κασκοδική συνδεσμολογία):

$$R_{\text{out}} = r_{o2} + [1+(g_{m2}+g_{mb2})r_{o2}]r_{o1} \qquad A_v = -A_0^2\frac{R_L}{R_L+A_0 r_o} \qquad f_H \cong \frac{1}{2\pi\tau_H}$$

$$\tau_H = R_{\text{sig}}[C_{gs1}+C_{gd1}(1+g_{m1}R_{d1})] + R_{d1}(C_{gd1}+C_{db1}+C_{gs2}) + (R_L \| R_{\text{out}})(C_L+C_{gd2})$$

$$R_{gd1} = (1+g_{m1}R_{d1})R_{\text{sig}} + R_{d1}$$

Ζεύγος Κοινού εκπομπού – κοινής βάσης (κασκοδική συνδεσμολογία):

$$A_M = -\frac{r_\pi}{r_\pi + r_x + R_{\text{sig}}} g_m(\beta r_o \| R_L) \qquad R_{c1} = r_{o1} \left\| \left[r_{e2}\left(\frac{r_{o2}+R_L}{r_{o2}+R_L/(\beta_2+1)}\right)\right]\right.$$

$$R'_{\text{sig}} = r_{\pi1} \| (r_{x1} + R_{\text{sig}})$$

$$R_{\pi1} = R'_{\text{sig}}$$

$$R_{\mu1} = R'_{\text{sig}}(1+g_{m1}R_{c1}) + R_{c1} \qquad f_H \simeq \frac{1}{2\pi\tau_H}$$

$$\tau_H = C_{\pi1}R_{\pi1} + C_{\mu1}R_{\mu1} + (C_{cs1}+C_{\pi2})R_{c1} + (C_L + C_{cs2} + C_{\mu2})(R_L \| R_{\text{out}})$$

Τελεστικός ενισχυτής MOS δύο βαθμίδων:

$$A_v = -g_{m1}\left(r_{ds2} \| r_{ds4}\right) \qquad g_{m1} = \sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_1 I_{D1}} = \sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_1 \frac{I_{bias}}{2}}$$

$$R_B = \frac{2}{\sqrt{2\mu_n C_{ox}(W/L)_{12} I_B}}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}}-1\right)$$

$$g_{m12} = \frac{2}{R_B}\left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}}-1\right) \qquad g_{mi} = g_{m12}\sqrt{\frac{I_{Di}(W/L)_i}{I_B(W/L)_{12}}} \qquad g_{mi} = g_{m12}\sqrt{\frac{\mu_p I_{Di}(W/L)_i}{\mu_n I_B(W/L)_{12}}}$$

$$C_1 = c_{gd4} + C_{db4} + C_{gd2} + C_{db2} + C_{gs6} \qquad C_2 = C_{db6} + C_{db7} + C_{gd7} + C_L$$

$$\omega_Z = \frac{G_{m2}}{C_C} \qquad \omega_{P1} = \frac{1}{C_1R_1 + C_2R_2 + C_C(G_{m2}R_2R_1 + R_1 + R_2)} \cong \frac{1}{R_1 C_C G_{m2} R_2}$$

$$\omega_{P2} = \frac{G_{m2}C_C}{C_1C_2 + C_C(C_1+C_2)} \qquad \omega_t = (G_{m1}R_1G_{m2}R_2)\omega_{P1}$$

Επιλογή C_C ώστε $\omega_t < \omega_Z$, ω_{P2}

$$\text{PSRR} = g_{mN}(r_{oP} \| r_{oN}) \qquad SR \equiv \frac{dV_{out}}{dt}\Big|_{\max} = \frac{I_{SS}}{C_L}$$

$$GB = A_v(0)\cdot|p_1| = (g_{m1}g_{m2}R_IR_{II})\cdot\left(\frac{1}{g_{m2}R_IR_{II}C_c}\right) = \frac{g_{m1}}{C_c}$$

$$Arg[AB] = \pm 180° - \tan^{-1}\left(\frac{\omega}{|p_1|}\right) - \tan^{-1}\left(\frac{\omega}{|p_2|}\right) - \tan^{-1}\left(\frac{\omega}{Z}\right)$$

Για περιθώριο φάσης 45º και z ≥ 10 GB: $|p2| \geq 1.22\mathrm{GB}$

Για περιθώριο φάσης 60º και z ≥ 10 GB: $|p2| \geq 2.22\mathrm{GB}$

$$Z = \frac{1}{C_c(1/g_{m2} - R_Z)}$$

Σχεδίαση Τελεστικού ενισχυτή MOS με είσοδο n-MOS

$$SR = \frac{I_5}{C_c} \qquad A_{v1} = \frac{-g_{m1}}{g_{ds2} + g_{ds4}} = \frac{-2g_{m1}}{I_5(\lambda_2 + \lambda_4)} \qquad A_{v2} = \frac{-g_{m6}}{g_{ds6} + g_{ds7}} = \frac{-g_{m6}}{I_6(\lambda_6 + \lambda_7)}$$

$$GB = \frac{g_{m1}}{C_c} \qquad p_2 = \frac{-g_{m6}}{C_L} \qquad Z = \frac{g_{m6}}{C_c} \qquad \boldsymbol{\beta = K' \frac{W}{L} \cong \mu_0 C_{ox} \frac{W}{L}} \quad \mathbf{(A/V^2)}$$

$$V_{in(\max)} = V_{DD} - \sqrt{\frac{I_5}{\beta_3}} - |V_{T03}|_{(\max)} + V_{T01(\min)} \qquad V_{in(\min)} = V_{ss} + \sqrt{\frac{I_5}{\beta_1}} + V_{T01(\max)} + V_{DS5(sat)} \qquad V_{DS(sat)} = \sqrt{\frac{2I_{DS}}{\beta}}$$

Για είσοδο p-MOS:

$$V_{in(\max)} = V_{DD} - \sqrt{\frac{I_5}{\beta_1}} - V_{SD5(sat)} - |V_{T01}|_{(\max)} \qquad V_{in(\min)} = V_{ss} + \sqrt{\frac{I_5}{\beta_3}} + V_{T03(\max)} - |V_{T01}|_{(\min)}$$

$$C_c > 0.22C_L \qquad I_5 = SR \cdot C_c \qquad S_3 = (W/L)_3 = \frac{I_5}{(K_3')[V_{DD} - V_{in}(\max) - |V_{T03}|(\max) + V_{T01}(\min)]^2}$$

$$\frac{g_{m3}}{2C_{gs3}} > 10GB \qquad g_{m1} = GB \cdot C_c \Rightarrow S_1 = S_2 = \frac{g_{m2}^2}{K_2' I_5}$$

$$V_{DS5}(sat) = V_{in}(\min) - V_{SS} - \sqrt{\frac{I_5}{\beta_1}} - V_{T01}(\max) \geq 100mV \qquad S_5 = \frac{2I_5}{K_5'[V_{DS5}sat]^2}$$

$$g_{m6} = 2.2g_{m2}(C_L/C_c) \qquad S_6 = S_4 \frac{g_{m6}}{g_{m4}} \qquad I_6 = \frac{g_{m6}^2}{2K_6' S_6}$$

$$S_6 = \frac{g_{m6}}{K_6' V_{DS6}(sat)} \qquad V_{DS6} = V_{DS6}(\min) = V_{DS6}(sat) = V_{DD} - V_{out}(\max) \qquad S_7 = (I_6/I_5)S_5$$

$$A_v = \frac{2g_{m2}g_{m6}}{I_5(\lambda_2 + \lambda_4)I_6(\lambda_6 + \lambda_7)} \qquad P_{diss} = (I_5 + I_6)(V_{DD} + |V_{SS}|)$$

Κυκλώματα ανόρθωσης

$$V_Z = V_{Z0} + r_z I_Z$$

$P_{DC}=I_{DC}^2R\ =\dfrac{I_m^2}{\pi^2}R$	$P_{AC}=I_{rms}^2R\ =\dfrac{I_m^2}{4}R$	$n=\dfrac{P_{DC}}{P_{AC}}100\%=40.6\%$	$r=\dfrac{\sqrt{I_{rms}^2-I_{DC}^2}}{I_{DC}}100\%=121\%$
$P_{DC}=I_{DC}^2R\ =\dfrac{4I_m^2}{\pi^2}R$	$P_{AC}=I_{rms}^2R\ =\dfrac{I_m^2}{2}R$	$n=\dfrac{P_{DC}}{P_{AC}}100\%=81.2\%$	$r=\dfrac{\sqrt{I_{rms}^2-I_{DC}^2}}{I_{DC}}100\%=48\%$

Ημιανορθωτής με φίλτρο πυκνωτή:

$$V_{DC}\equiv V_O = V_p-\tfrac{1}{2}V_r \qquad i_{D\text{av}}=I_L(1+\pi\sqrt{2V_p/V_r}) \qquad i_{D\max}=I_L(1+2\pi\sqrt{2V_p/V_r})$$

$$V_r = \frac{V_p}{fCR}=\frac{I_L}{fC} \qquad r=\frac{V_{AC(rms)}}{V_{DC}}=\frac{V_r}{2\sqrt{3}V_{DC}}\approx\frac{1}{2\sqrt{3}\,fCR}$$

Πλήρης ανορθωτής με φίλτρο πυκνωτή:

$$V_r=\frac{V_p}{2fCR} \qquad i_{D\text{av}}=I_L(1+\pi\sqrt{V_p/2V_r}) \qquad i_{D\max}=I_L(1+2\pi\sqrt{V_p/2V_r})$$

$$r=\frac{V_{AC(rms)}}{V_{DC}}=\frac{V_r}{2\sqrt{3}V_{DC}}\approx\frac{1}{4\sqrt{3}\,fCR}$$

Κυκλώματα αναφοράς

Πηγή Widlar:	$V_T\ \ln\dfrac{I_{\text{IN}}}{I_{\text{OUT}}}=I_{\text{OUT}}R_2$	$I_{\text{OUT}}R_2+\sqrt{\dfrac{2I_{\text{OUT}}}{k'(W/L)_2}}-V_{ov1}=0$ $\sqrt{I_{\text{OUT}}}=\dfrac{-\sqrt{\dfrac{2}{k'(W/L)_2}}+\sqrt{\dfrac{2}{k'(W/L)_2}+4R_2V_{ov1}}}{2R_2}$
Πηγή μεγίστου ρεύματος:	$I_{\text{OUT}}=I_{\text{IN}}\exp\left(-\dfrac{I_{\text{IN}}R}{V_T}\right)$ $R=\dfrac{V_T}{I_{\text{IN}}}\ln\dfrac{I_{\text{IN}}}{I_{\text{OUT}}}$	$I_D=\dfrac{W}{L}I_t\exp\left(\dfrac{V_{GS}-V_t}{nV_T}\right)\left[1-\exp\left(-\dfrac{V_{DS}}{V_T}\right)\right]$ $I_{\text{OUT}}\simeq\dfrac{W}{L}I_t\exp\left(\dfrac{V_{GS2}-V_t}{nV_T}\right)\simeq I_{\text{IN}}\exp\left(-\dfrac{I_{\text{IN}}R}{nV_T}\right)$ $I_{\text{OUT}}=\dfrac{k'(W/L)_2}{2}(V_{ov2})^2=\dfrac{k'(W/L)_2}{2}(V_{ov1}-I_{\text{IN}}R)^2$

$$S_{V_{\text{SUP}}}^{I_{\text{OUT}}}=\frac{V_{\text{SUP}}}{I_{\text{OUT}}}\frac{\partial I_{\text{OUT}}}{\partial V_{\text{SUP}}}$$

$$S_{V_{CC}}^{I_{\text{OUT}}}=\left(\frac{1}{1+\dfrac{I_{\text{OUT}}R_2}{V_T}}\right)\frac{V_{CC}}{I_{\text{IN}}}\frac{\partial I_{\text{IN}}}{\partial V_{CC}}=\left(\frac{1}{1+\dfrac{I_{\text{OUT}}R_2}{V_T}}\right)S_{V_{CC}}^{I_{\text{IN}}}$$

$$S_{V_{DD}}^{I_{\mathrm{OUT}}} = \frac{V_{ov1}}{\sqrt{V_{ov2}^2 + 4I_{\mathrm{OUT}}R_2V_{ov1}}} S_{V_{DD}}^{I_{\mathrm{IN}}}$$

$$TC_F = \frac{1}{I_{\mathrm{OUT}}}\frac{\partial I_{\mathrm{OUT}}}{\partial T} = \frac{1}{V_{BE1}}\frac{\partial V_{BE1}}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T}$$

$$TC_F = \frac{1}{I_{\mathrm{OUT}}}\frac{\partial I_{\mathrm{OUT}}}{\partial T} \simeq \frac{1}{V_t}\frac{\partial V_t}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T}$$

$$TC_F = \frac{1}{I_{\mathrm{OUT}}}\frac{\partial I_{\mathrm{OUT}}}{\partial T} = \frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R_2}\frac{\partial R_2}{\partial T}$$

$$V_{\mathrm{OUT}} = V_{BE(\mathrm{on})} + MV_T$$

$$V_{\mathrm{OUT}} = V_{G0} + V_T(\gamma - \alpha)\left(1 + \ln\frac{T_0}{T}\right)$$

$$V_{\mathrm{OUT}} = V_{BE2} + V_{R3} + V_{R2} = V_{BE2} + \left(1 + \frac{R_2}{R_3}\right)\Delta V_{BE}$$

$$= V_{BE2} + \left(1 + \frac{R_2}{R_3}\right)V_T \ln\frac{R_2}{R_1}\frac{I_{S2}}{I_{S1}} = V_{BE2} + MV_T$$

Ενισχυτές Ισχύος

Τάξη Α:

$$P_L = \frac{(\hat{V}_o/\sqrt{2})^2}{R_L} = \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$$

$$P_S = 2V_{CC}I$$

$$\eta = \frac{1}{4}\frac{\hat{V}_o^2}{IR_LV_{CC}} = \frac{1}{4}\left(\frac{\hat{V}_o}{IR_L}\right)\left(\frac{\hat{V}_o}{V_{CC}}\right)$$

Τάξη Β:

$$P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L}$$

$$P_{S+} = P_{S-} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L}V_{CC}$$

$$P_S = \frac{2}{\pi}\frac{\hat{V}_o}{R_L}V_{CC}$$

$$\eta = \left(\frac{1}{2}\frac{\hat{V}_o^2}{R_L}\right)\Big/\left(\frac{2}{\pi}\frac{\hat{V}_o}{R_L}V_{CC}\right) = \frac{\pi}{4}\frac{\hat{V}_o}{V_{CC}}$$

$$\eta_{\max} = \frac{\pi}{4} = 78.5\%$$

$$P_{L\max} = \frac{1}{2}\frac{V_{CC}^2}{R_L}$$

$$P_{DN\max} = P_{DP\max} = \frac{V_{CC}^2}{\pi^2 R_L}$$

Τάξη ΑΒ:

$$v_O = v_I + \frac{V_{BB}}{2} - v_{BEN}$$

$$i_N^2 - i_Li_N - I_Q^2 = 0$$

$$R_{\mathrm{out}} = \frac{V_T}{i_N}\Big\|\frac{V_T}{i_P} = \frac{V_T}{i_P + i_N}$$

$$T_J - T_A = \theta_{JA}P_D$$

$$\theta_{JA} = \frac{T_{J\max} - T_{A0}}{P_{D0}}$$

$$P_{D\max} = \frac{T_{J\max} - T_C}{\theta_{JC}}$$

$$\theta_{JA} = \theta_{JC} + \theta_{CA}$$

$$\theta_{CA} = \theta_{CS} + \theta_{SA}$$

$$T_J - T_A = P_D(\theta_{JC} + \theta_{CS} + \theta_{SA})$$

Ηλεκτρονικά ελέγχου ισχύος

$$V_{da}^{h} = \frac{1}{2\pi}\int_{a}^{\pi} V_{sm}\sin(\omega_s t)d(\omega_s t) = = \frac{V_{sm}}{\pi}\left[\frac{1+\cos a}{2}\right] = V_{do}^{h}\left[\frac{1+\cos a}{2}\right]$$

$$I_d = \frac{1}{2\pi R}\int_{a}^{\pi-\delta}(V_{sm}\sin\omega_s t - V_B)d(\omega_s t) \qquad \delta = \sin^{-1}(V_B/V_{sm}) \qquad \delta < a < \pi - \delta$$

$$V_{da}^{f} = \frac{1}{\pi}\int_{a}^{\pi} V_{sm}\sin(\omega_s t)d(\omega_s t) = \frac{V_{sm}}{\pi}(1+\cos a)$$

$$V_{da}^{f} = \frac{1}{\pi}\int_{a}^{\pi+a} V_{sm}\sin(\omega_s t)d(\omega_s t) = \frac{2V_{sm}}{\pi}\cos a = V_{do}^{f}\cos a \qquad \cos\phi_1 = \cos a$$

$$PF = \frac{I_{s1}}{I_s}\cos\phi_1 = \frac{2\sqrt{2}}{\pi}\cos a \qquad P_s = V_s I_{s1}\cos\phi_1 = V_{da}^{f} I_d = \frac{2V_{sm}}{\pi} I_d \cos a$$

$$V_{da}^{f} = \frac{1}{\pi}\int_{a}^{\pi+a} V_{sm}\sin(\omega_s t)d(\omega_s t) = \frac{2V_{sm}}{\pi}\cos a = V_{do}^{f}\cos a \qquad 0 < a < \cos^{-1}\left\{\frac{V_B\pi}{2V_{sm}}\right\} \qquad I_d = \frac{V_{da}^{f} - V_B}{R}$$

$$P_B = V_B I_d$$

$$P_{d|a>\pi/2} = P_s = V_{da}^{f} I_d = V_{do}^{f} I_d \cos a = V_s I_{s1}\cos\phi_1 < 0 \qquad I_d = \frac{V_{da}^{f} - V_B}{R} \qquad V_{da}^{f} = V_{do}^{f}\cos a$$