DIODOS DE POTENCIA

De uso general (10 a 25 μS)
De recuper. rápida (0,8 a 5 μS)
De recup ultra rép (30 a 800 nS)
Schottky (1 nS)

} t_{rr}

Encapsulados

- plásticos
- perno
- disco de Hockey
- pack
- bloque

Especificaciones:

V_{RSM}, V_{RRM}, V_R, $V_{(BR)}$, $I_{F(AV)}$, $I_{F(RMS)}$, I_{FSM}, $i^2.t$, V_{TO}, r_T

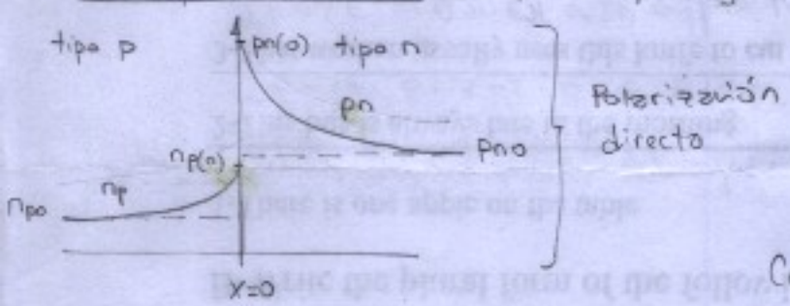
$$P_F = V_{TO}.\, i_F + r_T.\, i_F^2$$

$$P_{F(AV)} = V_{TO}.\, I_{F(AV)} + r_T.\, I_{F(RMS)}^2$$

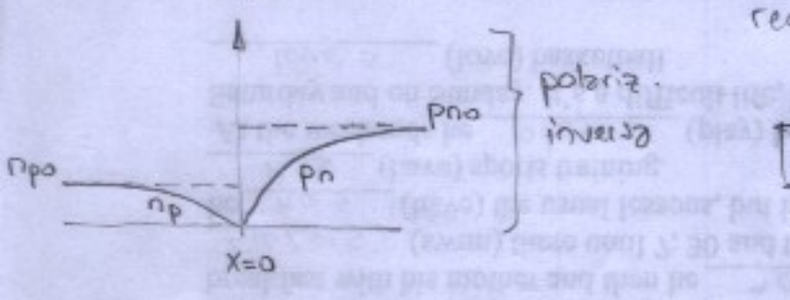
$$\frac{I_{F(RMS)}^2}{I_{F(AV)}^2} \rightarrow 2{,}5 \text{ (para pulsos senoidales de media onda)}$$

$$\rightarrow \frac{360°}{\theta} \text{ (para pulsos rectangulares)}$$

Tiempos del diodo [t_{rr}, t_{tr}, t_s, Q_{rr}]

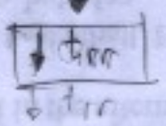


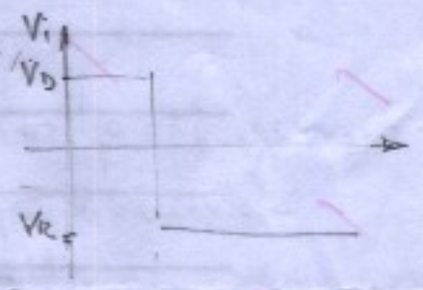
Polarización directa

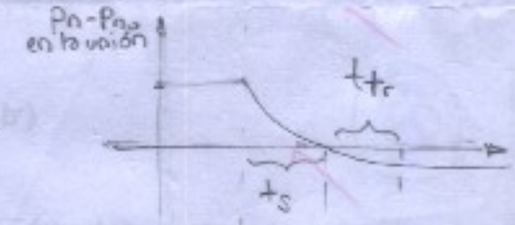


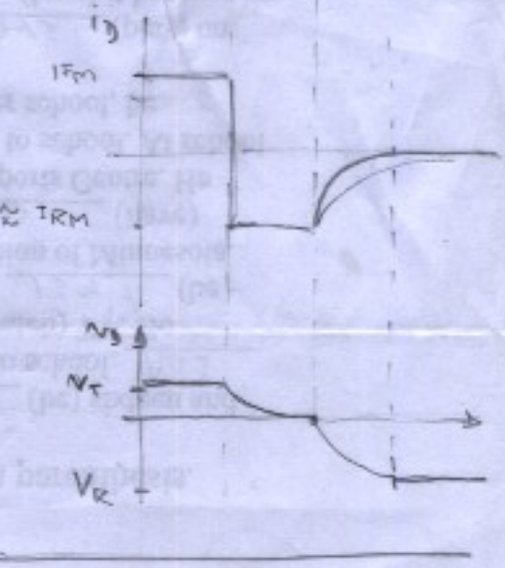
polariz. inversa

Centros de recombinación (oro)



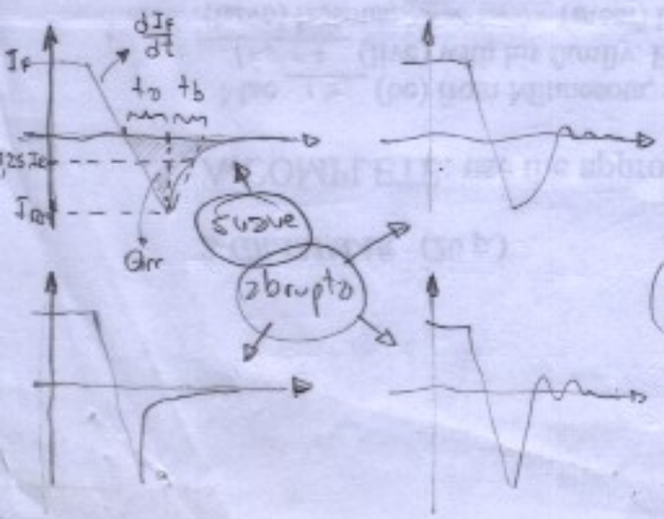






$$\frac{V_R}{R_L} \approx I_{RM}$$

Especificaciones de los fabricantes



Q_{rr} = carga inversa

$$t_a + t_b = t_{rr}$$

$$t_{rr} \approx t_a$$

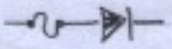
$$(\nabla)\; Q_{rr} = \frac{t_{rr}.\, I_{RM}}{2} \quad \therefore \quad I_{RM} = \frac{2\, Q_{rr}}{t_{rr}}$$

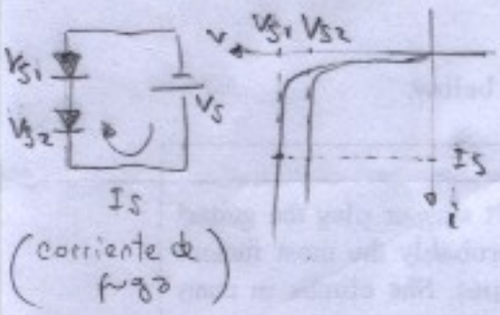
$$t_b = t_{rr} - \frac{I_{RM}}{\left(\frac{di_R}{dt}\right)} \Rightarrow \text{pero } t_b \ll t_a \; (\nabla)$$

$$I_{RM} = \sqrt{2\, Q_{rr}.\, \frac{di_R}{dt}}$$

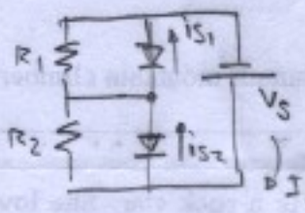
$$t_{rr} \approx \frac{I_{RM}}{di_R/dt} \quad \therefore \quad t_{rr} = \sqrt{\frac{2\, Q_{rr}}{(di_R/dt)}}$$

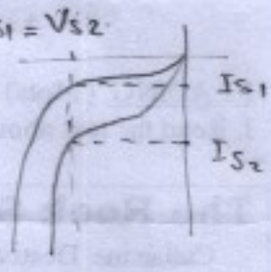
Otros ítems

- Recuperación en directa: Si $\uparrow \frac{di_F}{dt} \rightarrow$ ¡¡quema!! ; $t_{rf} << t_{rr}$
- Protección contra sobretensiones: 20 a 100 nF $\Rightarrow dv/dt$
- Protección contra cortocircuitos: 
- Conexión en serie:



solución



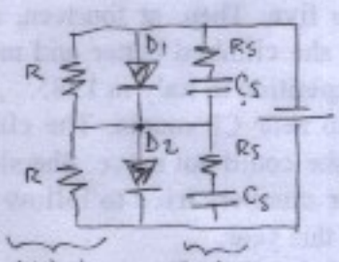


$$I_S = I_{S1} + \frac{V_{S1}}{R_1} = I_{S2} + \frac{V_{S2}}{R_2}$$

si $I_{S1} << \frac{V_{S1}}{R_1} \wedge I_{S2} << \frac{V_{S2}}{R_2} \wedge R_1 = R_2$

$\therefore \boxed{V_{S1} = V_{S2}} \rightarrow$ buscado.

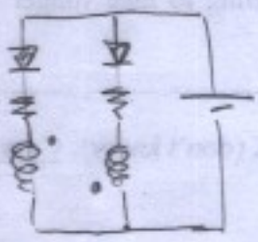
transitorios



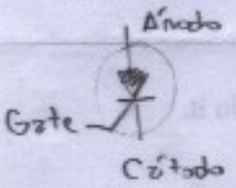
$R_S < R$

distrib voltaje est. perm — distrib. voltaje est. transit.

- Conexión en paralelo: selección de diodos con igual V_T o...

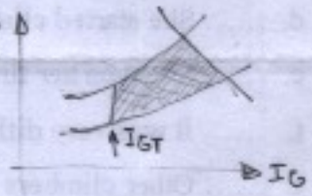


TIRISTORES

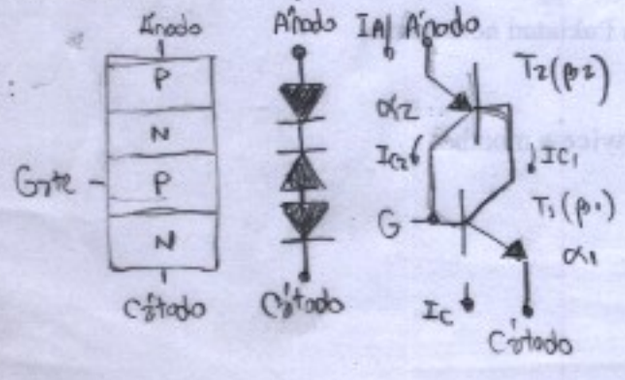


I_L : corriente de enganche
I_H : " " mantenimiento
t_q : tiempo de recuperación

} cebado



SCR:



$I_{C2} = I_A \cdot \alpha_2$

$I_{C1} = I_C \cdot \alpha_1$

$I_C = I_A \therefore$

$I_{C1} = I_A \cdot \alpha_1$

$I_A = I_{C1} + I_{C2} + I_{CX}$

I_{CX} = corriente de fuga

$I_A = I_A \cdot \alpha_1 + I_A \cdot \alpha_2 + I_{CX}$

$$I_A = \frac{I_{CX}}{1 - (\alpha_1 + \alpha_2)}$$

$\boxed{\alpha_1 \wedge \alpha_2 \text{ dependen de } I_{CX}}$

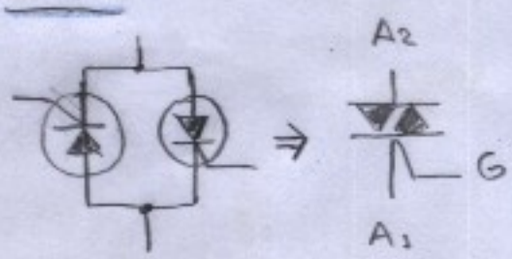
$\boxed{I_{CX} \text{ depende de } V_{AK}}$

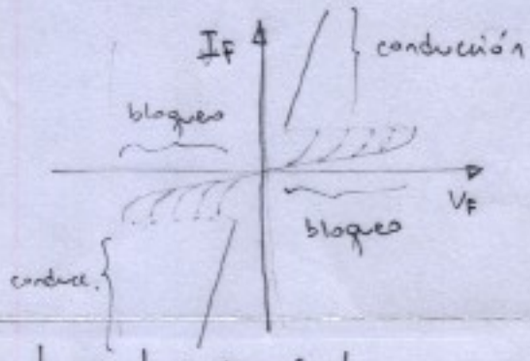
Aplicando I_G → $I_{C1} = \beta_1 . I_G \wedge I_{C2} = \beta_2 . I_{C1} = \beta_2 . \beta_1 . I_G$

Si $\beta_1 . \beta_2 < 1$ ⇒ I_G débil (no cebado)

Si $\beta_1 . \beta_2 \to 1$ ⇒ I_G suficiente (realimentación, conduce)

TRIAC





"Cuadrantes de polarización"	V_2	V_G	Notación
I	>0	>0	++
II	>0	<0	+−
III	<0	<0	−−
IV	<0	>0	−+

$V_2 = V_{A2}$

$V_1 = V_{A1} = 0$

Para c/cuadrante se define → I_H, I_L

Especificaciones

V_{RSM}, V_{DRM}, V_{RRM},

$I_{T(AV)}$, $I_{T(RMS)}$,

I_{TSM}, $I_{T(OV)}$, $i^2.t$

$\left(\frac{di}{dt}\right)_{cr}$ ⇒ disipación cercanías del gate

$\left(\frac{dv}{dt}\right)_{cr}$ ⇒ 2/3 de V_{DRM} (cebado no deseado)

I_H, I_L,

$V_{T(TO)}$, r_T

$P_{AV} = \frac{t_p}{T}\left\{\frac{2 V_{T(TO)} . I_{TM}}{\pi} + \frac{r_T}{2} I_{TM}^2\right\}$

$P_{AV} = \frac{t_p}{T}\left\{V_{T(TO)} . I_{TM} + r_T . I_{TM}^2\right\}$

I_{GT}, V_{GT}, I_{GD}, V_{GD}

t_q: tiempo de desactiv.

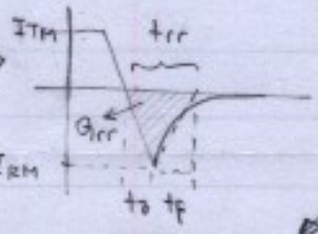
Q_{rr}: carga inversa

t_{rr}: tiempo de recup. inversa

t_{rc}: tiempo de recombinac

$\boxed{t_q = t_{rr} + t_{rc}}$

⇒

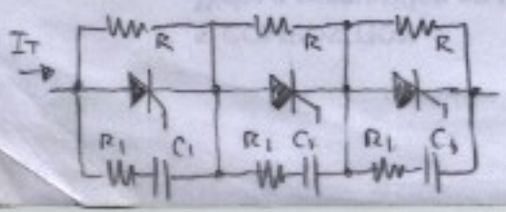


idem diodo +

$$t_{rr} = \sqrt{\frac{2 Q_{rr}}{\left(-\frac{di_T}{dt}\right)} + \frac{t_f^2}{4}} + \frac{t_f}{2}$$

$$I_{RM} = \sqrt{2 Q_{rr}\left(-\frac{di_T}{dt}\right) + \frac{t_f^2}{4}\left(-\frac{di_T}{dt}\right)^2} - \frac{t_f}{2}\left(-\frac{di_T}{dt}\right)$$

Conexión Serie y Paralelo

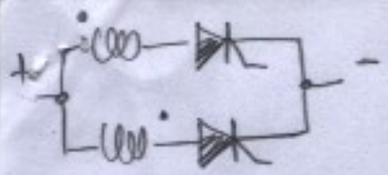


R → bloqueo inverso

→ estado off

R_1, C_1 → distrib. homogénea tensión transitoria durante apagado

→ protección dv/dt



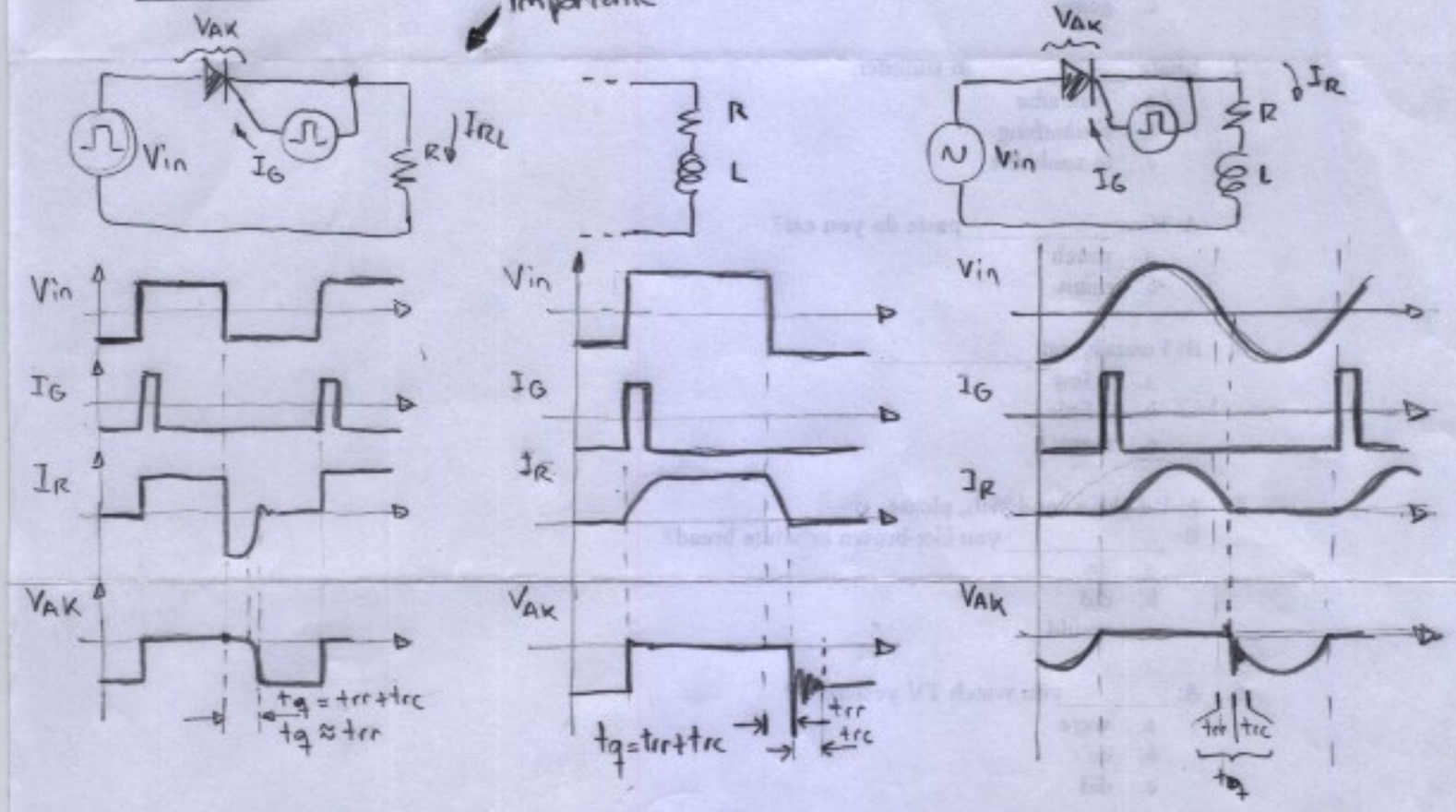
inductancias acopladas

Técnicas de Conmutación

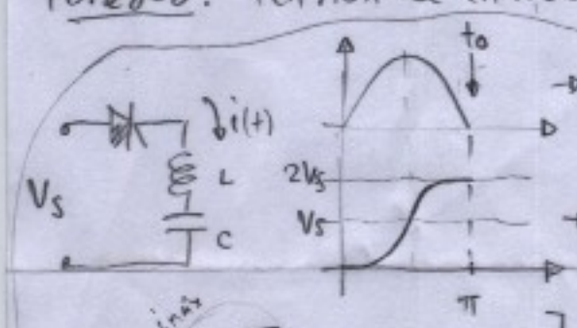
Natural: tensión de entrada CA → I_H (natural); "t_{rc} → unión J_2"

$\boxed{V_{in} = \text{cuadrada}}$ $\boxed{V_{in} = \text{senoidal}}$

más importante



Forzada: tensión de entrada CC → I_H (circuito externo) → AUTOCONMUTACIÓN, F.I. TENSIÓN, F.I. CORRIENTE



$$i(t) = V_s\sqrt{\frac{C}{L}}\,\text{sen}(\omega_m t)$$

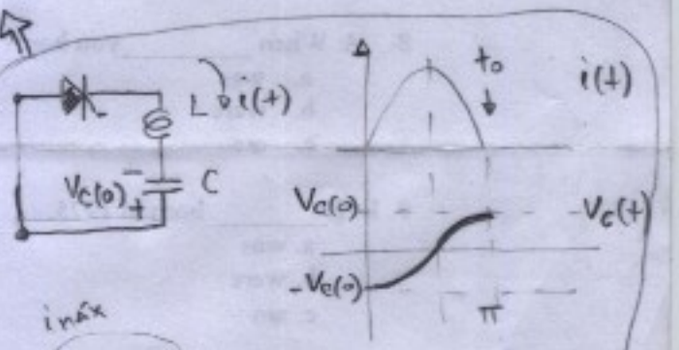
$$V_c(t) = V_s\left(1 - \cos(\omega_m t)\right)$$

$$\omega_m = \frac{1}{\sqrt{LC}}$$

$$t = t_0 = \pi\sqrt{LC}$$

(bloqueo)

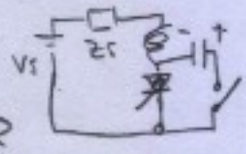
Autoconmutación



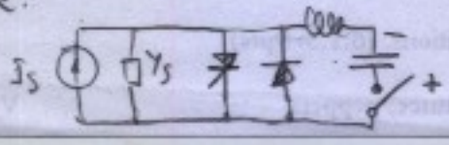
$$i(t) = V_c(0)\sqrt{\frac{C}{L}}\,\text{sen}(\omega_m t)$$

$$V_c(t) = -V_c(0)\cos(\omega_m t)$$

. Fuente Inversa de Tensión?



. Fuente Inversa de Corriente?

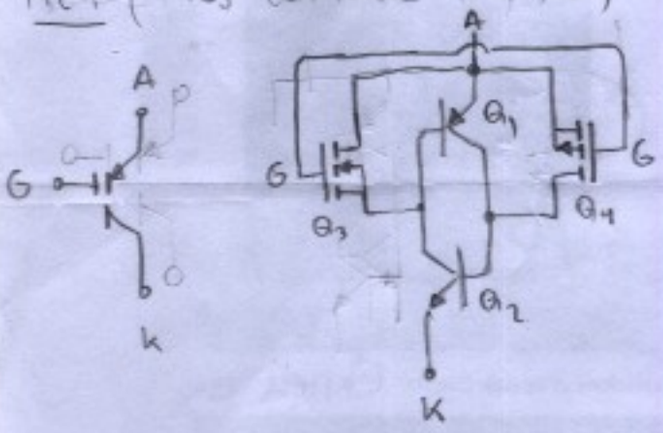


GTO (Gate turn off)

Contactos del gate y del cátodo son interdigitados

Ganancia → $\frac{\text{Corriente Circulante}}{\text{Corriente gate bloqueo (negativo)}} = 4 \text{ ó } 5 \text{ ó } 6$

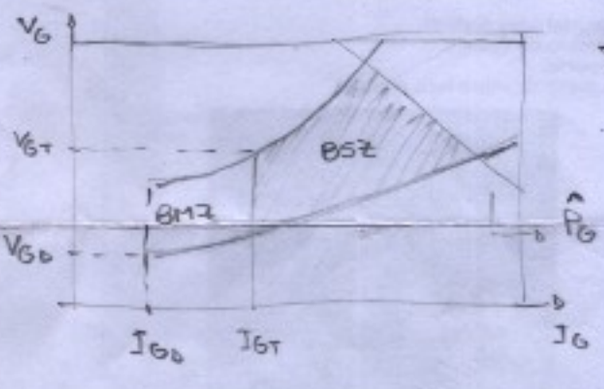
MCT (Mos Controlled Thiristor)



V_G ⊖ → Activo Q_4 (canal p) → Activo Q_2, Activo Q_1 → disparo el MCT

V_G ⊕ → Activo Q_3 (canal n) → Desactivo Q_1, Desactivo Q_2 → corto el MCT

DRIVER DE COMPUERTA DEL TIRISTOR

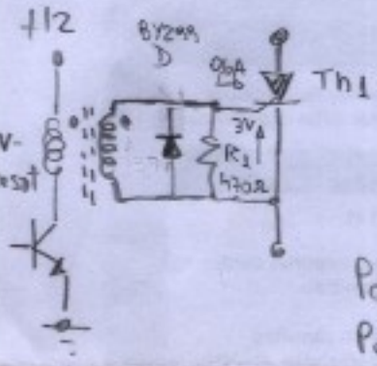


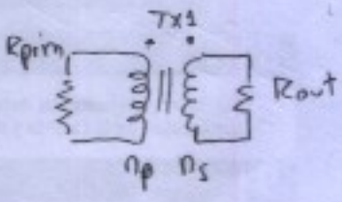
$I_G = 3$ a 5 veces I_{GT}

si $\Pi < 100\,\mu s$ $(1{,}4$ a $2\ I_{GT})$. 3 a 5 veces

Generalmente ⊓⊓⊓

$V_{GT} \approx 3V$ $\quad I_{GT} \approx 150\ mA$





$R_{out} = \frac{3V}{0{,}6A} = 5\ \Omega$

$R_{prim} = \left(\frac{N_p}{N_s}\right)^2 \cdot R_{out} = 15{,}47 \cdot 5 = 77{,}35\ \Omega$

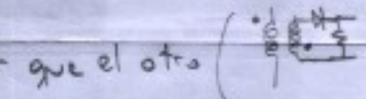
$P_{out} = 3V \cdot 0{,}6A = 1{,}8\ W$

$P_{out} = P_{in}\ \eta = P_{in}\ 0{,}8$

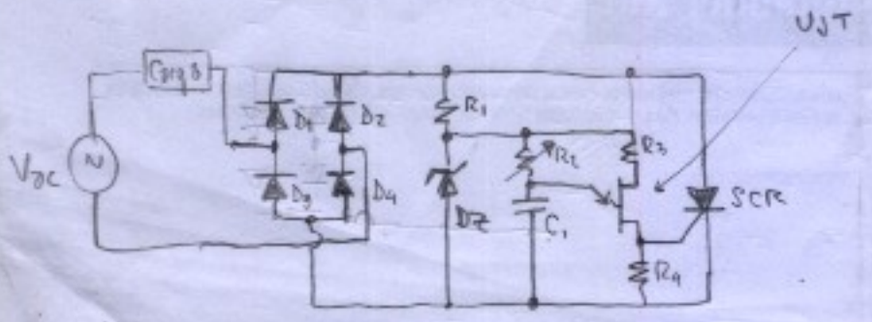
$P_{in} = 1{,}8 / 0{,}8 = 1{,}44\ W$

$I_{in} = \frac{1{,}44\ W}{12V - 0{,}2} = 122\ mA$

$\frac{V_p}{n_p} = \frac{V_s}{n_s} \Rightarrow \frac{n_p}{n_s} = \frac{11{,}8}{3} = 3{,}93$

Este es mejor que el otro () ya que requiere menos potencia y no tenemos la demora de 1 pulso.

Para Cin = CA:



TRANSISTORES BIPOLARES

Uso en bajo y mediana potencia

En alta potencia → SCR

Especificaciones

$V_{CEO(sus)}$ →

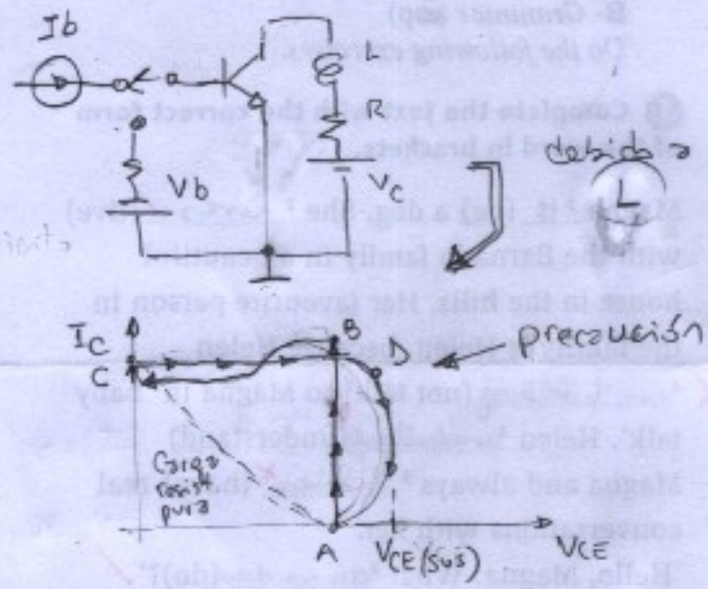
$V_{CER(sus)}$ →

$V_{CEV(sus)}$ → (V_{CEX})

Máx. tensión de mantenimiento

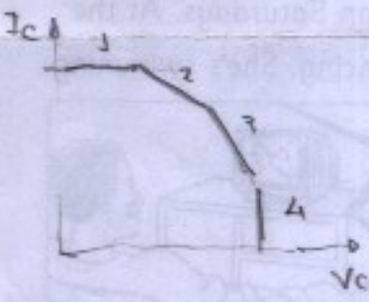
V_{EBM}, I_C, I_{CM}, I_B, I_{BM}

P_D, R_{thjc}



Área de Operación Segura

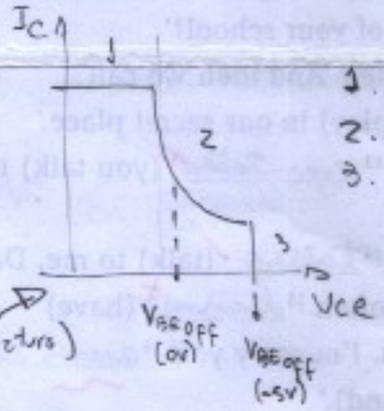
FBSOA (turn on)



1. Máx. corriente de colector
2. Máx. disip. de potencia
3. Ruptura secundaria
4. Máx. tensión col. emis.

factor de corrección (degradación por temperatura)

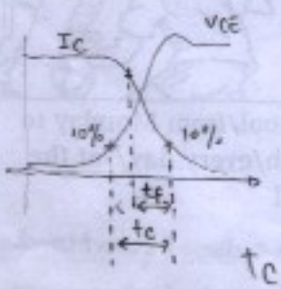
RBSOA (turn off)



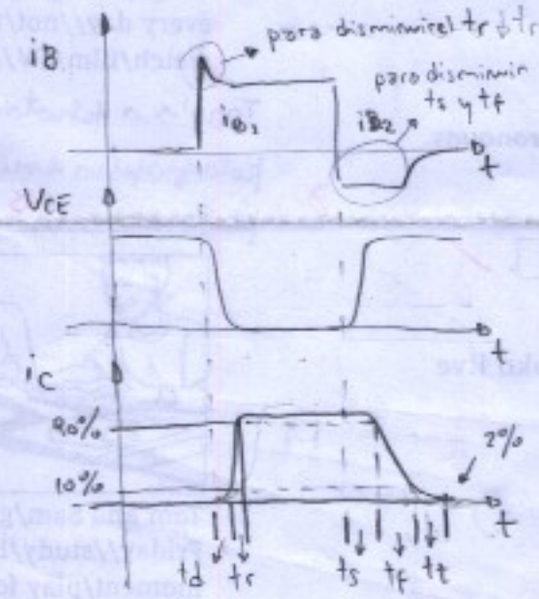
1. Máx. Ic
2. Rupt. secund.
3. Vce máx. (varía según si VCEO, VCER, VCEV)

Conmutación

Los tiempos de conmutación dependen de las condiciones del drive de base y del tipo de carga



tc: tiempo de cruce (para cálculo de potencia)

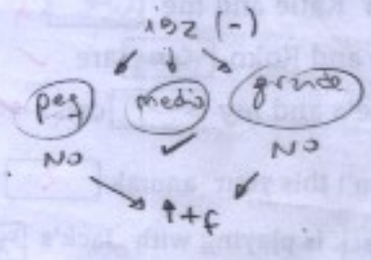


$t_{on} = t_d + t_r$ = tiempo de set. o encendido.

$t_{on} \approx t_r$

$t_{off} = t_s + t_f$

$i_{B2} = -3 i_{B1}$ (dibujo no a escala)



Temperaturas, Energía, Potencia

$W_{on}, W_{cond}, W_{off} \rightarrow P_{TOT(AV)} \rightarrow T_{vj(AV)} \rightarrow T_h$ (temp. disipador)

$P_{TOT(AV)} \rightarrow P_{TOTM} = f(R_{thjcp})$

I_{CM}

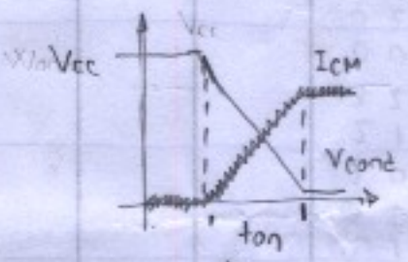
medimos

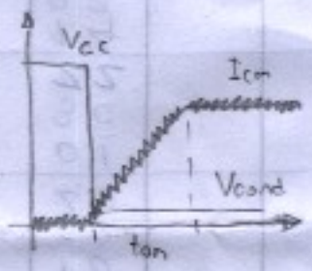
$$W_{on} = \int_{t_1}^{t_2} i(t)_{on}\, v(t)\, dt \qquad i(t)_{on} \approx \frac{I_{CM}}{t_2 - t_1} \cdot t = \frac{I_{CM}\, t}{t_{on}}$$

$$W_{cond} = \int_{t_2}^{t_3} i(t)_{cond}\, v(t)\, dt \qquad i(t)_{cond} \approx I_{CM}$$

$$W_{off} = \int_{t_3}^{t_4} i(t)_{off}\, v(t)\, dt \qquad i(t)_{off} \approx I_{CM}\left(1 - \frac{t}{t_4 - t_3}\right) = I_{CM}\left(1 - \frac{t}{t_{off}}\right)$$

Tres casos posibles (V_{ce}) para W_{on}:





$$W_{on} = \int_{t_1}^{t_2} \frac{I_{CM}\, t}{t_{on}} \cdot V_{cc}\, dt \qquad W_{on} = \int_{t_1}^{t_2} \frac{I_{CM}\, t}{t_{on}} V_{cc}\left(1 - \frac{t}{t_{on}}\right) dt \qquad W_{on} = \int_{t_1}^{t_2} \frac{I_{CM}\, t}{t_{on}} \cdot V_{cond}\, dt$$

$$W_{on} = \frac{I_{CM} \cdot V_{cc}\, t_{on}}{2} \qquad W_{on} = \frac{I_{CM} \cdot V_{cc}\, t_{on}}{6} \qquad W_{on} = \frac{I_{CM} \cdot V_{cond}\, t_{on}}{2}$$

$$W_{on} = \frac{I_{CM}\, V_{cc} \cdot t_{on}}{K_{on}}$$

; $K_{on} = 2$ 1er

; $K_{on} = 6$ 2do

; $K_{on} = \frac{V_{cc} \cdot 2}{V_{cond}}$ 3er

Un caso para W_{cond}:

$$W_{cond} = I_{CM} \cdot V_{cond} \cdot t_{cond}$$

Tres casos posibles (V_{ce}) para W_{off}:

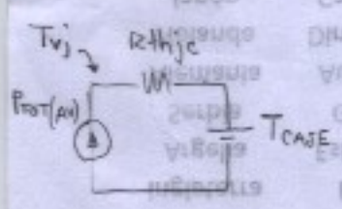
$$W_{off} = \frac{I_{CM}\, V_{cc}\, t_{off}}{K_{off}}$$

; $K_{off} = 2$ 1er

; $K_{off} = 6$ 2do

; $K_{off} = \frac{V_{cc} \cdot 2}{V_{cond}}$ 3er

($t_{off} = t_c$)



$$\boxed{T_{vj(AV)} = P_{TOT(AV)}\, R_{thjc} + T_{CASE}}$$

$$P_{TOT(AV)} = \frac{W_{on} + W_{cond} + W_{off}}{T}$$

Frec. Altas (> 3 khz) oscilaciones

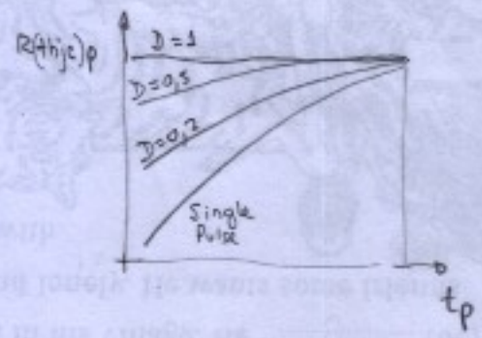
Inercia térmica → $T_{vj(AV)} = T_{vjM}$

Frec. bajas oscilaciones (< 3 khz)

$\Rightarrow R_{(thjc)p} = k \cdot R(thjc)$

$$P_{TOTM} = \frac{W_{on} + W_{cond} + W_{off}}{t_p}$$

$$T_{vjM} = P_{TOTM} \cdot R(thjc)_p + T_{CASE}$$



$$D = \frac{t_p}{T}$$

Cálculo de I_{CM}:

Frec > 3 khz $\Rightarrow$ $(T_{vj(av)} = T_{vjM})$

$$P_{TOT(av)} = \frac{W_{on} + W_{cond} + W_{off}}{T} = \frac{T_{vj(av)} - T_{case}}{R_{thjc}}$$

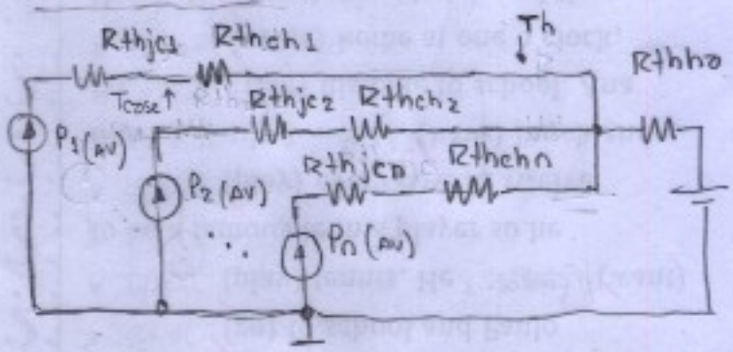
$$I_{CM} = \frac{T_{vj(av)} - T_{case}}{F\left[V_{cc}\left(\frac{t_{on}}{k_{on}} + \frac{t_{off}}{k_{off}}\right) + V_{cond}\, t_{cond}\right] \cdot R_{thjc}}$$

Frec < 3 khz $\Rightarrow$ $(T_{vj(av)} \neq T_{vjM})$

$$P_{TOTM} = \frac{W_{on} + W_{cond} + W_{off}}{t_p} = \frac{T_{vjM} - T_{case}}{R(thjc)_p}$$

$$I_{CM} = \frac{(T_{vjM} - T_{case}) \cdot t_p}{\left[V_{cc}\left(\frac{t_{on}}{k_{on}} + \frac{t_{off}}{k_{off}}\right) + V_{cond} \cdot t_{cond}\right] \cdot R(thjc)_p}$$

Cálculo de Th:



$$T_{case_1} = P_{1(av)} \cdot R_{thch_1} + T_h$$

$$T_h = T_{amb} + R_{thha} \sum P_{TOT(av)}$$

Medición de Energía:

Montaje
- 1 Tx
- 1 Vertil. chico
- 1 Disip. chico
- 2 sensores

1º

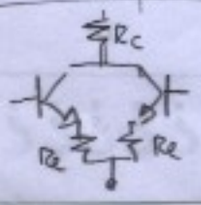
$$R_{thha} = \frac{T_h - T_{amb}}{P_{DC}}$$

S1 S2 tester

2º

$$P_{TOT(av)} = \frac{T_h - T_{amb}}{R_{thha}}$$

Conexión en paralelo



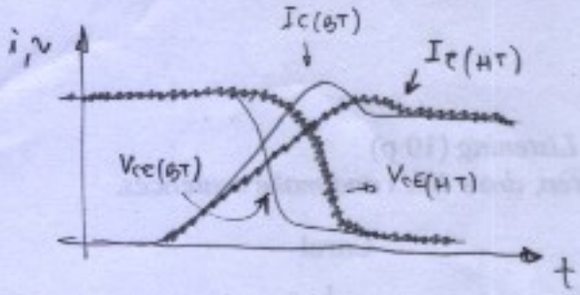
continua

Repartición dinámica

BJT → coef. temperatura negativo

¡Cuidado!

Comportamiento Estático



Puntos de trabajo (lineal, casi sat., sat., sobresat.)

lineal

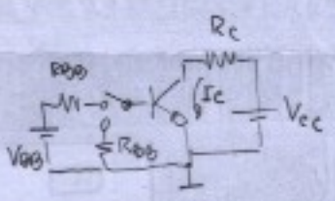
$I_C = \beta . I_B$

cond. no cond.
no rápido

V_{CE} alto

$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}}$

$V_{CE} = V_{CC} - I_C . R_C$



$V_{CE} = V_{CB} + V_{BE}$

$V_{CB} = V_{CE} - V_{BE} > 0$

$V_{CB} > 0$ $V_{CE} > V_{BE}$

casi saturado

$V_{CE} = V_{BE}$

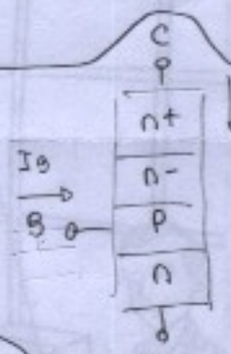
$V_{CB} = 0$

I_{CM} (lineal) $= \frac{V_{CC} - V_{CE}}{R_C}$

$I_{BM} = \frac{I_{CM}}{\beta}$

coef. temp. positivo

normaliz. repartición corriente



Una parte de la zona resistiva n^- se dopa a p^+ por inyección de port. minorit.

La resist. de la zona n^- ↓.

Saturado

$I_{B\,sat} > I_{BM}$

$V_{CE} < V_{BE}$

$I_{CE(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$

$I_{B(sat)} = \frac{I_{C(sat)}}{\beta}$

La zona n^- ha sido total. invadida por la p^+ y perdió su resistividad.

Aumentan tiempos de conmutación → grandes cantid. carga paso evacuar.

Sobresaturado

Factor de sobresat. $= ODF = \frac{I_B}{I_{B(sat)}}$

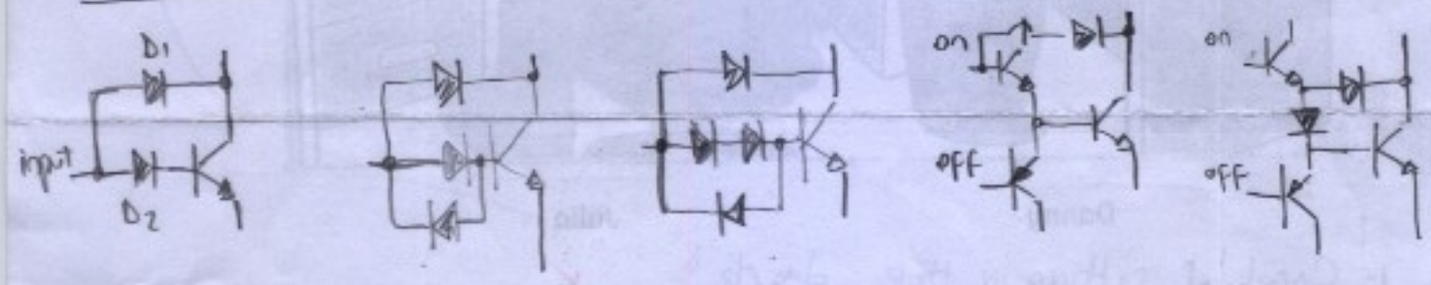
$\beta_{forzado} = \frac{I_{C(sat)}}{I_B}$

$V_{BE} - V_{CE} > 0{,}55\ V$

Diodo BC → conduce

Se pierde la repartic. homog. corriente

Enclavador Baker (Red antisaturadora)



$V_{CE} \approx -V_{D1} + V_{D2} + V_{BE}$

$V_{CE} \approx V_{BE}$

} los diodos no dejan que $V_{CB} < 0$

Modulación de la conductividad ⇒

pequeña señal → red → ↓ t_s

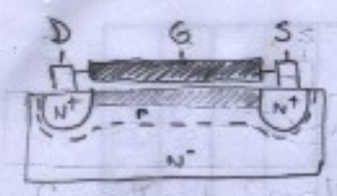
tx potencia → red → ↓ t_f

ancho base ↓ → V_{CE} ↑

↑ → ↓

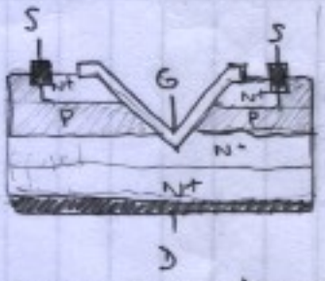
"Es el proceso por el cual la zona de concentración n^- del colector se inunda con portadores móviles que provienen de la base aumentando el ancho efectivo" de la base

TRÁNSISTORES MOSFET

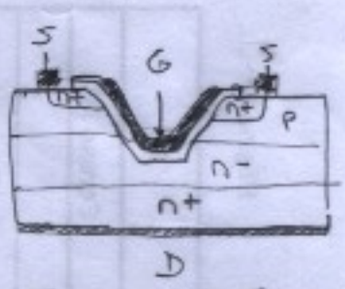


Conventional Small Signal
Long Lateral Channel

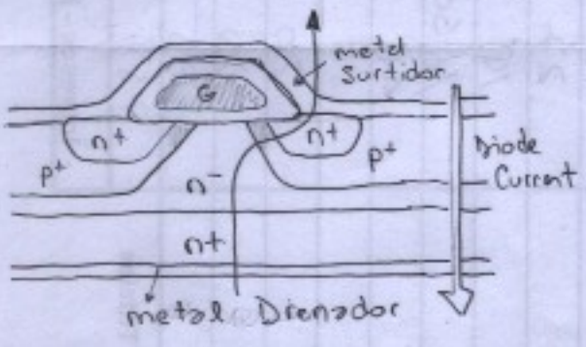
Lateral Doble Diffused
Uso ineficiente del silicio

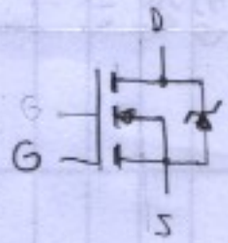


V-Groove Trench Mospet
Costoso, no planar



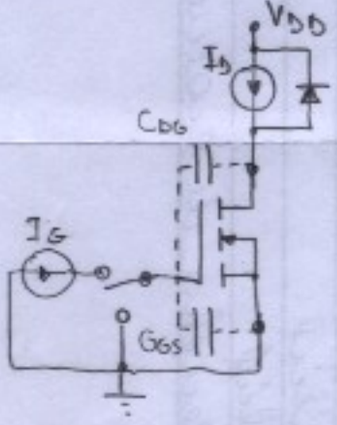
Truncated V-Groove
Costoso, no planar

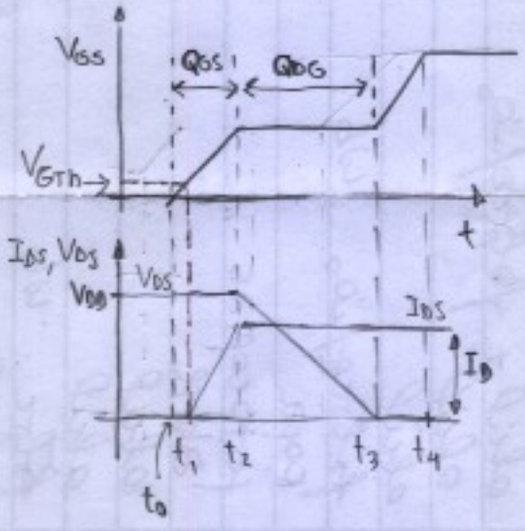




- portadores mayoritarios
- caída tensión directa incrementa con la temp.
- Para $V_{DS} > 200$, $R_{DS(on)}$ ↑ mucho

Carga de compuerta





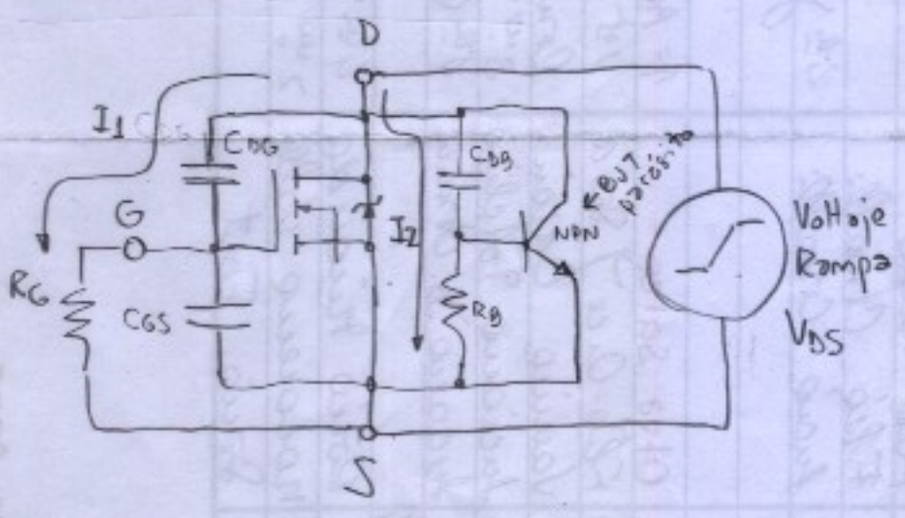
La carga de compuerta $Q_{GS} + Q_{DG} \Rightarrow t_3$ es la carga mínima → "on"

$Q_G \Rightarrow t_4 \Rightarrow$ Drive del gate

$$I_G = \frac{\Delta Q_G}{t_{conmutación}}$$

t_4

Capacidad dV_{DS}/dt estática



(1) $I_1 = C_{GD} \cdot \frac{dV_{DS}}{dt}$

$V_{GS} = I_1 \cdot R_G = R_G \cdot C_{GD} \frac{dV_{DS}}{dt}$

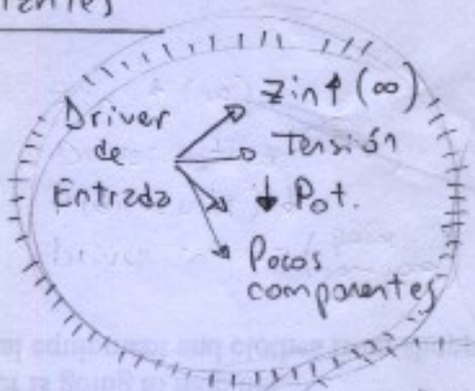
$$\frac{dV_{DS}}{dt} = \frac{V_{G(th)}}{R_G \cdot C_{GD}}$$

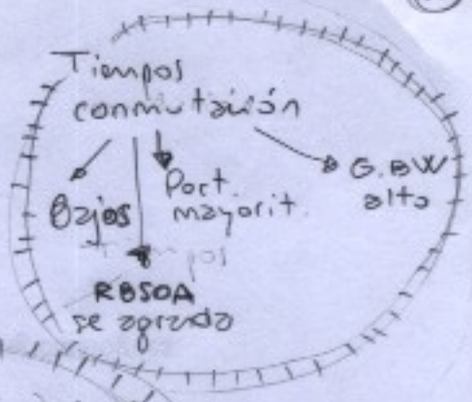
(2) $I_2 = C_{DB} \frac{dV_{DS}}{dt}$

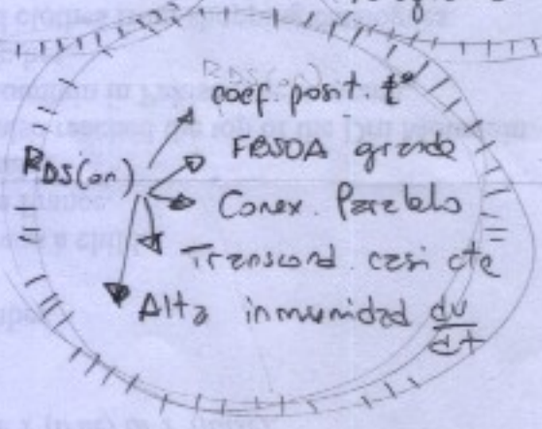
$$\frac{dV_{DS}}{dt} = \frac{V_{BE}}{R_B \cdot C_{DB}}$$

Especificaciones más importantes

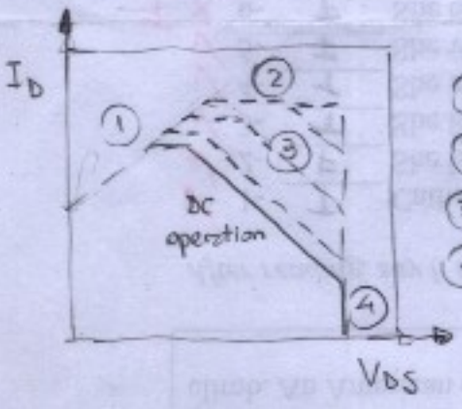
V_{DSS}, $V_{(BR)DS}$, I_D, I_{DM}, V_{GS}, V_{GSM}, $V_{GS(TH)}$, P_D, $R_{DS(on)}$, T_j, T_{stg}, R_{thjc},





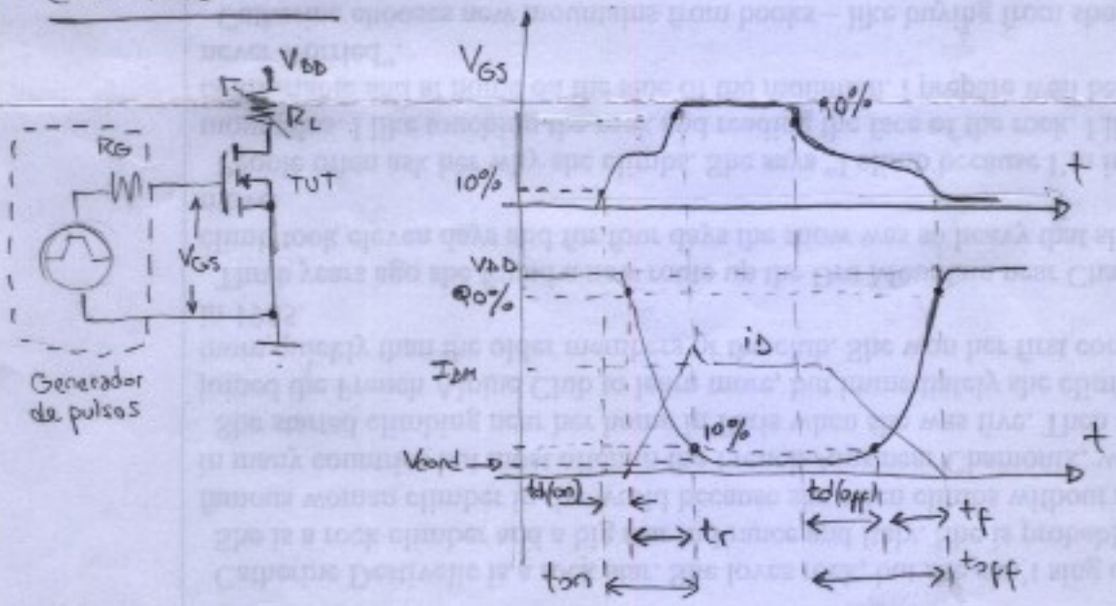


SOA (FBSOA, SSOA)



① $R_{DS(on)}$
② $I_{D\,máx}$
③ Pot máx
} f(D)
④ $V_{(BR)DS}$

Conmutación



Zener entre G y S → proteger de V_{GSM}

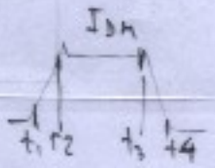
Temperaturas, Energía, Potencia

idem BJT (pág 7 del resumen)

$V_{cond} = R_{DS(on)} \cdot I_{DM}$

$t_{on} \Rightarrow$ reemplazar por $t_{ir} = t_2 - t_1$

$t_{off} \Rightarrow$ " " $t_{if} = t_2 - t_1$



Cálculo de I_{DM}:

despejar I_{DM} de:

(idem BJT)

$$I_{DM}^2 + I_{DM} \cdot \left[\frac{V_{DD}}{R_{DS(on)} \cdot t_{cond}} \left(\frac{t_{ir}}{K_{on}} + \frac{t_{if}}{K_{off}} \right) \right] - \frac{T_{j(AV)} - T_{case}}{F \cdot R_{thjc} \cdot R_{DS(on)} \cdot t_{cond}} = 0$$

$T_{j(AV)}$ ó T_{jM} (si frec < 3khz)

$F = \frac{1}{t_p}$ (si frec < 3khz)

R_{thjc} → R_{thp} (si frec. < 3khz)

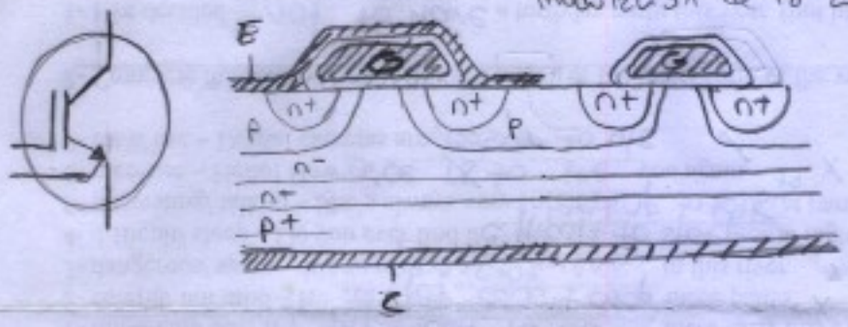
Cálculo de Th: (idem BJT)

TRANSISTORES IGBT

Mosfet + → juntura p^+

→ reduce considerablemente disip. potencia estado "on"
→ inyección portadores minoritarios modulación de la conductividad

} dispositivo de portadores minoritarios



Similitudes

MOSFET:
- Compuerta controlada por tensión, fácil driver
- Gran SOA
- La capacidad de entrada debe ser cargada y descargada
- Peligro por cargas electrostáticas
- No tiene ruptura secundaria

BJT:
- Tensión de saturación poco dependiente de I_C
- Corriente de cola (bajo)
- No tiene diodo parásito
- Tiene tiempo de almacenamiento
- Port. minorit. pero son más rap. que el BJT

- ⊗ No aplic. lineales
- ⊗ Se incorpora diodo de ↓ trr y ↑ P
- ⊗ No autoenganche

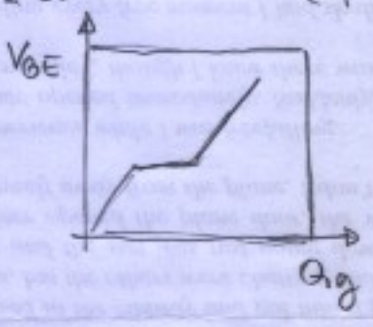
Otras caract.

Especificaciones

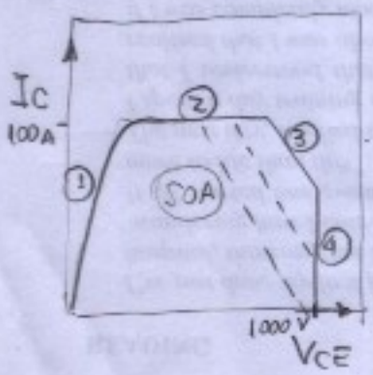
$V_{(BR)CE}$, V_{CER}, I_C, I_{CM}, V_{GE}, V_{GEM}, V_{GEth}, P_D, T_j, T_{stg}, R_{thjc},

Carga de compuerta

Idem MOSFET (pág 10)

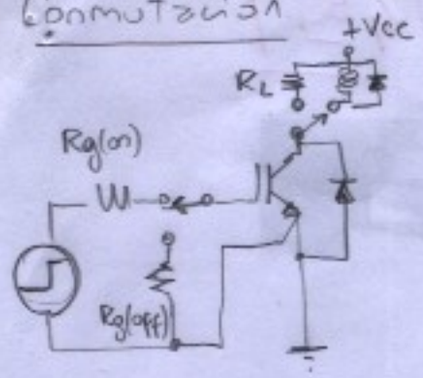


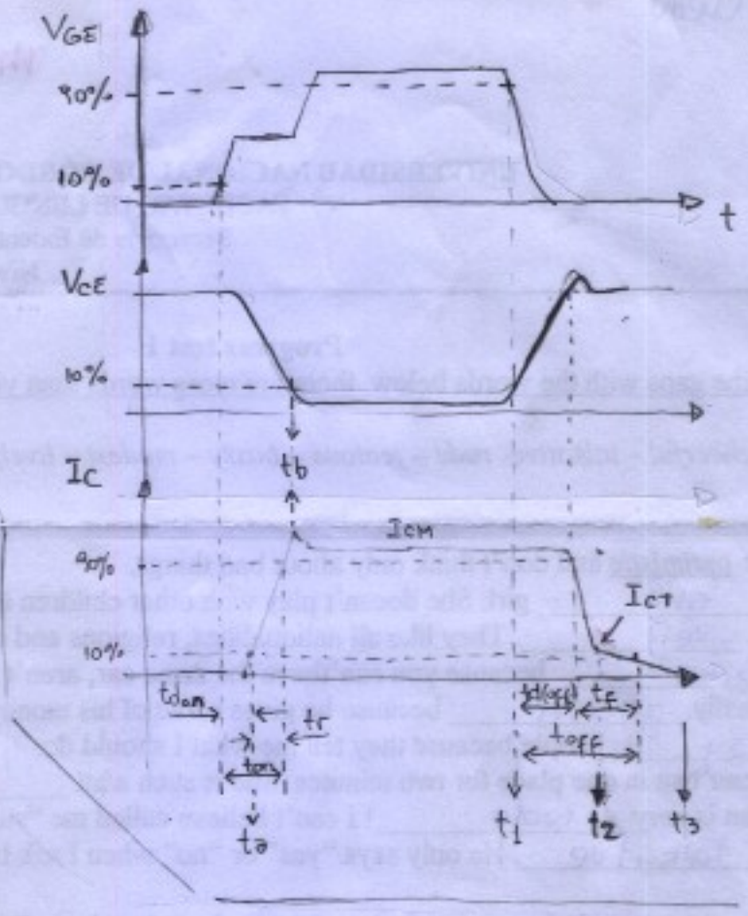
SOA



1. Resist. de saturación.
2. $I_{CMÁX}$ (Zener → proteger gate)
3. Pot. máx
4. $V_{CE(BR)}$

Conmutación





Temp., Energía, Potencia

(idem BJT)

$W_{on} \rightarrow t_{on} = t_b - t_0$

$W_{cond} \rightarrow t_{cond} = t_1 - t_b$

$W_{off12} \rightarrow t_{off12} = t_2 - t_1$

$W_{off23} \rightarrow t_{off23} = t_3 - t_2$

$$W_{off12} = \frac{I_{CM} \cdot V_{CCE} \cdot t_{off12}}{K_{off}} \qquad K_{off} = 2 \quad (1^{er})$$

$$K_{off} = 6 \quad (2^{do})$$

$$W_{off23} = \frac{I_{CT} \cdot V_{CCE} \cdot t_{off23}}{K_{off}} \qquad K_{off} = \frac{2 \cdot V_{CCE}}{V_{cond}} \quad (3^{er})$$

$$P_{TOT(AV)} = \frac{W_{on} + W_{cond} + W_{off12} + W_{off23}}{T}$$

$$P_{TOT(M)} = \frac{W_{on} + W_{cond} + W_{off12} + W_{off23}}{t_p}$$

Cálculo de ICM:

$$I_{CM} = \frac{\overbrace{\frac{T_{j(AV)} - T_{case}}{F \cdot R_{thjc}}}^{T_{jM}/t_p} - \frac{I_{CT} \cdot V_{CCE} \cdot \frac{t_{off-23}}{2}}{}}{V_{CCE}\left(\frac{t_{on}}{K_{on}} + \frac{t_{off-12}}{K_{off}}\right) + V_{cond} \cdot t_{cond}}$$

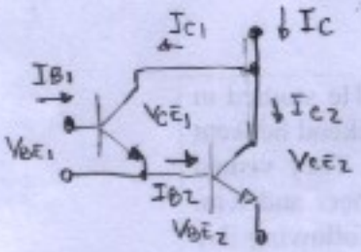
$K_{off} = 2$

R_{thp}

Cálculo de Th: (idem BJT)

MONTAJES

• Darlington:

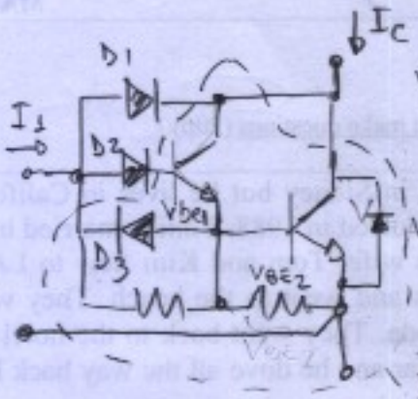


$$V_{CE2} = V_{CE1} + V_{BE2}$$

$$I_{B1} \approx \frac{I_C}{\beta_1 \cdot \beta_2}$$

$$I_C = I_{C2} + I_{C1}$$

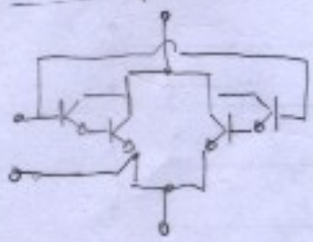
$$I_{B2} = I_{B1} + I_{C1}$$



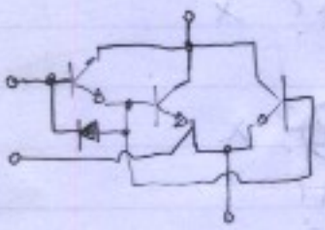
$$V_{CE2} = V_{BE2} + V_{BE1} + V_{D2} - V_{D1}$$

Darlington integrado

Conex. paralelo:



NO

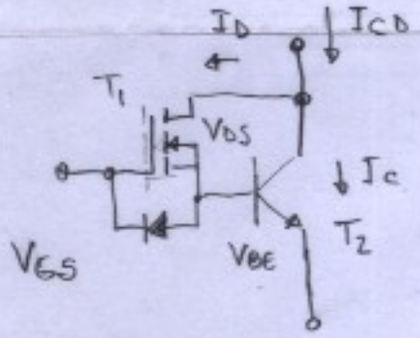


SI

• Bipmos:

$$V_{CE(SAT)} = V_{BE(SAT)} + V_{DS(SAT)} = V_{BE(SAT)} + I_D \cdot R_{DS(on)}$$

$$= V_{BE(SAT)} + \frac{I_C}{\beta_f} \cdot R_{DS(on)}$$

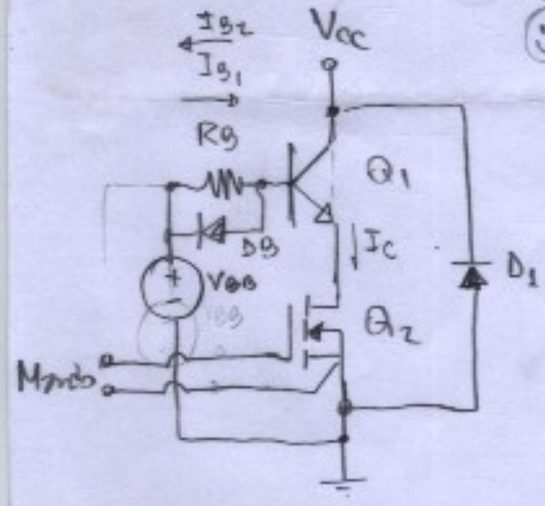


"$R_{DS(on)}$ → efecto se divide por β_f"

• Switch por emisor:

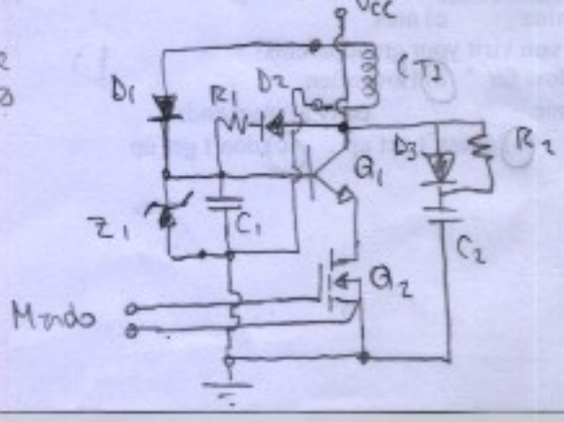
☺ Conmutación rápida de un tx de baja potencia (Q_2)

☺ Conmutación de alta potencia de un tx de ↑ tensión (Q_1) (Darlington en B.C)



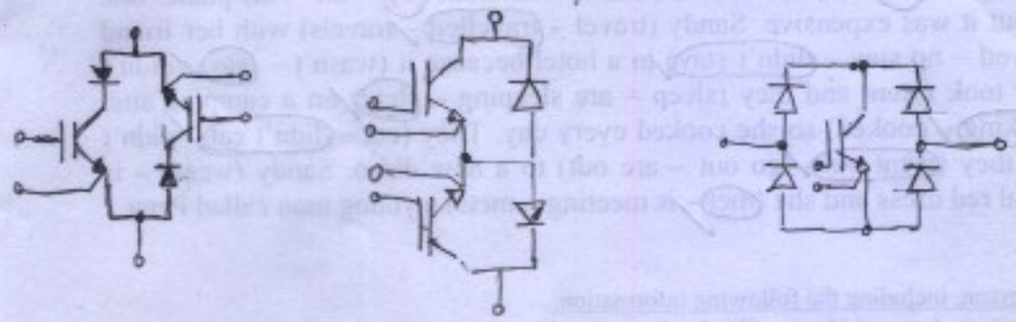
$$I_{B1} = \frac{V_{BB} - V_{BE(SAT)} - V_{DS(SAT)}}{R_B}$$

Fuente única



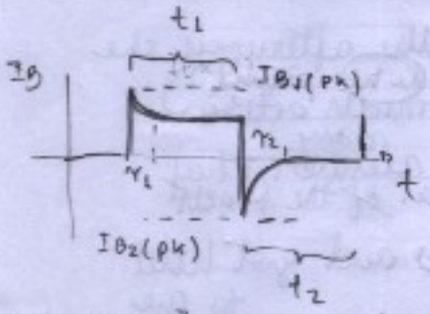
- D_2 y R_1 cargan C_1 en OFF
- CT_1 carga C_1 en ON
- Z_1 mantiene tensión de V_{BB}

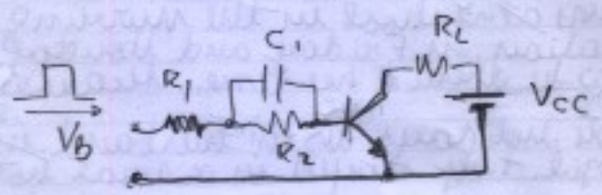
Aplicaciones Bidireccionales:



DRIVE DE BASE DEL BJT

Se busca reducir
- t_{on}: pico I_B encendido ($\downarrow t_r$)
- t_{off}: I_B negativa de apagado ($\downarrow t_s$ y $\downarrow t_f$)

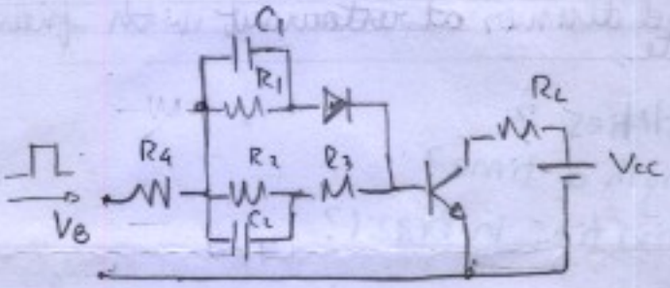




$t_1 = 5.\tau_1$
$t_2 = 5.\tau_2$

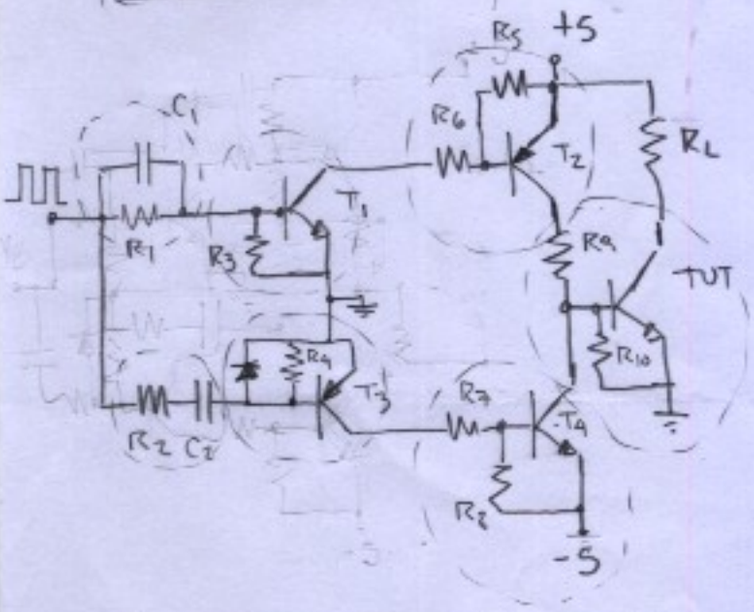
$F = \frac{1}{T} = \frac{1}{5(\tau_1+\tau_2)}$

$F = \frac{0.2}{\tau_1+\tau_2}$



independizamos los tiempos de encendido y apagado.

1) Control de encendido y apagado



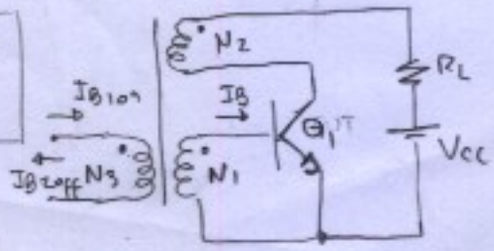
$$I_{B1} = \frac{5 - V_{CEsat2} - V_{BETUT}}{R_9}$$

$\tau_1 \cong R_1 . C_1$

$\tau_2 \cong R_2 . C_2$

$I_{B2(pk)} \approx 5$ a 6 veces I_{B1}

2) Control proporcional de la base



I_{B1on} = pulso de corta duración

satura Q_1

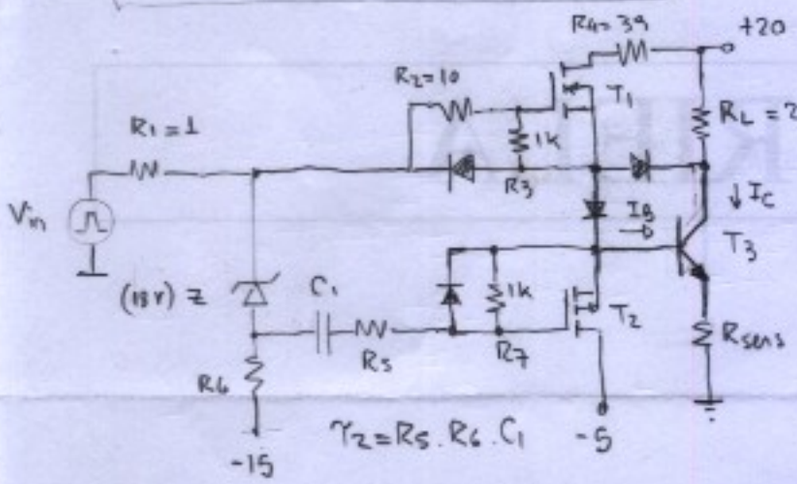
Q_1 se autoenclava con $\frac{I_C}{I_B} = \frac{N_2}{N_1} = \beta_F$

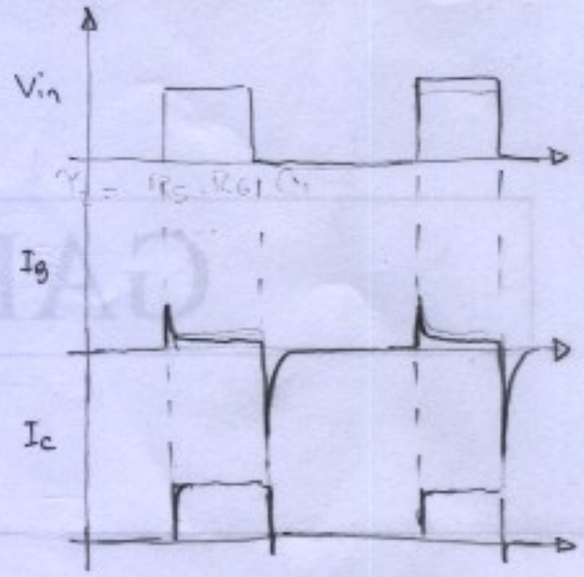
Determinando $\frac{N_2}{N_1} \rightarrow \beta_F$

$D = 50\%$ máx.

Con I_{B2off} se apaga → desenclava.

3) Control de Antisaturación con enclavador Baker

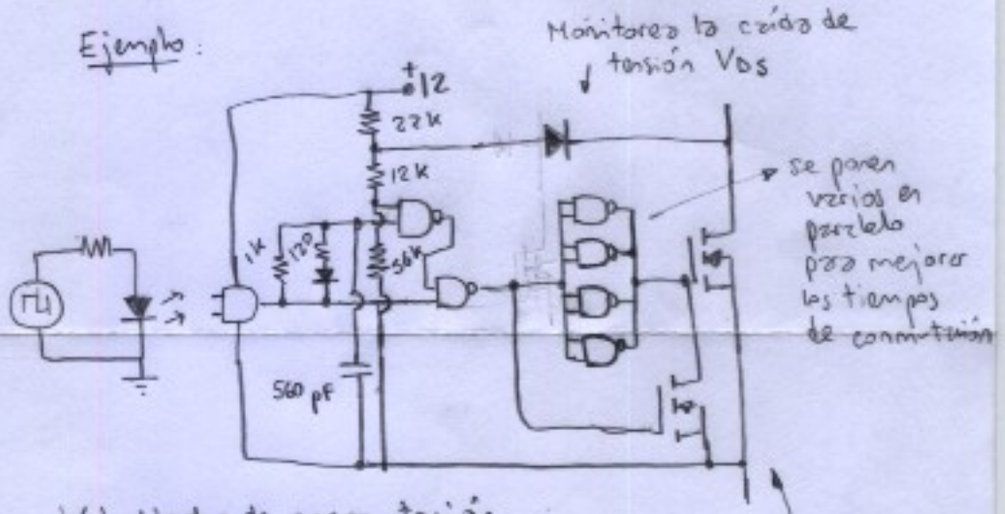




DRIVE DE COMPUERTA DEL MOSFET E IGBT

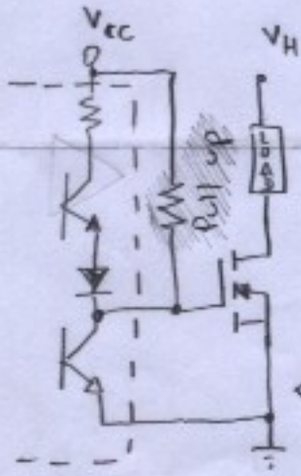
Durante la conmutación C_{GS} y C_{DG} deberán cargarse o descargarse en forma rápida → circulación de corriente (solo durante la carga o descarga).

Ejemplo:

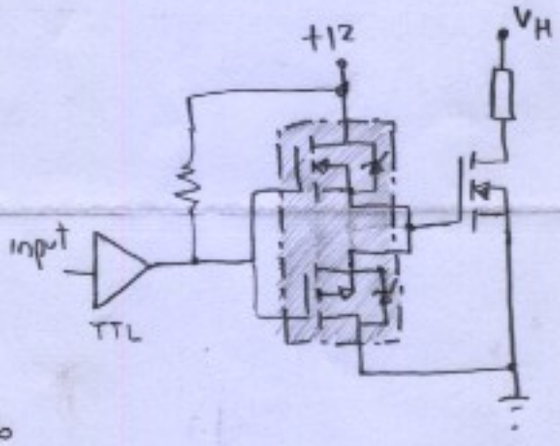


Velocidades de conmutación de 100 ns a 250 ns → drivers de motores de DC con f = 20 a 30 khz.

- Drive con TTL:



mejor ⇒



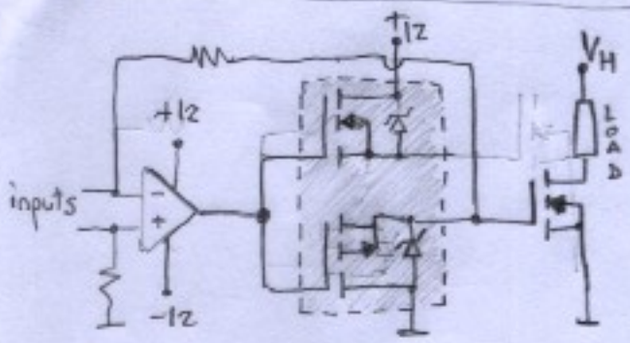
mejor en el apagado

- Drive con CMOS:

mejor en el encendido

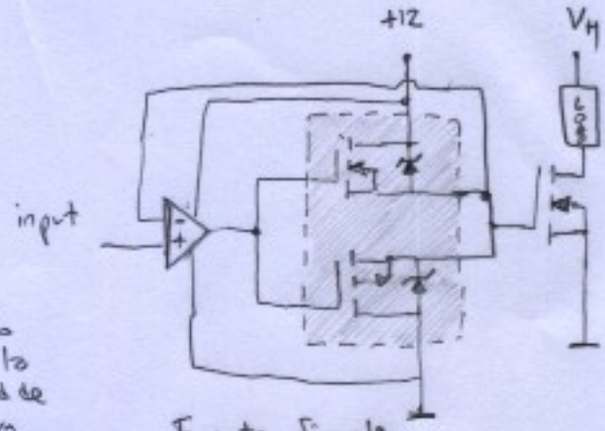
- Se puede garantizar la saturación del mosfet, ya q' operan con tensiones > 5V
- Mayores tiempos de conmutación que el TTL.
- Imped. de salida alta (1KΩ), no se garantiza eficiente apagado

- Drive con circuitos lineales:



Fuente Partida

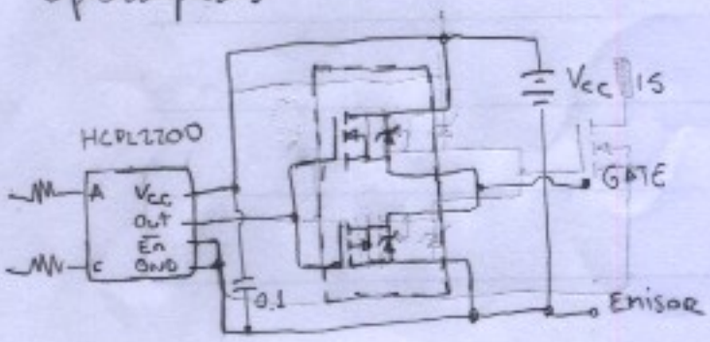
debido al A.O. la velocidad de subida es un poco más lenta.

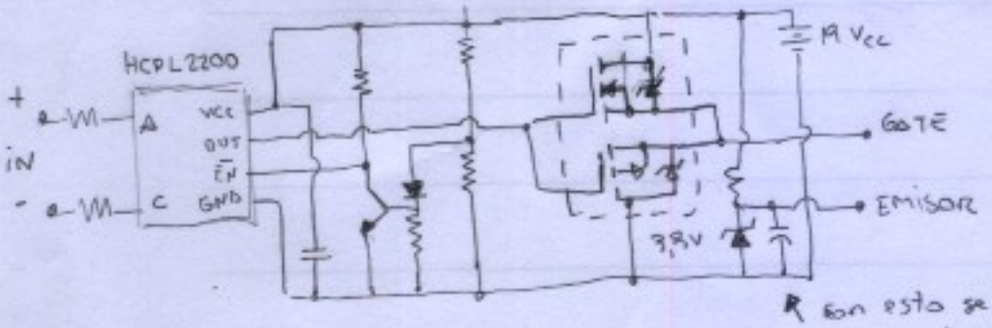


Fuente Simple

- Drive de circuitos no referenciados a masa:

Optoacoplados

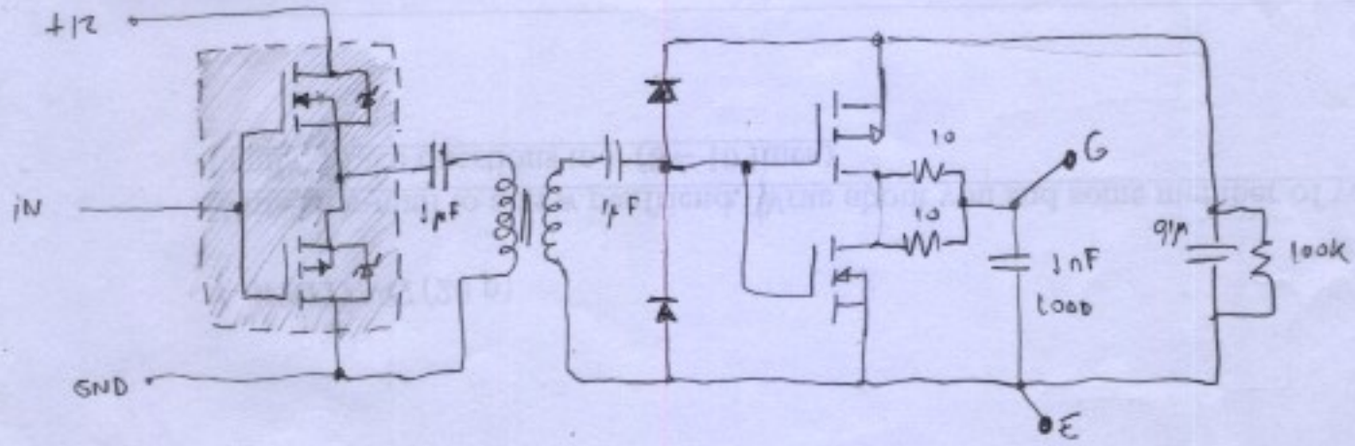


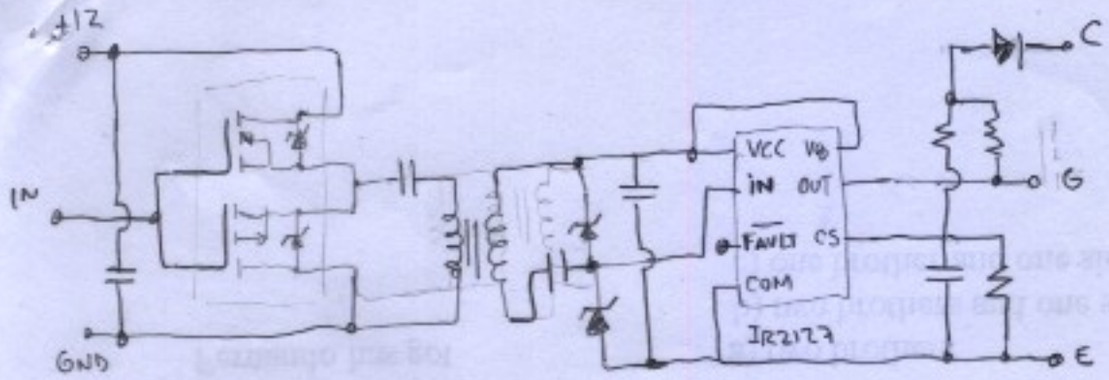


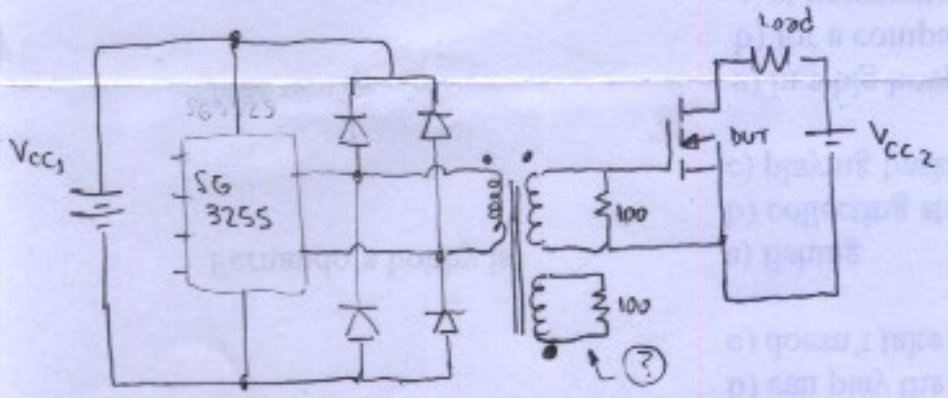
Protección contra tensiones bajas.

con esto se logra bloquear la compuerta con tensión negativa.

Transformadores de pulso

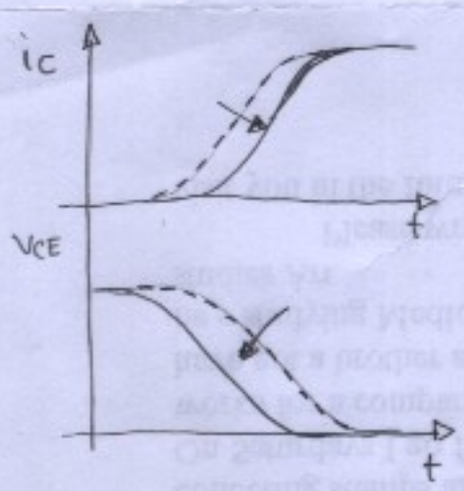




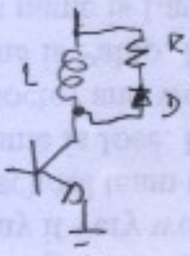


REDES DE AYUDA A LA CONMUTACIÓN

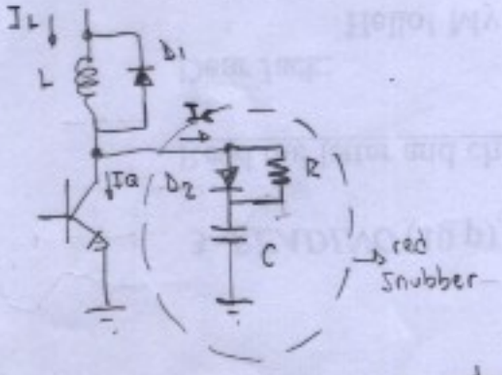
- Durante el encendido: se retarda la subida de la corriente de colector.

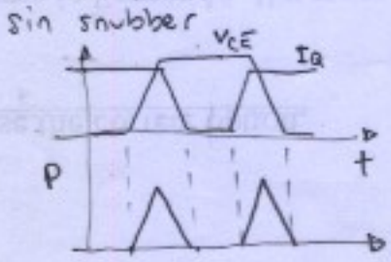


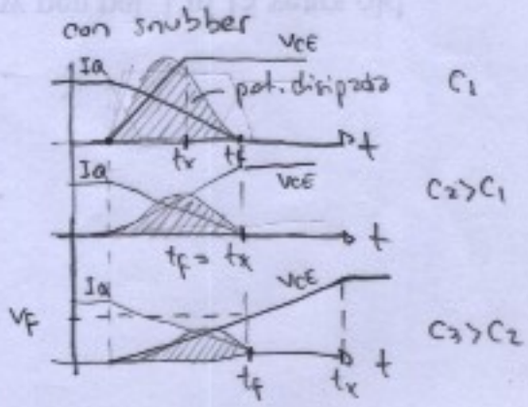
inductor que limita la di/dt ⇒ se carga con una energía $E = \frac{1}{2} L i^2$ ⇓ deberá descargarse durante el bloqueo



- Durante el apagado: la disipación es más crítica.







se retarda la subida de la tensión colector-emisor.

$I_L = I_a + I_c$; para $C = C_3 \rightarrow V_c(t_f) = \frac{I_L \cdot t_f}{2C} = V_f \Rightarrow C = \frac{I_L \cdot t_f}{2 \cdot V_f}$

para $C = C_2 \rightarrow V_{CE_off} = \frac{I_L \cdot t_f}{2C} \therefore \boxed{C = \frac{I_L \cdot t_f}{2 \cdot V_{CE_off}}}$ $(V_{CE_off} = V_f)$

El cap. se descarga durante la saturación del tx $\Rightarrow RC = \tau \leq \frac{t_{on}}{5} \therefore \boxed{R = \frac{t_{on}}{5 \cdot C}}$

Se juega con ambos valores para lograr un buen resultado.

La $I_{disc} \leq 0{,}25\ I_{CMÁX} = \frac{V_{CE}}{R} \therefore \boxed{R \geq \frac{V_{CE}}{0{,}25 \cdot I_{CMÁX}}}$

RECTIFICACIÓN DE POTENCIA

PARÁMETROS CARACTERÍSTICOS

- $V_{AV} = \frac{1}{T}\int_0^T v(t)\,dt$
- $I_{AV} = \frac{1}{T}\int_0^T i(t)\,dt$
- $P_{AV} = \frac{1}{T}\int_0^T v(t)\,i(t)\,dt$
- $V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt}$
- $I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,dt}$
- $P_{rms} = I_{rms} \cdot V_{rms}$
- $\eta = \frac{P_{AV}\,(out)}{P_{rms}\,(in)}$ = eficiencia

- $FF = \frac{V_{rms}}{V_{AV}} = \frac{V_{rms}}{V_{CD}}$ = factor de forma
- $CF = \frac{V_{max}}{V_{rms}}$ = factor de cresta
- $V_{rms}^2 = V_{AV}^2 + V_{AC}^2 \Rightarrow$ comp. ondulatoria
- $RF = \frac{V_{AC}}{V_{AV}} = \frac{\sqrt{V_{RMS}^2 - V_{AV}^2}}{V_{AV}} = \sqrt{FF^2 - 1}$ = factor de rizado
- $THDi = \frac{\sqrt{I_{RMS}^2 - I_{1_RMS}^2}}{I_{1_RMS}} = \sqrt{\frac{I_{RMS}^2}{I_{1RMS}^2} - 1}$ = Distorsión armónica total
- $TUF = \frac{P_{AV}}{V_{rms_S} \cdot I_{rms_S}}$ = factor de utilización del transformador

Factor de potencia

$$\boxed{PF = \frac{P_{CD}}{P_{rms}} = \frac{P_{AV}}{V_{rms} \cdot I_{rms}} \qquad 0 \leq PF \leq 1}$$

Indica la efectividad de la transmisión de la energía entre la fuente y la carga.

(1) Tensión sinusoidal, carga no lineal:

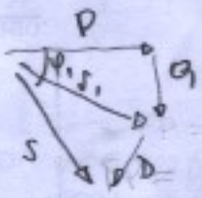
$v(t) = V_1 \cdot \text{sen}(\omega_0 t + \theta_1)$

$i(t) = I_0 + \sum_{n=1}^{\infty} I_n \cdot \text{sen}(n\omega_0 t + \phi_n)$

$P_{AV} = V_1 \cdot I_1 \cdot \frac{1}{T}\int_0^T \text{sen}(\omega_0 t + \theta_1) \cdot \text{sen}(\omega_0 t + \phi_1)\,dt$

$P_{AV} = \frac{V_1 \cdot I_1}{2} \cos(\theta_1 - \phi_1) = V_{1rms} \cdot I_{1rms} \cdot \cos\varphi$

$FP = \frac{V_{1rms} \cdot I_{1rms}}{V_{rms} \cdot I_{rms}} \cos\varphi = \boxed{\frac{I_{1rms}}{I_{rms}} \cos\varphi = FP}$



$P = V_{rms} \cdot I_{1_rms} \cdot \cos\varphi_1$
$Q = V_{rms} \cdot I_{1_rms} \cdot \text{sen}\,\varphi_1$
$S_1 = V_{rms} \cdot I_{1_rms}$
$S = V_{rms} \cdot I_{rms}$
$D = V_{rms} \cdot \sqrt{\sum_{n=2}^{\infty} I_{n_rms}^2}$

$FP = \frac{DPF}{\sqrt{1 + THDi^2}}$

DPF = factor de potencia de desplazamiento

$PF = \cos\varphi$

(3) Tensión sinusoidal, corriente sinusoidal:

(2) Tensión no sinusoidal, carga lineal:

$I_n = \frac{V_n}{R}$; $I_{AV} = \frac{V_{AV}}{R}$

$I_{RMS} = \sqrt{I_{AV}^2 + \sum \frac{I_n^2}{2}} = \sqrt{\left(\frac{V_{AV}}{R}\right)^2 + \sum \left(\frac{V_n}{R}\right)^2 \cdot \frac{1}{2}}$

$V_{RMS} = \sqrt{V_{AV}^2 + \sum V_n^2/2}$ $\therefore I_{RMS} = \frac{V_{RMS}}{R}$

$P_{AV} = V_{AV} \cdot I_{AV} + \sum \frac{V_n I_n}{2} \cos\varphi^{=0^\circ}$

$P_{AV} = V_{AV}^2/R + \sum V_n^2/2R = \frac{V_{RMS}^2}{R}$

$PF = \frac{V_{RMS}^2}{R} \cdot \frac{1}{V_{RMS}^2/R} = 1$ → $V_{rms} \cdot I_{rms}$

- RECTIF. NO CONTROLADOS
  - MONOFÁSICOS
    - 1/2 ONDA
    - ONDA COMPLETA
      - C/TOMA INTERMEDIA
      - S/TOMA INTERMEDIA
  - TRIFÁSICOS
    - 1/2 ONDA
    - ONDA COMPLETA
      - Puente de Graëtz (PD3)
      - Puente de Graëtz de 12 pulsos
  - Q-FÁSICOS

- RECTIF. CONTROLADOS
  - MONOFÁSICOS
    - TOTAL CONTROL
      - 1/2 ONDA
      - ONDA COMPLETA → PUENTE
    - SEMI-CONTROL
    - DUAL
  - TRIFÁSICOS
    - TOTAL CONTROL
      - 1/2 ONDA
      - ONDA COMPLETA
        - Graëtz
        - Graëtz 12 pulsos
    - SEMI-CONTROL
    - DUAL
  - Q_FÁSICOS

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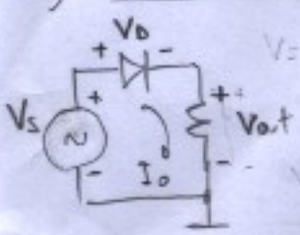
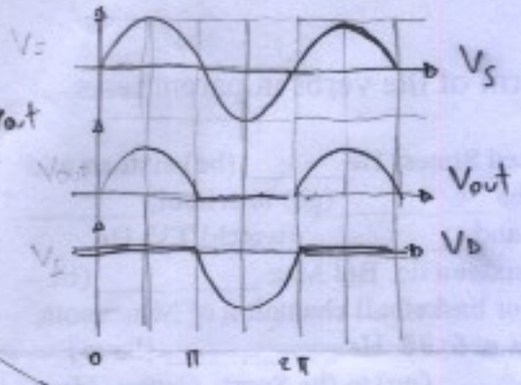
RECTIFICADORES NO CONTROLADOS

A) Rectificador monofásico de media onda:



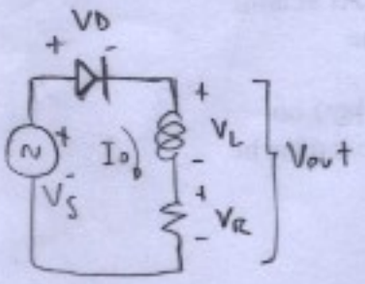


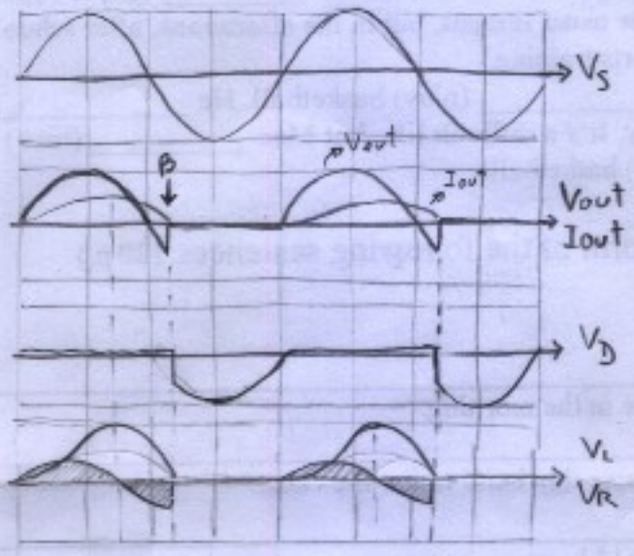
$$V_{AV} = \frac{V_{max}}{\pi}$$

$$I_{AV} = \frac{V_{AV}}{R} = \frac{V_{max}}{\pi R}$$

$$V_{rms} = \frac{V_{max}}{2}$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{V_{max}}{2R}$$





$$V_{máx}\,sen(\omega t) = V_R + V_L = R\,i(t) + L\frac{di(t)}{dt}$$

$$i(t) = i_f(t) + i_n(t)$$

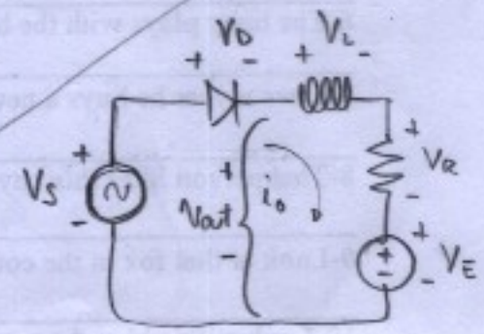
$$i_f(t) = \frac{V_{máx}}{Z}\,sen(\omega t - \theta)$$

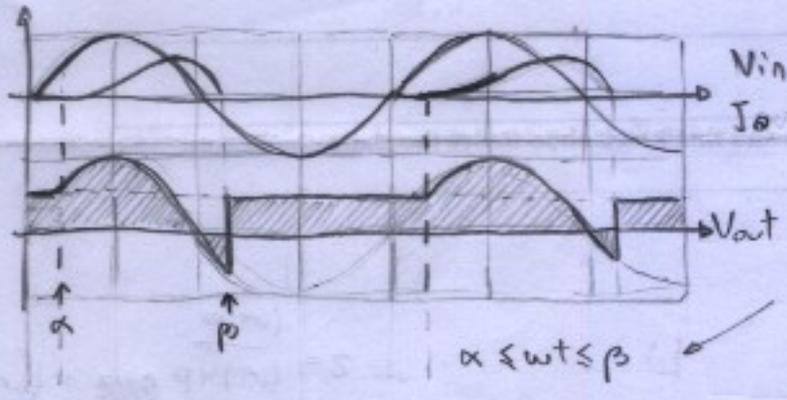
$$i_n(t) = A\,e^{-t/\tau} = A\,e^{-\omega t/\omega\tau}$$

$$i(\omega t) \Rightarrow \frac{V_{max}}{Z}\left[sen(\omega t - \theta) + sen\,\theta\,.\,e^{-\omega t/\omega\tau}\right] \quad \text{para } 0 \leq \omega t \leq \beta$$

$$\Rightarrow 0 \quad \text{para } \beta \leq \omega t \leq 2\pi$$

$$I_{RMS} = \left(\frac{1}{2\pi}\int_0^{\beta} i^2(\omega t)\,.\,d\omega t\right)^{1/2} \qquad I_{AV} = \frac{1}{2\pi}\int_0^{\beta} i(\omega t)\,d\omega t$$





$$V_{max}\,.\,sen\,\alpha = V_E$$

$$i(\omega t) \Rightarrow \frac{V_{max}}{Z}\,sen(\omega t - \theta) - \frac{V_{cc}}{R} + A\,.\,e^{-\omega t/\omega\tau}$$

$$\alpha \leq \omega t \leq \beta$$

$$A = \frac{V_{cc}}{R} - \frac{V_{max}}{Z}\,sen(\alpha - \theta)\,.\,e^{\alpha/\omega\tau}$$

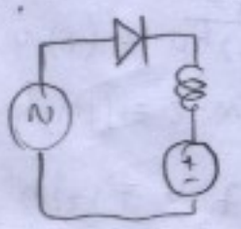
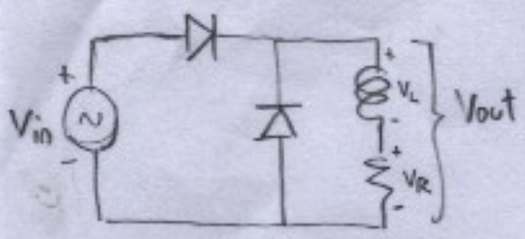


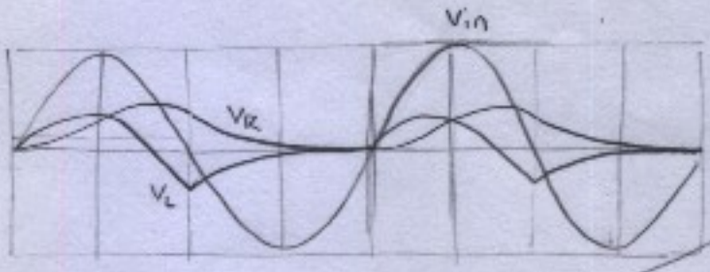
Gráfico idem

$$i(\omega t) \Rightarrow \frac{V_{máx}}{\omega L}\left(\cos\alpha - \cos\omega t\right) + \frac{V_{cc}}{\omega L}\left(\alpha - \omega t\right) \quad \text{para } \alpha \leq \omega t \leq \beta$$

$$\Rightarrow 0 \quad \text{para otro valor}$$

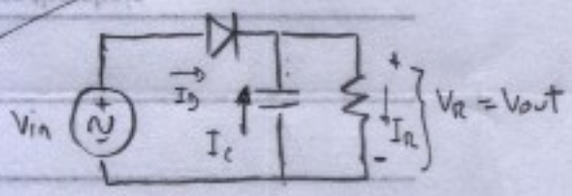
6) El diodo de carrido libre:





sin diodo volante $\rightarrow V_{\Delta V} = \frac{V_{máx}}{2\pi}\left(1-\cos(\pi+\theta)\right)$; $\pi+\theta=\beta$

con diodo volante $\rightarrow \theta = 0°$



$V_{out} = V_{máx} \cdot sen(\omega t) \rightarrow$ (diodo polar. dir)

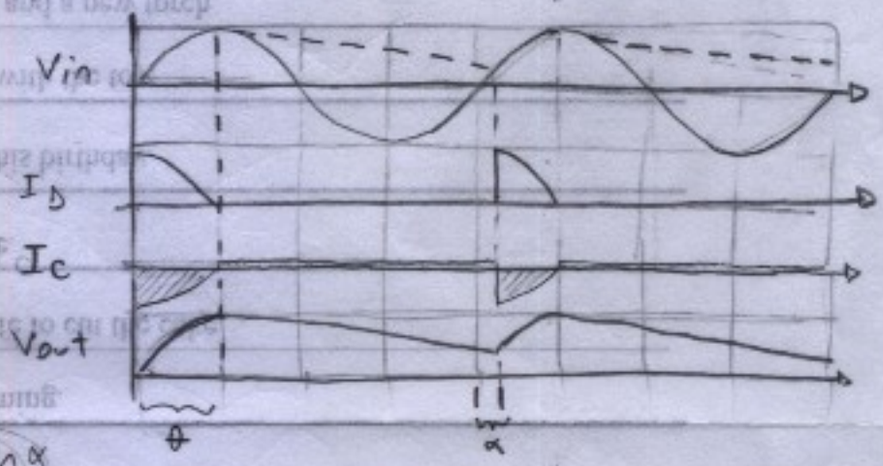
$V_{out} = V_\theta \cdot e^{-(\omega t-\theta)/\omega\tau}$ $\tau \rightarrow RC$

$V_\theta = V_{máx} \cdot sen(\theta)$

$sen\,\alpha = sen(\theta)\, e^{-(2\pi+\alpha-\theta)/\omega RC}$

$i_R = \frac{V_{out}}{R}$

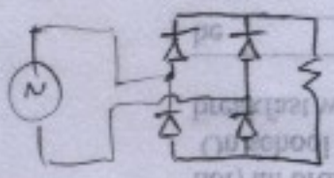
$i_C = C \cdot \frac{dV_{out}}{dt}$ $\quad I_{C(máx)}$ $\quad I_{R(2\pi+\alpha)}$



$I_{D(máx)} = \omega C V_{máx} \cdot \cos\alpha + \frac{V_{máx} \cdot sen\,\alpha}{R}$

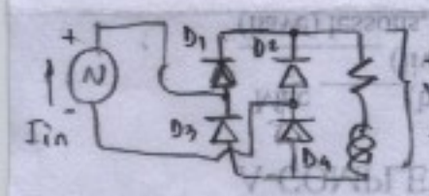
$\Delta V_{out} = V_{máx}(1-sen\,\alpha)$; si $\theta = \frac{\pi}{2}$, $\alpha = \pi/2$ $\therefore \Delta V_{out} \approx \frac{V_{máx}}{4RC}$

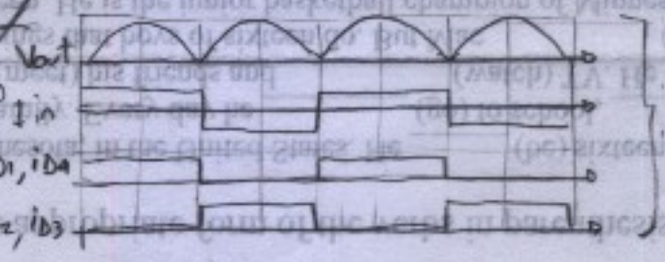
B) Rectificador monofásico de onda completa:



$V_{out_{AV}} = \frac{2V_{máx}}{\pi}$ $\quad I_{out_{AV}} = \frac{2V_{máx}}{\pi R}$ (también puede ser con trafo con punto medio)

$V_{out_{RMS}} = \frac{V_{máx}}{\sqrt{2}}$ $\quad I_{out_{RMS}} = \frac{V_{máx}}{\sqrt{2}R}$



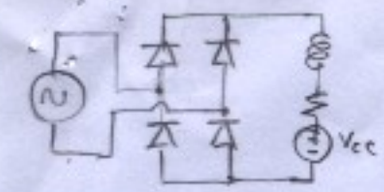


Fourier

$V_{out} = \frac{2V_{máx}}{\pi} - \frac{4V_{máx}}{3\pi}\cos(2\omega t) - \frac{4V_{máx}}{15\pi}\cos(4\omega t) - \frac{4V_{máx}}{35\pi}\cos(6\omega t) - \cdots$

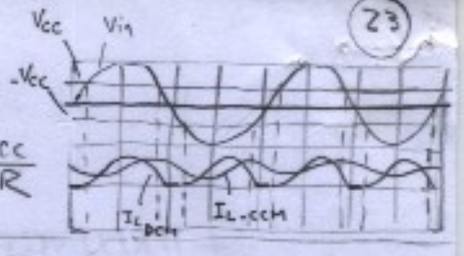
Si RL $\rightarrow$ $I_n = \frac{V_n}{Z_n} = \frac{V_n}{|R+j\omega L|}$ (salida) $\rightarrow$ Desarrollo en serie de Fourier

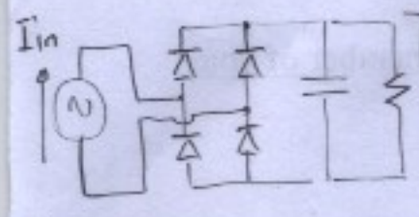
Si $L \rightarrow \infty$ $\rightarrow$ $I_{in_n} = \frac{4}{n\pi} \cdot I_{máx}$ (entrada) $\leftarrow$ Fourier de una onda cuadrada

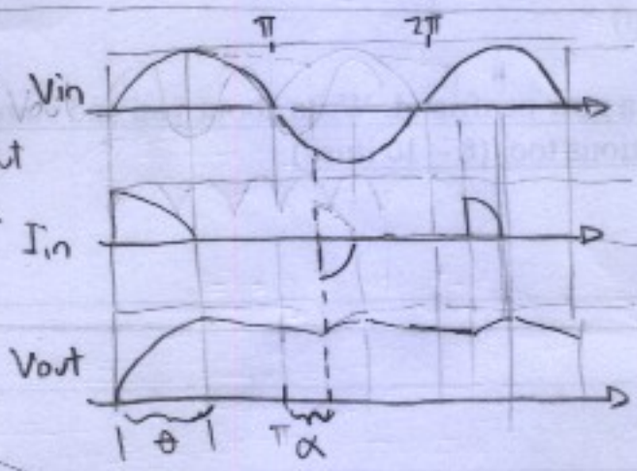


$$L\frac{di}{dt} + Ri + V_{cc} = V_{máx}\,\text{sen}(\omega t)$$

$$i = \frac{V_{máx}}{Z}\,\text{sen}(\omega t - \theta) + A\,e^{-\frac{R}{L}t} - \frac{V_{cc}}{R}$$







$V_{out} = |V_{máx}\,\text{sen}(\omega t)|$

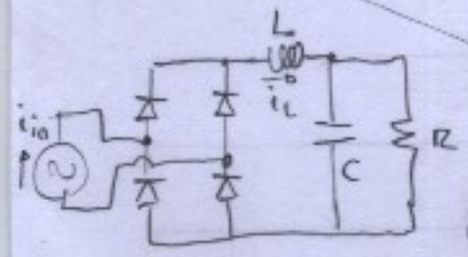
diodo polariz. directamente

$V_{out} = V_\theta \cdot e^{-(\omega t - \theta)/\omega\tau}$

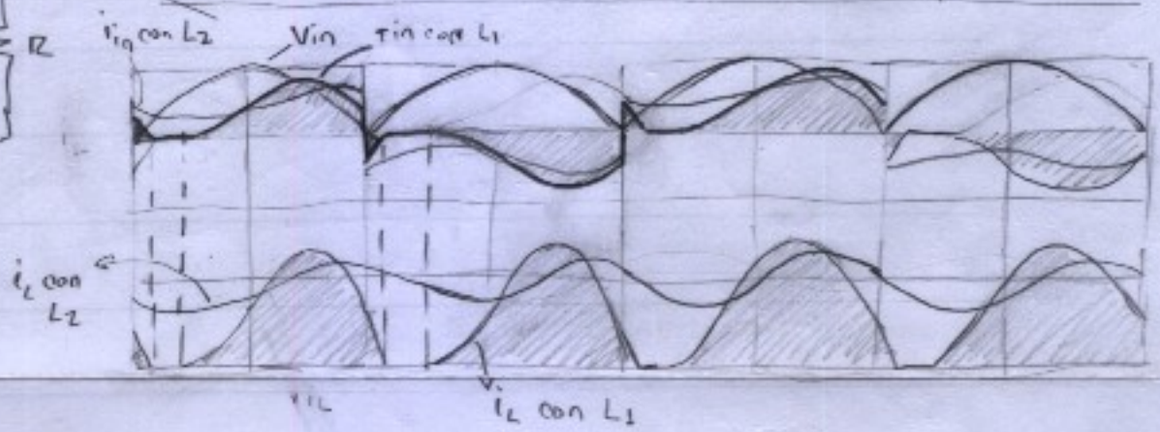
$\Delta V_{out} = V_{máx}(1 - \text{sen}\,\alpha)$

si $\theta \approx \frac{\pi}{2}$ y $\alpha \approx \frac{\pi}{2}$

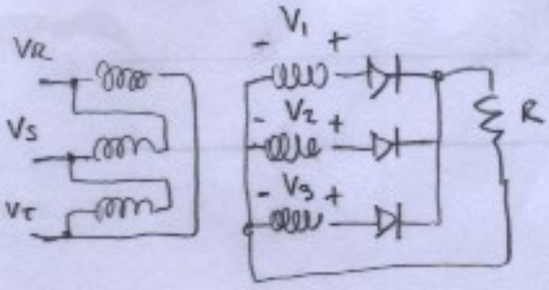
$\Delta V_{out} \approx \frac{V_{max}}{2fRC}$

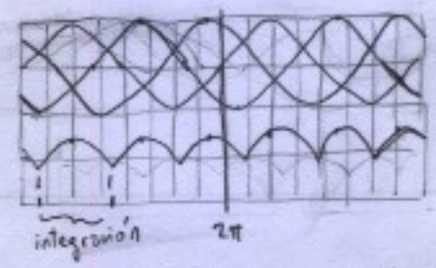


$L_2 > L_1$



c) Rectificador trifásico de media onda:





$V_1 = V_{máx} \cdot \text{sen}(\omega t)$

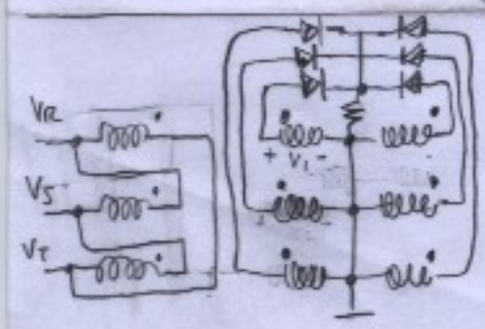
$V_2 = V_{máx} \cdot \text{sen}\left(\omega t - 2\frac{\pi}{3}\right)$

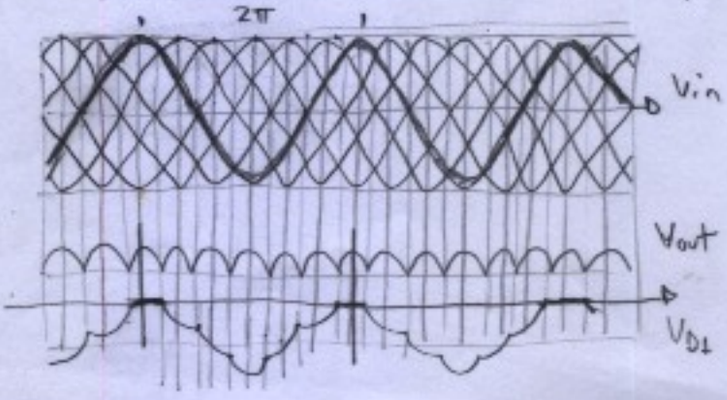
$V_3 = V_{máx}\,\text{sen}\left(\omega t - 4\frac{\pi}{3}\right)$

$$V_{\Delta v} = \frac{3}{\pi}\,V_{máx} \cdot \text{sen}\left(\frac{\pi}{3}\right)$$

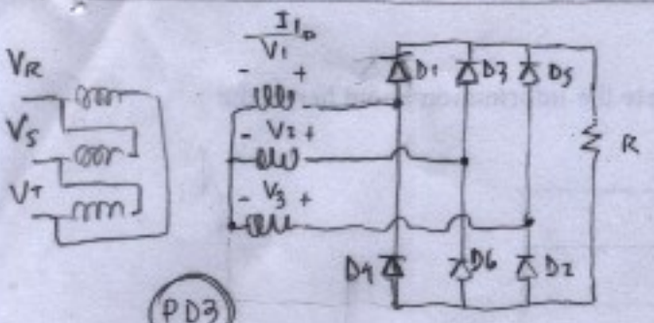
$$V_{rms} = V_{max}\left[\frac{3}{2\pi}\left(\frac{\pi}{3} + \frac{1}{2}\,\text{sen}\left(\frac{2\pi}{3}\right)\right)\right]^{1/2}$$

$$I_{1\,\Delta v} = \frac{I_{\Delta v}}{3} = \frac{V_{\Delta v}}{3R}$$

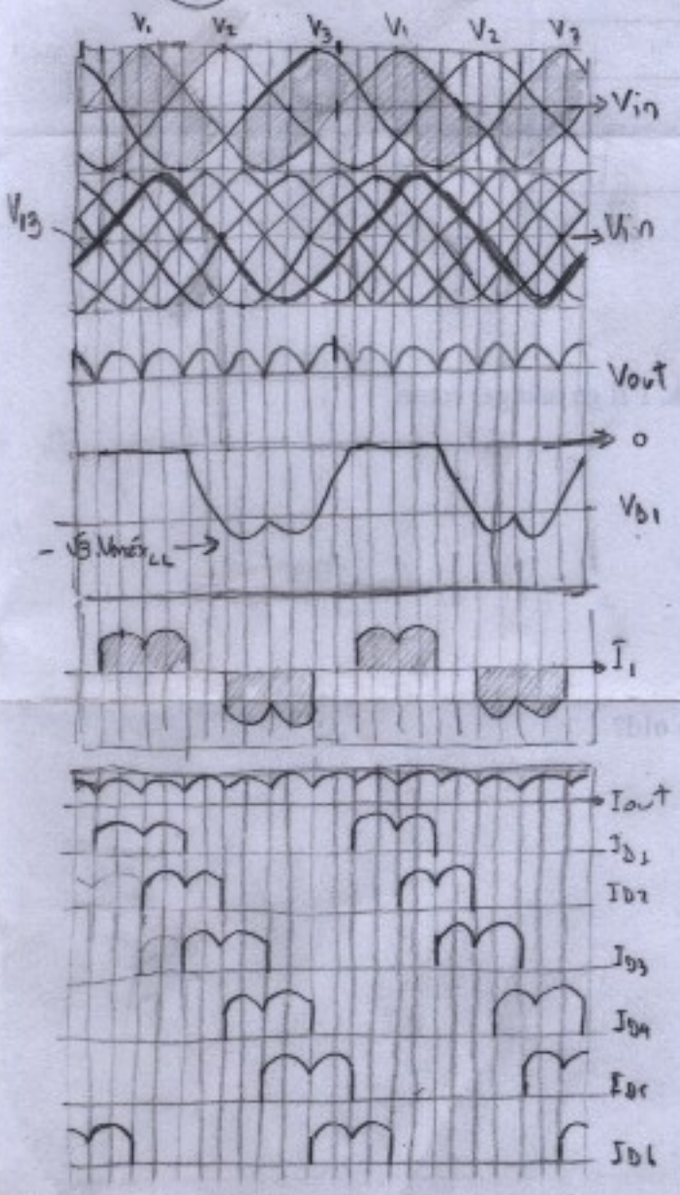




D) Rectificador trifásico de onda completa:



PD3



$$V_{AV} = \frac{3 \cdot V_{máx_{LL}}}{\pi} \; ; \; V_{rms} = \sqrt{\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}} \cdot V_{máx_{LL}}$$

$$I_{D_av} = I_{out_av}/3 \; ; \; I_{D_rms} = \frac{I_{out_rms}}{\sqrt{3}}$$

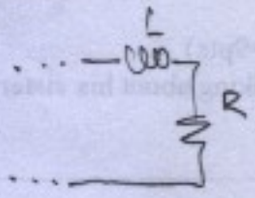
$$I_{in_rms} = \sqrt{\frac{2}{3}} \cdot I_{out_rms}$$

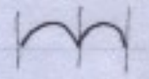
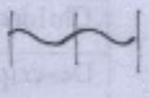
$$V_{out} = V_{AV} + \sum_{n=6,12,18,\ldots}^{\infty} V_n \cdot \cos(n\omega t)$$

$$|V_n| = \frac{6\, V_{máx_{LL}}}{\pi (n^2-1)} \; ; n = 6,12,18\ldots$$

armónicos

$$S_{generador} = \sqrt{3} \cdot V_{LL_rms} \cdot I_{in_rms}$$

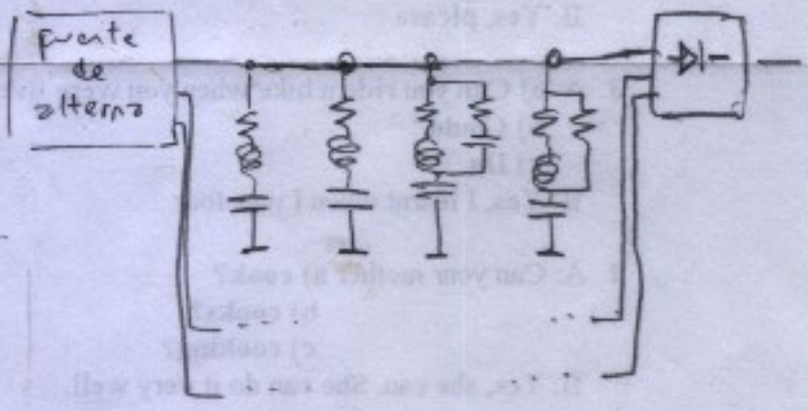


Los gráficos son iguales salvo que en vez de  es  para las corrientes.

si $L \to \infty$ entonces $I_{out} = cte$

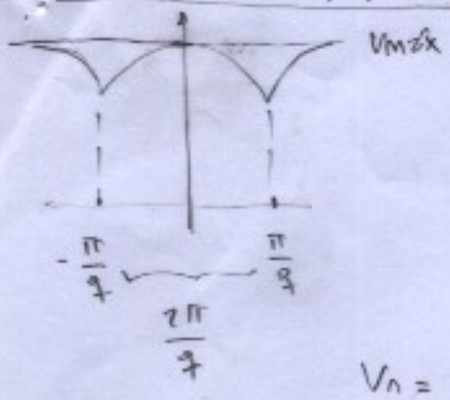
$$i_1(t) = \frac{2\sqrt{3}\, I_{out}}{\pi}\left(\cos(\omega_0 t) - \frac{\cos(5\omega_0 t)}{5} + \frac{\cos(7\omega_0 t)}{7} - \frac{\cos(11\omega_0 t)}{11} + \frac{\cos(13\omega_0 t)}{13} - \ldots\right)$$

fundamental + armónicos de $6k \pm 1$; $k = 1,2,3,\ldots$ $\Rightarrow$ Filtros



Z_i para frec. red

E) Rectificador q-fásico de media onda:

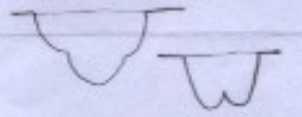


$$V_{AV} = \frac{q}{\pi} \cdot V_{máx} \cdot \operatorname{sen}\left(\frac{\pi}{q}\right)$$

$$V_{rms} = V_{máx}\left[\frac{1}{2} + \frac{q}{4\pi}\operatorname{sen}\left(\frac{2\pi}{q}\right)\right]^{1/2}$$

$$V_{out} = V_{AV} + \sum_{n=q,2q,3q\ldots}^{\infty} V_n \cdot \cos(n\omega t)$$

$$V_n = -\frac{V_{máx} \cdot 2 \cdot q}{\pi(n^2-1)} \cdot \operatorname{sen}\frac{\pi}{q} \cdot \cos\frac{n\pi}{q}$$



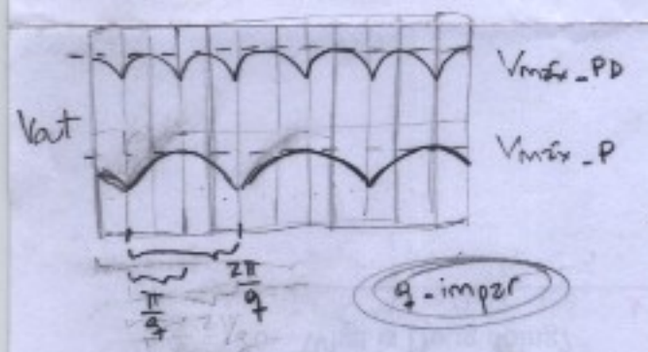
$$V_{out} = \frac{V_{máx} \cdot q}{\pi}\operatorname{sen}\frac{\pi}{q} \cdot \left(1 - \sum_{n=q,2q,\ldots}^{\infty} \frac{2}{n^2-1} \cdot \cos\frac{n\pi}{q} \cdot \cos(n\omega t)\right)$$

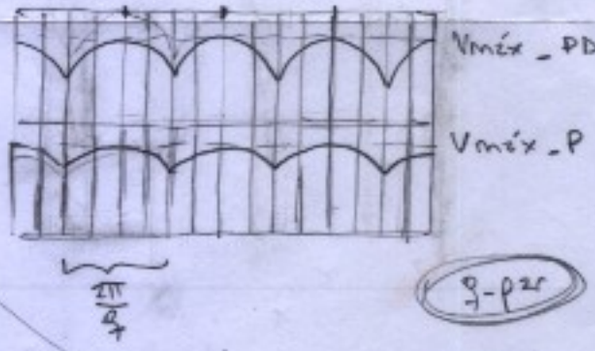
$V_{D\,inverso\,(máx)} \Rightarrow 2\,V_{máx} \cdot \cos\left(\frac{\pi}{2q}\right)$ para q = impar

$\searrow 2\,V_{máx}$ para q = par

si $L \to \infty$ $\therefore$ $I_{D\,máx} = I_0$; $I_{D\,AV} = I_0/q$; $I_{D\,rms} = \frac{I_0}{\sqrt{q}}$

F) Rectificador q-fásico de onda completa:





Análisis idem anterior pero reemplazando Vmáx por Vmáx_PD → $V_{máx_{LL}_q\,par}$

Análisis diferente a q_impar

$$V_{AV} = \frac{2q}{\pi} V_{máx_PD} \cdot \operatorname{sen}(\pi/2q)$$

$$V_{rms} = V_{máx_PD}\left(\frac{1}{2} + \frac{q}{2\pi}\operatorname{sen}\left(\frac{\pi}{q}\right)\right)^{1/2}$$

$$V_{out} = V_{AV} + \sum_{n=2q,4q,6q\ldots}^{\infty} V_n \cdot \cos(n\omega t)$$

$$V_n = -\frac{4q \cdot V_{máx_PD}}{\pi(n^2-1)} \cdot \operatorname{sen}\left(\frac{\pi}{2q}\right) \cdot \cos\left(\frac{n\pi}{2q}\right)$$

$$V_{out} = \frac{2q}{\pi} \cdot V_{máx_PD}\operatorname{sen}\left(\frac{\pi}{2q}\right) \cdot \left(1 - \sum_{n=2q,4q,\ldots}^{\infty} 2\frac{2}{n^2-1}\cos\frac{n\pi}{2q} \cdot \cos n\omega t\right)$$

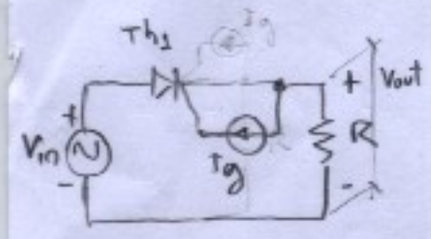
$V_{D_inverso} \Rightarrow 2\,V_{máx_PD}$ (q-par)

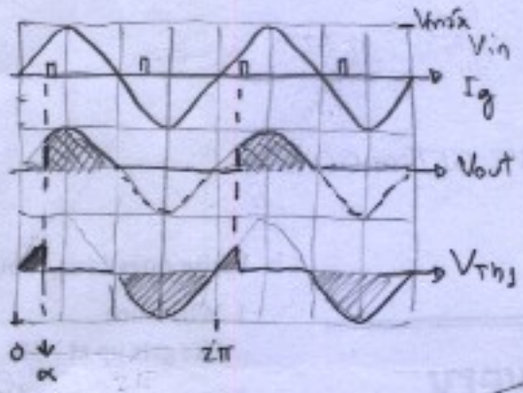
$\searrow 2\,V_{máx}\cos\left(\frac{\pi}{2q}\right)$ (q-impar)

si $L \to \infty$ $\therefore$ $I_{D\,máx} = I_0$; $I_{D\,AV} = \frac{I_0}{q}$; $I_{D\,rms} = \frac{I_0}{\sqrt{q}}$

RECTIFICADORES CONTROLADOS

A) Rectificador monofásico de media onda:

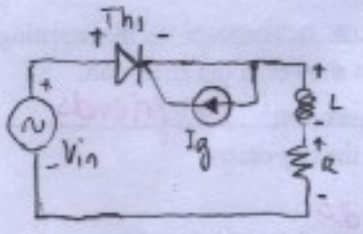


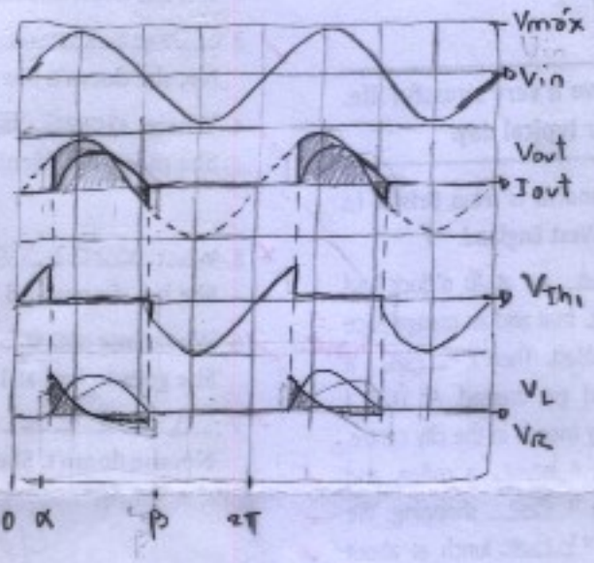


$$V_{AV} = \frac{V_{máx}}{2\pi}\left(1 + \cos\alpha\right)$$

$$V_{rms} = \frac{V_{máx}}{2}\left(1 - \frac{\alpha}{\pi} + \frac{\operatorname{sen}(2\alpha)}{2\pi}\right)^{1/2}$$

$$i(\omega t) = i_f(\omega t) + i_n(\omega t)$$



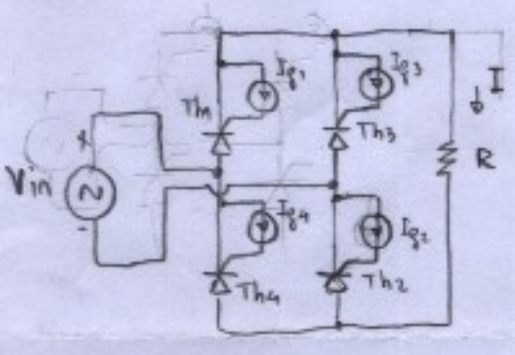


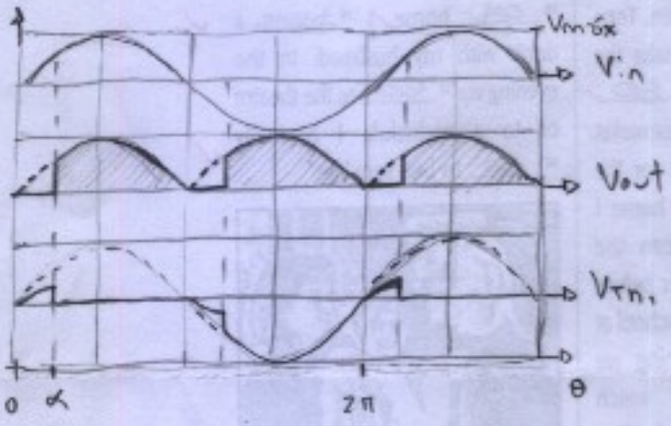
$$i(\omega t) = \frac{V_{máx}}{Z}\left[\operatorname{sen}(\omega t - \theta) - \operatorname{sen}(\alpha - \theta)\cdot e^{\frac{\alpha - \omega t}{\omega \tau}}\right]$$

para $\alpha \leq \omega t \leq \beta$

$$V_{AV} = \frac{V_{máx}}{2\pi}\left[\cos\alpha - \cos\beta\right]$$

B) Rectificador monofásico de onda completa:





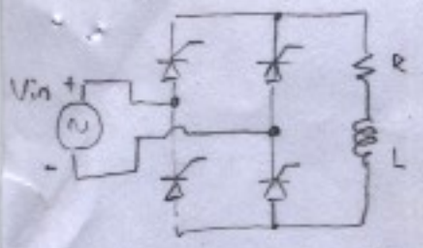
(también puede ser con trafo y punto medio)

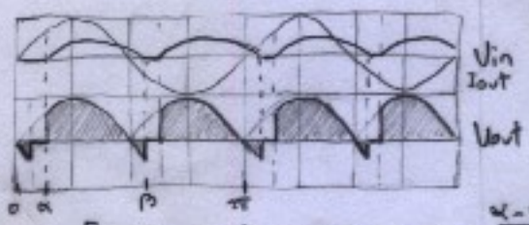
$$V_{AV} = \frac{V_{máx}}{\pi}\left(1 + \cos\alpha\right) \qquad V_{n-AV} = \frac{V_{AV}}{V_{AV(\alpha=0)}} = \frac{1 + \cos\alpha}{2}$$

$$V_{rms} = V_{máx}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\operatorname{sen} 2\alpha}{4\pi}}$$

$$I_{AV} = \frac{V_{AV}}{R} \qquad I_{RMS} = \frac{V_{RMS}}{R}$$

DCM $\alpha = 45°$



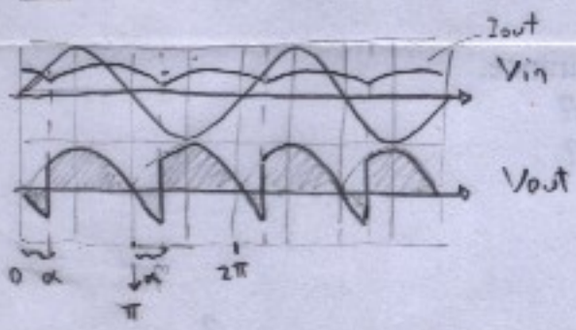


$$V_{AV} = \frac{V_{máx}}{\pi}(\cos\alpha - \cos\beta)$$

$$i(\omega t) = \frac{V_{máx}}{Z}\left[\operatorname{sen}(\omega t - \theta) - \operatorname{sen}(\alpha - \theta) \cdot e^{\frac{\alpha - \omega t}{\omega \tau}}\right] \quad \text{para } \alpha \leq \omega t \leq \beta$$

$$= 0 \rightarrow \text{para otros } \omega t$$

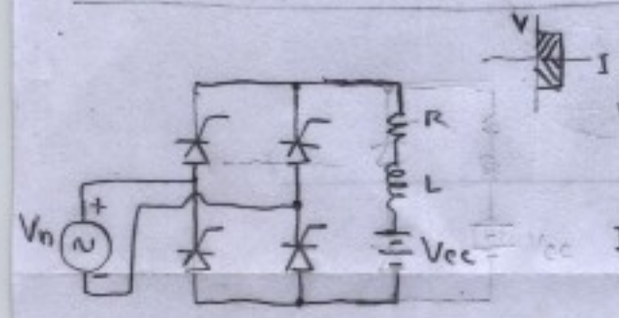
CCM $\alpha = 45°$

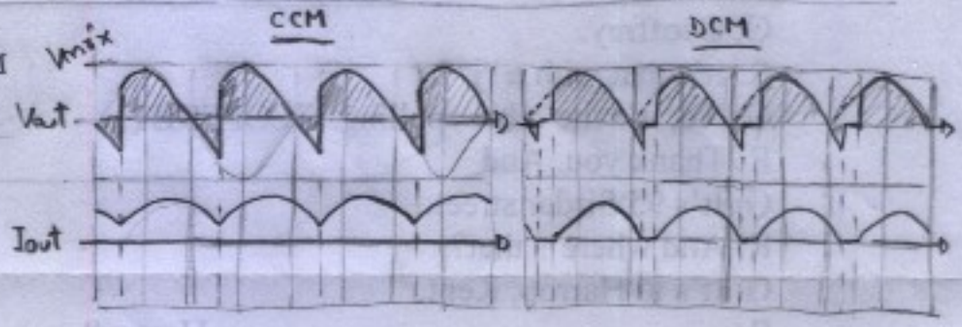


$$V_{AV} = \frac{2 V_{máx}}{\pi} \cos\alpha$$

$$V_{out}(\omega t) = V_{AV} + \sum_{n=2,4,6\ldots}^{\infty} V_n \cos(n\omega t + \theta_n)$$

$$I_{out}(\omega t) = I_{AV} + \sum_{n=2,4,6,8\ldots}^{\infty} I_n \cos(n\omega t + \phi_n)$$





condición de conducción $\Rightarrow \alpha_{mín} = \operatorname{sen}^{-1}\left(\frac{V_{cc}}{V_{máx}}\right)$

CCM $\Rightarrow V_{AV} = \frac{2 V_{máx}}{\pi} \cos\alpha$

$\Rightarrow I_{AV} = \frac{V_{AV} - V_{cc}}{R}$

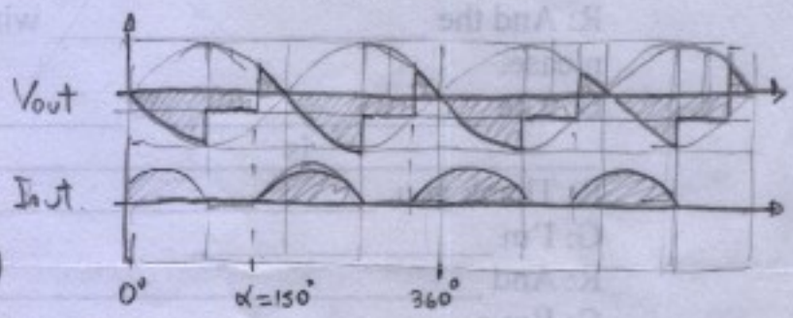
$\Rightarrow P_{cc} = V_{cc} \cdot I_{AV}$

INVERSOR

$V_{cc} \rightarrow$ invertir su polaridad

$\alpha \rightarrow 90° \leq \alpha \leq 180°$

$L \rightarrow$ debe generar f.c.e.m p' mantener los tiristores en conducción.

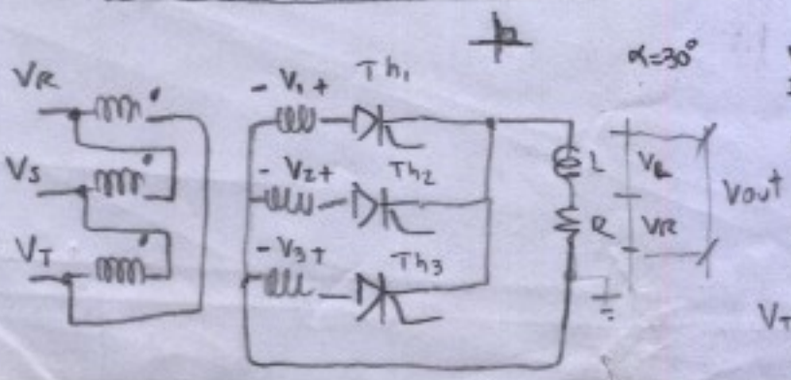


$0 \leq \alpha \leq 90°$ Rectif. $V_{out} > 0$

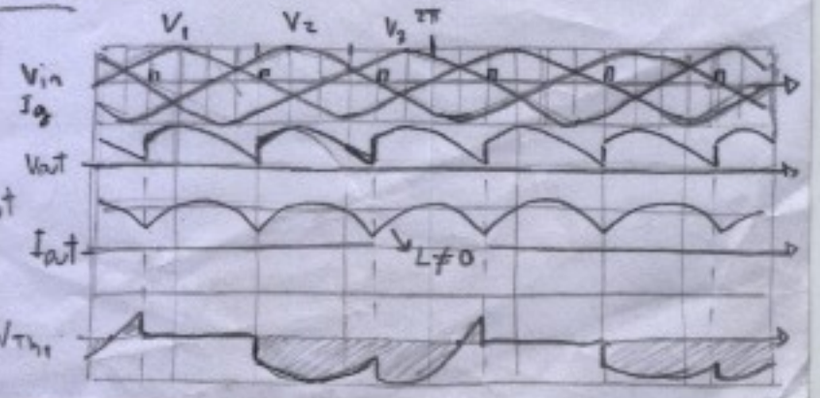
$90° \leq \alpha \leq 180°$ Inversor $V_{out} < 0$

P_{cc} (pot recibe del generador de CC por el gener. de CA) $= -I_{out} \cdot V_{out}$ (ideal)

c) Rectificador trifásico de media onda:



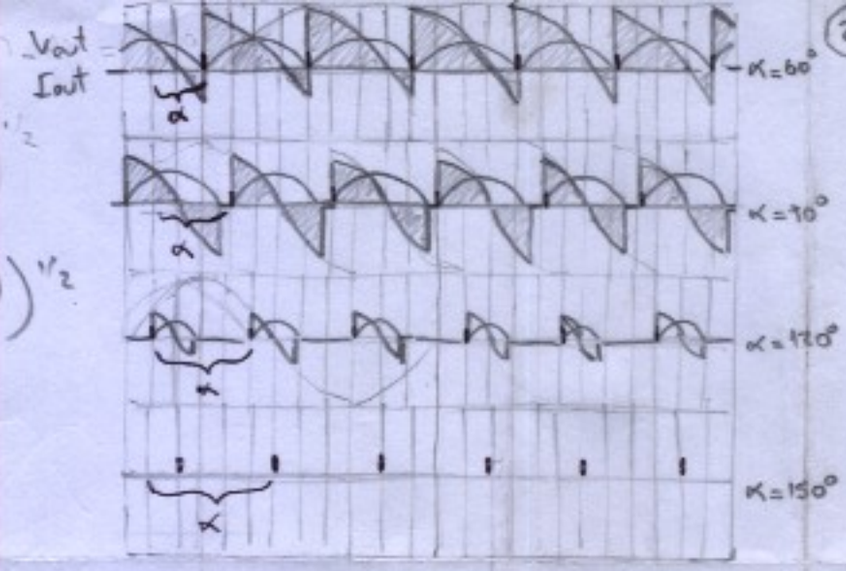
$\alpha = 30°$



$$V_{AV} = \frac{3\sqrt{3}\,V_{máx}}{2\pi}\cos(\alpha)$$

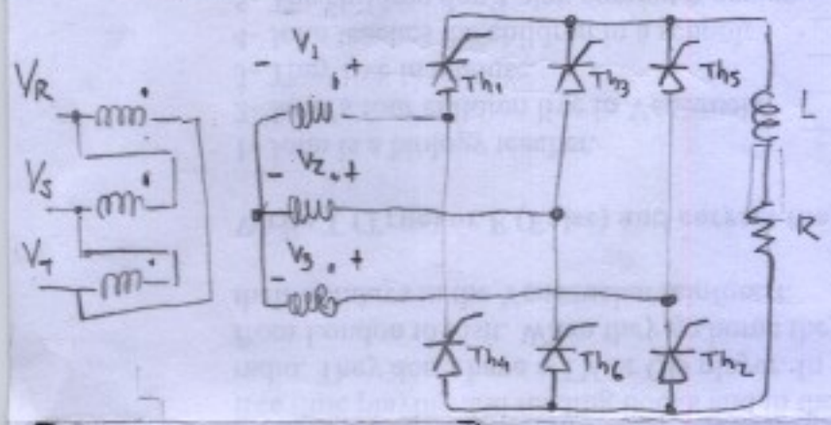
$$V_{n_AV} = \cos\alpha$$

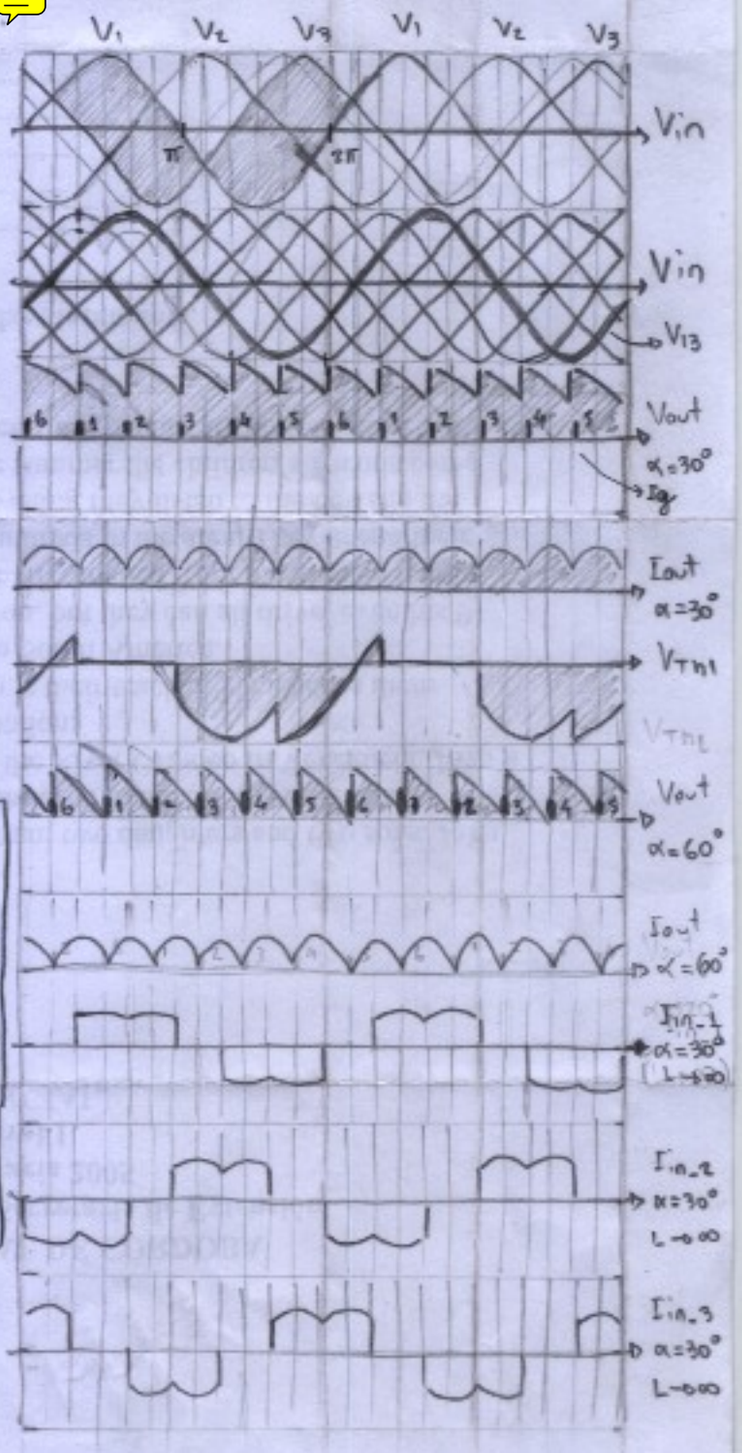
$$V_{rms} = \sqrt{3}\,V_{máx}\left(\frac{1}{6} + \frac{\sqrt{3}}{8\pi}\cos(2\alpha)\right)^{1/2}$$



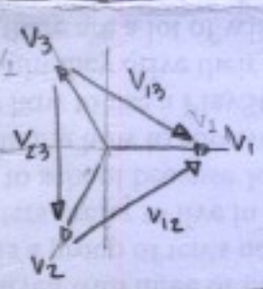
D) Rectificador trifásico de onda completa

<220 V



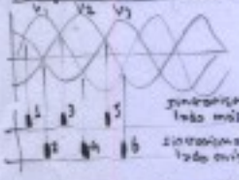


$$V_1 = V_{máx}\,\text{sen}(\omega t)$$
$$V_2 = V_{máx}\,\text{sen}\left(\omega t - \frac{2\pi}{3}\right)$$
$$V_3 = V_{máx}\,\text{sen}\left(\omega t - \frac{4\pi}{3}\right)$$



$$V_{12} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t + \frac{\pi}{6}\right)$$
$$V_{13} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t - \frac{\pi}{6}\right)$$
$$V_{21} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t - \frac{5\pi}{6}\right)$$
$$V_{23} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t - \frac{\pi}{2}\right)$$
$$V_{31} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t + \frac{5\pi}{6}\right)$$
$$V_{32} = \sqrt{3}\,V_{máx}\,\text{sen}\left(\omega t + \frac{\pi}{2}\right)$$

Disparo de tiristores



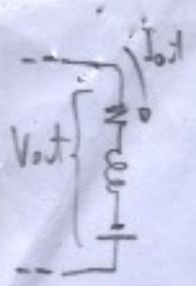
Th1 → V13>V23	Th2 → −(V23>V21)
Th3 → V21>V31	Th4 → −(V31>V32)
Th5 → V32>V12	Th6 → −(V12>V13)
lado más posit.	lado más negativo

$$V_{AV} = \frac{3\sqrt{3}\,V_{máx}}{\pi}\cos\alpha$$

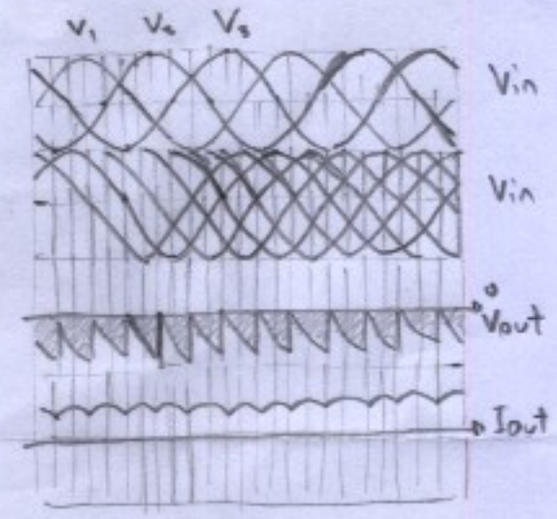
$$V_{n_AV} = \cos\alpha$$

$$V_{rms} = \sqrt{3}\,V_{máx}\left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right)^{1/2}$$

- No tiene componente de DC
- Consideraciones para el arranque:
  1) Con C/disp. se dispara además el tiris. que debería estar ya conduciendo
  2) Durante el arranque se dispara con un tren de pulsos durante un ángulo > 60° → se va disminuyendo



Operando como inversor:



- $90° \leq \alpha \leq 180°$
- Se necesita una fcem para asegurar conducción de los tiristores
- Para $\alpha > 180°$ el tiristor que debería estar bloqueado esta conduciendo, viceversa
- Para evitar el "vuelco del inversor"

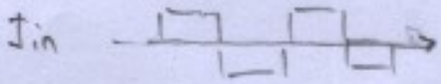
$$\alpha_{máx} = 180° - \mu(°) - \underbrace{\frac{tg(°) \cdot 360}{0{,}02}}_{\text{margen de seg.}}$$

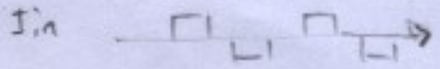
$$\alpha_{máx} \approx 150°$$

Armónicos del lado de la línea:

Si $\alpha = 0°$ los armónicos de corriente son prec de

$$\boxed{\begin{array}{l} n = k \cdot p \pm 1 \\ p = \text{nº de pulsos} \\ k = 1, 2, 3, \ldots \end{array}}$$

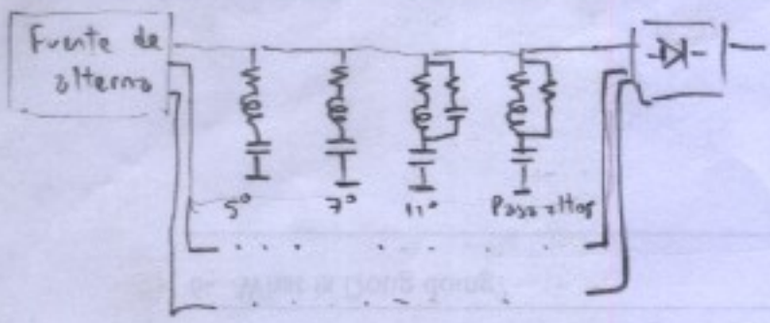




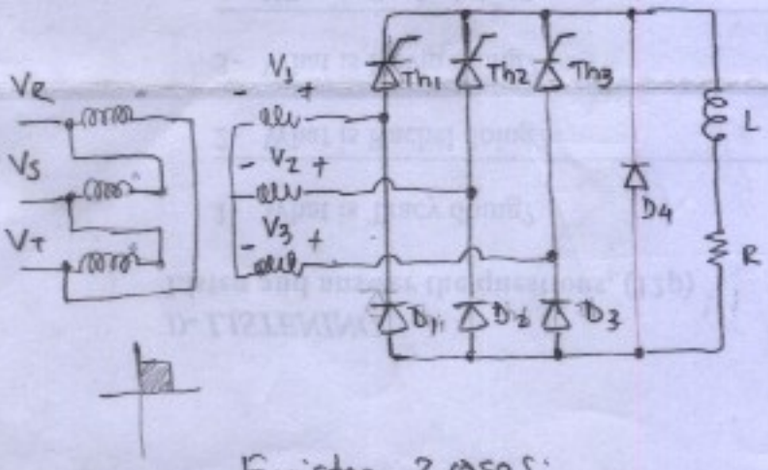
Para PD3 $p=6$ entonces $n = 5, 7, 11, 13, \ldots$

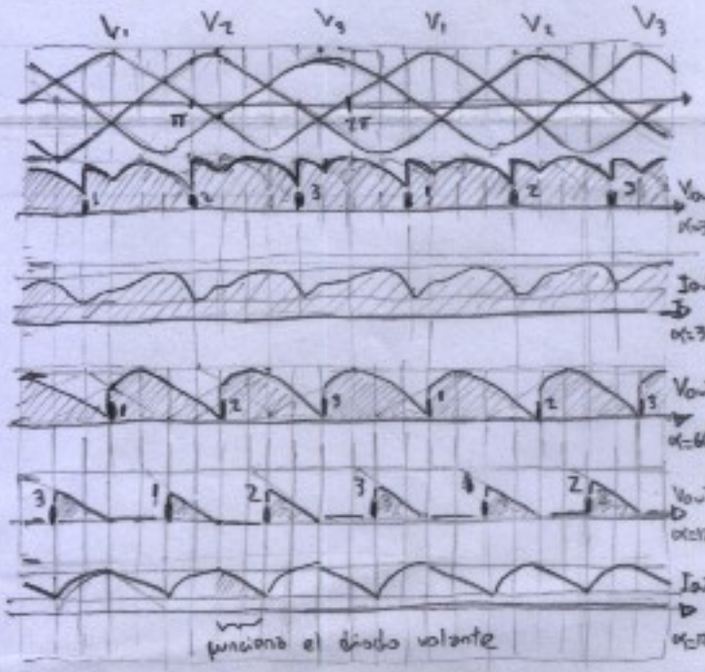
$$I_n = \frac{\sqrt{6}\, I_{out}}{\pi \cdot n}$$

se filtran



E) Rectificador trifásico de onda completo semicontrolado:





Existen 2 casos:

$\alpha < \pi - \frac{2\pi}{q}$ Vout CONTINUA ; si $q=3 \therefore \alpha < 60°$

$$V_{\Delta V} = \frac{3\sqrt{3}\, V_{máx}}{2\pi}\left(1+\cos\alpha\right) \; ; \; V_{n\text{-}\Delta V} = \frac{1+\cos\alpha}{2}$$

$$V_{rms} = \sqrt{3}.V_{máx}.\left\{\frac{3}{4\pi}\left[\frac{2\pi}{3}+\sqrt{3}\cos^2(\alpha)\right]\right\}^{1/2}$$

$\alpha > \pi - \frac{2\pi}{q}$ Vout DISCONTINUA ; sig=3 $\therefore \alpha > 60°$

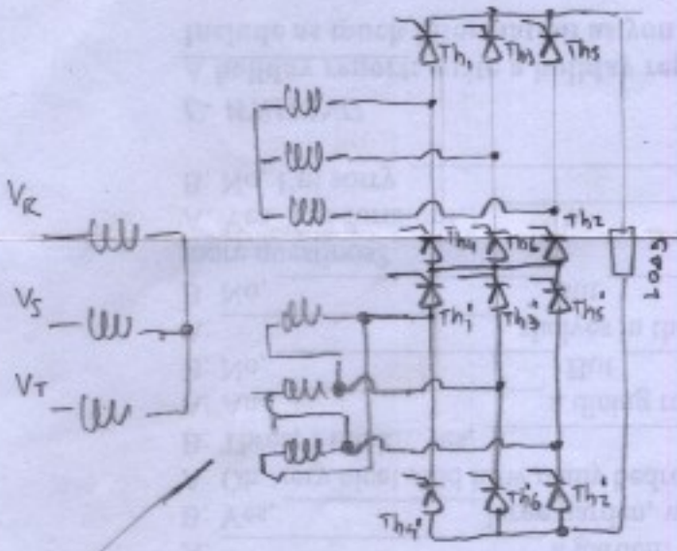
$$V_{\Delta V} = \frac{3\sqrt{3}}{2\pi} V_{máx}.\left(1+\cos\alpha\right) \; ; \; V_{n\text{-}\Delta V} = \frac{1+\cos\alpha}{2}$$

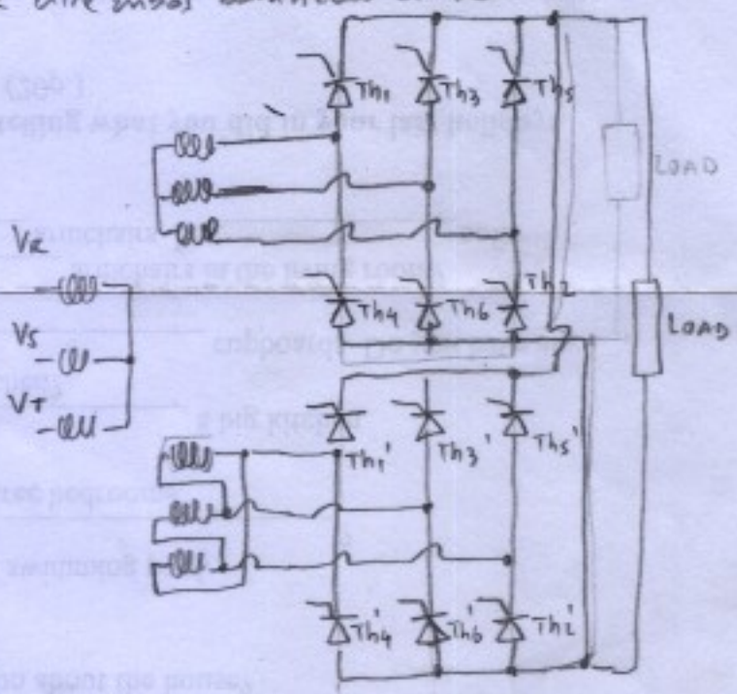
$$V_{rms} = \sqrt{3}\, V_{máx}\left[\frac{3}{4\pi}\left(\pi-\alpha+\frac{1}{2}\sin 2\alpha\right)\right]^{1/2}$$

F) Rectificador de 12 pulsos:

Se combinan dos puentes trifásicos de onda completa en serie o paralelo

Mediante transformador con un secundario en triángulo y el otro en estrella se logra un desplazamiento de fase entre ambos bobinados de 30°.



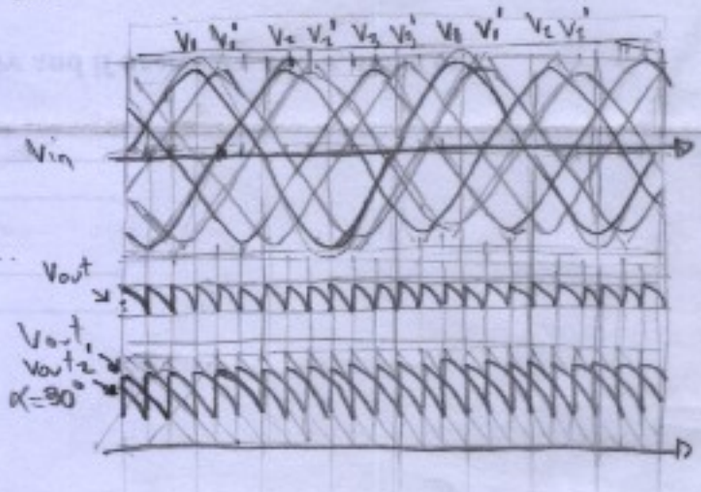


Es el mismo α para c/convertidor ∴ los ángulos de disp. de un convertidor respecto al otro es de 30°.

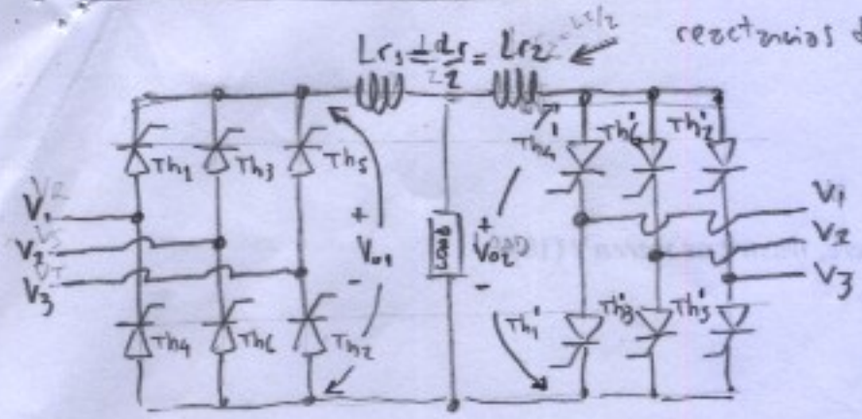
→ Vout = doble de c/puente.

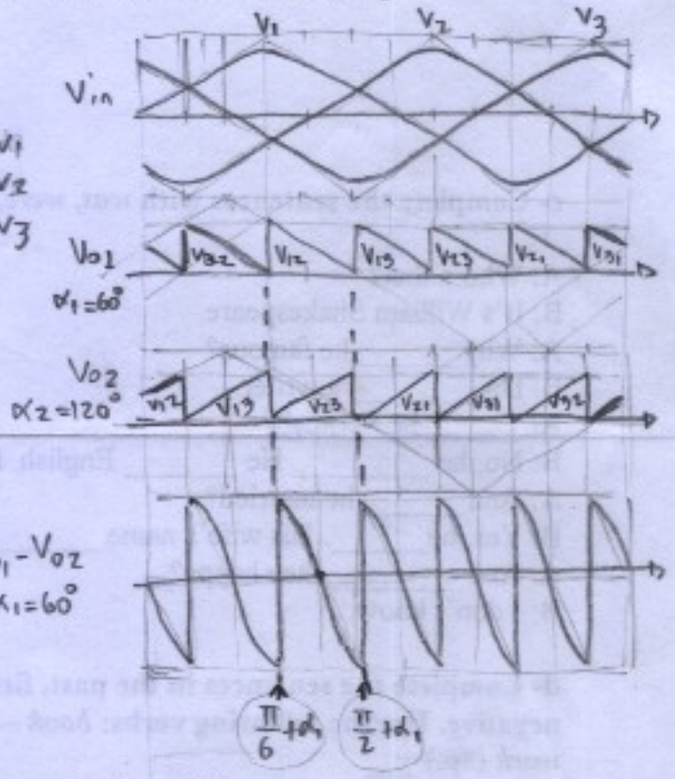
armónicos $12k \pm 1$; $k=1,2,3\ldots$

se anulan armónicos $6(2n-1)\pm 1$; $n=1,2,3,\ldots$



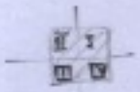
G) Rectificador Trifásico Dual:





Convertidor 1 → α_1

Convertidor 2 → $\alpha_2 = \pi - \alpha_1$



→ carga regenerativa

- Por asimetría de los convertidores y tolerancia de los retardos → L_{r1} y L_{r2}

$V_1 = V_{max} \operatorname{sen}(\omega t)$

$V_2 = V_{max} \operatorname{sen}\left(\omega t - \frac{2\pi}{3}\right)$

$V_3 = V_{max} \operatorname{sen}\left(\omega t + \frac{2\pi}{3}\right)$

$V_{12} = \sqrt{3}\, V_{máx} \cdot \operatorname{sen}\left(\omega t + \frac{\pi}{6}\right)$

$V_{23} = \sqrt{3}\, V_{máx} \cdot \operatorname{sen}\left(\omega t - \frac{\pi}{2}\right)$

$V_{31} = \sqrt{3}\, V_{máx} \cdot \operatorname{sen}\left(\omega t - \frac{7\pi}{6}\right)$

- Durante el intervalo $\frac{\pi}{6} + \alpha_1 \leq \omega t \leq \frac{\pi}{2} + \alpha_1$

$$V_r = V_{o1} - V_{o2} = V_{12} - V_{23} = \sqrt{3}\, V_{máx} \left[\operatorname{sen}\left(\omega t + \frac{\pi}{6}\right) - \operatorname{sen}\left(\omega t - \frac{\pi}{2}\right)\right]$$

$$V_r = \sqrt{3}\, V_{máx} \cdot 2 \cdot \cos\left(\omega t - \frac{\pi}{6}\right) \cdot \operatorname{sen}\left(\frac{\pi}{3}\right) = \boxed{3\, V_{máx} \cdot \cos\left(\omega t - \frac{\pi}{6}\right) = V_r}$$

- Corriente circulante:

$$\boxed{i_r(t) = \frac{3\, V_{máx}}{\omega \cdot L_r}\left[\operatorname{sen}\left(\omega t - \frac{\pi}{6}\right) - \operatorname{sen}(\alpha_1)\right]}$$

¡ojo con el "t"!

→ no debe superar el 10% de la I_{out}

→ $I_{rmáx}$ para $\omega t = \frac{2\pi}{3}$ y $\alpha_1 = 0$

Sin carga externa existe corriente circulante.

Permite una regulación suave de la I_{out}

Permite una resp. dinámica rápida.

H) Análisis de las funciones de α:

para $0 \leq \alpha \leq \pi$ → $\cos \alpha$ (TOTALMENTE CONTROLADO) Ⓐ

→ $\frac{1 + \cos \alpha}{2}$ (SEMICONTROLADO) Ⓑ

Ⓐ Si $\alpha = 0$ → $+V_{av}$ } sólo carga

$\alpha = \pi$ → $-V_{av}$ } es regenerativo

$0 \leq \alpha \leq 90°$ → Rectificador → si $\alpha \uparrow$ ∴ $V_{av} \downarrow$

si $\alpha < \frac{\pi}{2} - \frac{\pi}{q}$ ∴ tensión siempre positiva

si $\alpha > \frac{\pi}{2} - \frac{\pi}{q}$ ∴ tensión intervalos negativos

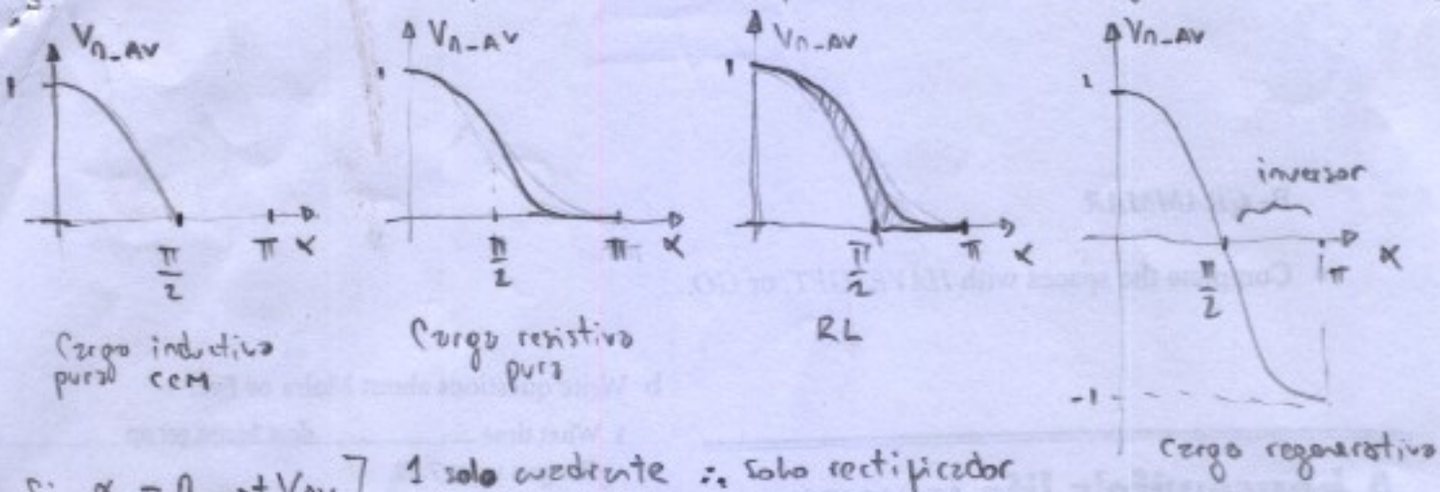
$90° \leq \alpha \leq 180$ → Inversor → si $\alpha \uparrow$ ∴ V_{av} más negativo

carga regenerativa

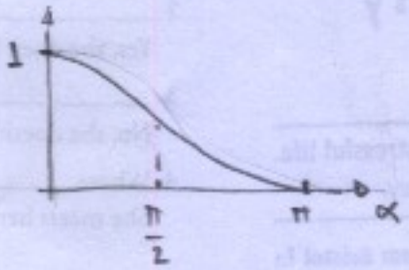
La red sigue suministr. pot. red

No autónomo, la red impone freq, forma onda, fase

Variación de V_{n_av} en función de α y distintas cargas



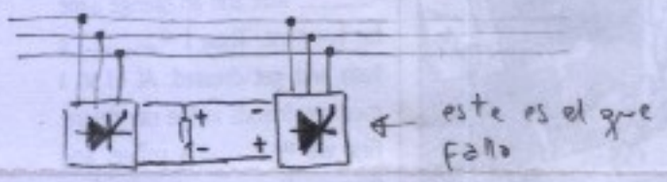
⑧ Si $\alpha = 0 \rightarrow +V_{av}$
$\alpha = \pi \rightarrow 0$ } 1 solo cuadrante ∴ solo rectificador



I) Precauciones a tener en cuenta en inversor c/carga regenerativa:

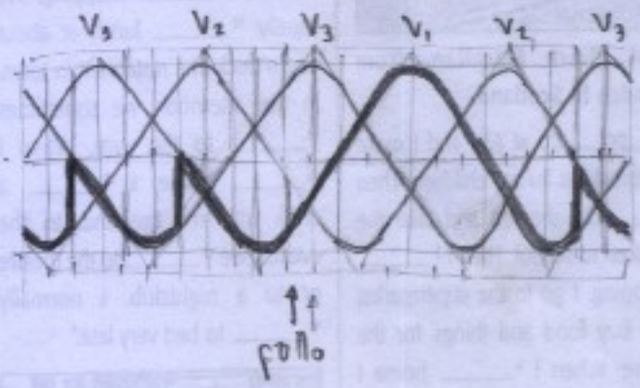
① Falla en el bloqueo

Osea → tendencia a funcionar como rectificador → cortocircuito → $\alpha = 0$

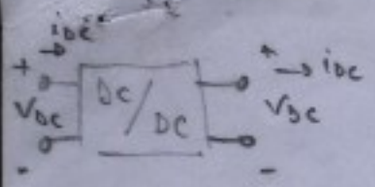


② Falla en el encendido:

Se pierde control → una falla en el cebado del tiristor siguiente produce una falla en el bloqueo del tiristor anterior.



FUENTES CONMUTADAS



Son sistemas electrónicos que convierten un nivel de energía en otro nivel de energía regulada a través de la conmutación.

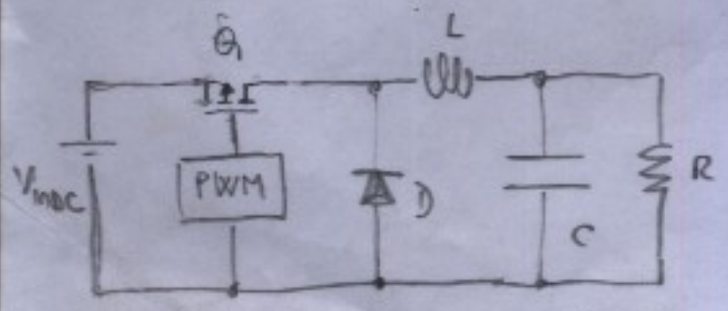
- FUENTES CONMUTADAS
  - C. NO AISLADAS
    - A.1 _ Reductores (BUCK)
    - A.2 _ Elevadores (BOOST)
    - A.3 _ Elev./Reductores (BUCK-BOOST)
    - A.4 _ CUK
    - A.5 _ SEPIC
    - A.6 _ ZETA
  - C. AISLADAS
    - B.1 _ EXITACIÓN DE NÚCLEO UNIDIRECCIONAL
      - B.1.1. FLY BACK
      - B.1.2. FORWARD
      - Utilizan 1° cuadrante B/H
    - B.2. EXITACIÓN DE NÚCLEO BIDIRECCIONAL
      - B.2.1. PUSH PULL
      - B.2.2. HALF BRIDGE
      - B.2.3 FULL BRIDGE
      - Utilizan 1° y 3° cuadrante B/H

Características:

VENTAJAS
- → Eficiencia hasta 90%
- → Uso más eficiente del transistor
- → Puede ser elevador, reductor, inversor
- → No usa trafo de línea

DESVENTAJAS
- → Respuesta transitoria lenta
- → Diseño complicado
- → Mayor ruido hacia la entrada y salida.

A.1 BUCK



L: redistribuye la energía

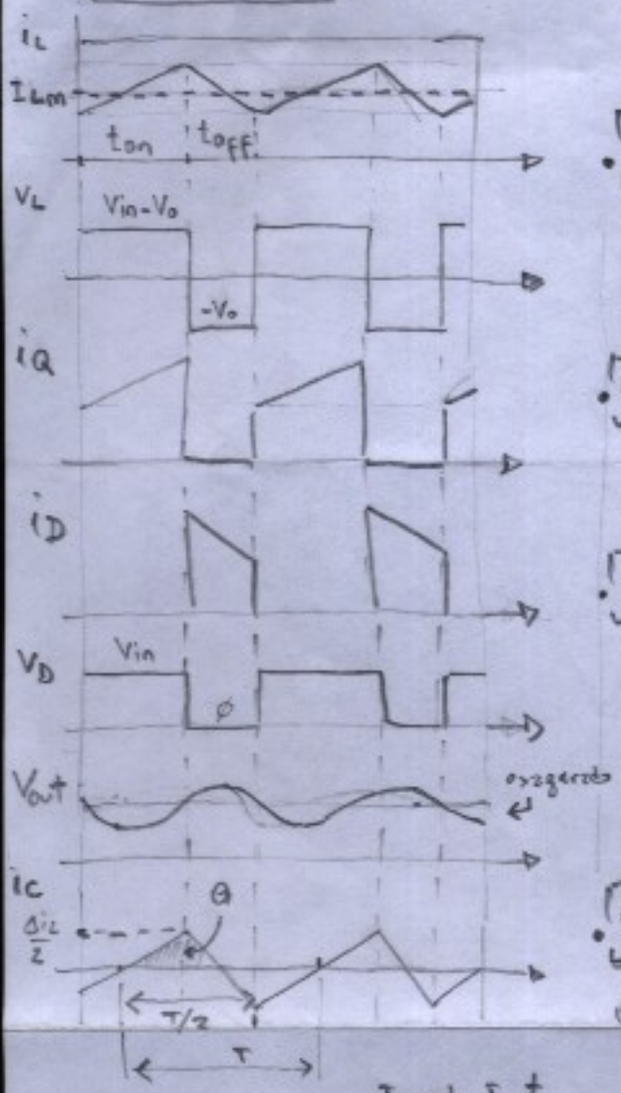
D: evita discontinuidad de la corriente

C: evita ripple de tensión en la carga.

Q: llave conmuta

$D = \frac{t_{on}}{T}$ $t_{on} = DT$ $t_{off} = T(1-D)$

MODO CONTINUO



- $\boxed{t_{on}}$ → $\Delta i_L^+ = \dfrac{V_{in}-V_{out}}{L} \cdot t_{on}$

$$t_{on} = \frac{\Delta i_L^+ \cdot L}{V_{in}-V_{out}}$$

- $\boxed{t_{off}}$ → $\Delta i_L^- = \dfrac{V_{out} \cdot t_{off}}{L}$

$$t_{off} = \frac{\Delta i_L^- \cdot L}{V_{out}}$$

- $\boxed{\text{Reg. Permanente}}$ → $\Delta i_L^+ = \Delta i_L^- \therefore V_{out} = V_{in} \cdot D$

$M(D) = D$ = Relación de conversión de tensión

- $\boxed{\text{Cálculo de L}}$ $T = t_{on} + t_{off}$

$$\left.\begin{aligned} \Delta i_L &= \frac{D(1-D) \cdot V_{in}}{f_s \cdot L} \\ L &= \frac{D(1-D)\, V_{in}}{f_s \cdot \Delta i_L} \end{aligned}\right\} \text{no depende de la carga.}$$

- $\boxed{\text{Cálculo de C}}$ $Q_{carga} = \frac{T}{2} \cdot \frac{\Delta i_L}{2} \cdot \frac{1}{2} = Q$

$$Q = \frac{D(1-D)\, V_{in}}{f_s^2 \cdot L \cdot 8} \; ; \; C = \frac{\Delta Q}{\Delta V_c} \; ; \; \Delta V_c = \Delta V_{out}$$

$i_L = i_c + i_{out}$ → $I_{Lmed} = I_{out}$, $\Delta i_L = \Delta i_C$

$$C = \frac{1-D}{8 f_s^2 L \left(\frac{\Delta V_{out}}{V_{out}}\right)} \; ; \; \frac{\Delta V_{out}}{V_{out}} = \frac{1-D}{8 \cdot C \cdot L \cdot f_s^2}$$

- $\boxed{\text{Eficiencia}}$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_D + P_{SAT} + P_Q + P_{SW} + P_L}$$

P_Q: corriente stand-by y driver

P_{SW}, P_L: Pérdidas dinámicas

MODO DISCONTINUO

Si aumenta la carga disminuye la corriente, pero Δi_L no se modifica, luego pero

$I_L > \frac{\Delta i_L}{2}$ → CCM

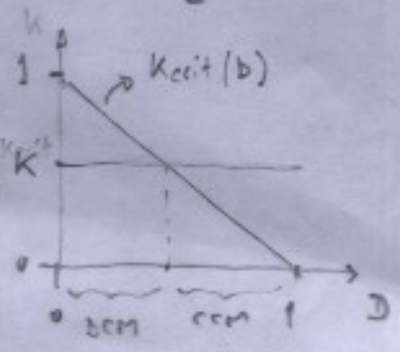
$I_L < \frac{\Delta i_L}{2}$ → DCM

valor crítico

$$\left.\begin{aligned} \frac{\Delta i_L}{2} &= \frac{V_{out}(1-D) \cdot T}{2L} \\ I_L &= \frac{V_{out}}{R} \end{aligned}\right\}$$

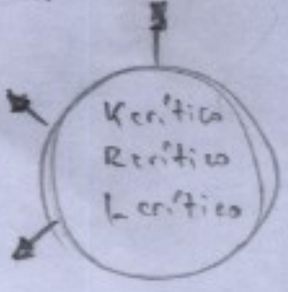
$\frac{2L}{RT} < 1-D$ → DCM

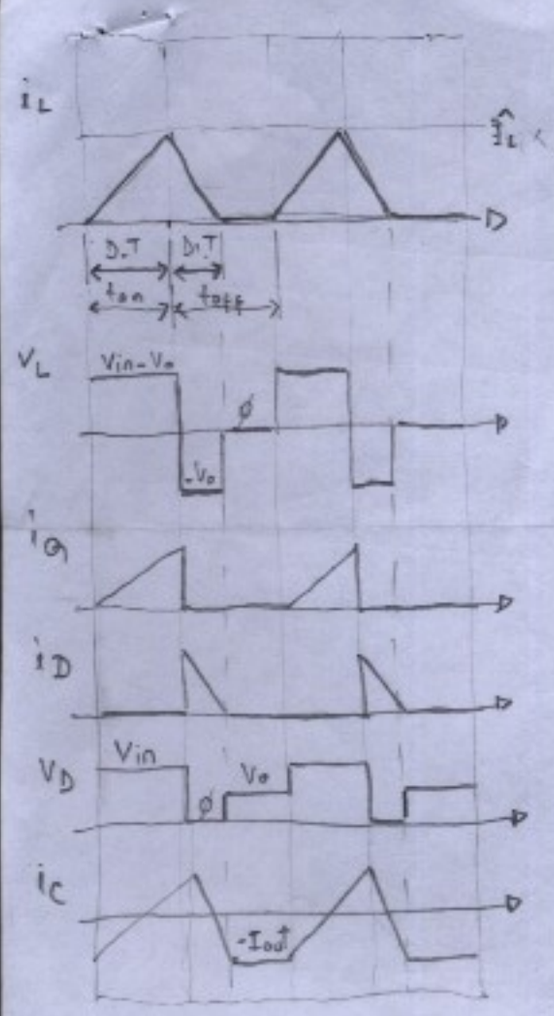
$K < K_{crit}$ → DCM



También:

$$\left\{\begin{aligned} R_{crit} &= \frac{2L}{(1-D) \cdot T} \\ L_{crit} &= \frac{R(1-D)\,T}{2} \end{aligned}\right.$$





$\boxed{t_{on}}$ $\Delta i_L^+ = \frac{V_{in} - V_{out}}{L} \cdot D.T$ $\boxed{0 < t < t_{on}}$

$\boxed{t_{off}}$ $\Delta i_L^- = + \frac{V_{out}}{L} \cdot D_1.T$ $\boxed{t_{on} < t < t_1}$

• $\boxed{\text{Régimen Permanente}}$ $\Delta i_L^+ = \Delta i_L^-$

$\frac{V_{out}}{V_{in}} = \frac{D}{D+D_1}$ → Buscamos D_1 →

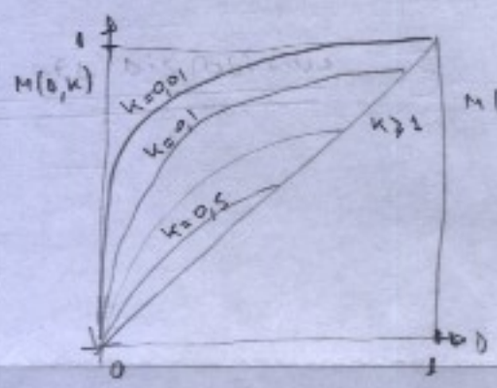
$I_L^- = \frac{\hat{I}_L}{2}(D+D_1)$

$\hat{I}_L = \frac{D_1 . V_{out} . T}{L}$

$I_L^- = \frac{V_{out}}{R}$

$D_1^2 + D_1 . D - \frac{2L}{RT} = 0$

$M(D,K) = \frac{2}{1 \pm \sqrt{1 + \frac{4K}{D^2}}}$



$M(D,K) = \frac{D}{\frac{2}{1+\sqrt{1+\frac{4K}{D^2}}}}$

$K > K_{crit}$

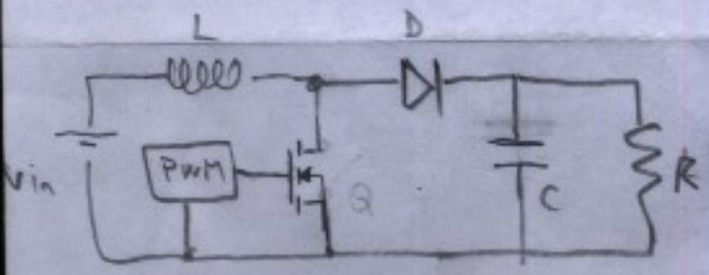
$K < K_{crit}$

SELECCIÓN DEL DISPOSITIVO

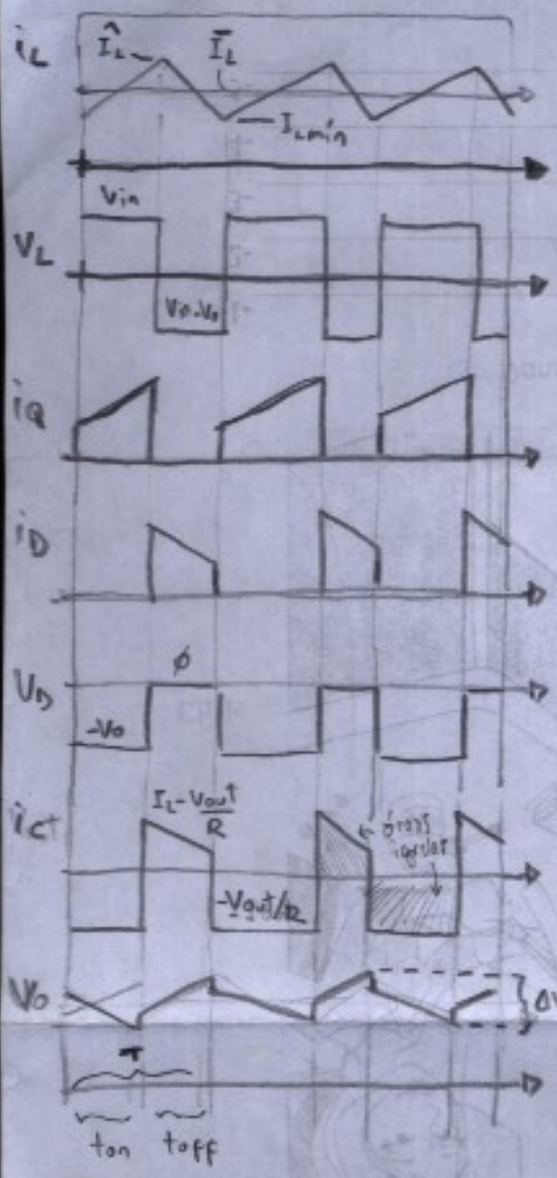
Tx → $V_{CEV} > V_{in-máx}$
→ $I_{Cmáx} > I_{out} + \Delta i_L/2$

Diodo → $V_{RRM} > V_{in-máx}$
→ $I_{F(AV)} \geq I_{out}(1-D)$

A 2 BOOST



MODO CONTINUO



- $\boxed{t_{on}}$ $\Delta i_L^+ = \frac{V_{in} \cdot D \cdot T}{L}$; $t_{on} = \frac{\Delta i_L^+ \cdot L}{V_{in}}$

- $\boxed{t_{off}}$ $\Delta i_L^- = \frac{(V_o - V_i)}{L} \cdot (1-D)T$; $t_{off} = \frac{\Delta i_L^- \cdot L}{V_o - V_i}$

- $\boxed{\text{Régimen permanente}}$ $\Delta i_L^+ = \Delta i_L^-$

$$\frac{V_o}{V_i} = \frac{1}{1-D} = M(D)$$

- $\boxed{\text{Cálculo de L}}$ $T = t_{on} + t_{off}$

$$\Delta i_L = \frac{V_i (V_o - V_i)}{f_s \cdot V_o \cdot L} = \frac{V_i \cdot D}{f_s \cdot L}$$

$$L = \frac{V_i (V_o - V_i)}{f_s \cdot V_o \cdot \Delta i_L} = \frac{V_i \cdot D}{\Delta i_L \cdot f_s}$$

- $\boxed{\text{Cálculo de C}}$ En el $t_{on} \rightarrow \Delta V_{out} = \frac{V_{out} \cdot DT}{RC}$

$$C = \frac{V_{out}}{R} \cdot \frac{DT}{\Delta V_{out}} \; ; \; \frac{\Delta V_o}{V_o} = \frac{DT}{RC}$$

- $\boxed{\text{Eficiencia}}$ $\eta = \frac{P_{out}}{P_{in}}$ (idem anterior)

MODO DISCONTINUO

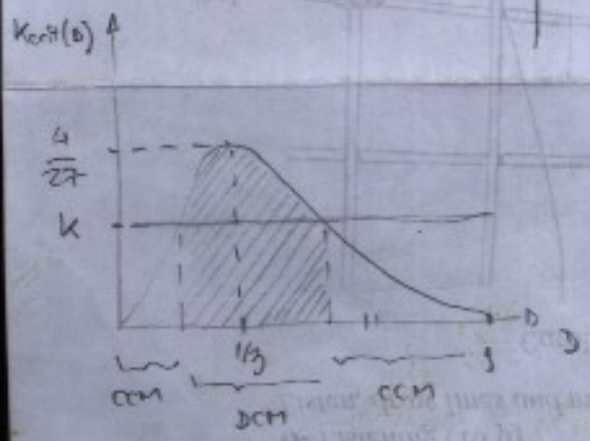
$I_L > \frac{\Delta i_L}{2} \rightarrow$ CCM
$I_L < \frac{\Delta i_L}{2} \rightarrow$ DCM

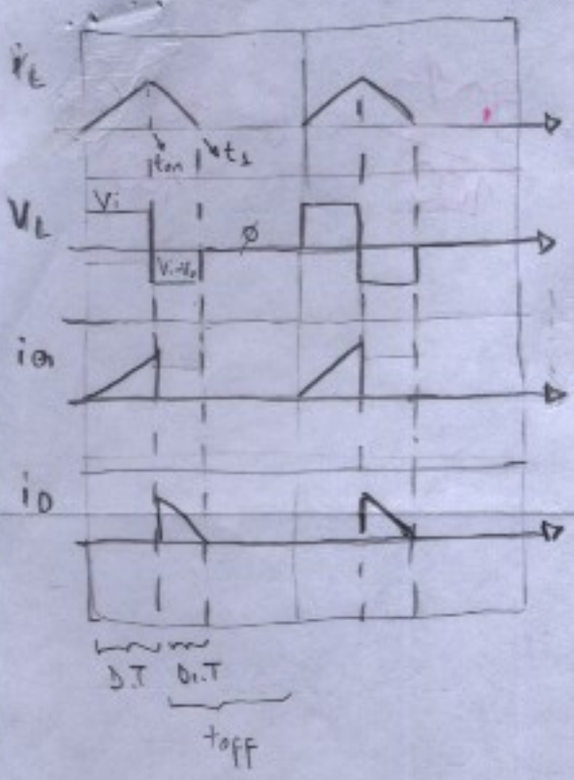
Valor crítico

$$\int_0^T i_C(t) \cdot dt = 0 \Rightarrow \begin{cases} t_{on} \rightarrow \bar{I}_C = -\frac{V_{out}}{R} \\ t_{off} \rightarrow \bar{I}_C = \bar{I}_L - \frac{V_{out}}{R} \end{cases} \Rightarrow \bar{I}_L = \frac{V_{in}}{R(1-D)^2}$$

$$\frac{\Delta i_L}{2} = \frac{V_{in} \cdot D \cdot T}{2L} \rightarrow (1-D)^2 \cdot D > \frac{2L}{RT} \text{ para DCM}$$

$K_{crit} > K$ para DCM





$\boxed{t_{on}}$ $\Delta i_L^+ = \dfrac{V_{in} \cdot DT}{L} \cdot DT$ $\boxed{0 < t < t_{on}}$

$\boxed{t_{off}}$ $\Delta i_L^- = \dfrac{V_o - V_{in}}{L} \cdot (D_1 \cdot T)$ $\boxed{t_{on} < t < t_1}$

$\boxed{\text{Régimen permanente}}$ $\Delta i_L^+ = \Delta i_L^-$

$$\frac{V_o}{V_i} = \frac{D + D_1}{D_1} \longrightarrow \text{Buscamos } D_1 \ldots$$

$$\bar{I}_D = \frac{V_{out}}{R}$$

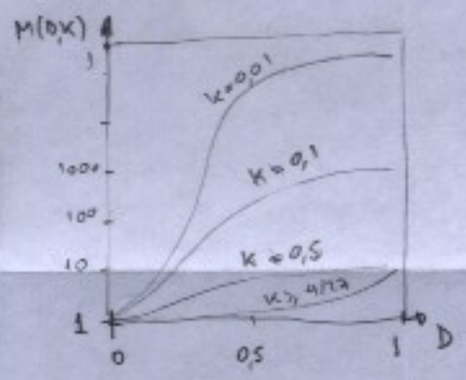
$$\bar{I}_D = \frac{\hat{I}_L \cdot D_1}{2}$$

$$\hat{I}_L = \frac{V_{in} \cdot DT}{L}$$

$$D_1 = \frac{V_{out}}{V_{in}} \cdot \frac{2L}{RDT}$$

$$M^2 - M - \frac{D^2}{K} = 0$$

$$M(K,D) = \frac{1 \pm \sqrt{1^2 + \frac{4D^2}{K}}}{2}$$



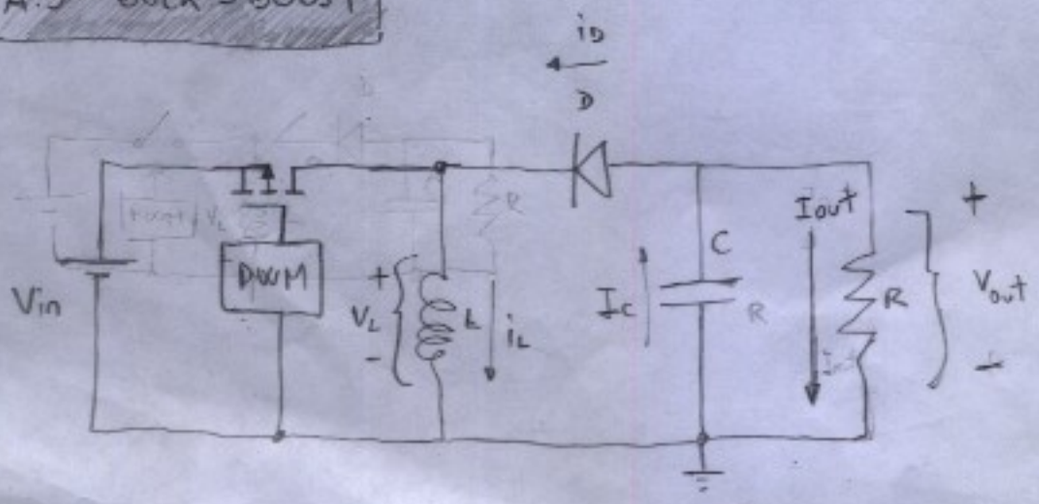
$$M(D,K) = \begin{cases} \dfrac{1}{1-D} & \text{para } K > K_{crít} \\[2ex] \dfrac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2} & \text{para } K < K_{crít} \end{cases}$$

SELECCIÓN DE DISPOSITIVO

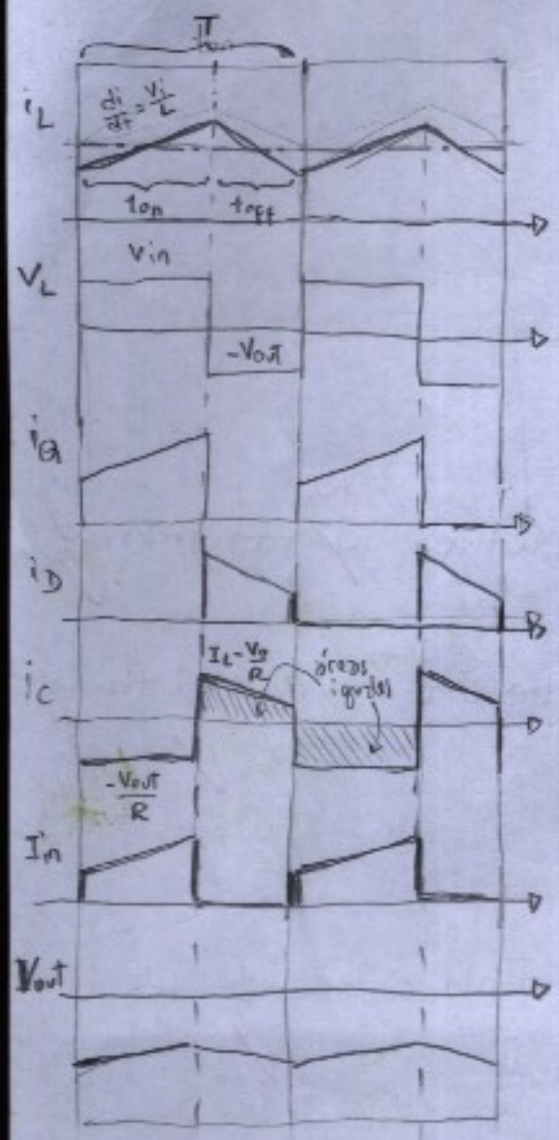
T_x → $V_{CEV} > V_{out}$
T_x → $I_{CMÁX} > \dfrac{I_{out}}{1-D} + \dfrac{\Delta i_L}{2}$

D_x → $V_{RRM} > V_{out}$
D_x → $I_{F(AV)} > I_{out}$

A.3 BUCK - BOOST



MODO CONTINUO



- t_{on}: $\Delta i_L^+ = \frac{V_{in}}{L} D.T \quad 0 < t < t_{on}$

- t_{off}: $\Delta i_L^- = -\frac{V_o}{L} .(1-D)T \quad t_{on} < t < T_{off}$

- Régimen permanente: $T = t_{on} + t_{off}$ (pero es más fácil despejar directamente de Δi_L^+)

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}$$

- Cálculo de L — de Δi_L^+

$$\Delta i_L = \frac{V_{in} . D}{f_s . L} \qquad L = \frac{V_{in} . D}{f_s . \Delta i_L}$$

- Cálculo de C: En el $t_{on} \rightarrow \Delta V_{out} = \frac{V_{out} . D.T}{RC}$

$$C = \frac{V_{out}}{R} \frac{DT}{\Delta V_{out}}$$

$$\frac{\Delta V_o}{V_o} = \frac{D.T}{RC}$$

MODO DISCONTINUO

$\bar{I}_L > \frac{\Delta i_L}{2} \rightarrow$ CCM
$\bar{I}_L < \frac{\Delta i_L}{2} \rightarrow$ DCM

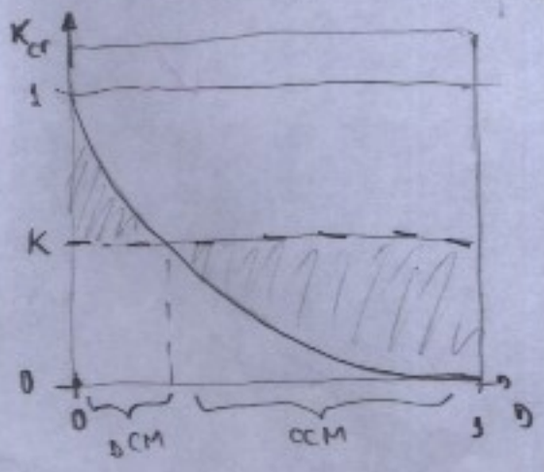
Valor crítico

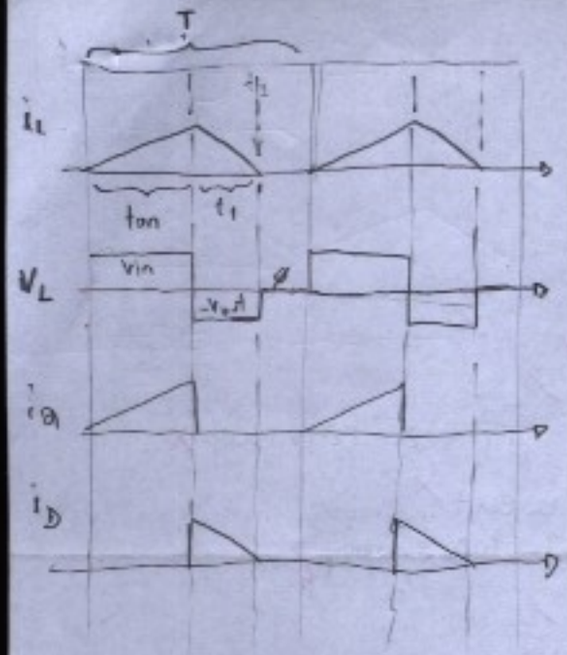
$$P_{in} = P_{out}$$
$$V_{in} . \bar{I}_{in} = \frac{V_{out}^2}{R}$$
$$\bar{I}_{in} = \frac{1}{T}\int_0^{t_{on}} \bar{I}_L . dt$$

$$\bar{I}_L = \frac{V_{in}}{R} \frac{D}{(1-D)^2} \rightarrow \frac{2L}{RT} < (1-D)^2 \rightarrow DCM$$

$$\frac{\Delta i_L}{2} = \frac{V_{in} . D.T}{2L}$$

$K < K_{crit} \rightarrow$ DCM



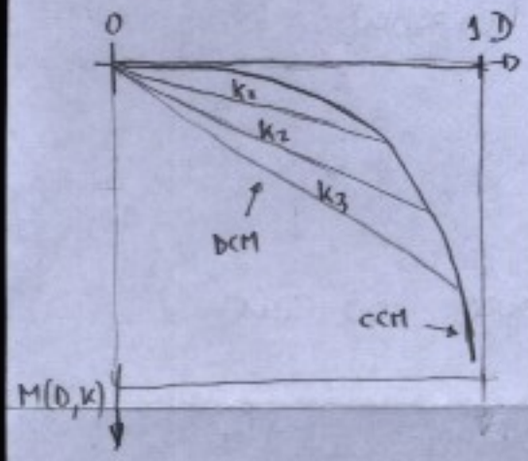


$\boxed{t_{on}}$ $\Delta i_L^+ = \frac{V_{in} \cdot D \cdot T}{L}$

$\boxed{t_{off}}$ $\Delta i_L^- = -\frac{V_o \cdot D_1 \cdot T}{L}$

$\boxed{\text{Rég. permanente}}$ $\frac{V_o}{V_i} = -\frac{D}{D_1}$ → Buscamos D_1...

$$\left.\begin{aligned} \bar{I}_D &= \frac{V_{out}}{R} \\ \bar{I}_D &= \frac{\hat{I}_L \cdot D_1}{2} \\ \hat{I}_L &= \frac{V_{in} \cdot D \cdot T}{L} \end{aligned}\right\} \quad D_1 = \frac{V_{out} \cdot 2L}{R D T V_{in}} \qquad M(D,K) = -\frac{D}{\sqrt{K}}$$



$K_1 > K_2 > K_3$

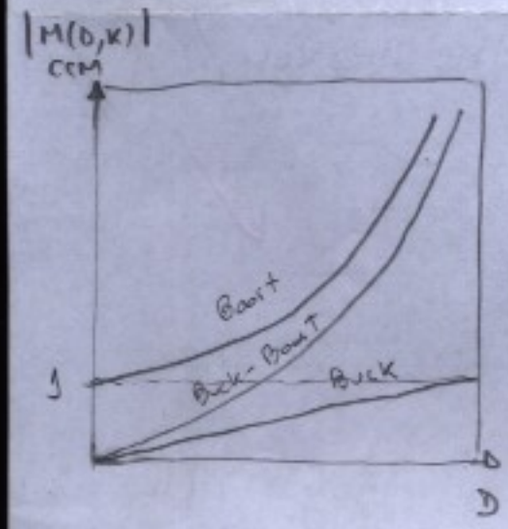
$M(D,K) = \begin{cases} -\frac{D}{1-D} & \text{para } K > K_{crit} \\ -\frac{D}{\sqrt{K}} & \text{para } K < K_{crit} \end{cases}$

SELECCIÓN DE DISPOSITIVO

T_x
- $V_{CEV} > V_{in\,máx} + V_{out}$
- $I_{C\,máx} > I_L + \frac{\Delta i_L}{2} = \frac{-I_{out}}{1-D} + \frac{\Delta i_L}{2}$

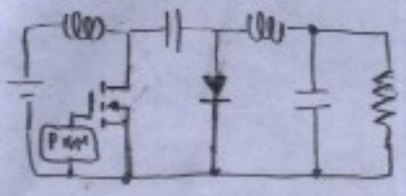
D_x
- $V_{RRM} > V_{in\,máx} + V_{out}$
- $I_{F(AV)} > I_{out}$

Resumen Comparativo



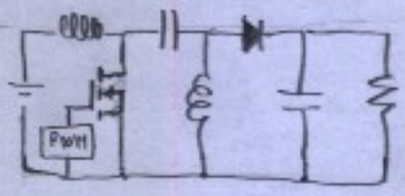
	Buck	Boost	Buck/Boost
$M_{CCM}(D)$	D	$\frac{1}{1-D}$	$-\frac{D}{1-D}$
$M_{DCM}(D,K)$	$\frac{2}{1+\sqrt{1+4K/D^2}}$	$\frac{1+\sqrt{1+\frac{4D^2}{K}}}{2}$	$-\frac{D}{\sqrt{K}}$
$K_{crit}(D)$	$1-D$	$D\cdot(1-D)^2$	$(1-D)^2$
$\frac{\Delta V_o}{V_o}$	$\frac{1-D}{8CLf_s^2}$	$\frac{DT}{RC}$	$\frac{DT}{RC}$

A.4 ĆUK



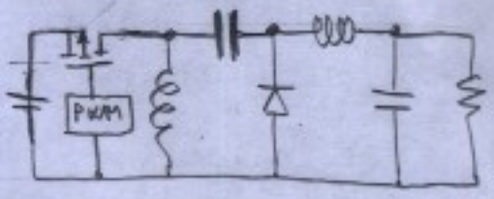
$$M(D) = -\frac{D}{1-D}$$

A.5 SEPIC



$$M(D) = \frac{D}{1-D}$$

A.6 ZETA

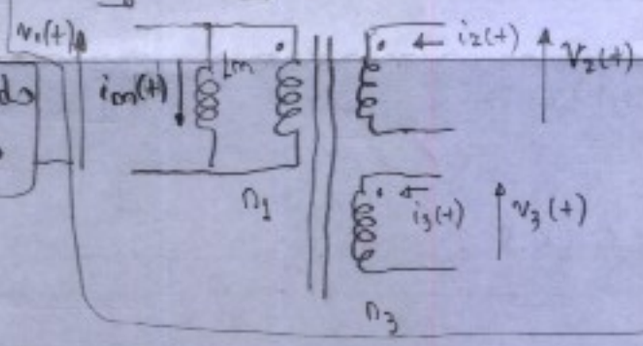


$$M(D) = \frac{D}{1-D}$$

Fuentes Aisladas Conmutadas

- Transformador de aislación
  1) P/apropiada nº de vueltas minimiza la sobrecargo de V ∗ I sobre los dispositivos
  2) A altas frec (100 khz) reduce volumen del trafo.
  3) Las pérdidas pueden ser menores
  4) Posibilidad de salidas múltiples.

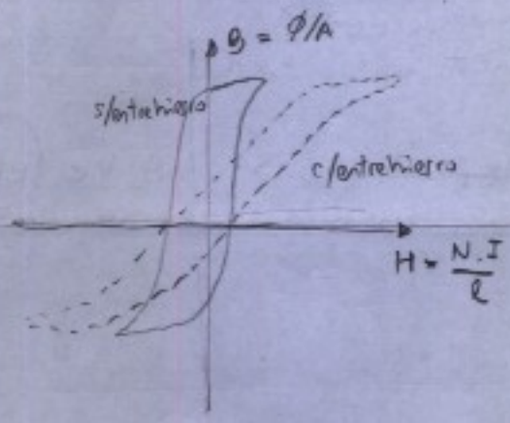
- Modelo simplificado más usado



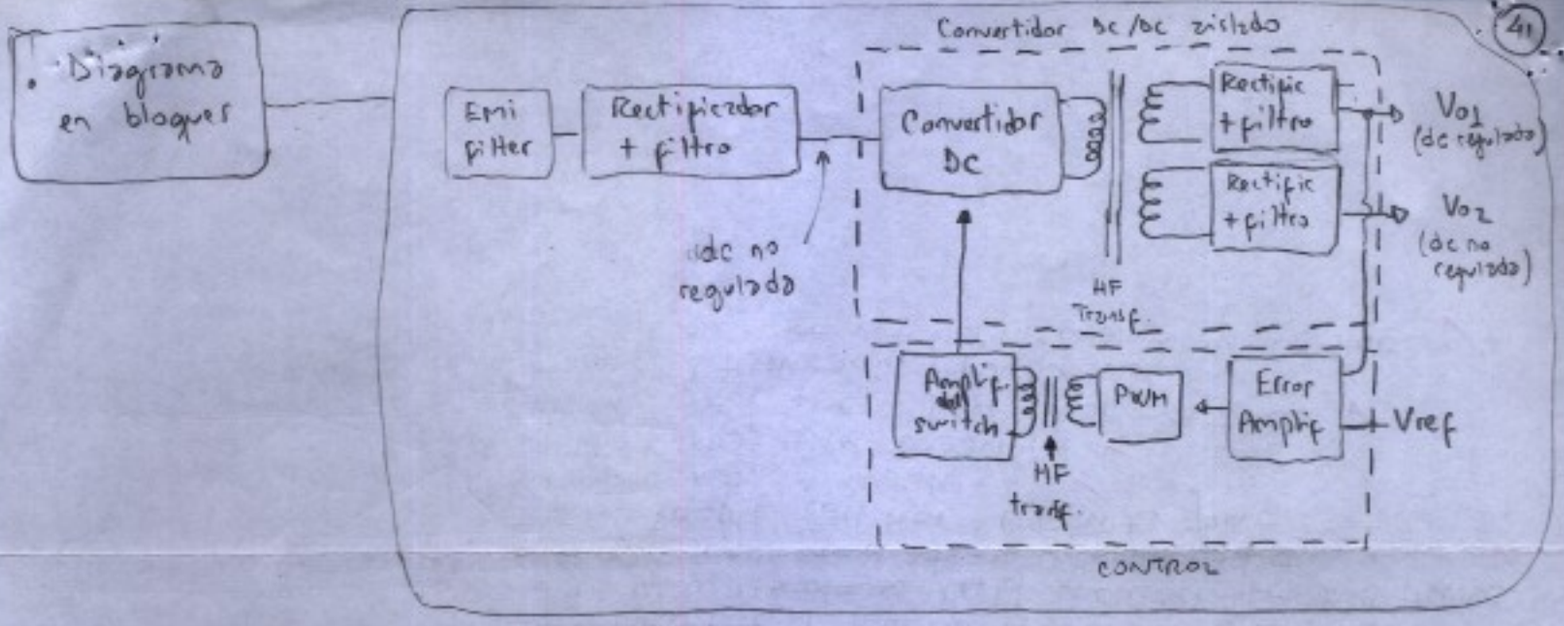
$$\frac{V_1(t)}{n_1} = \frac{V_2(t)}{n_2} = \frac{V_3(t)}{n_3}$$

$$i_1'(t) \cdot n_1 + i_2(t) \cdot n_2 + i_3(t) \cdot n_3 = 0$$

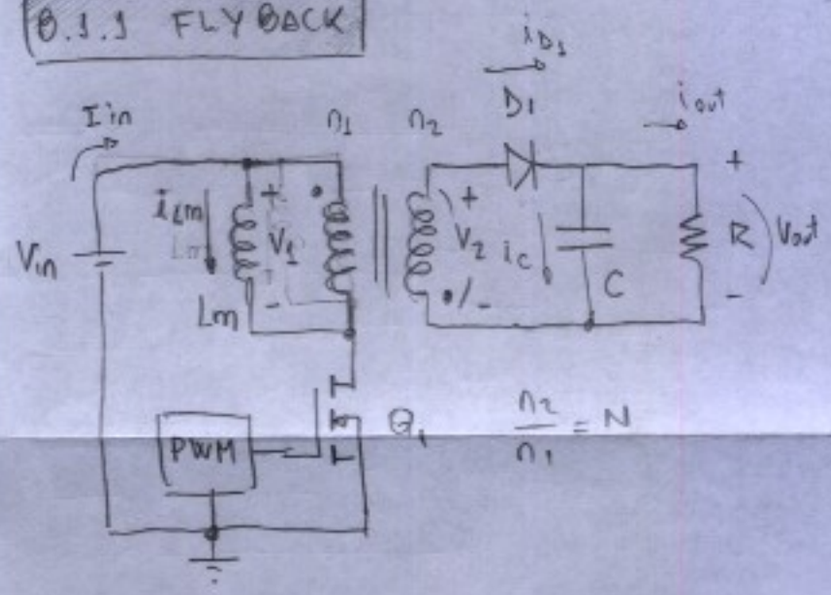
- Ciclo magnético del núcleo



- Si la corriente magnetizante Im es muy grande ∴ H provoca la saturación del núcleo haciendo que Lm → ∅ y poniendo en corto al trafo
- TRAFO BIEN DISEÑADO → Xm debe ser MUY GRANDE pero el rango de frec. de operación de manera que: $i_1'(t) \gg i_m(t)$ ∴ $i_1'(t) \approx i_1(t)$



8.1.1 FLYBACK



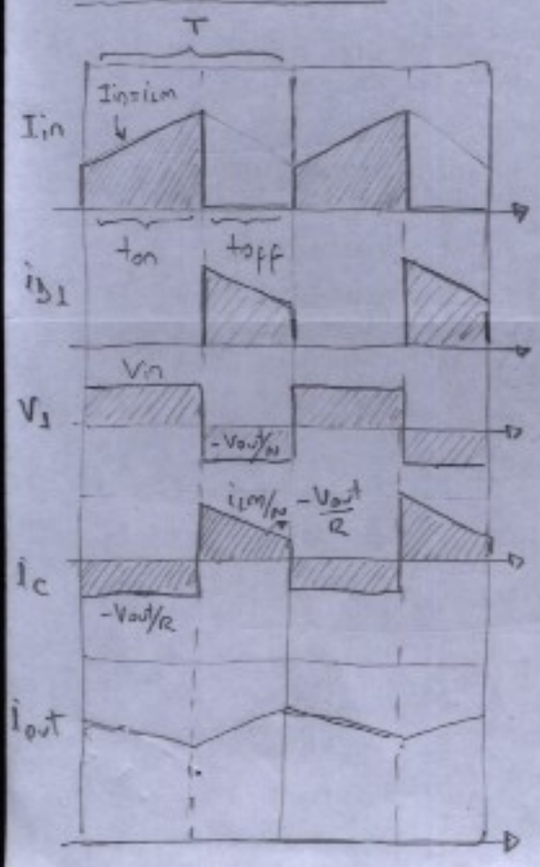
$$\frac{n_2}{n_1} = N$$

✓ El trafo se comporta como una inductancia de 2 devanados

✓ La corriente no circula simultaneamente por los 2 devanados

✓ Se almacena Energía en Lm durante ton y se entrega a la carga en toff

MODO CONTINUO



• $\boxed{t_{on}}$ $\quad \Delta i_{Lm}^{+} = \dfrac{V_{in}\, D.T}{L_m}$ (ENTRADA)

$$i_c = -\frac{V_{out}}{R} \quad \text{(SALIDA)}$$

• $\boxed{t_{off}}$ $\quad \Delta i_{Lm}^{-} = \dfrac{V_{out}\,(1-D)\,T}{N \cdot L_m}$ (IN)

$$i_c = \frac{i_{Lm}}{N} - \frac{V_o}{R} \quad \text{(OUT)}$$

• $\boxed{\text{Régimen permanente}}$ $\quad \Delta i_{Lm}^{+} = \Delta i_{Lm}^{-}$

$$\frac{V_{out}}{V_{in}} = \frac{D}{1-D} \cdot N$$

• $\boxed{\text{Cálculo de } L_m}$ $\quad \int_0^T i_c(t)\,dt = 0 \rightarrow \overline{I}_{Lm} = \dfrac{V_{out} \cdot N}{R\,(1-D)}$

$I_{Lm} > \dfrac{\Delta i_{Lm}}{2}$ para CCM $\therefore$ $L_{m_min} = \dfrac{(1-D)^2 \cdot R}{2N^2 \cdot f_s}$ para CCM

$\bar{I}_{Lm_mín} = \bar{I}_{Lm} - \frac{\Delta i_{Lm}}{2}$

$\bar{I}_{Lm_máx} = \bar{I}_{Lm} + \frac{\Delta i_{Lm}}{2}$

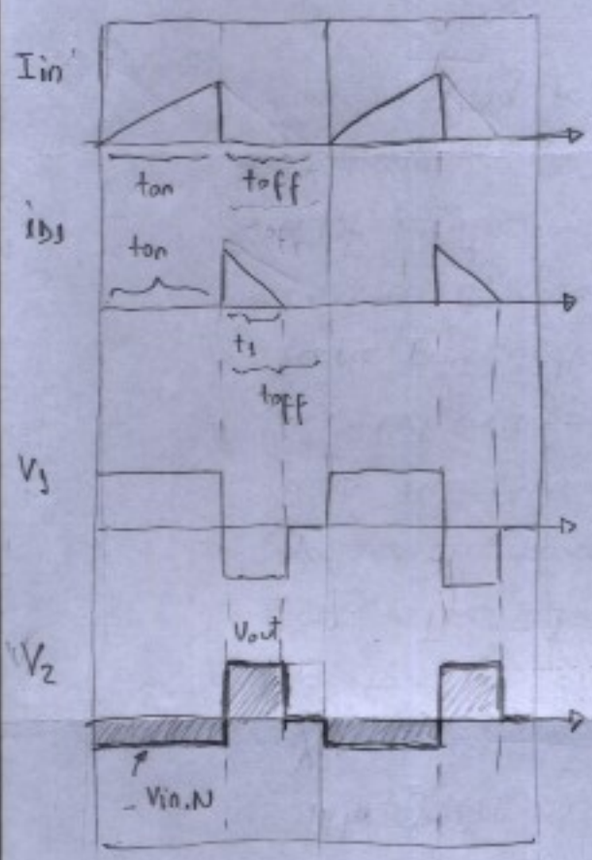
$\bar{I}_{in} = D \cdot \bar{I}_{Lm}$

Cálculo de C En el ton → $\Delta V_C = \Delta V_{out} = \frac{V_{out} \cdot D \cdot T}{RC}$

$$C = \frac{V_{out}}{\Delta V_{out}} \cdot \frac{D \cdot T}{R}$$

$$\frac{\Delta V_o}{V_o} = \frac{D \cdot T}{RC}$$

MODO DISCONTINUO



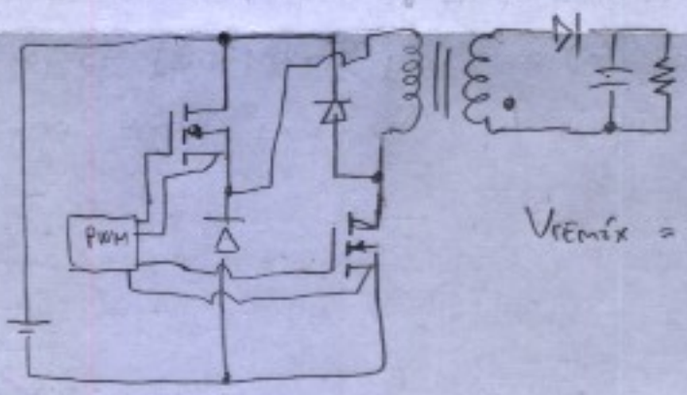
$I_{Lm} < \frac{\Delta i_{Lm}}{2}$ para DCM ∴ $\frac{2 L_m}{RT} < \left(\frac{1-D}{N}\right)^2$

para DCM ← $K < K_{crit.}$

- Requiere RED SNUBBER → limitar picos de tensión en el Tx en el corte (toff).
- Ciclo de trabajo típico $D = 0{,}5$

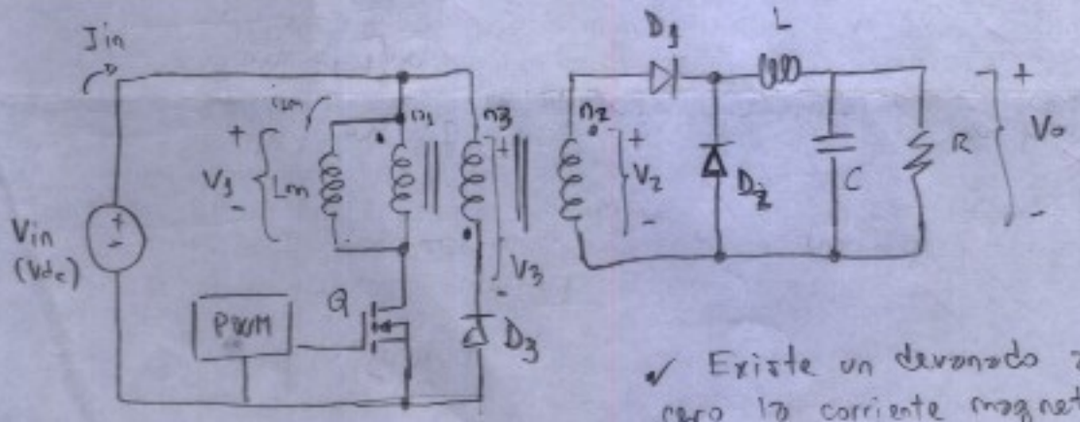
$V_{CEmáx} = V_{in} + \frac{V_{out}}{N}$

FLYBACK CON 2 TX

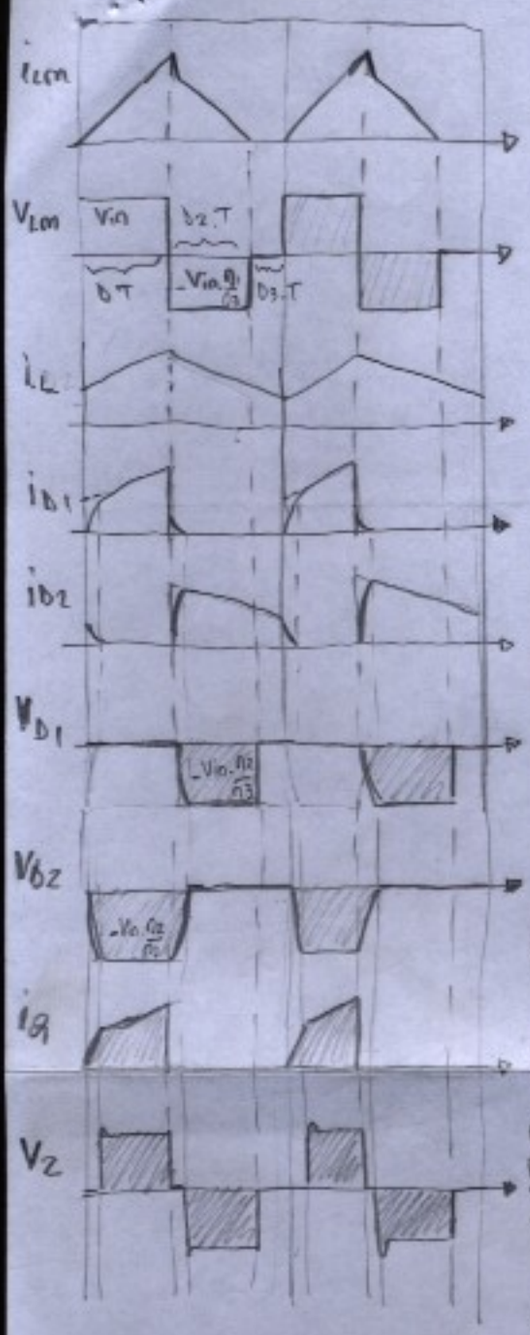


$V_{CEmáx} = V_{in} + 0{,}7$

B.1.2 FORWARD



- ✓ Existe un devanado adicional para llevar a cero la corriente magnetizante
- ✓ Se usa en aplicaciones de alta corriente en carga
- ✓ Lm y D3 → DCM L y D2 → CCM ó DCM



Modo 1:

• $\boxed{t_{on}}$ $\Delta i_{Lm} = \dfrac{V_{in} \cdot D \cdot T}{L_m}$

$\Delta i_L^+ = \left(V_{in} \cdot \dfrac{n_2}{n_1} - V_o\right) \dfrac{DT}{L}$

$V_1 = V_{in}$

$V_2 = -V_{in} \cdot \dfrac{n_2}{n_1}$

$V_3 = -V_{in} \cdot \dfrac{n_3}{n_1}$

Modo 2:

• $\boxed{t_{off}}$ $\Delta V_{Lm} = L_m \dfrac{di_{Lm}}{dt} = -V_{in} \cdot \dfrac{n_1}{n_3}$

$\Delta i_L^- = \dfrac{V_o (1-D) T}{L}$

$V_1 = -V_{in} \cdot \dfrac{n_1}{n_3}$

$V_2 = -V_{in} \cdot \dfrac{n_2}{n_3}$

$V_3 = V_{in}$

Modo 3:

• $\boxed{t_{off}}$ I_{Lm} se extinguió

Solo funciona la salida (si CCM)

$V_1 = \emptyset$

$V_2 = \emptyset$

$V_3 = \emptyset$

Régimen permanente:

• $\boxed{\Delta i_L^+ = \Delta i_L^-}$ $\therefore \dfrac{V_o}{V_1} = D \cdot N = D \cdot \dfrac{n_2}{n_1}$

• $\boxed{\text{Balance de E en Lm}}$ $V_{in} \cdot DT - V_{in} \dfrac{n_1}{n_3} \cdot D_2 T + 0 \cdot D_3 T = 0$

Requisito para que se desmagnetice el trafo $\begin{cases} D_2 T = \dfrac{n_3}{n_1} \cdot DT \\ D_2 T = t_{on} \quad (\text{si } n_3 = n_1) \end{cases}$

$D + D_2 + D_3 = 1 \quad (D_3 \geq 0)$

$D \leq \dfrac{1}{1 + \dfrac{n_3}{n_1}}$ $\therefore$ si $n_3 = n_1$ $\therefore D \leq 0{,}5$

• $\boxed{\dfrac{\Delta V_o}{V_o}}$

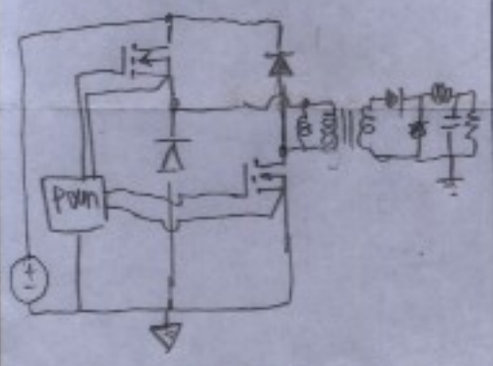
$\Delta Q = \dfrac{T \cdot \Delta i_L}{8} = C \cdot \Delta V_c$

$\Delta i_L = \dfrac{V_{in} \cdot N \cdot D (1-D)}{L \cdot f_s}$

$\Delta V_c = \Delta V_o$

$\dfrac{\Delta V_o}{V_o} = \dfrac{1-D}{8 L C f_s^2}$

FORWARD CON 2 TX



No necesita devanado auxiliar

$V_{CEV} > V_{in_máx}$

$V_{RRM} > V_{in.máx}$

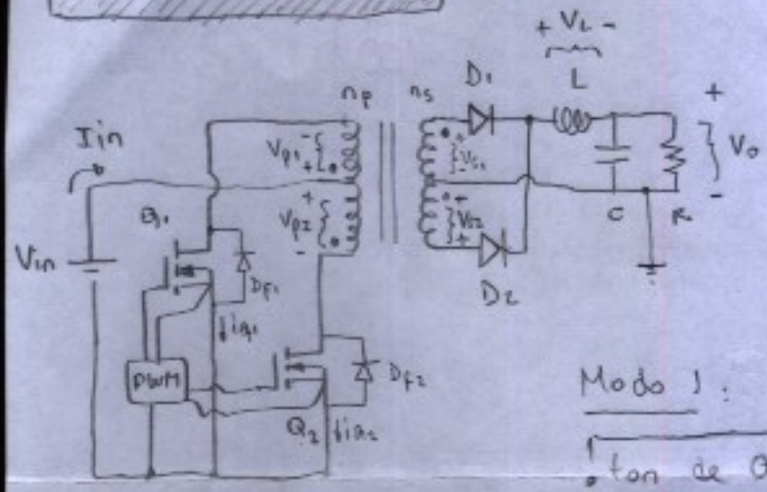
Selección del dispositivo:

T_x → $V_{CEV} > V_{in}\left(1 + \dfrac{n_1}{n_3}\right)$

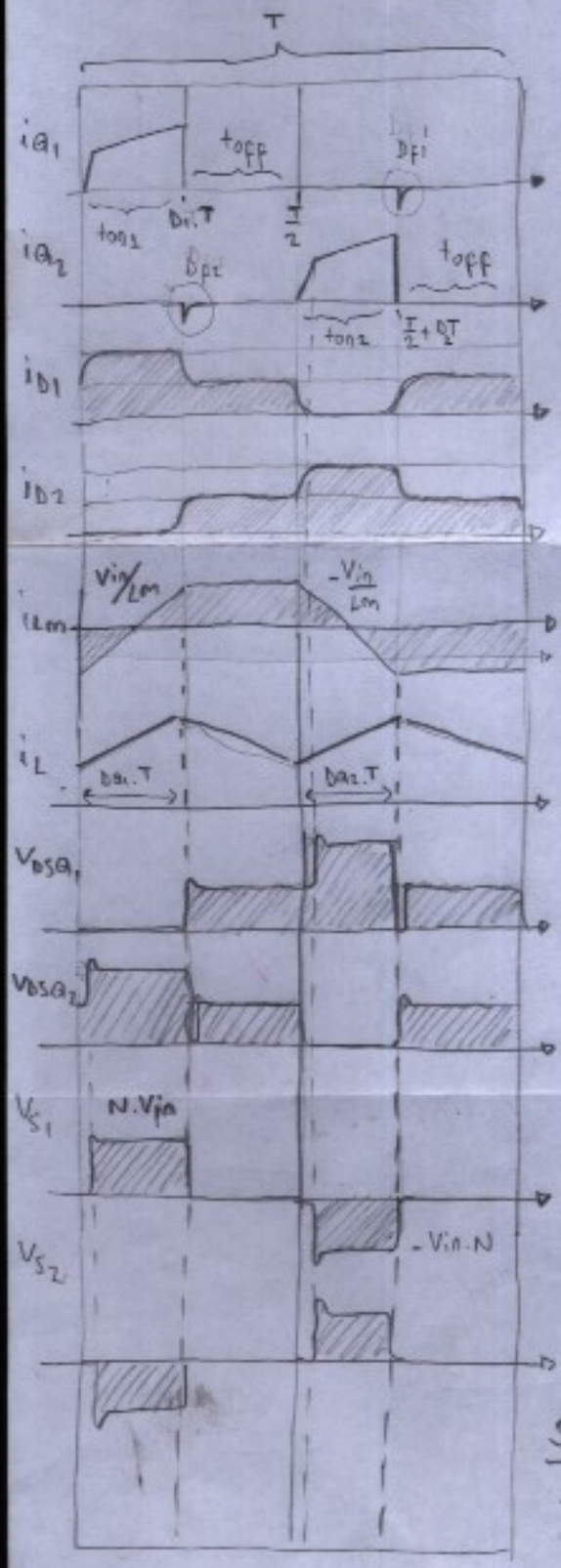
→ $I_{cmáx} > I_{Lmáx} \dfrac{n_2}{n_1} + \Delta i_{Lm} = \left(\dfrac{V_{out}}{R} + \dfrac{\Delta i_L}{2}\right) \dfrac{n_2}{n_1} + \Delta i_{Lm}$

D_3 → $V_{RRM} > 2 V_{in}$ (si $n_3 = n_1$)

8.2.1 PUSH PULL



- Combinación de dos forward en contrafase
- Dmáx de c/tx es 50%, si más → cortocirc. por lo que → td = tiempos muertos.



Modo 1:

$\boxed{\text{ton de } Q_1 \text{ ó } Q_2}$

$V_{p1} = V_{in} \rightarrow V_{s1} = N \cdot V_{p1} = \frac{n_s}{n_p} \cdot V_{in}$

$V_L = N \cdot V_{in} - V_{out}$

$\Delta i_L^+ = \frac{N \cdot V_{in} - V_{out}}{L} \cdot DT$

$D = D_{Q1} + D_{Q2}$

$(D = D_1 + D_2)$

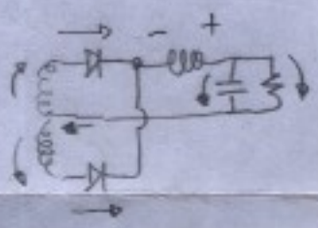
$D_1 = D_{Q1}$

Modo 2:

$\boxed{\text{toff de } Q_1 \text{ y } Q_2}$

$I_{in} = 0 \qquad V_L = -V_{out}$

$\Delta i_L^- = \frac{V_{out}}{L}(1-D)T$



Régimen permanente:

$\Delta i_L^+ = \Delta i_L^- \rightarrow (N \cdot V_{in} - V_{out}) DT = V_{out}(1-D)T$

$\frac{V_{out}}{V_{in}} = N \cdot D \qquad \frac{\Delta V_o}{V_o} = \frac{1-D}{32 LC f_s^2}$

Ventajas:
- Simple drivers, ambos ref. a masa (se aplica para bajas tensiones Vin)

Desventajas:
- $V_{CEV} > 2 \cdot V_{in}$
- Los transistores hacen que el núcleo tienda a saturarse debido a un desbalance del flujo (por asimetría de los tx)

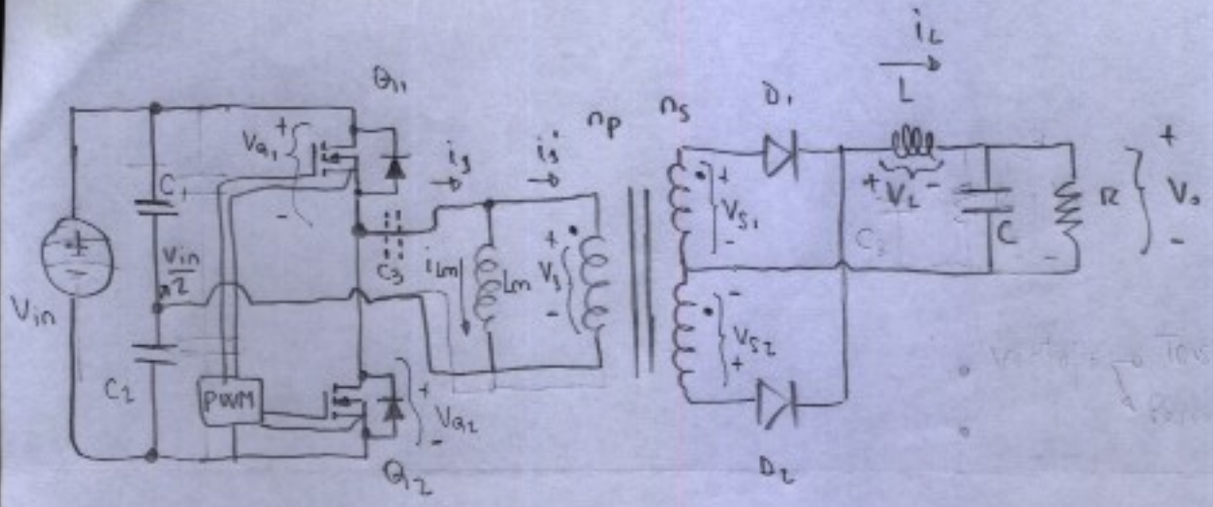
La solución:
1) Entrehierro
2) Mosfet
3) Control de asimetría

Selección de dispositivos:

Tx: V_{CEV} ó $V_{DSS} > 2 V_{in}$; $I_{CMÁX}$ ó $I_{DSS} > N \cdot I_{out}$

Dx:

B.2.2 · HALF BRIDGE

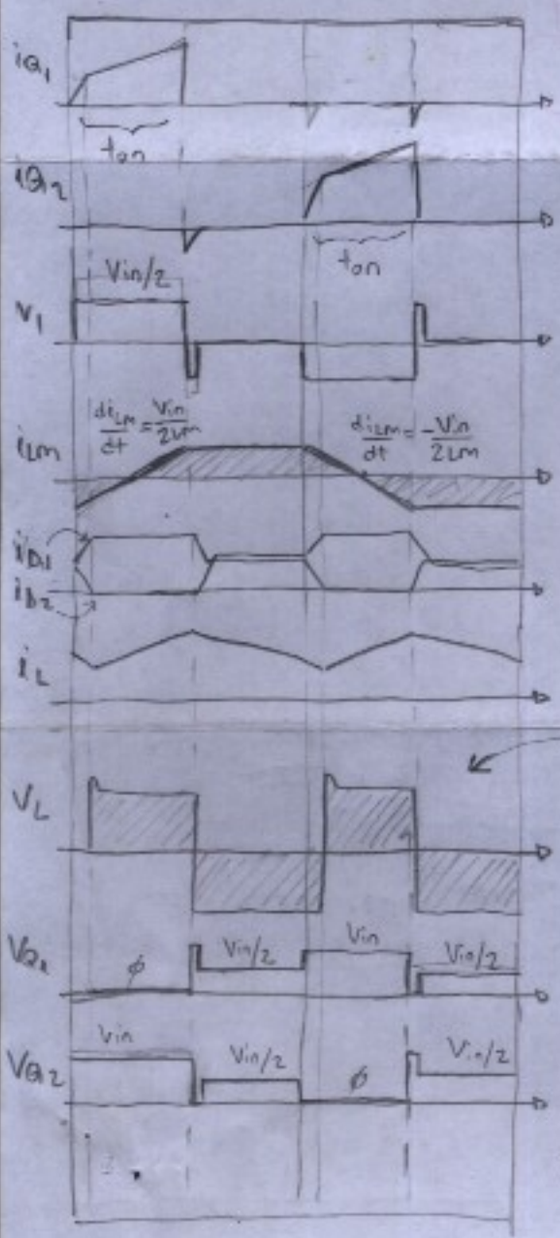


• Vantajes → Tensión bloqueo de Q = Vin
→ Permite balancear

Ventajas:

$C_1 = C_2$

1) La tensión de bloqueo de los tx es Vin (no como antes q'2Vin)
2) Permite balancear los Volts-Seg. de cada transistor automáticamente para prevenir saturación (gracias a C_1 y C_2)
3) Por lo anterior no necesito de núcleo con entrehierro ni controles de simetría.



• **Modo 1 = ton de Q1 y Q2**

$V_1 = \frac{V_{in}}{2}$; $V_{S1} = V_1 \cdot N = V_1 \cdot \frac{n_s}{n_p}$

$V_{S2} = -V_1 \cdot N$; $V_{DSQ2} = V_{in}$

$V_L = \frac{V_{in} \cdot N}{2} - V_o = L \cdot \frac{\Delta i_L}{t_{on}}$; $\frac{\Delta i_{Lm}}{\Delta t} = \frac{V_{in}}{2L_m}$

• **Modo 2 = toff de Q1 y Q2**

$V_L = -V_o$

$i_{D1,2}(t) = \frac{i_{out}(t)}{2} + \frac{i_{Lm}(t)}{2N}$

V_L se invierte para mantener en conducción D1 y D2

$V_{S1} = V_{S2} = \phi$

~~• Modo 3 y 4 procedimiento similar a 1 y 2~~

• **Balance de Energía en L**

$$\left(\frac{V_{in} \cdot N - V_o}{2}\right) \cdot \Delta T = (+V_o)(1-D)\,T$$

$$\frac{V_o}{V_i} = \frac{N \cdot D}{2} \qquad (0 < D < 1)$$

• **Selección Disp.**

?

• **Agregado de C_3**

$C_1 \neq C_2$ ∴ $\frac{V_{in}}{2}$ no se logra si usamos BJT

$$C_3 = \frac{1}{\left(2\pi \cdot f_R \frac{n_p}{n_s}\right)^2 \cdot L}$$

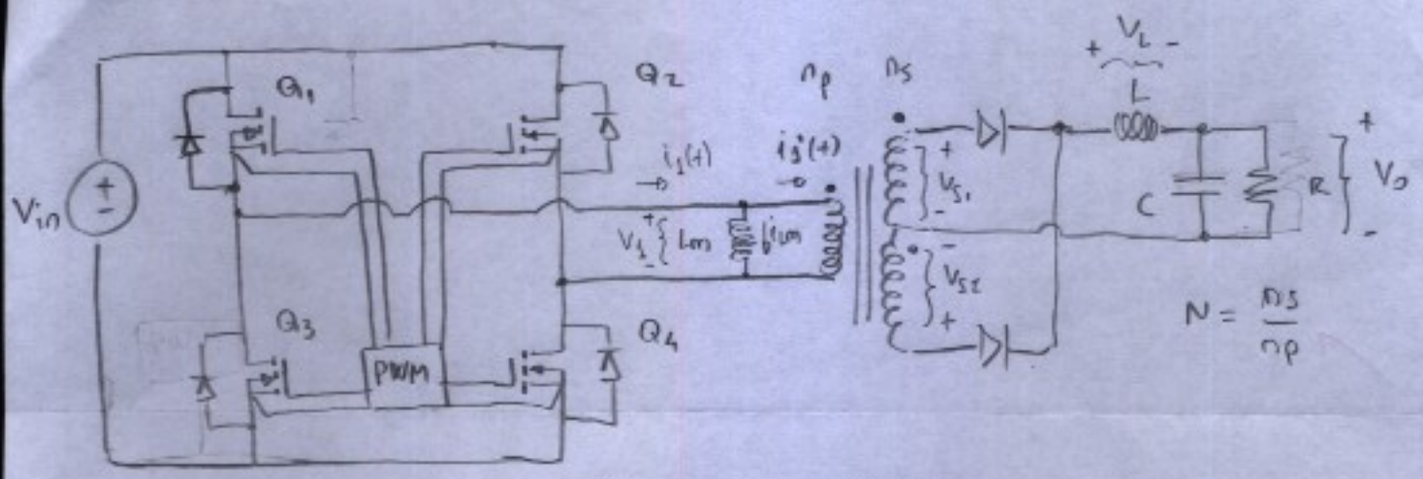
$F_R = 0{,}25 \cdot f_s$

$$C_3 = \frac{\bar{I} \cdot \Delta t}{\Delta V_{C\,máx}}$$

$\Delta V_C = 10\%$ de $\frac{V_{in}}{2}$

6.2.3 FULL BRIDGE

$500W < P_{out} \leq 2kW$



- Tiene propiedad de I (push pull) (forward) y de V (half bridge) (reverse)
- Los Tx diagonal opuestos conmutan conjuntamente

iguales gráficos que el half-bridge (temporalmente hablando) "Varían los módulos"

Modo 1 = ton de Q1 y Q4

$V_1 = V_{in}$

$V_{S1} = N \cdot V_{in}$

$V_{S2} = -N \cdot V_{in}$

$V_{DSQ2} = V_{in}$

$V_{DSQ3} = V_{in}$

$V_L = N \cdot V_{in} - V_o = L \frac{\Delta i_L}{D \cdot T}$

$\frac{\Delta i_{Lm}}{\Delta t} = \frac{V_{in}}{L_m}$

Modo 2 = toff de Q1, Q4 (también Q2 y Q3 en toff)

V_L se invierte → conducen D1 y D2

$i_{D1}(t) = \frac{i_{out}(t)}{2} - \frac{i_{Lm}(t)}{2 \cdot N}$

$i_{D2}(t) = \frac{i_{out}(t)}{2} + \frac{i_{Lm}(t)}{2N}$

$V_L = -V_{out} = \frac{L \cdot \Delta i_L}{(1-D)T}$

Modo 3 y 4 similar procedimiento

Balance de E en L

$\frac{V_o}{V_i} = N \cdot D$

Selección de dispositivos

Tx
- V_{CEV} ó $V_{DSS} \geq V_{in\,máx}$
- $I_{cmáx}$ ó $I_{DSS} \geq N \cdot I_{out}$

Dx
- $V_{BR} \geq 2 \cdot N \cdot V_{in}$
- $I_{Dmáx} \geq I_{out}/2 + I_{Lm}/2N$
- $I_{F(AV)} \geq I_{out}/2$

RESTRICCIONES DEL CICLO DE TRABAJO

Buck: $0 \leq D \leq 1$ (Entre 5% y 95%)

Boost: } $0 \leq D \leq 1$ ($D_{máx} = 0,5$ porque la $M(D)$ se vuelve muy alineal, el convertidor empieza a tener problemas)
Buck-Boost: }

Forward: $0 \leq D \leq \frac{1}{1+\frac{m_3}{m_1}}$ si $m_3 = m_1$ ∴ $0 \leq D \leq 0,5$

Flyback: $0 < D < 0,5$ (típico) pero puede ir de $0 < D < 1$

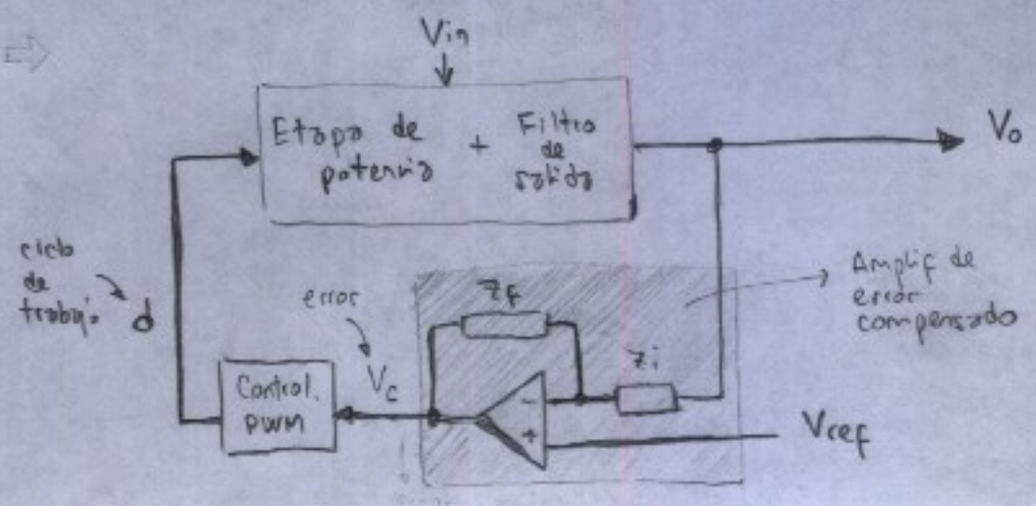
Half-Bridge: } $0 < D < 0,5$ ó $0 < D < 1$
Push-Pull: } (para c/tx) (analizando sobre L → salida)
Full-Bridge: }

MODELIZACIÓN Y CONTROL DE FUENTES CONMUTADAS

⇨ Las tensiones de salida son regulados dentro de MARGEN DE TOLERANCIA ante variaciones: Δ_{LOAD}, ΔV_{in}

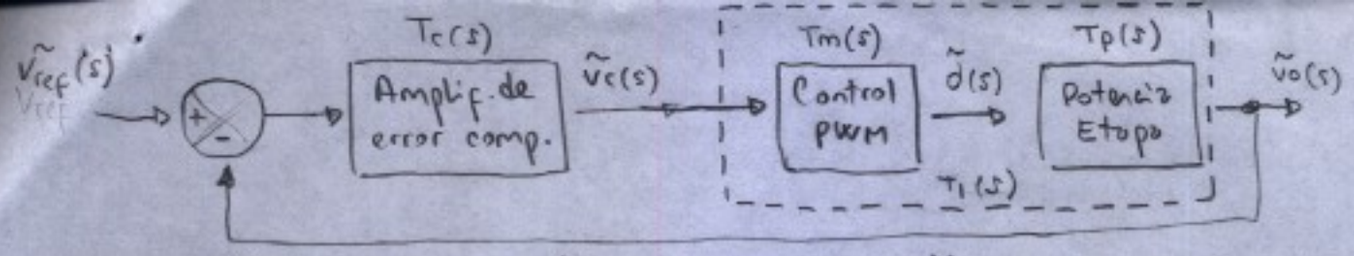
⇨ El Control se hace mediante REALIMENTACIÓN, el ERROR producido de comparar la salida y la referencia se utiliza para variar el ciclo de trabajo

⇨



⇨ El Análisis del COMPORTAMIENTO DINÁMICO (de L y C, elementos almacenadores de energía, y analizando cómo afecta a la salida los Δ_{LOAD}, ΔV_{in}, ΔD) nos permite aplicar el Criterio de Estabilidad de Nyquist y el Diagrama de Bode para:

1) Determinar una compensación adecuada en la realimentación
2) Predecir
   - margen de estabilidad
   - rechazo al ripple de la tensión de entrada
   - respuesta transitoria
   - impedancia de salida.



$$T_m(s) = \frac{\tilde{d}(s)}{\tilde{v}_c(s)} \; ; \quad T_p(s) = \frac{\tilde{v}_o(s)}{\tilde{d}(s)} \; ; \quad T_1(s) = \frac{\tilde{v}_o(s)}{\tilde{v}_c(s)} = T_m(s) \cdot T_p(s)$$

$$T_{OL}(s) = T_c(s) \cdot T_1(s)$$
(open loop)

⇒ Métodos para el análisis dinámico → Numérico (simulaciones)
→ Analítico (técnica de espacio-estado promediado)

$$\boxed{F.T. = \frac{\tilde{v}_o(s)}{\tilde{d}(s)} \Rightarrow \text{"FORWARD" (CCM)}}$$

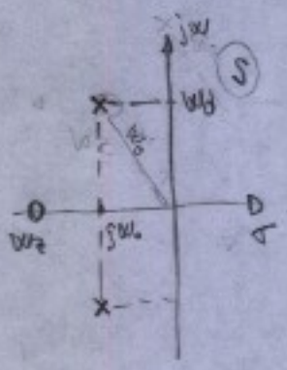
⊙ $M(D) = N.D. \dfrac{R + r_c}{R + r_c + r_L} \approx N.D$ ⇒ Función de transferencia en D.C.

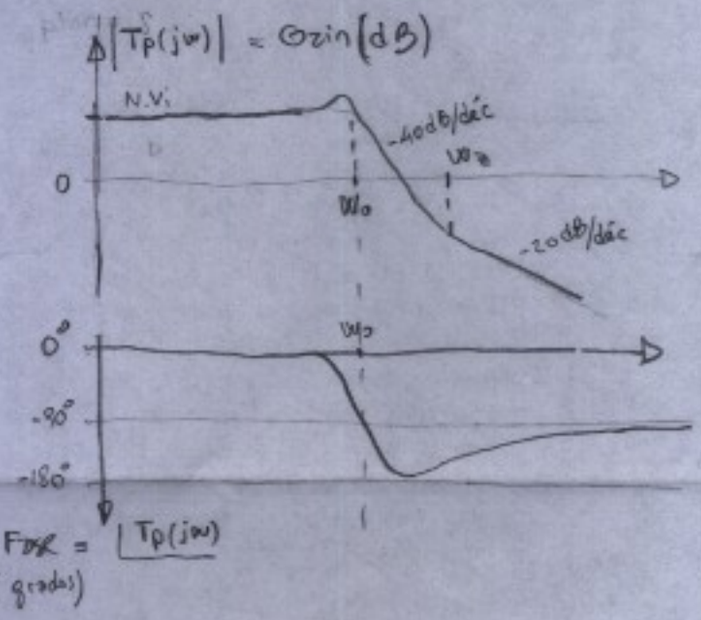
⊙ $T_p(s) = \dfrac{\tilde{v}_o(s)}{\tilde{d}(s)} \approx N.V_i \dfrac{\omega_o^2}{\omega_z} \dfrac{\left(1 + \frac{s}{\omega_z}\right)}{s^2 + 2\xi\omega_o s + \omega_o^2}$ ⇒ Función de transf. en A.C.

$$\omega_o = \frac{1}{\sqrt{LC}}$$

$$\omega_z = \frac{1}{r_c \cdot C}$$

$$2\xi\omega_o = \left(\frac{1}{RC} + \frac{r_c + r_L}{L}\right)$$





$$\boxed{F.T = \frac{\tilde{v}_o(s)}{\tilde{d}(s)} \Rightarrow \text{"FLYBACK" (CCM)}}$$

⊙ $T_p(s) = \dfrac{\tilde{v}_o(s)}{\tilde{d}(s)} \cong V_i \cdot f(D) \dfrac{\left(1 + \frac{s}{\omega_{z1}}\right)\left(1 - \frac{s}{\omega_{z2}}\right)}{s^2 + 2\xi\omega_o s + \omega_o^2}$ ⇒ Función de transf. en A.C.

$$\omega_0 = \frac{1-D}{\sqrt{LC}} = \frac{1}{\sqrt{L_E \cdot C}}$$

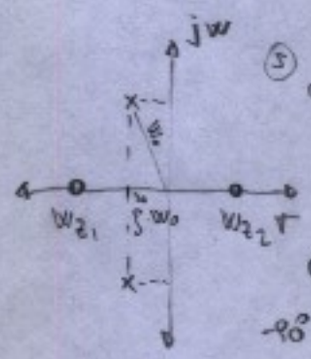
$$\omega_{z1} = \frac{1}{r_c \cdot C}$$

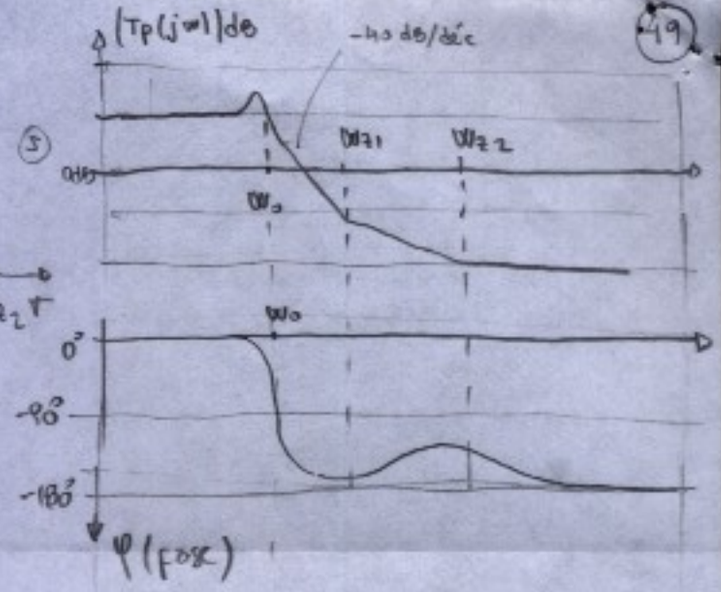
$$\omega_{z2} = \frac{R}{L_E \cdot D}$$

$$L_E = \frac{L}{(1-D)^2}$$

$$2\xi\omega_0 = \frac{r_L/D^2 + r_c/D}{L_E} + \frac{1}{RC}$$

$$F(D) = \frac{N}{1-D} \quad \text{(F. no lineal)}$$



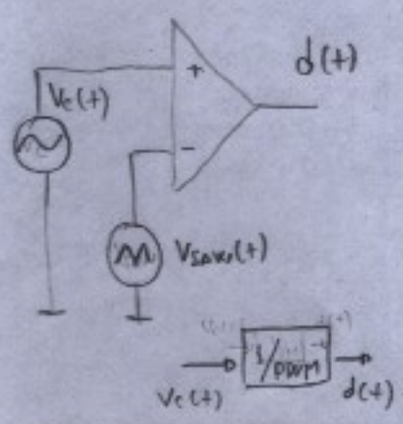


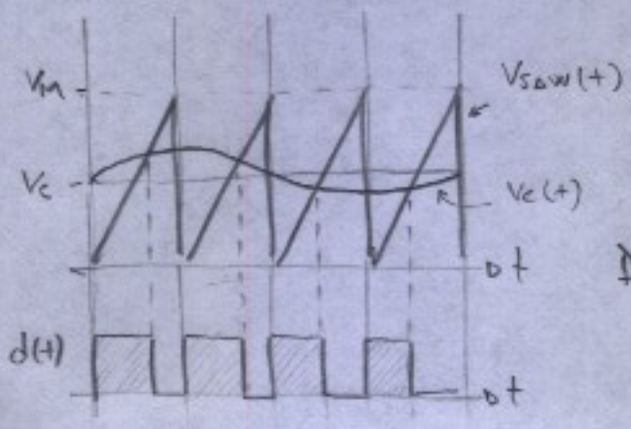
(*) ω_{z2} → ante un incremento instantáneo de D la salida decrece momentáneamente (La I_L no puede crecer instantáneamente)

(*) ω_{z2} → hace "MÁS DIFICIL" la compensación → introduce un retardo de fase.

↳ Razón por la cual el flyback se usa en DCM y controlado por corriente.

$$\boxed{F.T. = \frac{\tilde{d}(s)}{\tilde{V}_c(s)} \Rightarrow \text{"PWM"}}$$





$$d(t) = \frac{V_c(t)}{V_M}$$

$$V_c(t) = V_c + \tilde{v}_c(t)$$

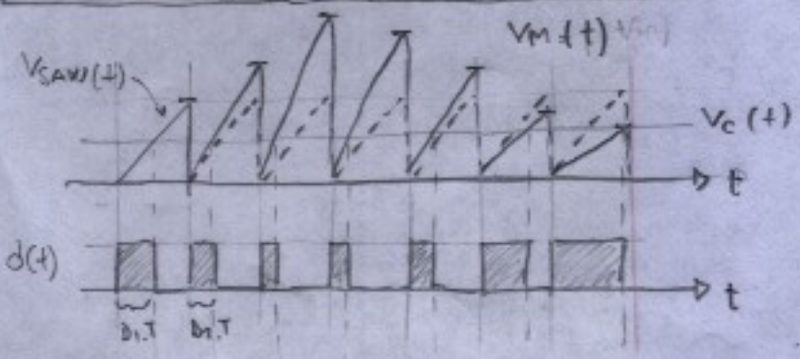
$$d(t) = D + \tilde{d}(t)$$

$$D + \tilde{d}(t) = \frac{V_c + \tilde{v}_c(t)}{V_M}$$

$$D = \frac{V_c}{V_M} \; ; \; \tilde{d}(t) = \frac{\tilde{v}_c(t)}{V_M}$$

$$\boxed{F.T = \frac{\tilde{d}(s)}{\tilde{V}_c(s)} \Rightarrow \text{"PWM FEED FORWARD"}}$$

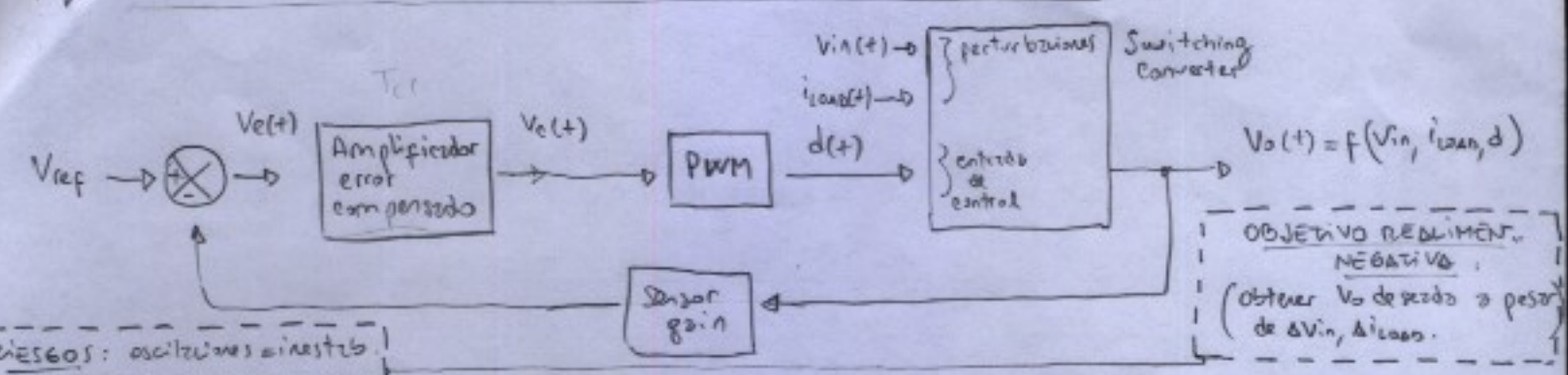
ΔV_{in} ⇒ Modifica la pendiente M ⇒ Ajusta D ⇒ V_o cte (error = ∅)



$$V_M(t) = K \cdot V_{in}(t)$$

$$D + \tilde{d}(t) = \frac{V_c + \tilde{v}_c(t)}{K \cdot V_i(t)}$$

⇨ Diseño de Control Directo de D utilizando PWM:



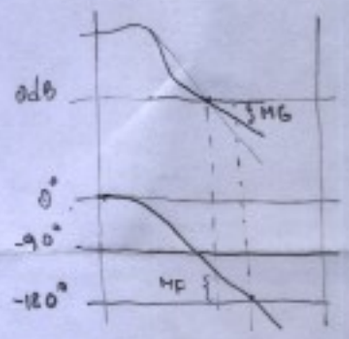
$T_{OL}(s) = T_c(s) \cdot \underbrace{T_m(s) \cdot T_p(s)}$

$T_{OL}(s) = T_c(s) \cdot T_1(s)$

Para un $T_1(s)$ determinado el $T_c(s)$ deberá ser apropiadamente elegido de manera que $T_{OL}(s)$ cumpla los requerimientos esperados en la fuente conmutada.

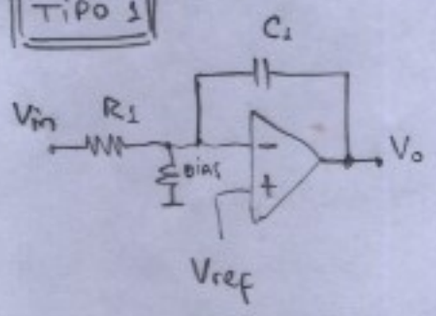
$T_{OL}(s)$
- Alta Ganancia a Baja Frec. (reducir error en régimen permanente)
- ω_c lo más alta posible (buena resp. dinámica) pero $\omega_c = \frac{\omega_s}{5}$
- $\phi_m = 60°$ $(30° \leq \phi_m \leq 90°)$ (Resp. transit. frente a cambios de Vin)

Los requerimientos se logran con redes de compensación



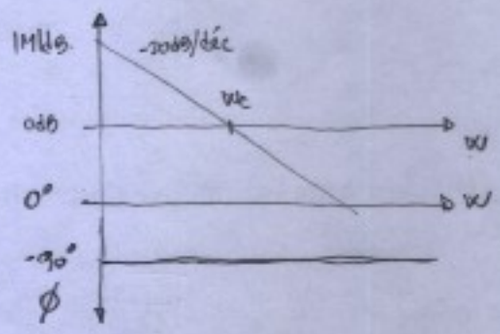
$\phi_m = 180° - \phi_{OL}$

TIPO 1

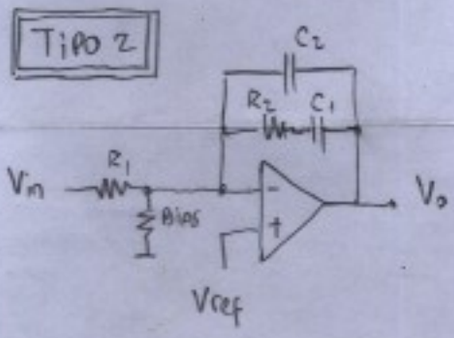


$$T_c(s) = \frac{1}{s \cdot R_1 \cdot C_1}$$

$$\omega_c = \frac{1}{R_1 \cdot C_1}$$



TIPO 2

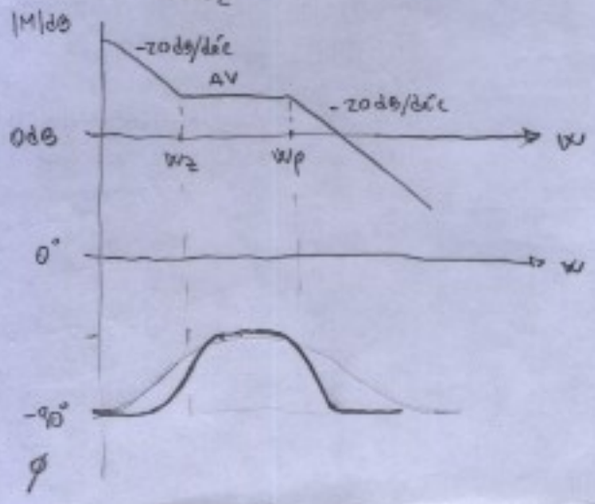


$$T_c(s) = \frac{1}{R_1 \cdot (C_1 + C_2)} \cdot \frac{1}{s} \cdot \frac{1 + s \cdot C_1 \cdot R_2}{1 + s \cdot \frac{C_1 \cdot C_2 \cdot R_2}{C_1 + C_2}}$$

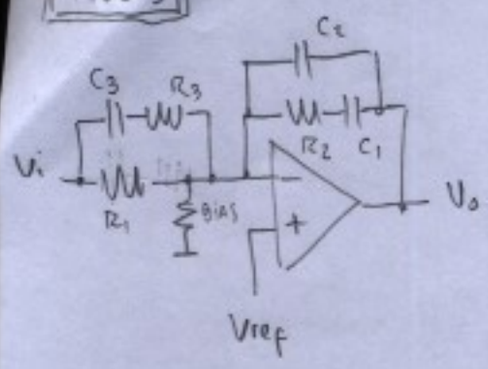
$$\omega_z = \frac{1}{C_1 \cdot R_2}$$

$$\omega_p = \frac{1}{R_2 (C_1 // C_2)}$$

$$A_V = \frac{R_2}{R_1} \quad (C_1 \gg C_2)$$

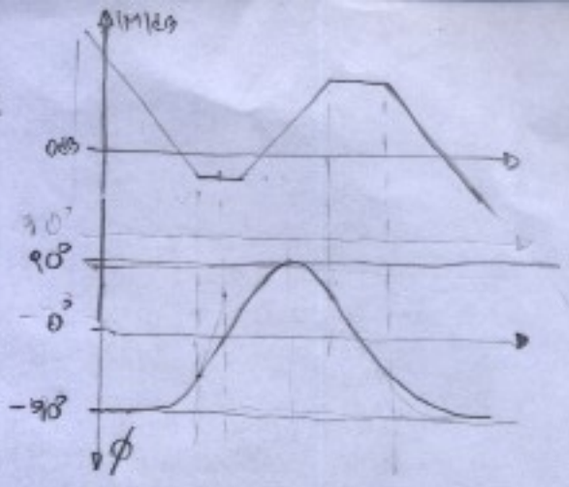


TIPO 3



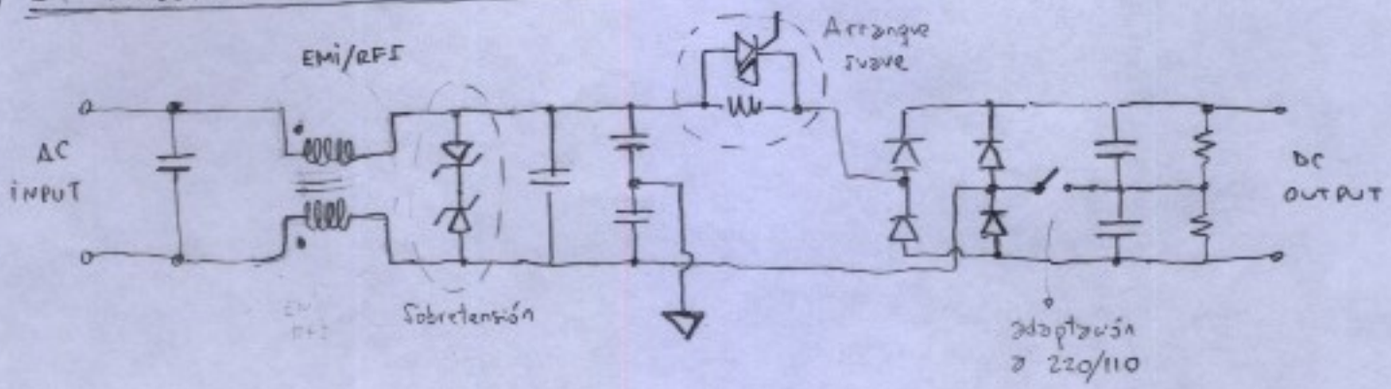
Introduce 3 polos (1 origen) y 2 ceros

Introduce avance de fase

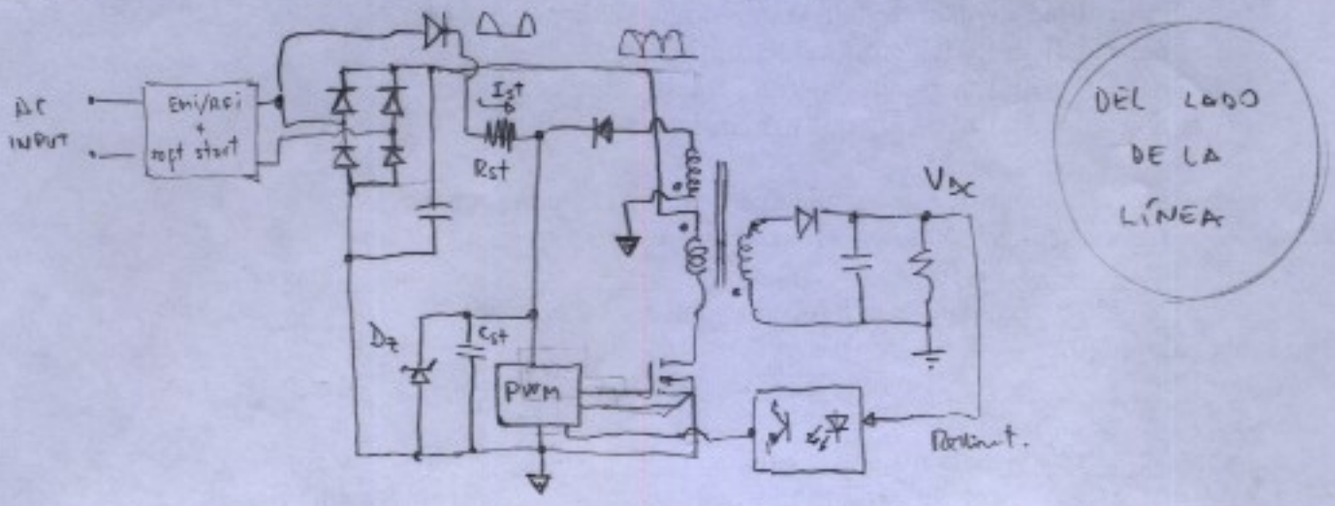


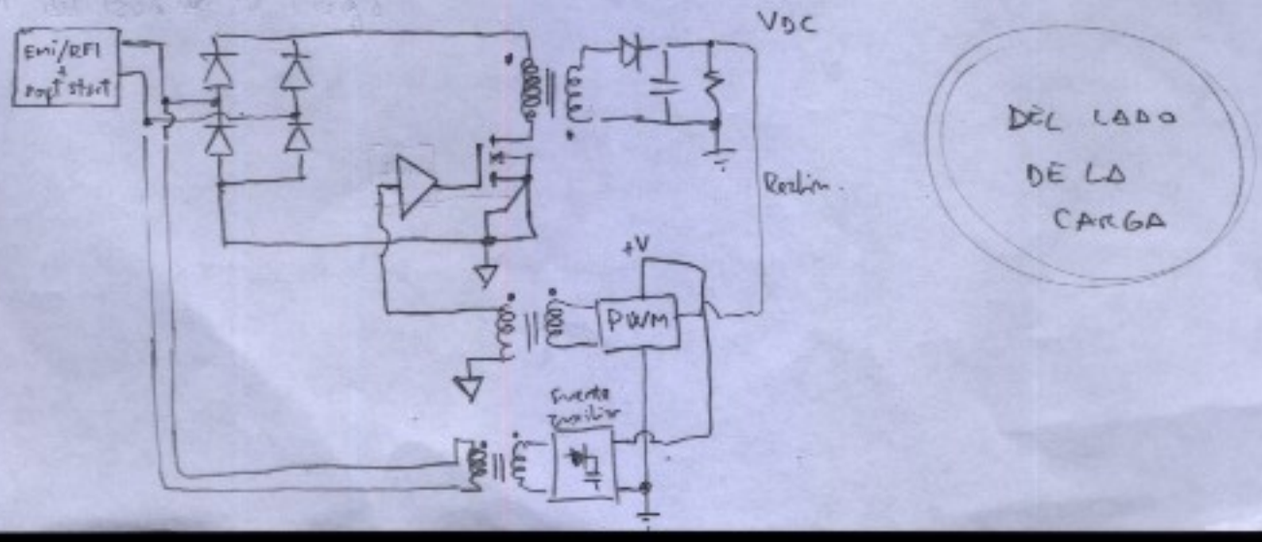
CIRCUITOS COMPLEMENTARIOS

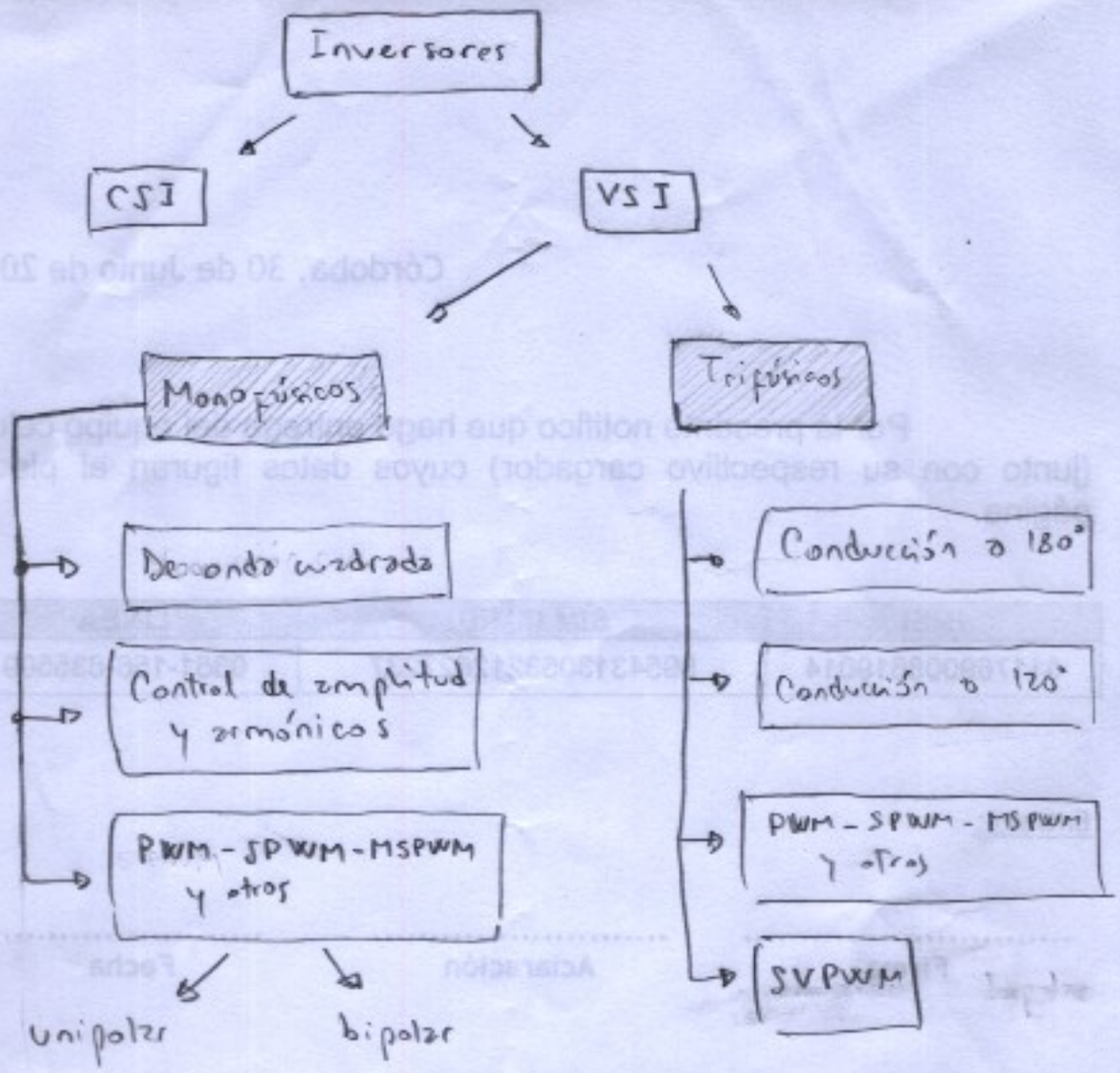
El circuito de entrada de línea:



Alimentación del PWM en el arranque: (ejemplo: flyback)






Inversores
CSI
VSI
Monofásicos
Trifásicos
Onda cuadrada
Control de amplitud y armónicos
PWM - SPWM - MSPWM y otros
unipolar
bipolar
Conducción a 180°
Conducción a 120°
PWM - SPWM - MSPWM y otros
SVPWM

INVERSORES

PARÁMETROS DE RENDIMIENTO

1) Factor Armónico $= HF_n = \dfrac{V_n}{V_1}$

2) $THD_v = \dfrac{\sqrt{V_{rms}^2 - V_{1rms}^2}}{V_{1rms}} = \dfrac{\sqrt{\sum_{n=2,3,\dots}^{\infty} V_{n\text{-}rms}^2}}{V_{1rms}}$

$THD_i = \dfrac{\sqrt{I_{rms}^2 - I_{1rms}^2}}{I_{1rms}}$

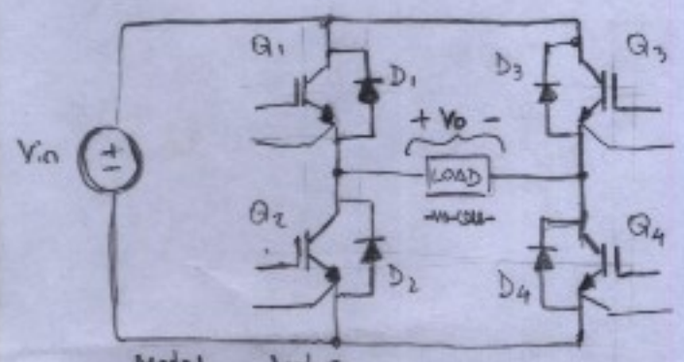
3) Factor de Distorsión $= DF = \dfrac{\sqrt{\sum_{n=2,3,\dots}^{\infty} \left(\frac{V_n}{n^2}\right)^2}}{V_1}$

$DF_n = \dfrac{V_n}{n^2 \cdot V_1}$

4) Armónico de menor orden = comp. frec. más cercana a fundamental y $\geq$ 3% fund.

INVERSORES MONOFÁSICOS

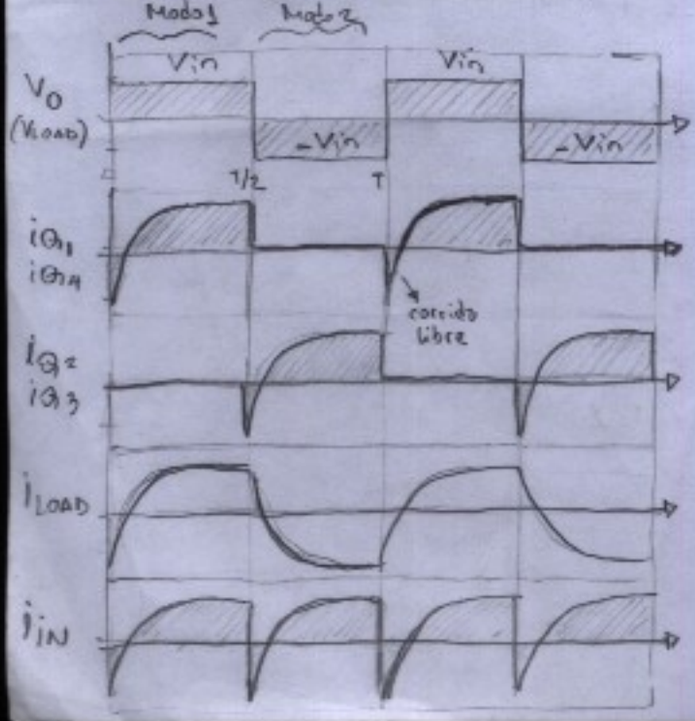
• Inv. Monofásico de puente completo (onda cuadrada)



LLAVES CERRADAS	V_o
(M1) Q_1 y Q_4	Vin
(M2) Q_2 y Q_3	-Vin
Q_1 y Q_3	∅
Q_2 y Q_4	∅

⊙ Los tx de la misma rama nunca conducen simultaneamente (Q_1 y Q_2 por ejemplo) → cortocircuito

⊙ $t_{apagado} > t_{encendido}$ ∴ tiempo muerto sino ¡cortocircuito!



CARGA RESISTIVA

$V_{o_rms} = V_{in}$

$V_o = \sum_{n=1,3,5}^{\infty} \dfrac{4 \cdot V_{in}}{n\pi} \operatorname{sen}(n\omega_o t)$

$V_{1_rms} = \dfrac{4 \cdot V_{in}}{\sqrt{2} \cdot \pi} = 0{,}9 \cdot V_{in}$

CARGA RESISTIVA PURA

$I_o = I_{LOAD} = \dfrac{V_o}{R}$

$I_{o_rms} = \dfrac{V_{in}}{R}$

CARGA RESISTIVA INDUCTIVA

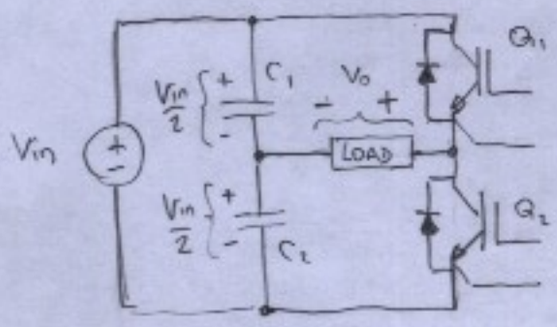
$$i_o(t) = \begin{cases} \frac{V_{in}}{R} + \left(I_{min} - \frac{V_{in}}{R}\right) \cdot e^{-t/\tau} & \text{para } 0 < t < \frac{T}{2} \\ -\frac{V_{in}}{R} + \left(I_{máx} + \frac{V_{in}}{R}\right) e^{-(t-\frac{T}{2})/\tau} & \text{para } \frac{T}{2} < t < T \end{cases}$$

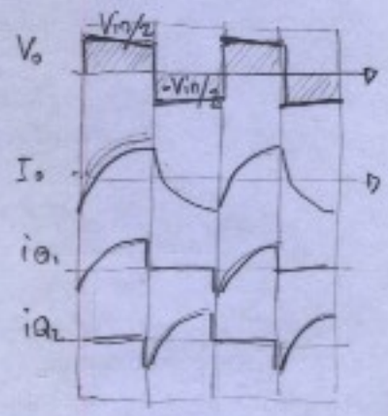
$$|I_{máx}| = |I_{mín}| = \frac{V_{in}}{R}\left(\frac{1 - e^{-T/2\tau}}{1 + e^{-T/2\tau}}\right)$$

Corrido Libre → Conducen los diodos → Q_1, Q_2, Q_3, Q_4 apagados

$$I_{o_rms} = \sqrt{\frac{1}{T}\int_0^T i_o(t)^2\, dt}$$

Inv. Monofásico Medio Puente





$$V_{o_rms} = \frac{V_{in}}{2}$$

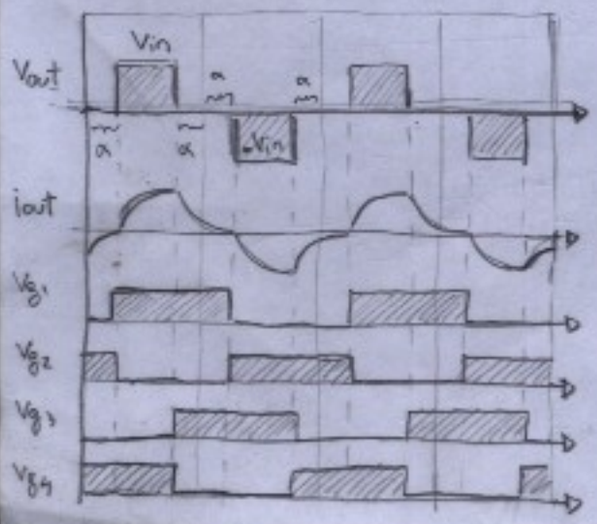
$$V_o = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_{in}}{n\pi} \operatorname{sen}(n\omega t)$$

Tipos de Modulación del pulso de mando

modulación pulso ⇨ controlar tensión carga

1) CONTROL DE AMPLITUD Y ARMÓNICOS (X DECALADO)
2) MODULACIÓN SENOIDAL DEL ANCHO DE PULSO (SPWM)
3) MODULACIÓN DE VECTOR ESPACIAL (SV-PWM)

1) INV. CON CONTROL DE AMPL. Y ARMÓNICOS:



Consiste en desfasar un ang. α el disparo de los tx de la diagonal.

$$V_{o_rms} = V_{in}\sqrt{1 - \frac{2\alpha}{\pi}}$$

$$V_o = \sum_{n=1,3,\ldots}^{\infty} V_n \cdot \operatorname{sen}(n\omega t)$$

$$V_n = \frac{4 \cdot V_{in}}{n\pi} \cos(n\alpha)$$

Eliminar armónicos → $n\alpha = 90°$ → $\alpha = \frac{90°}{n}$

2) MODULACIÓN SENOIDAL DEL ANCHO DE PULSO:

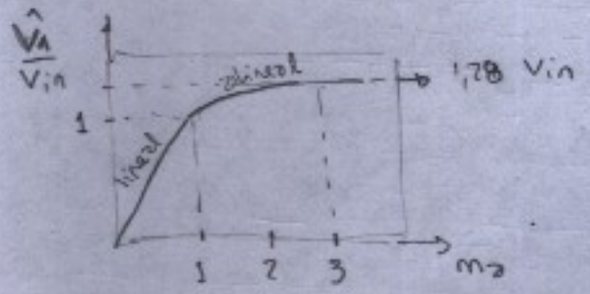
- Disminuye el THD considerablemente
- Se comparan Vsenoidal con Vtriangular → varios pulsos (requiere)
- Vsen → modulante ; Vtri → portadora

$$\boxed{m_f = \frac{f_{tri}}{f_{sen}}}$$

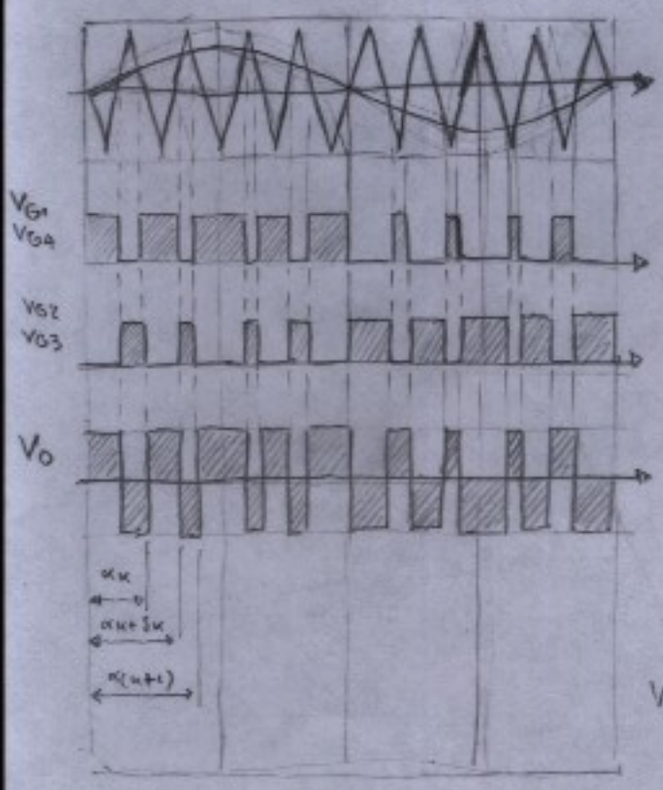
→ entero (SPWM síncrono : ↓THD)
→ no entero (SPWM asíncrono : ↑THD)

$$\boxed{m_a = \frac{\hat{V}_{sen}}{\hat{V}_{tri}}}$$

→ $0 < m_a < 1 \therefore \hat{V}_1 = m_a . V_{in}$
→ $m_a > 1 \therefore$ satura el modulador → $\hat{V}_1 = \frac{4 . V_{in}}{\pi}$ $(m_a \geq 3)$



- SPWM BIPOLAR



Si → $V_{sen} > V_{tri} \therefore Q_1$ y Q_4 (ON) $\therefore V_o = +V_{in}$
→ $V_{sen} < V_{tri} \therefore Q_2$ y Q_3 (ON) $\therefore V_o = -V_{in}$

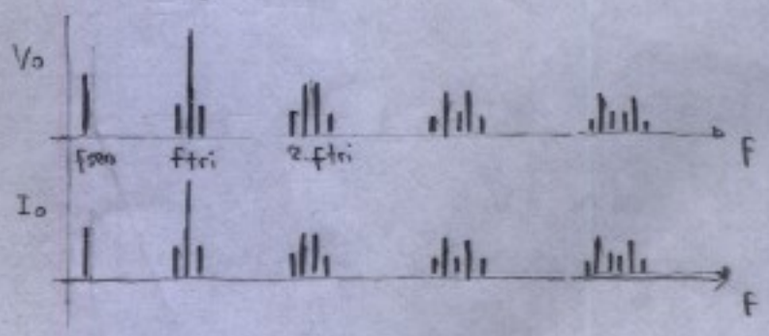
[m_f = ENTERO, IMPAR ; $0 < m_a < 1$]

$$V_o = \sum_{n=1,2..}^{\infty} V_n . sen(n\omega t)$$

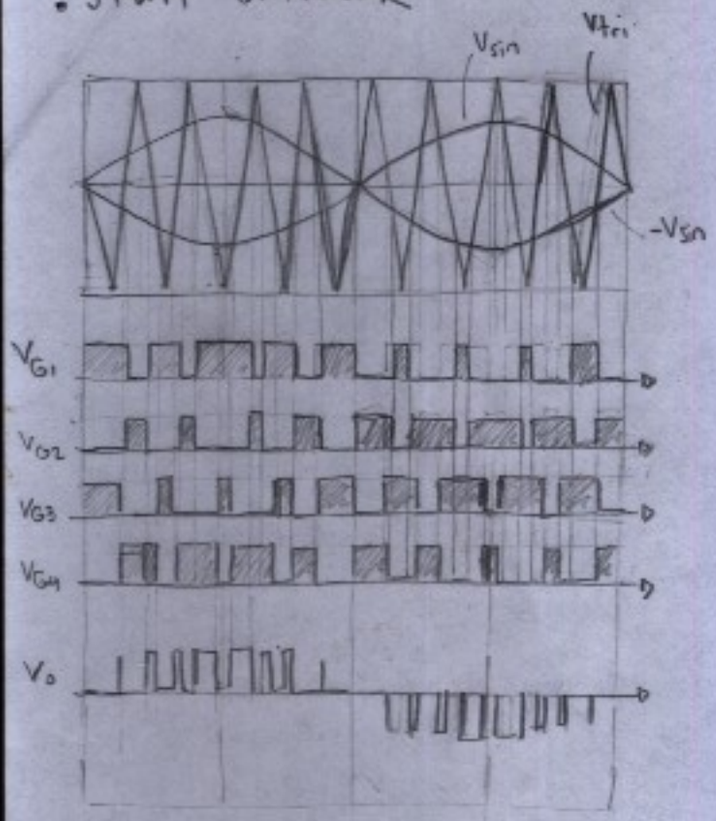
$$V_n = \sum_{k=1}^{p} V_{nk} \; ; \; p = \text{cant. pulsos en } T_{sen}$$

$$V_{nk} = \frac{2 V_{in}}{n\pi} \left\{ \cos(n . \alpha_k) + \cos(n . \alpha_{(k+1)}) - 2\cos[n(\alpha_k + \delta_k)] \right\}$$

↓ Si carga resistiva pura ↓



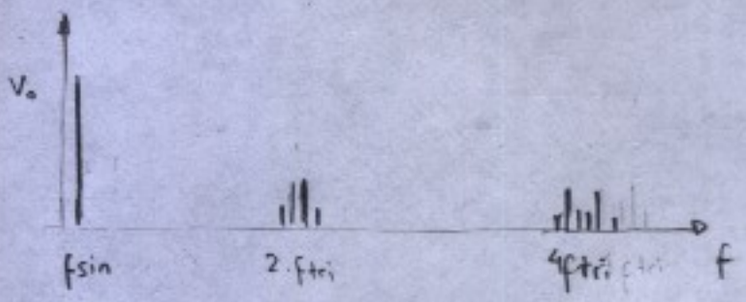
• SPWM UNIPOLAR



si $V_{sin} > V_{tri}$ ∴ Q_1 (ON) } RAMA 1
$V_{sin} < V_{tri}$ ∴ Q_2 (ON)

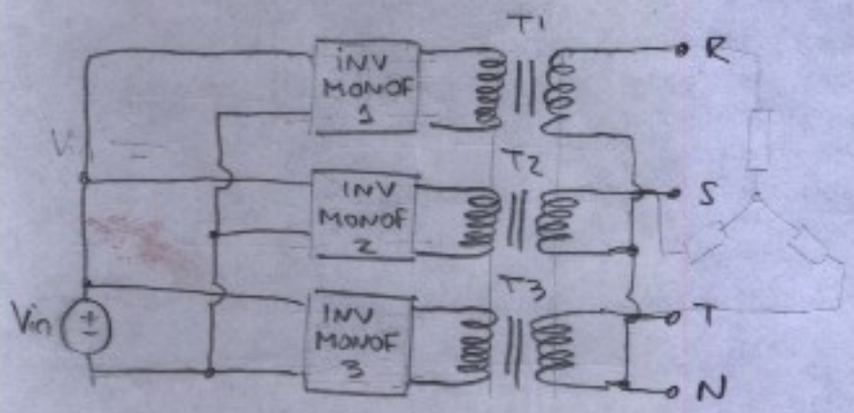
$-V_{sin} > V_{tri}$ ∴ Q_3 (ON) } RAMA 2
$-V_{sin} < V_{tri}$ ∴ Q_4 (ON)

Vo tiene menor contenido armónico y menor THD que el bipolar.



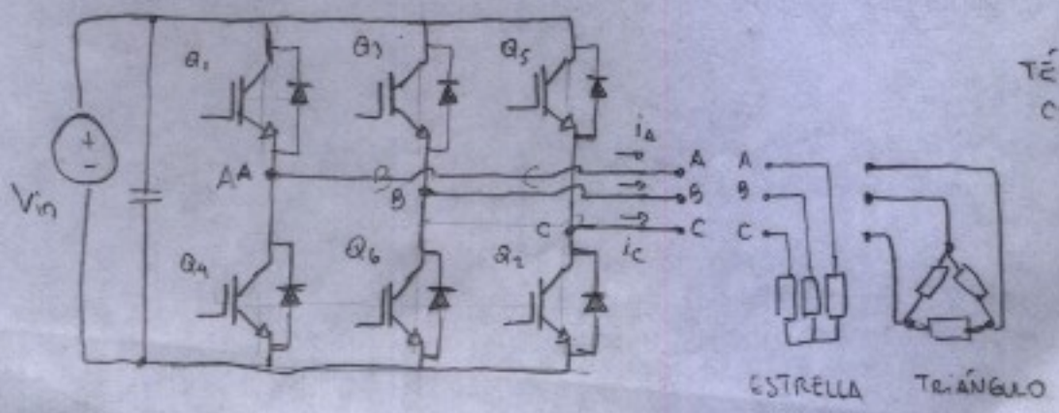
INVERSORES TRIFÁSICOS

Inv. trif. con 3 convert. monofásicos:



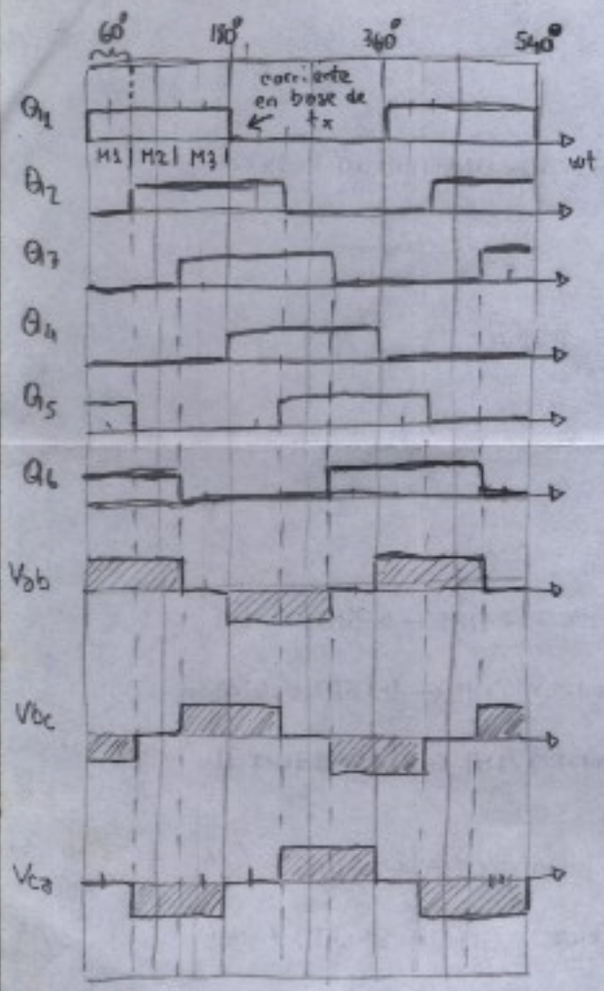
- Aplic. ALTA POTENCIA
- Señales de disparo desfasadas 120° de un inversor al otro para obtener salida trifásica equilibrada
- Con secund. en estrella se eliminan armónicos múltiplos de 3 salida
- Requiere → 3 Trafos, 12 TX, 12 DX

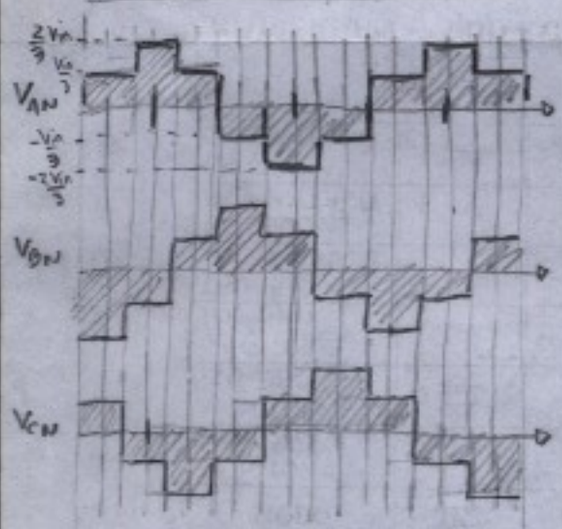
Inv. trifásico con 6 transistores:



TÉCNICAS CONTROL →
- COND A 180°
- COND A 120°
- SPWM
- SV-PWM

• Conducción a 180°





- Siempre 3 tx conduciendo
- Existen 6 modos de cond por c/ciclo (c/u dura 60°)
- c/ea tx conduce 180°.
- Señales de excitación desfasadas 60°
- Tiempos muertos reales → sino cortocircuito (tx mismo ramo)

$$\begin{cases} V_{ab} = \sum_{n=1,3,5,\dots}^{\infty} \frac{4 \cdot V_{in}}{n \cdot \pi} \cdot \cos\frac{n\pi}{6} \cdot \operatorname{sen}\left(n\omega t + \frac{\pi}{6}\right) \\ V_{bc} = \sum_{n=1,3,5\dots}^{\infty} \frac{4 \cdot V_{in}}{n \cdot \pi} \cos\frac{n\pi}{6} \operatorname{sen}\left(n\omega t - \frac{\pi}{2}\right) \\ V_{ca} = \sum_{n=1,3,5\dots}^{\infty} \frac{4 V_{in}}{n\pi} \cdot \cos\frac{n\pi}{6} \operatorname{sen}\left(n\omega t - \frac{7\pi}{6}\right) \end{cases}$$

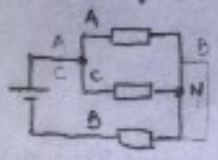
Si $\frac{n\pi}{6} = \frac{\pi}{2}$

$n=3$ → ANULA ARMÓNICO

$n=3,9,15,21\dots$ SE ANULA ARMÓNICO

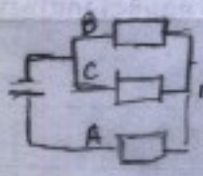
Tensiones V_{IN} conexión estrella

• Modo 1) $0 \leq \omega t \leq \frac{\pi}{3}$ (Q_1, Q_5, Q_6) → ON



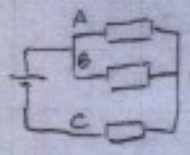
$Z_{eq} = \frac{3Z}{2}$ $V_{AN} = \frac{V_{in}}{3}$ $V_{BN} = -\frac{2}{3} V_{in}$ $V_{CN} = \frac{V_{in}}{3}$

• Modo 2) $\frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3}$ (Q_1, Q_2, Q_6)



$Z_{eq} = \frac{3Z}{2}$ $V_{AN} = \frac{2}{3} V_{in}$ $V_{BN} = -\frac{V_{in}}{3}$ $V_{CN} = -\frac{V_{in}}{3}$

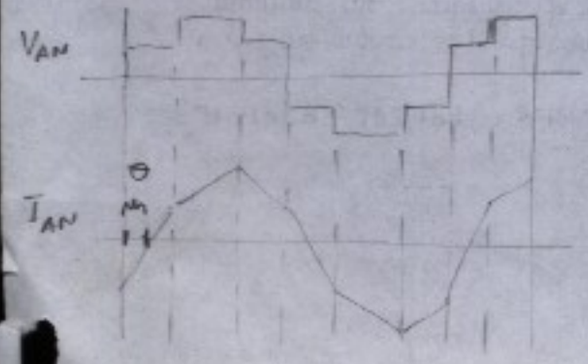
• Modo 3) $\frac{2\pi}{3} \leq \omega t \leq \pi$ (Q_1, Q_2, Q_3)



$Z_{eq} = \frac{3Z}{2}$ $V_{AN} = \frac{V_{in}}{3}$ $V_{BN} = \frac{V_{in}}{3}$ $V_{CN} = -\frac{2V_{in}}{3}$

$V_{LL_rms} = \sqrt{\frac{2}{3}} \cdot V_{in}$ $V_{LL_n_rms} = \frac{4 \cdot V_{in}}{\sqrt{2}\, n\pi} \cos\frac{n\pi}{6}$ $V_{LN_rms} = \frac{V_{LL_rms}}{\sqrt{3}} = \frac{\sqrt{2}\, V_{in}}{3}$

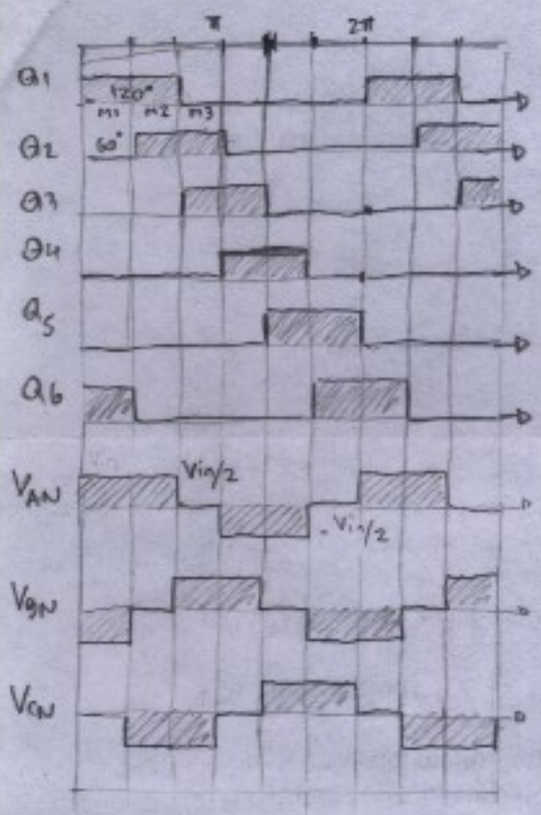
Para carga inductiva:



θ = ang. de atraso

↳ hace funcionar los diodos.

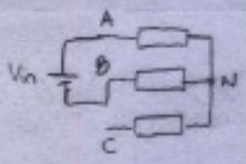
• Conducción a 120°



- Siempre 2 tx conduciendo
- Existen 6 modos de cond. por c/ciclo. (c/u 60°)
- Señales de excitac. desf. 60°
- Cada tx conduce 120°
- Tiempos muertos No necesarios

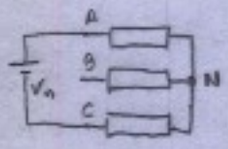
Tensiones V_{LN} conexión estrella:

- Modo 1) $0 \le \omega t \le \pi/3$ (Q_1, Q_6)



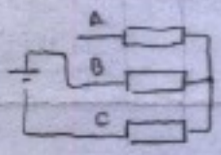
$V_{AN} = \frac{V_{in}}{2}$ $V_{BN} = -\frac{V_{in}}{2}$ $V_{CN} = \phi$

- Modo 2) $\pi/3 \le \omega t \le 2\pi/3$ (Q_1, Q_2)



$V_{AN} = \frac{V_{in}}{2}$ $V_{BN} = \phi$ $V_{CN} = -\frac{V_{in}}{2}$

- Modo 3) $\frac{2\pi}{3} \le \omega t \le \pi$ (Q_2, Q_3)



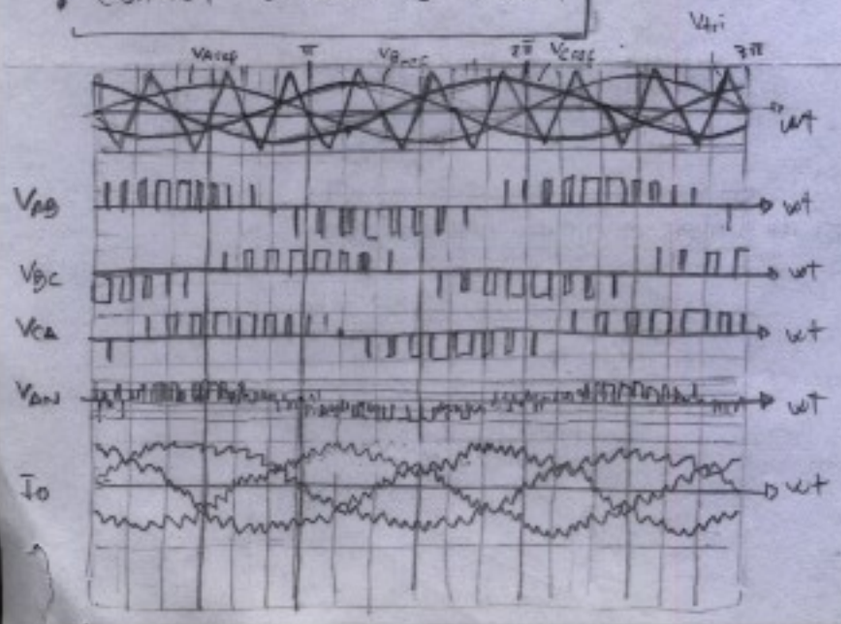
$V_{AN} = \phi$ $V_{BN} = \frac{V_{in}}{2}$ $V_{CN} = -\frac{V_{in}}{2}$

$$\begin{cases} V_{AN} = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_{in}}{n\pi} \cos\frac{n\pi}{6} \operatorname{sen}\left(\omega t + \frac{\pi}{6}\right) \\ V_{BN} = \sum \frac{2V_{in}}{n\pi} \cos\frac{n\pi}{6} \operatorname{sen}\left(\omega t - \frac{\pi}{2}\right) \\ V_{CN} = \sum \frac{2V_{in}}{n\pi} \cos\frac{n\pi}{6} \operatorname{sen}\left(\omega t - \frac{7\pi}{6}\right) \end{cases}$$

"idem a 180°"

En realidad $\sum_{n = 1,5,7,11,13,17\ldots}$ (~~3~~ ~~9~~ ~~15~~)

• Control SPWM ó PWM



$V_{A_ref} > V_{tri} \rightarrow Q_1$

$V_{B_ref} > V_{tri} \rightarrow Q_3$

$V_{C_ref} > V_{tri} \rightarrow Q_5$

$V_{A_ref} < V_{tri} \rightarrow Q_4$

$V_{B_ref} < V_{tri} \rightarrow Q_6$

$V_{C_ref} < V_{tri} \rightarrow Q_2$

Control SV-PWM

Los tx $a_1, a_2, a_3, a_4, a_5, a_6$ son controlados por las variables de control a, a', b, b', c, c'. Donde $a = \bar{a}'$, $b = \bar{b}'$, $c = \bar{c}'$

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{in} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Vector Tensión Línea a Línea

variable vectorial

$$V_{ab} = V_{in}.a - V_{in}.b$$
$$V_{bc} = V_{in}.b - V_{in}.c$$
$$V_{ca} = V_{in}.c - V_{in}.a$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{in}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

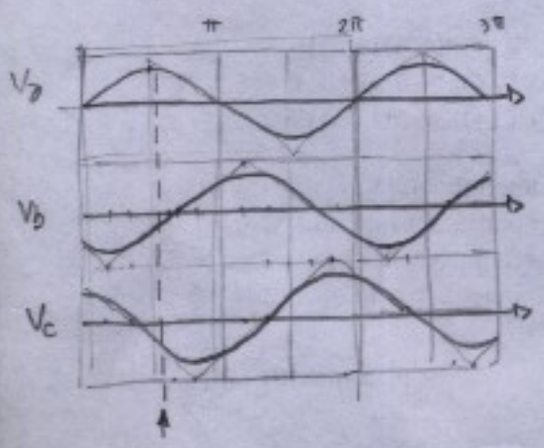
Vector Tensión Fase a Neutro

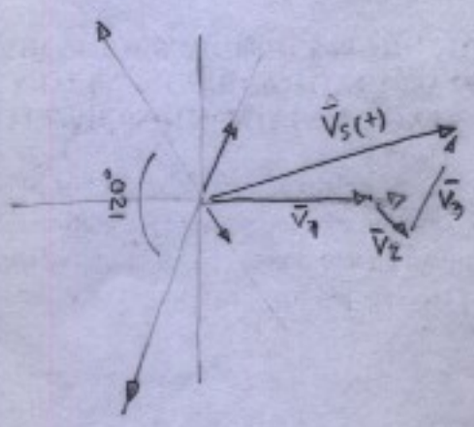
$$V_{an} = \frac{V_{in}}{3}(2a - b - c)$$
$$V_{bn} = \frac{V_{in}}{3}(-a + 2b - c)$$
$$V_{cn} = \frac{V_{in}}{3}(-a - b + 2c)$$

a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0	0	0	0
0	0	1	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	0	-1	1
0	1	0	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	-1	1	0
0	1	1	$-\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	0	1
1	0	0	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	1	0	-1
1	0	1	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	1	-1	0
1	1	0	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	0	1	-1
1	1	1	0	0	0	0	0	0

de Vin

Síntesis del vector espacial de tensión del estator en un motor de inducción





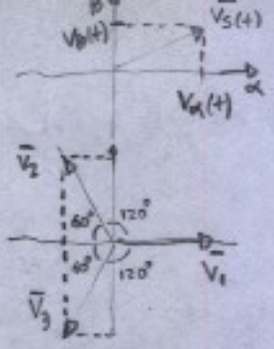
$$\bar{V}_s(t) = \bar{V}_1(t) + \bar{V}_2(t) + \bar{V}_3(t)$$

$$\bar{V}_1(t) = V_a(t).\, e^{j0°}$$

$$\bar{V}_2(t) = V_b(t).\, e^{j\frac{2\pi}{3}}$$

$$\bar{V}_3(t) = V_c(t).\, e^{j\frac{4\pi}{3}}$$

TRANSFORMACIÓN DIRECTA ⇒

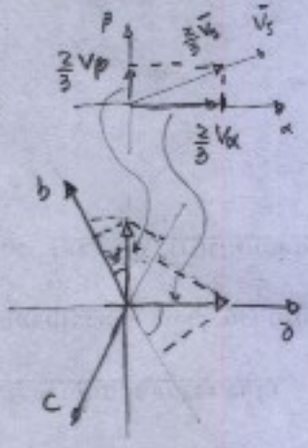


NO VA

$$V_\alpha(t) = V_a(t).e^{j0°} - \frac{1}{2} Vb(t).e^{j\frac{2\pi}{3}} - \frac{1}{2} Vc(t).e^{j\frac{2\pi}{3}}$$

$$V_\beta(t) = \frac{\sqrt{3}}{2}\left(Vb(t).e^{j\frac{2\pi}{3}} - Vc(t).e^{j\frac{4\pi}{3}} \right)$$

TRANSFORMACIÓN INVERSA ⇒



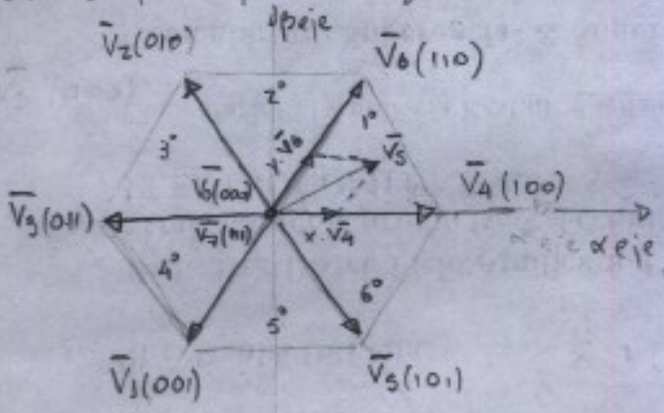
NO VA

$$\bar{V}_a(t) = \frac{2}{3} V_\alpha(t)$$

$$Vb(t) = \frac{2}{3}\left[\frac{\sqrt{3}}{2} V_\beta(t) - \frac{1}{2} V_\alpha(t) \right]$$

$$V_c(t) = \frac{2}{3}\left[-\frac{\sqrt{3}}{2} V_\beta(t) - \frac{1}{2} V_\alpha(t) \right]$$

Con el circuito inversor trifásico podemos obtener los siguientes "vectores básicos" para poder luego con éstos sintetizar $\bar{V}_s$ de manera óptima.



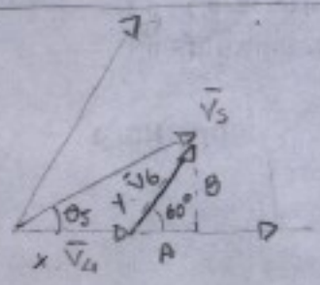
$$\bar{V}_s(000) = \bar{V}_0 = \emptyset$$
$$\bar{V}_s(001) = \bar{V}_1 = Vin.e^{j\frac{4\pi}{3}}$$
$$\bar{V}_s(010) = \bar{V}_2 = Vin.e^{j2\pi/3}$$
$$\bar{V}_s(011) = \bar{V}_3 = Vin.e^{j\pi}$$
$$\bar{V}_s(100) = \bar{V}_4 = Vin.e^{j0}$$
$$\bar{V}_s(101) = \bar{V}_5 = Vin.e^{j\pi/3}$$
$$\bar{V}_s(110) = \bar{V}_6 = Vin.e^{j\pi/3}$$
$$\bar{V}_s(111) = \bar{V}_7 = \emptyset$$

Análisis sobre el primer sector ⇒ sintetizamos un vector de tensión promedio:

$$\bar{V}_s = \hat{V}_s.e^{j\theta_s} = \frac{1}{T_s}\left(x.T_s.\bar{V}_4 + y.T_s.\bar{V}_6 + z.T_s.\emptyset \right)$$

$$\bar{V}_s = x.\bar{V}_4 + y.\bar{V}_6 = x.Vin.e^{j\emptyset} + y.Vin.e^{j\pi/3}$$

$$T_s = x.T_s + y.T_s + z.T_s \quad \therefore \quad 1 = x + y + z$$

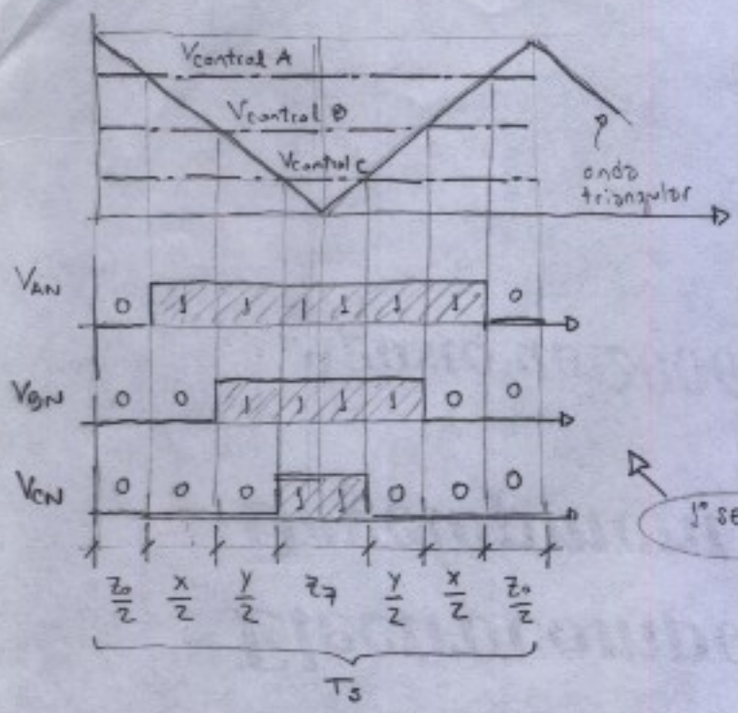


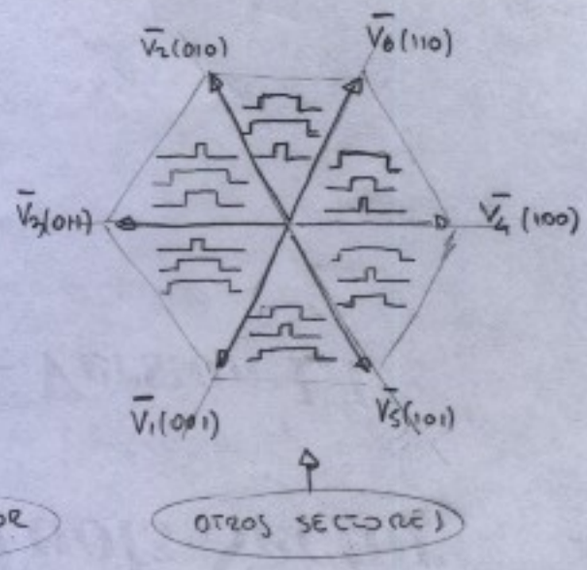
$$x = \frac{\hat{V}_s}{\bar{V}_4}\left(\cos\theta_s - \frac{1}{\sqrt{3}} \operatorname{sen}\theta_s \right)$$

$$y = \frac{2}{\sqrt{3}} . \frac{\hat{V}_s \operatorname{sen}\theta_s}{\bar{V}_6}$$

Despejando x e y

• Las tensiones de control del SV-PWM no son sinusoidales:





Límite de la amplitud $\hat{V}_s$ para limitar distorsión de corriente:

$$\bar{V}_s = \hat{V}_s \, e^{j\theta_s}$$

$$\odot \; \hat{V}_{s\,máx} = \frac{\sqrt{3}}{2} V_{in}$$

$$\odot \; \hat{V}_{phase} = \frac{2}{3} \hat{V}_{s\,máx} = \frac{V_{in}}{\sqrt{3}}$$

$$\odot \; \hat{V}_{LL\text{-}rms} = \frac{V_{in}}{\sqrt{2}}$$

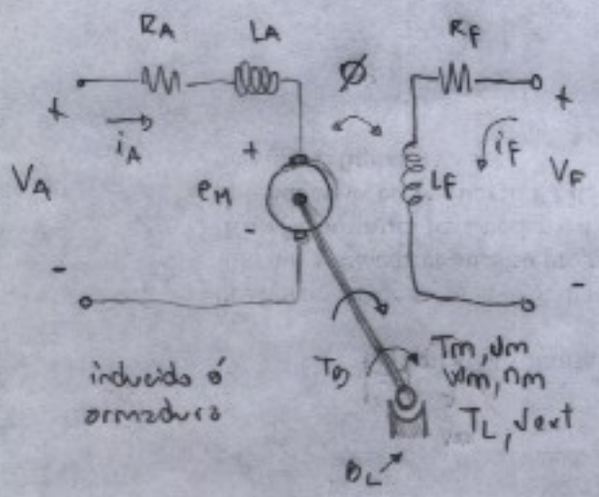
(SV-PWM utiliza el límite de tensión disponible en un factor 1,15 veces más alto que el PWM.)

MOTORES DE CC

VENTAJAS
- a) Alto par de arranque
- b) Gran margen de velocidad
- c) Reguladores simples y económicos

DESVENTAJAS
- a) Necesitan alimentaciones especiales en continua
- b) A igual potencia que M.C.A mayor costo
- c) Mantenimiento, desgaste de escobillas
- d) Medidas especiales en el arranque (evitar sobrecorriente)

Circuito Equivalente



V_A = tensión de armadura
R_A = resistencia del inducido (Ω)
L_A = inductancia del inducido (Hy)
e_M = tensión contraelectromotriz del inducido (V)
i_f = corriente del inductor (A)
ϕ = flujo magnético inducido (Wb)
ω_m = velocidad angular del motor ($\frac{rad}{s}$)
n_m = velocidad del motor (rpm)
R_f = resist. del inductor (Ω)
L_f = inductancia del inductor (Hy)

V_f = tensión del inductor (V)
T_m = torque desarrollado por el motor (Nm)
T_L = torque de carga reflejado al eje del motor (N.m)
T_B = torque de aceleración (N.m)

J_m = momento inercial del motor ($kg.m^2$)
J_{ext} = momento inercial externo reflejado al eje del motor ($kg.m^2$)
B = coeficiente de rozamiento viscoso ($\frac{N.m}{rad/s}$)
C_M = cte del motor ($\frac{N.m}{A}$)
e_b = caída de tensión en escobillas

Ecuaciones básicas para excitación independiente

$$T_m = K_1 \phi . i_A = K_t . i_A = C_M . i_A$$

$$e_m = K_2 \phi . \omega_m = K_E . \omega_m = C_M . \omega_m$$

$$\phi = K_f . i_f \quad (\text{si } i_f = cte \therefore \phi = cte)$$

$$V_A - e_m - e_b = i_A . R_A + L_A . \frac{di_A}{dt}$$

$$V_F = i_F . R_F + L_F . \frac{di_F}{dt}$$

$$T_B = J_{trem} . \frac{d\omega_m}{dt} \quad (J_{trem} = J_M + J_{ext})$$

$$T_M = T_L + T_B$$

$$P = i_A . e_m = T_m . \omega_m$$

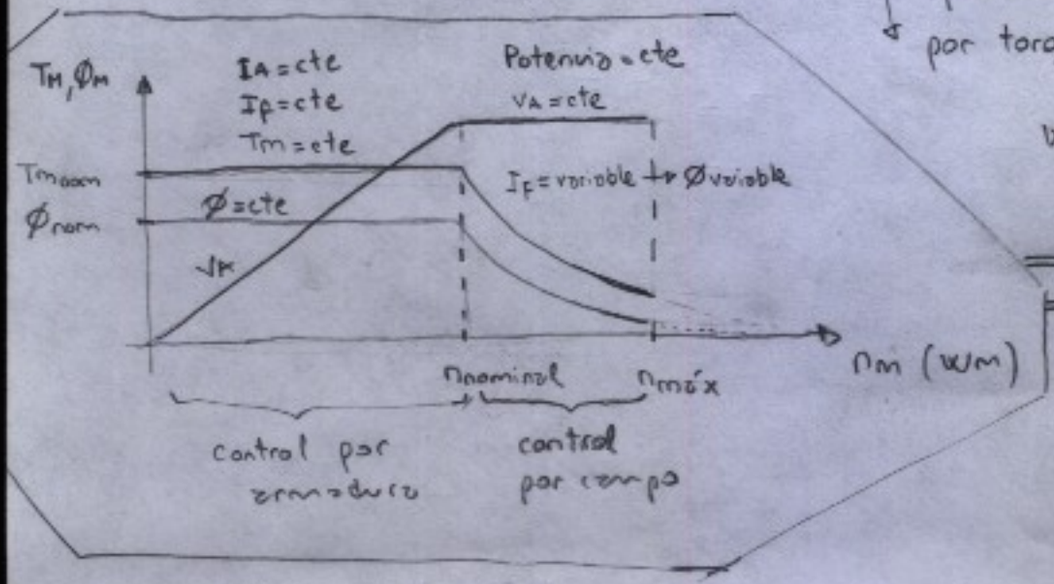
• Régimen permanente: $\left(d\omega_m/dt = 0 \right)$

$$V_A = I_A \cdot R_A + e_m = I_A \cdot R_A + K_2 \phi \omega_m \therefore$$

$$\omega_m = \frac{V_A - R_A \cdot I_A}{K_2 \cdot \phi} = \boxed{\frac{1}{K_2 \cdot \phi_F} \cdot \left\{ V_A - \frac{R_A}{K_T} \cdot T_M \right\} = \omega_M}$$

$\phi_F (I_F)$, V_A, $T_M (I_A)$

La velocidad del motor se puede controlar → por tensión de armadura (V_A)
→ por campo ($\phi_F (I_F)$)
→ por torque (I_A, con I_F = cte)



$\omega_m = 2\pi \cdot n_m$ → vueltas por segundo

En la práctica

$n_m < n_{nom} \therefore \omega_m = f(V_A)$
si $V_A \uparrow \rightarrow \omega_m \uparrow$

$n_m > n_{nom} \therefore \cancel{\uparrow V_A}$
$\omega_m = f(I_F)$
si $I_F \downarrow \rightarrow \omega_m \uparrow$ pero $T_m \downarrow$

Ecuación diferencial:

Motor controlado por armadura

$$V_A - e_m = i_A \cdot R_A + L_A \frac{di_A}{dt} \qquad (\text{reemplazo } i_A)$$

$$\frac{V_A - C_M \cdot \omega_M}{R_A} = \frac{T_L}{C_M} + \frac{J_{rem}}{C_M} \frac{d\omega_M}{dt} + \frac{L_A}{R_A \cdot C_M} \frac{dT_L}{dt} + \frac{L_A}{R_A \cdot C_M} \cdot J_{rem} \cdot \frac{d^2 \omega_M}{dt^2}$$

$\boxed{\frac{L_A}{R_A} = \tau_{elA}}$ cte eléctrica de armadura

$\boxed{\omega_{máx}}$ vel. ang. máx. en vacío

$\boxed{V_{Amáx} = E_{máx} = C_M \cdot \omega_{máx}}$ Máxima tensión de armadura en vacío

$\boxed{T_{sto} = C_M \cdot I_{Amáx} = C_M \cdot \frac{V_{máx}}{R_A} = \frac{C_M^2 \cdot \omega_{máx}}{R_A}}$ Torque máximo motor con tensión máxima y eje bloqueado

Multiplicando todo por $\frac{R_A}{C_M \cdot \omega_{máx}}$ y reemplazando:

$$\frac{V_A}{V_{Amáx}} - \frac{\omega_M}{\omega_{máx}} = \frac{T_L}{T_{sto}} + \frac{J_{rem}}{T_{sto}} \frac{d\omega_M}{dt} + \frac{\tau_{elA}}{T_{sto}} \frac{dT_L}{dt} + \frac{\tau_{elA} \cdot J_{rem}}{T_{sto}} \frac{d^2 \omega_M}{dt^2}$$

$\boxed{\tau_{mechA} = \frac{J_{rem} \cdot \omega_{máx}}{T_{sto}}}$ cte mecánica del motor

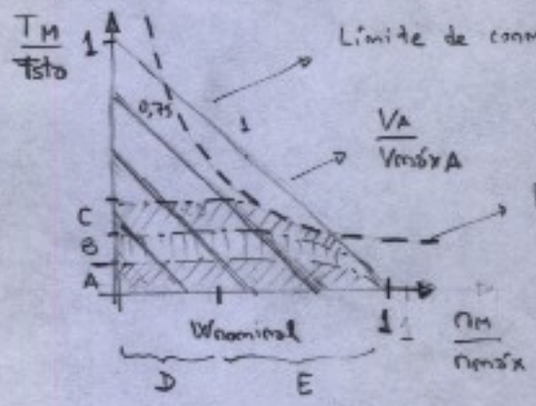
$$\tau_{elA} \cdot \tau_{mechA} \cdot \frac{d^2\left(\frac{\omega_M}{\omega_{máx}}\right)}{dt} + \tau_{mechA} \cdot \frac{d\left(\frac{\omega_M}{\omega_{máx}}\right)}{dt} + \frac{\omega_M}{\omega_{máx}} = \frac{V_A}{V_{Amáx}} - \frac{T_L}{T_{sto}} - \tau_{elA} \cdot \frac{d\left(\frac{T_L}{T_{sto}}\right)}{dt}$$

"Ec. dif. de 2° orden del motor de d.c."

⊙ Régimen estacionario ($d\omega_m/dt = 0$; $T_L = T_M$) :

$$\frac{\omega_M}{\omega_{máx}} = \frac{V_A}{V_{máxA}} - \frac{T_L}{T_{sta}} \Rightarrow$$

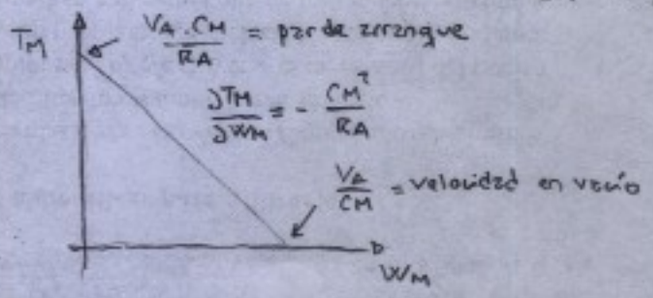
$$\boxed{\frac{T_M}{T_{sta}} = \frac{V_A}{V_{máx}} - \frac{n_M}{n_{máx}}}$$

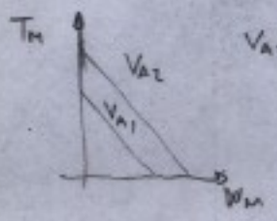


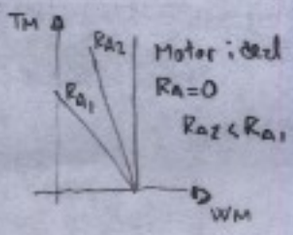
A : Ciclo continuo
B : Ciclo intermitente
C : Trabajos breves
D : Rango de climat.
E : Rango de cual rápido

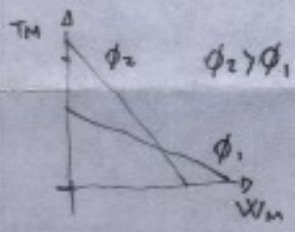
⊙ También en régimen estacionario:

$$\boxed{T_M = \frac{V_A \cdot C_M}{R_A} - \frac{C_M^2\, \omega_M}{R_A}}$$





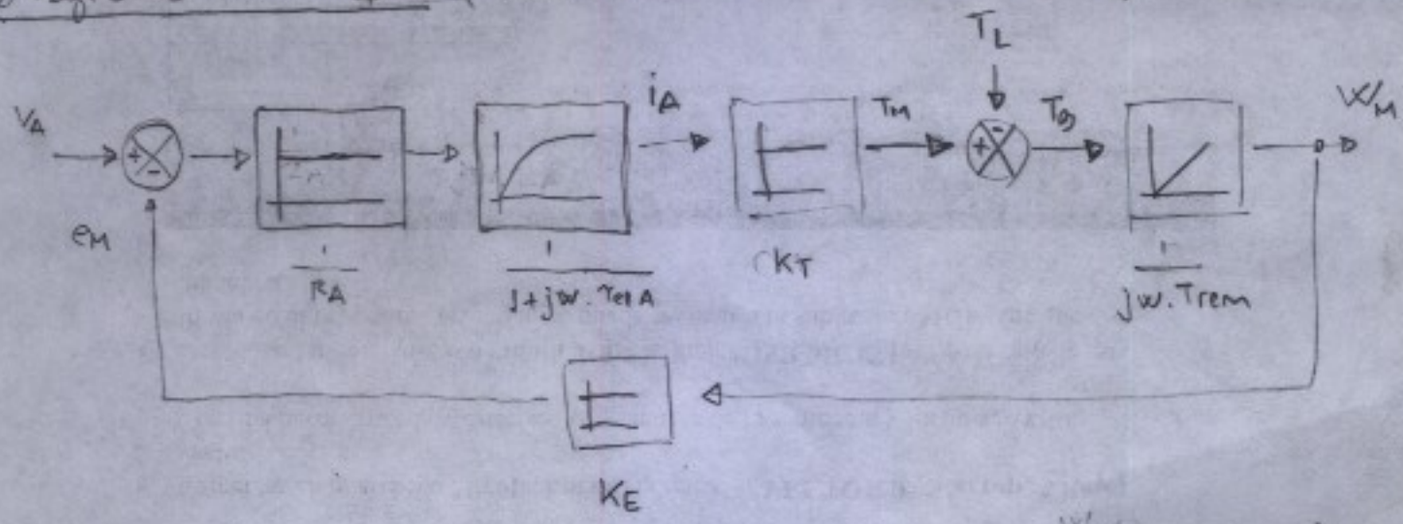




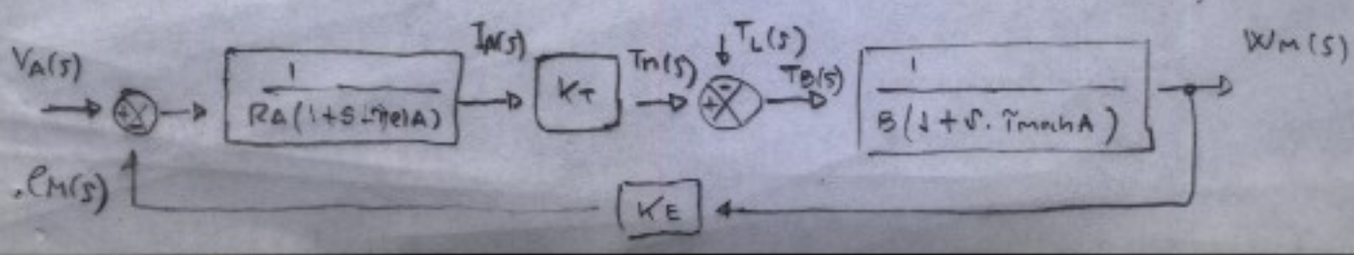
Con V_A = cte → para ↑ T_M hay que ↓ ω_M (↑ ϕ)
→ para ↑ ω_M hay que ↓ T_M (↓ ϕ)

Con T_M = cte → para ↑ ω_M hay que ↑ V_A

Diagrama en bloques (lazo abierto : motor no controlado)

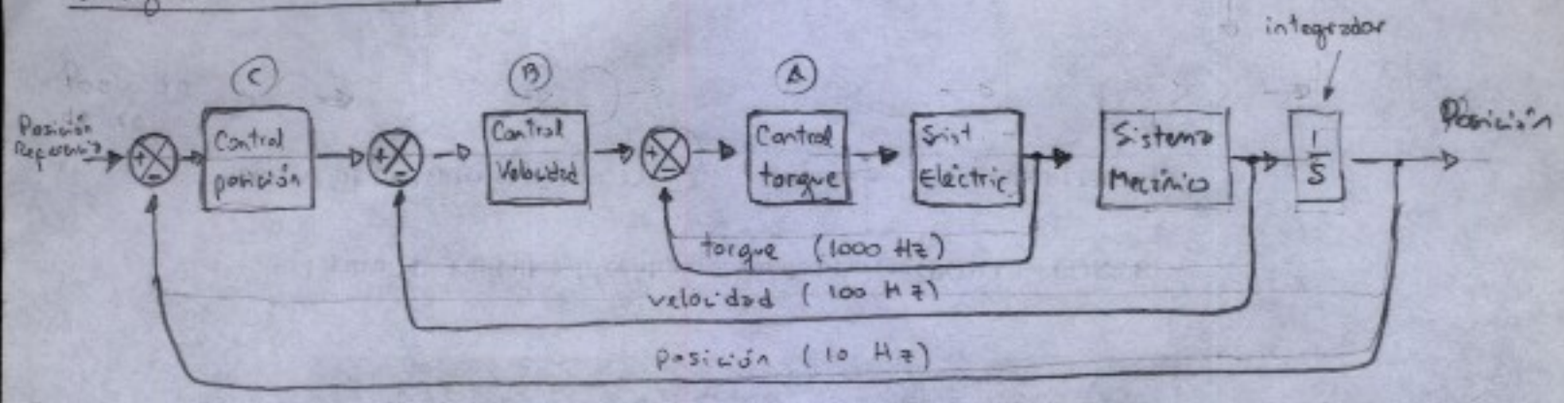


Comportamiento Dinámico en lazo abierto ($\frac{\omega_M(s)}{V_A(s)}$; $\frac{\omega_M(s)}{T_L(s)}$; $\frac{I_A(s)}{V_A(s)}$)



CONTROL MOTOR DC - CONTROL EN CASCADA

Diagrama en bloques



Realimentación → Sistema estable

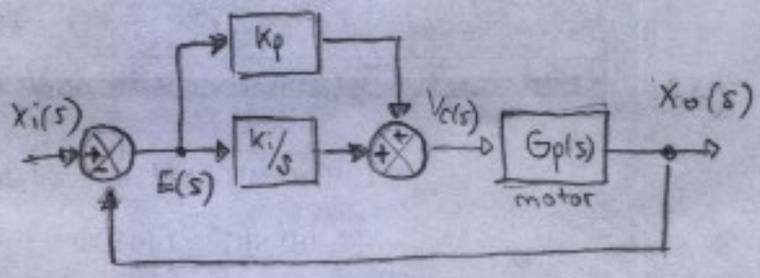
Control → error estado estacionario cero, buena resp. dinámica.

Compensador PI

$$\frac{V_c(s)}{E(s)} = K_p + \frac{K_i}{s}$$

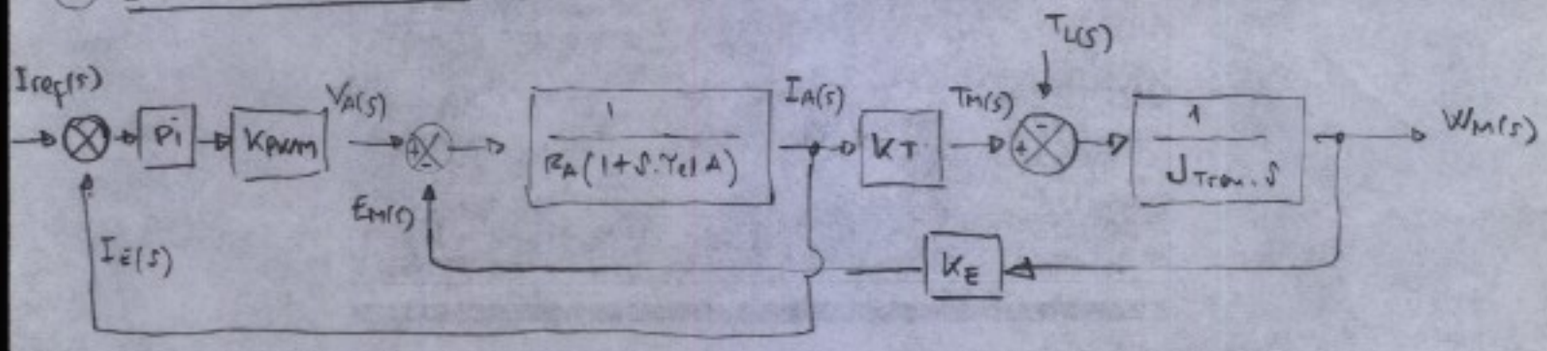
$$= \frac{K_p}{s}\left(s + \frac{K_i}{K_p}\right)$$

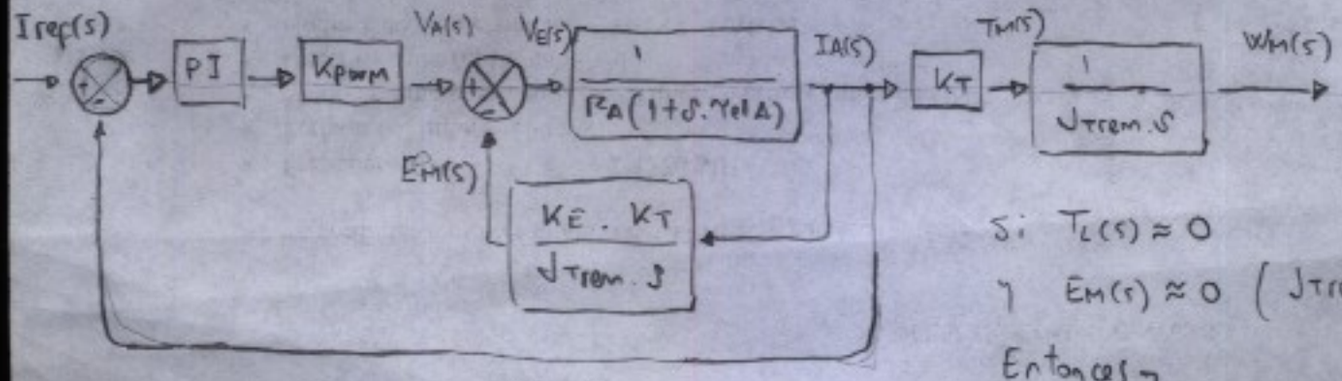
$$\boxed{\frac{V_c(s)}{E(s)} = \frac{K_i}{s}\left(s + \frac{s}{K_i/K_p}\right)}$$



error ∅ ante entrada escalón.

(A) Control de torque:

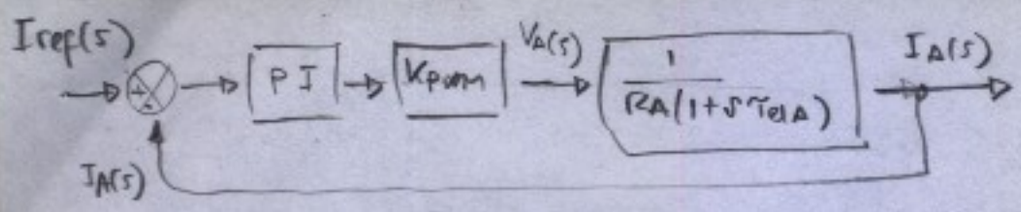


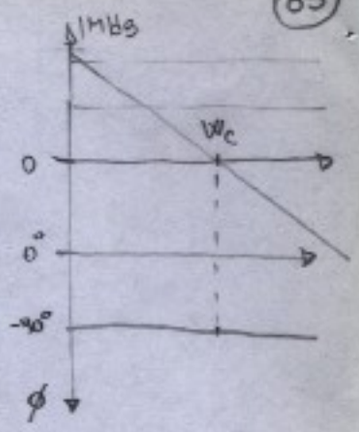


Si $T_L(s) \approx 0$

y $E_M(s) \approx 0$ $(J_{Trem} \to \infty)$

Entonces ↓





$\phi_f = cte \therefore T_m = f(I_a)$

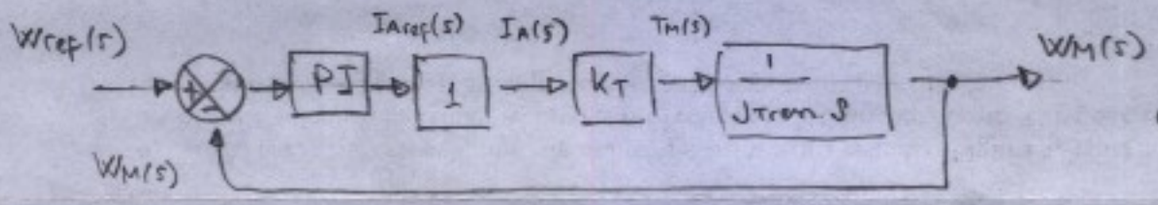
$$G_{I(OL)} = \frac{K_{iI}}{s}\left(1 + \frac{s}{\frac{K_{iI}}{K_{pI}}}\right) \cdot K_{pwm} \cdot \frac{1}{R_A\left(1 + s \cdot \tau_{elA}\right)}$$

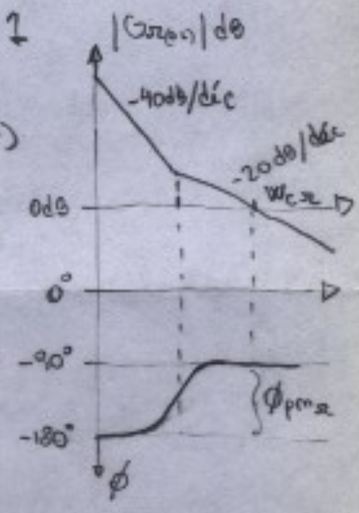
Diseño: cero (PI) = polo (motor) $\therefore \frac{K_{iI}}{K_{p\cdot I}} = \frac{1}{\tau_{elA}} \therefore G_{I(OL)} = \frac{K_{iI} \cdot K_{pwm}}{R_A} \cdot \frac{1}{s}$

elegimos $W_{c_I} = \frac{K_{iI} \cdot K_{pwm}}{R_A} \Rightarrow$ 1 década menor que frec. del PWM.

(B) Control de Velocidad:

$BW_{vel} < BW_{torque}$ en 1 década $\therefore$ Lazo de corriente = ideal = 1





$$G_{r(OL)} = \frac{K_{ir}}{s}\left(1 + \frac{s}{\frac{K_{ir}}{K_{pr}}}\right) \cdot \frac{K_T}{J_{Trem} \cdot s}$$

Diseño: $W_{c_r} = \frac{W_{cI}}{10}$

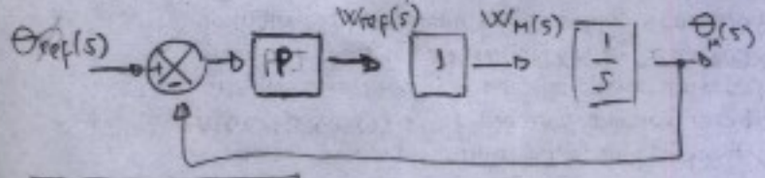
$\Rightarrow$ Las ctes se obtienen resolviendo estas 2 ecuaciones (2 incógnitas)

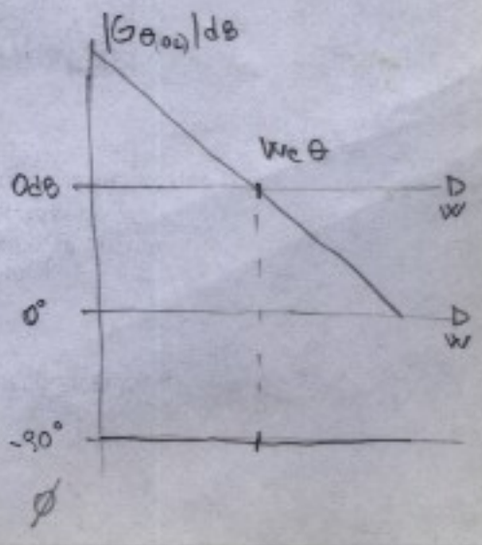
$$\left| G_{r(OL)} \right|_{s = jW_{cr}} = 1$$

$$\angle G_{r(OL)} \Big|_{s = jW_{cr}} = -180° + \phi_{PM_r}$$

(C) Control de posición:

$BW_{pos} < BW_{vel}$ en 1 década, $\therefore$ Lazo de velocidad = ideal = 1



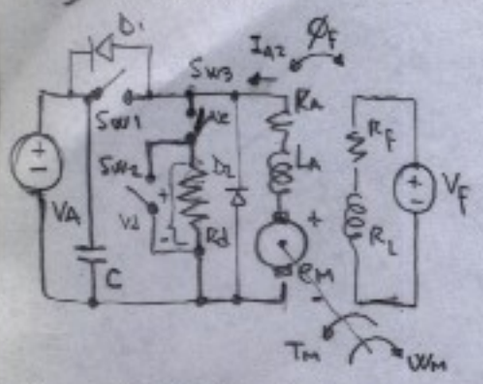


$$G_{\theta(OL)} = \frac{K_{p\theta}}{s}$$

Diseño: $W_{c\theta} = \frac{W_{cr}}{10} = K_{p\theta}$

FRENADO DINÁMICO Y REGENERATIVO

A) DINÁMICO



$R_{eq} = (1-D) \cdot R_d + R_A$

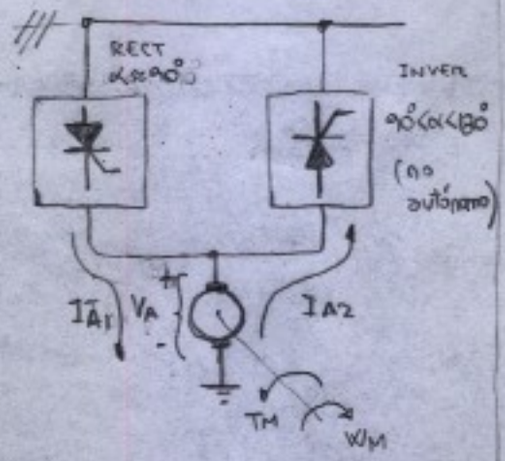
$R_D = R_d (1-D)$ = Resist. efect.

$V_{RD} = I_{A2} \cdot R_d (1-D)$

$P_{RD} = I_{A2}^2 \cdot R_d (1-D)$

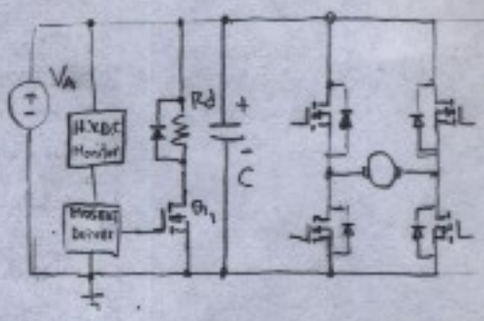
Energía cinética del motor ⇒ Calor en Rd

B) REGENERATIVO



Energía cinética del motor ⇒ Devuelve a la alimentación

C) DINÁMICO - REGENERATIVO



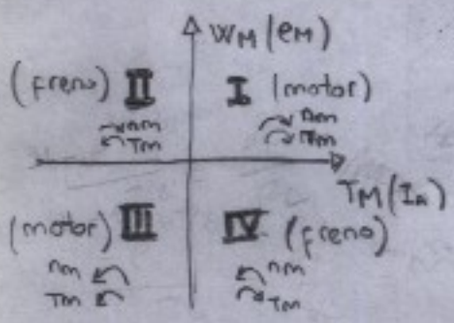
- C almacena la energía regenerat.
- Se muestrea la tensión V_A
- Si $\Delta V_A > 20\%$ del típico se transfiere el frenado regenerativo a dinámico.
- $R_{efect} = f(R_d, \text{chopper})$

Si toda la energía va al capacitor ∴ $W_{LA} = W_C = \frac{1}{2} L_A \cdot I_A^2 = \frac{1}{2} C \cdot V_A^2$

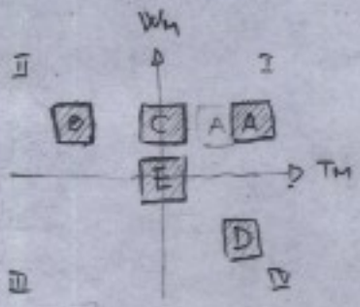
$$C = L_A \left(\frac{I_A}{V_A}\right)^2$$

CONVERTIDORES PARA CONTROL DE MOTORES DE CC

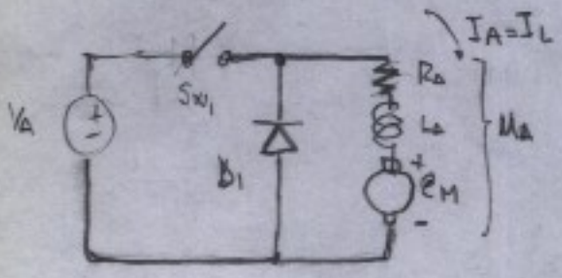
Cuadrantes de operación



CUADR	TM	WM	Sent	Acel
I	+	+	+	+
II	−	+	+	−
III	−	−	−	+
IV	+	−	−	−



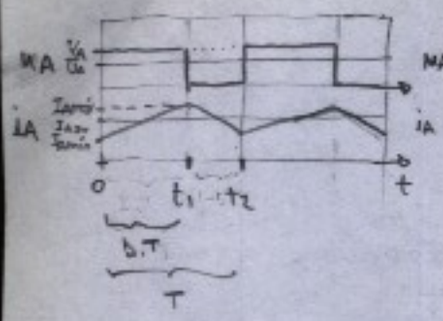
CLASE A:



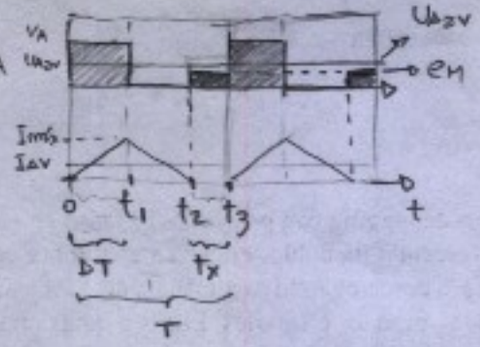
SW1 ON: V_A se aplica sobre la carga (motor), I_A crece.

SW1 OFF: e_M se aplica sobre R_A y L_A, pero D se polariza directamente y evita la discontinuidad de corriente, I_A decrece (gracias a L_A).

CCM



DCM



Análisis (CCM y DCM): $\boxed{0<t<t_1}$ $\quad i_L(t) = \dfrac{V_A - e_M}{R_A} + \left(I_{Lmín} - \dfrac{V_A - e_M}{R_A}\right) e^{-t/\tau_{eLA}}$

CCM : $I_{Lmín} \neq 0$ $\qquad$ DCM : $I_{Lmín} = 0$

$\boxed{t_1<t<t_2}$ $\quad i_L(t) = -\dfrac{e_M}{R_A} + \left(I_{Lmáx} + \dfrac{e_M}{R_A}\right) e^{-(t-t_1)/\tau_{eLA}}$

Cálculo $I_{Lmín}$ e $I_{Lmáx}$:

$$I_{Lmín} = \frac{V_A}{R_A}\left(\frac{1-e^{DT/\tau}}{1-e^{T/\tau}}\right) - \frac{e_M}{R_A} \qquad (CCM)$$

$$I_{Lmáx} = \frac{V_A}{R_A}\left(\frac{1-e^{-DT/\tau}}{1-e^{-T/\tau}}\right) - \frac{e_M}{R_A} \qquad (CCM)$$

$$I_{Lmáx} = \frac{V_A - e_M}{R_A}\left(1 - e^{-DT/\tau}\right) \qquad (DCM)$$

Cálculo de $\Delta I_{Lmáx}$:

$\Delta i_L = I_{Lmáx} - I_{Lmín}$

$\Delta I_{Lmáx}$ se logra con $D = 0{,}5 \rightarrow$ haciendo $\dfrac{d\Delta i_L}{dD} = \emptyset$

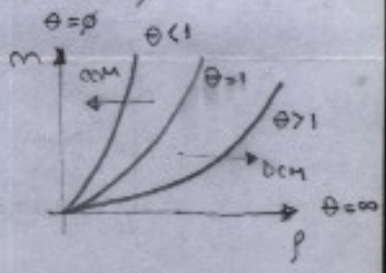
Y si $4.f.L \gg R_A$ $\therefore$ $\boxed{\Delta I_{Lmáx} = \dfrac{V_A}{4.f.L_A}}$

$$\boxed{I_{LAV} = \frac{V_A.D - e_M}{R_A}}$$

Límite entre CCM y DCM:

$$I_{Lmín} = \frac{V_A}{R_A}\left(\frac{1-e^{DT/\tau}}{1-e^{T/\tau}}\right) - \frac{e_M}{R_A} = 0 \quad \text{(en el límite)}$$

$$\frac{e_M}{V_A} = \boxed{m = \frac{e^{\rho}-1}{e^{\theta}-1}} \qquad \rho = \frac{DT}{\tau_{eLA}} \qquad \theta = \frac{T}{\tau_{eLA}}$$



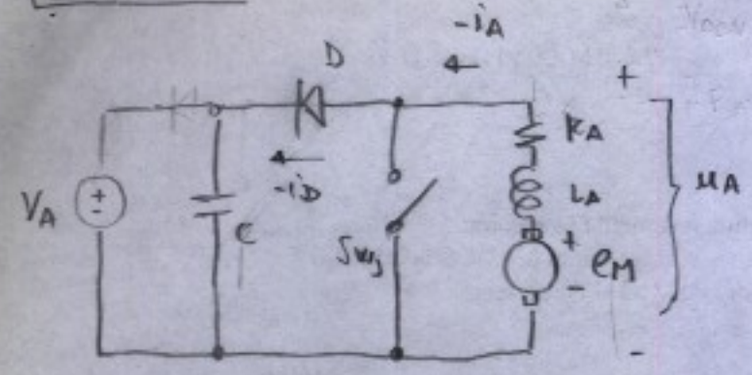
$$D_{mín} = \frac{\tau_{eLA}}{T} \ln\left[1 + \frac{e_M}{V_A}\left(e^{T/\tau_{eLA}} - 1\right)\right]$$

Función de transferencia:

CCM $\quad \bar{U}_A = \dfrac{1}{T}\displaystyle\int_0^T u_a\,dt = \boxed{D.V_A = \bar{U}_A}$

DCM $\quad \bar{U}_A = \dfrac{1}{T}\displaystyle\int_0^T u_a.dt = \boxed{D.V_A + e_M\left(\dfrac{t_x}{T}\right) = \bar{U}_A}$

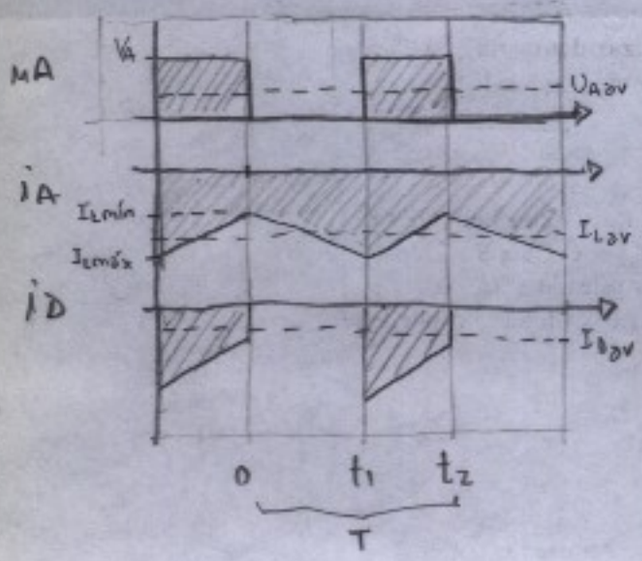
CLASE B :



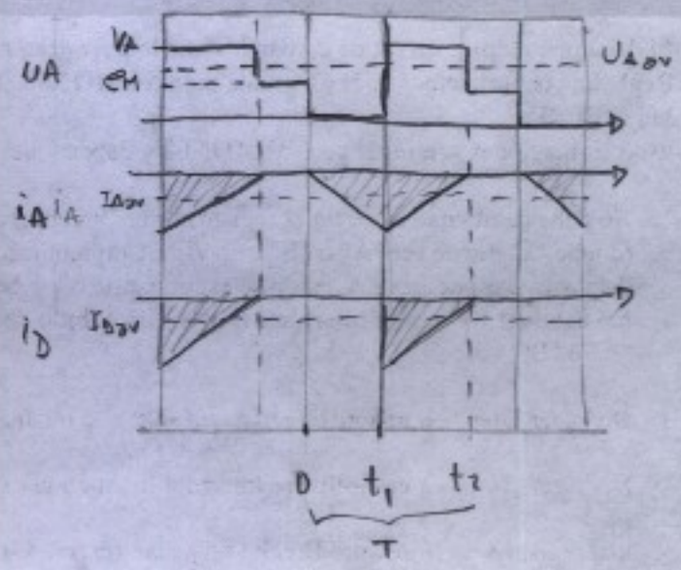
Sw_1 ON : e_M se aplica sobre R_A y L_A (se transf. la energía cinética a L_A)

Sw_1 OFF: la tensión en L_A se invierte y se suma a e_M. La energía acumulada en L_A se suma a la energía cinética (e_M) y se transfiere a la carga.

CCM



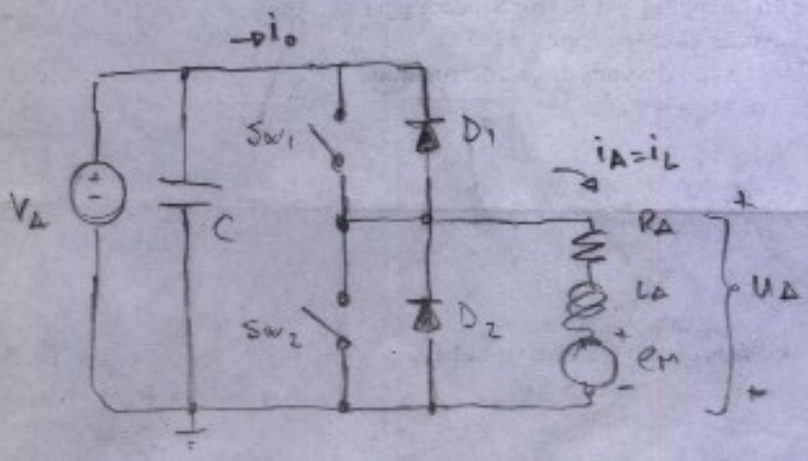
DCM

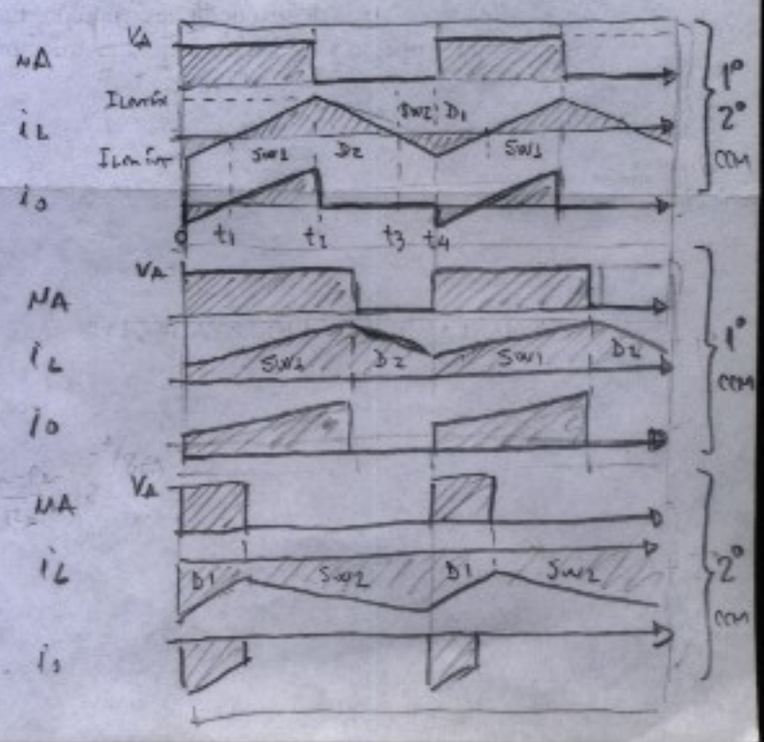


Análisis (CCM y DCM) : $\boxed{0<t<t_1}$ $i_L(t) = -\frac{e_M}{R_A} + \left(I_{Lmin} + \frac{e_M}{R_A}\right) \cdot e^{-t/\tau_{eLA}}$

$\boxed{t_1<t<t_2}$ $i_L(t) = \frac{V_A - e_M}{R_A} + \left(I_{Lmáx} - \frac{V_A - e_M}{R_A}\right) e^{-(t-t_1)/\tau_{eLA}}$

CLASE C :



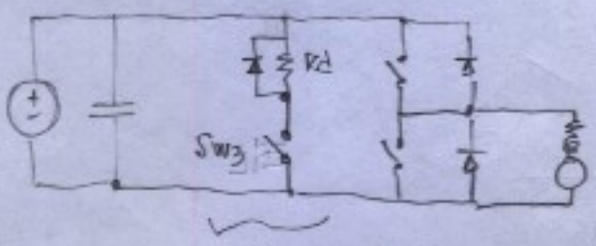


Para 1° y 2° :

$\boxed{0<t<t_2}$ $i_L(t) = \frac{V_A - e_M}{R_A} + \left(I_{Lmín} - \frac{V_A - e_M}{R_A}\right) \cdot e^{-t/\tau_{eLA}}$

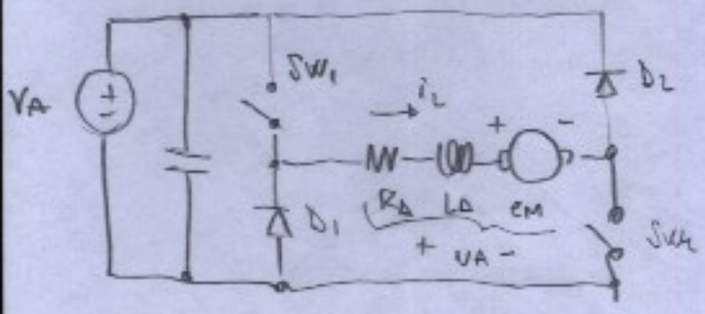
$\boxed{t_2<t<t_4}$ $i_L(t) = \frac{-e_M}{R_A} + \left(I_{Lmáx} + \frac{e_M}{R_A}\right) \cdot e^{-(t-t_2)/\tau_{eLA}}$

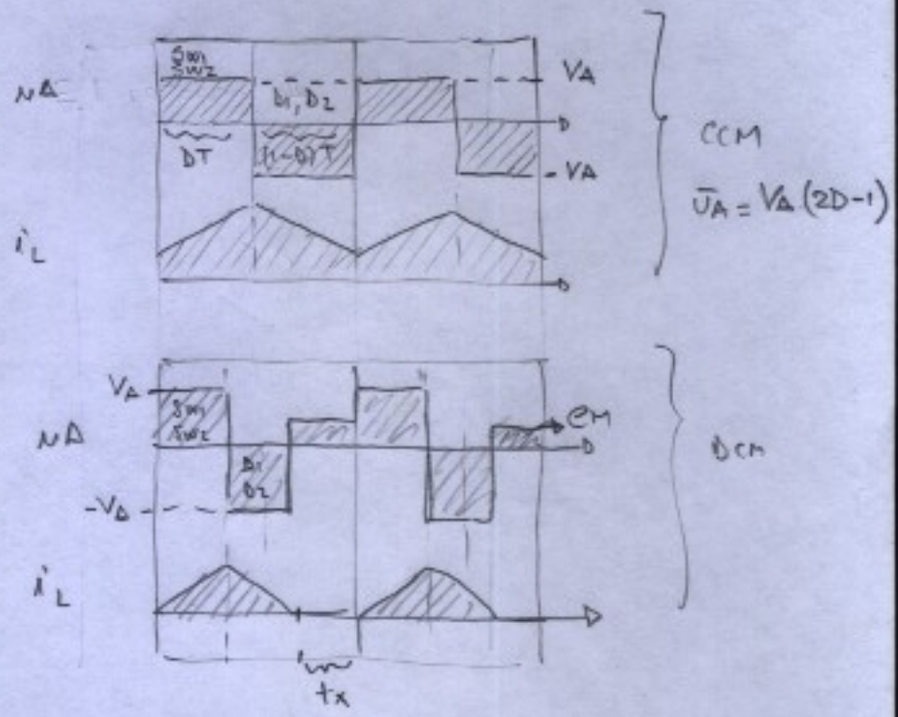
Funcionamiento en los dos cuadrantes con frenado regenerativo y dinámico



Evita aumento excesivo de tensión de entrada.

CLASE D :

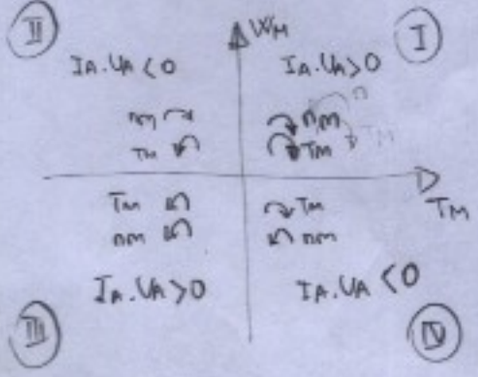




El retorno de energía hacia la fuente ocurre por la absorción de la energía acumulada en LA, pero no hay una disminución de la energía presente en la masa acoplada al rotor

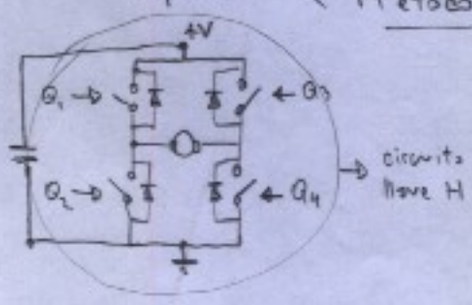
CLASE E :

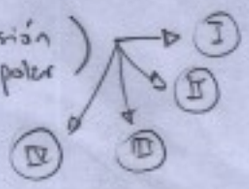
Llave H



Comando Simultáneo
- Método 1: (2 conv. clase D)
- Método 2: (llave H clásica)

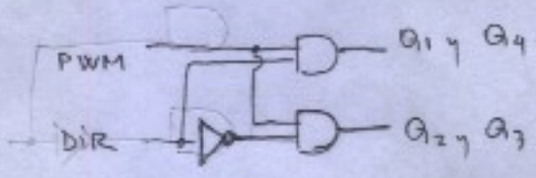
Comando Separado
- Método 3: (similar clase A)
- Método 4: (tensión unipolar)





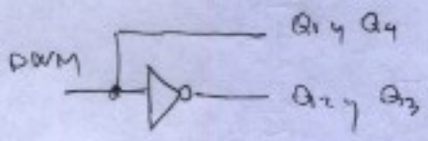
Método 1

Se mantiene una diagonal permanente abierta y se suministra un ciclo de trabajo a la otra diagonal.



Método 2

Se aplica el PWM a las diagonales de forma alternada.



t_{on} → Q_1 y Q_4 ON
→ Q_2 y Q_3 OFF

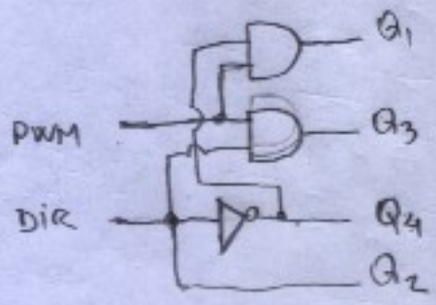
t_{off} → Q_1 y Q_4 OFF
→ Q_2 y Q_3 ON

¡¡ Aplicar tiempos muertos !!

D
- < 0,5 ↷ TM
- = 0,5 ↷ motor detenido (firmemente)
- > 0,5 ↷ TM

Método 3

Mientras una diagonal permanece permanente abierta, en la otra diagonal un tx está cerrado y el otro con el PWM.



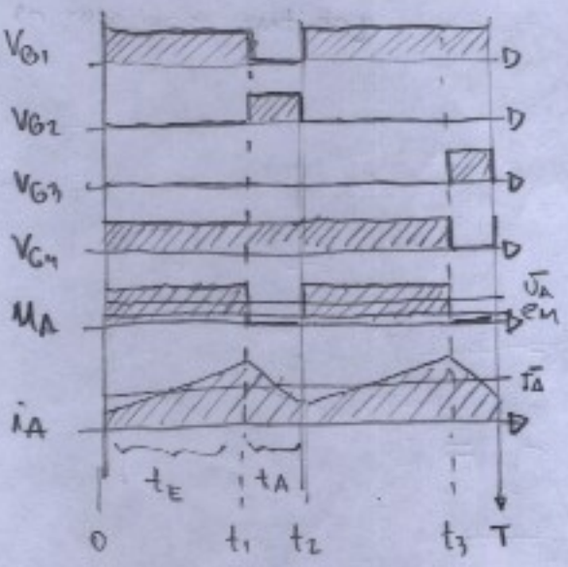
similar clase A (aplica mismos inversiones)

Método 4

Los tx de la misma rama se conmutan en forma complementaria.

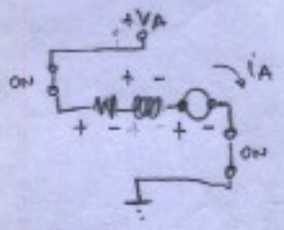
El motor puede ser acelerado y frenado en ambos sentidos.

• PWM UNIPOLAR (I): $(t_E > t_A)$



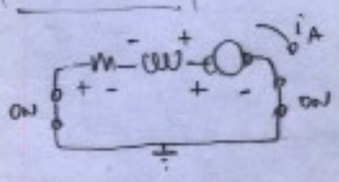
"motor giro directo"

$0 < t < t_1$ y $t_2 < t < t_3$



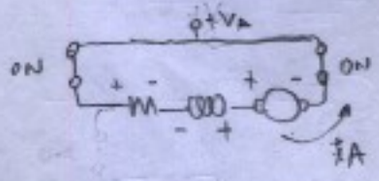
$U_A = V_A$
I_A = rampa positiva
L_A se carga

$t_1 < t < t_2$



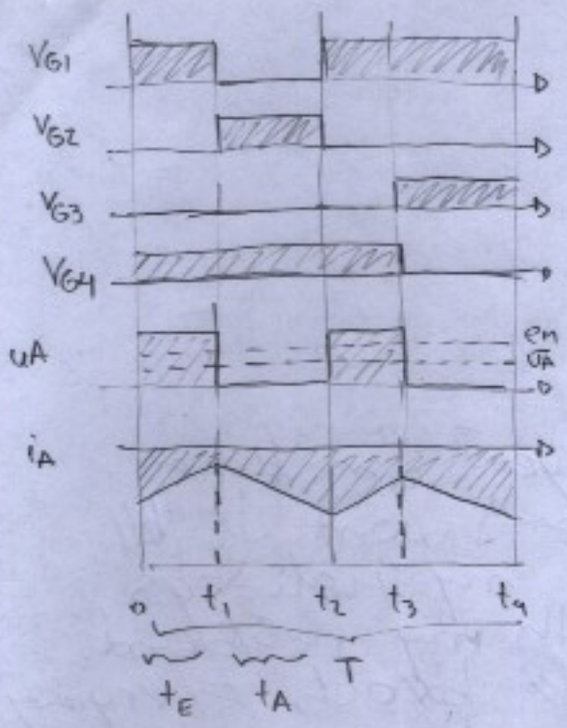
$U_A > 0$
I_A = rampa negativa
L_A se descarga (invierte tensión)

$t_3 < t < t_4$

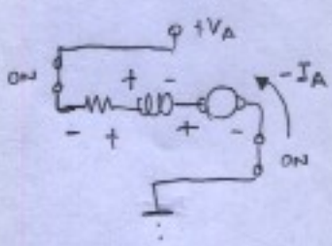


$U_A = 0$
I_A = rampa negativa
L_A se descarga (invierte tensión)

• PWM UNIPOLAR II : $(t_E < t_A)$ "frenado en giro directo"



$\boxed{0 < t < t_1 \text{ y } t_2 < t < t_3}$



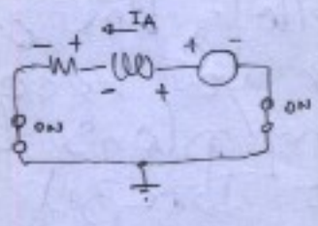
$u_A = V_A$

I_A = decrece (valor absoluto)

L_A = descarga ($\xrightarrow[\text{energ}]{}$ C)

$e_M + L_A \frac{di_A}{dt} > V_A$

$\boxed{t_1 < t < t_2}$



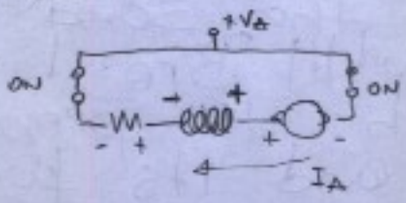
$u_A = 0$

I_A = crece (valor absoluto)

L_A = carga ($\xleftarrow[\text{energía}]{}$ rotor)

e_M se aplica a R_A y L_A

$\boxed{t_3 < t < t_4}$



$u_A = 0$

I_A = decrece (valor absol)

L_A = carga ($\xleftarrow[\text{energ}]{}$ rotor)

e_M se aplica a R_A y L_A

• PWM UNIPOLAR III : $(t_E > t_A)$ "motor giro inverso"

idem cuadrante I intercambiando : V_{G1} con V_{G3}

V_{G2} con V_{G4}

u_A es $-u_A$

i_A es $-i_A$

• PWM UNIPOLAR IV $(t_E < t_A)$ "frenado en giro inverso"

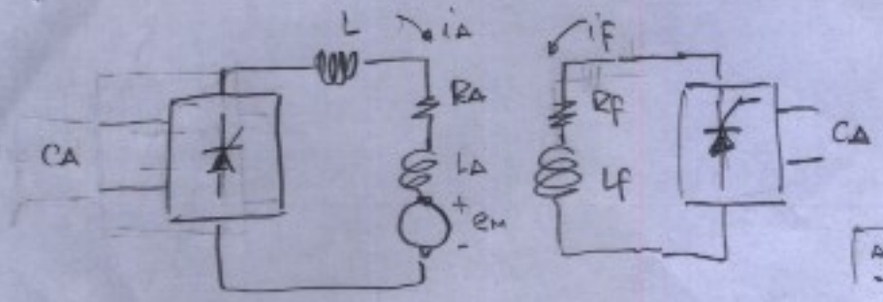
idem cuadrante II intercambiando : V_{G1} con V_{G3}

V_{G2} con V_{G4}

u_A es $-u_A$

i_A es $-i_A$

CIRCUITOS CON TIRISTORES



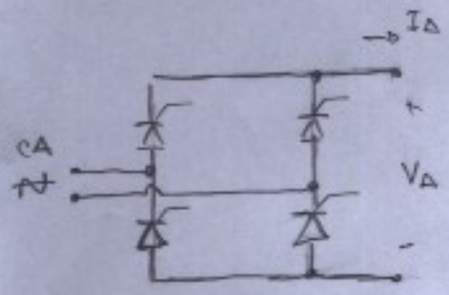
Se utiliza un rectificador controlado

ARMADURA: variando el ángulo de retardo α variamos V_A

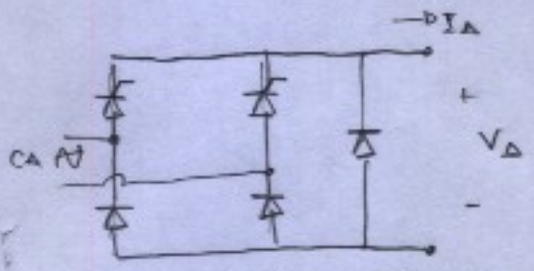
CAMPO: variando α variamos I_f y por ende el ϕ_f.

Montajes no reversibles: (I cuadrante)

1) Montajes alimentados con tensión monofásica (baja potencia):

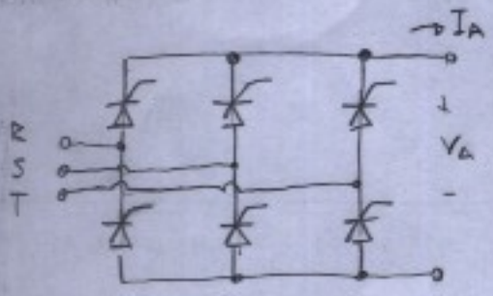


TOTALMENTE CONTROLADO

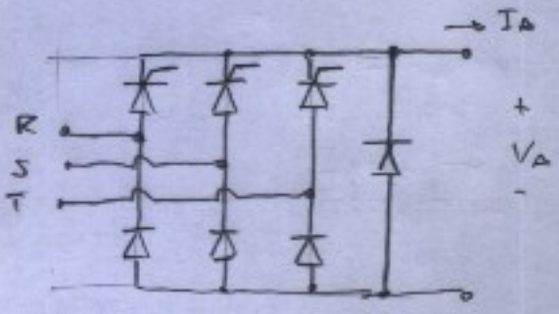


SEMI-CONTROLADO

2) Montajes aliment. con tensión trifásica (baja y media potencia):

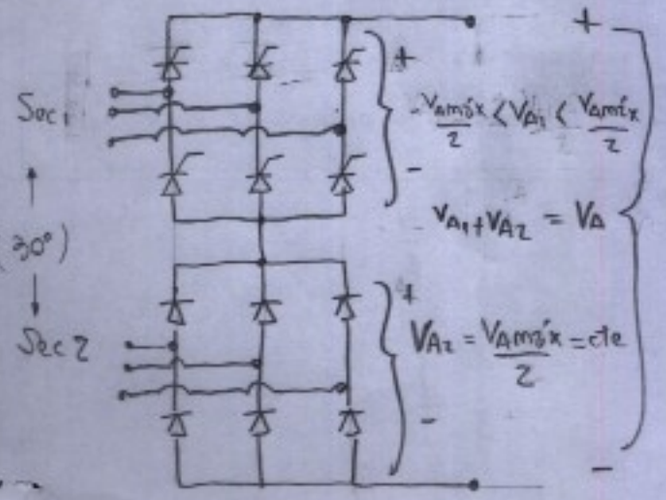


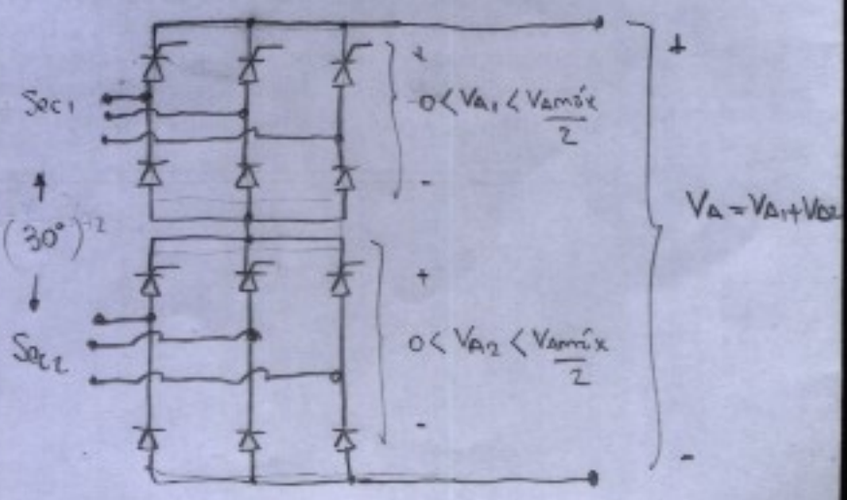
TOTALMENTE CONTROLADO



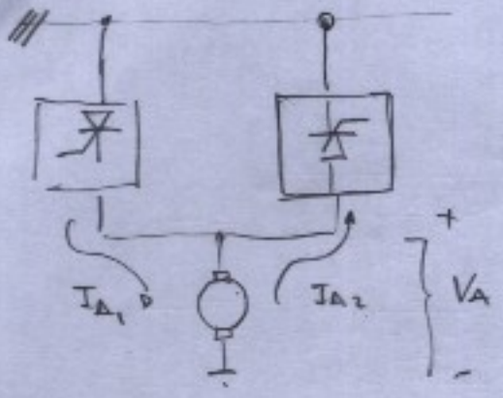
SEMI CONTROLADO

3) Montajes de gran potencia alim con tensión trifásica:



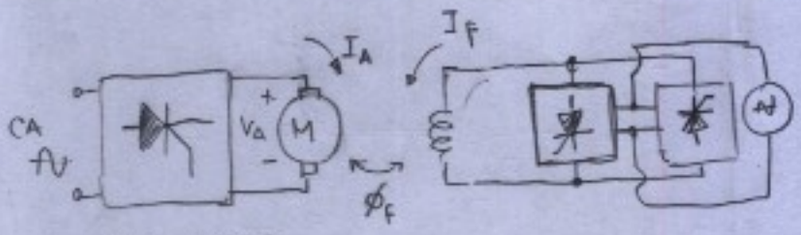


MONTAJES REVERSIBLES : (4 cuadrantes)



- Sist. que permite la variación rápida del sentido de giro
- Se implementa mediante 2 "Rect. Control" para poder invertir el sentido de la corriente
- Debido a tiempo de apagado y encendido del tiristor $\alpha \leq 150°$.

① Montaje con inversión de la corriente del inductor :



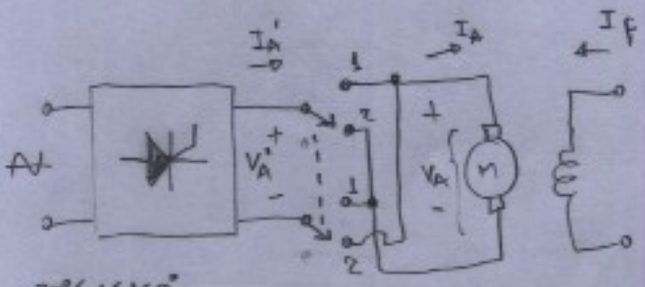
$30° \leq \alpha \leq 150°$

- El par se invierte invirtiendo I_F y por ende ϕ_F ya que $T_M \propto (\phi_F, I_A)$

- La inversión solo es posible cuando $I_A = 0$ → se utiliza para tiempos muertos de inversión de par elevados

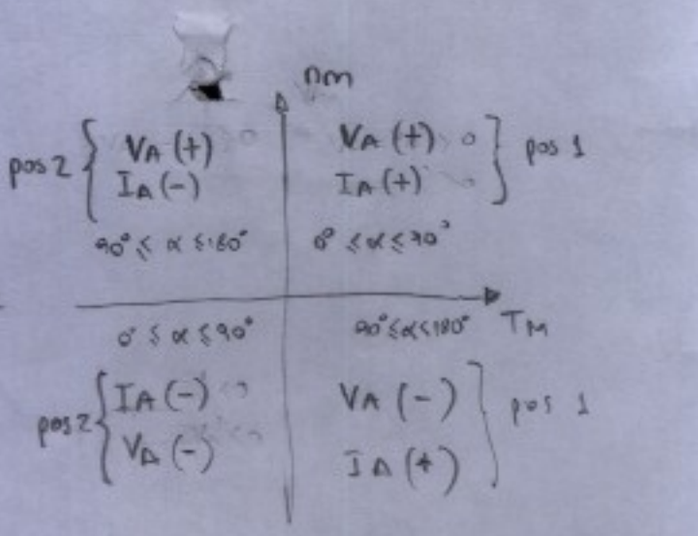
tiempo muerto de inversión de par	= 0,5 a 1 seg

② Montaje con inversión de la corriente del inducido :



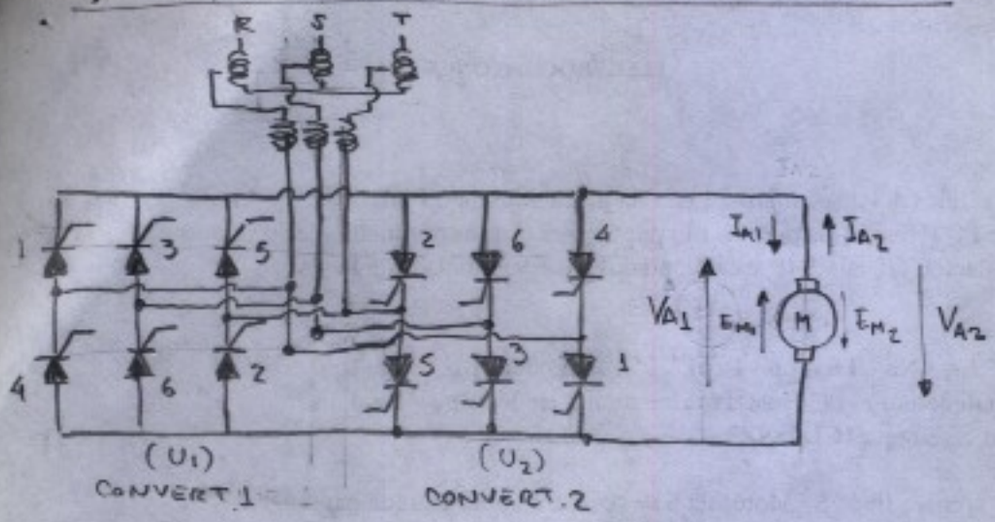
$30° \leq \alpha \leq 150°$

- El par se invierte, invirtiendo I_A mediante un contactor bipolar → pos 1 : $V_A = V_A'$, $I_A = I_A'$; pos 2 : $V_A = -V_A'$, $I_A = -I_A'$

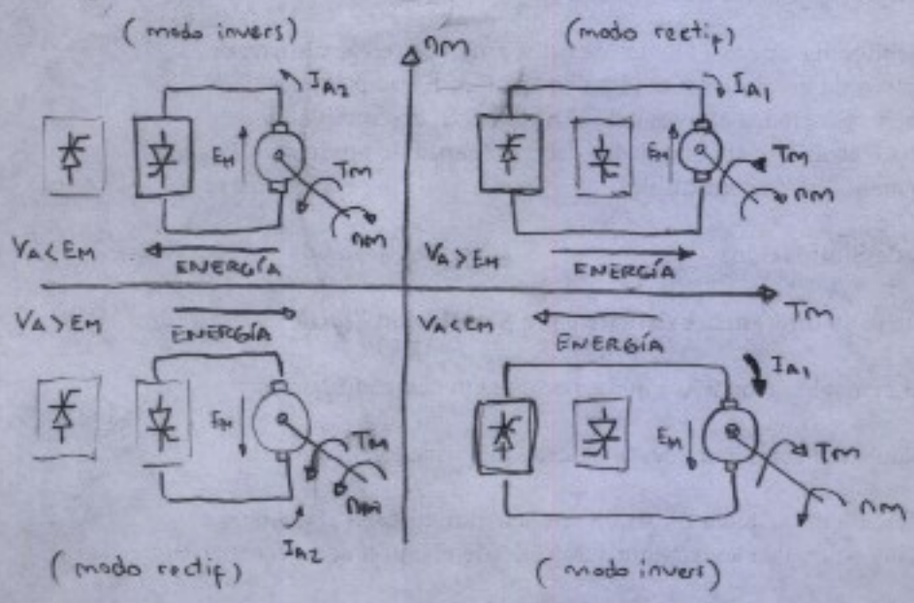


tiempo muerto de inversión de par	= 100 a 300 ms

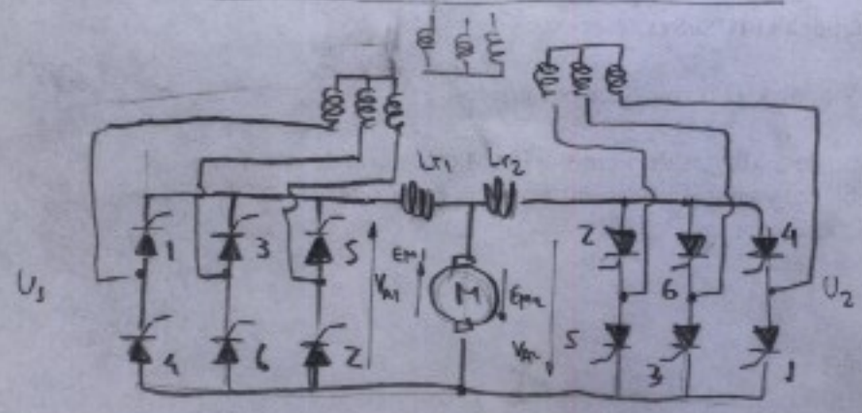
3) Montaje reversible sin corriente circulante:



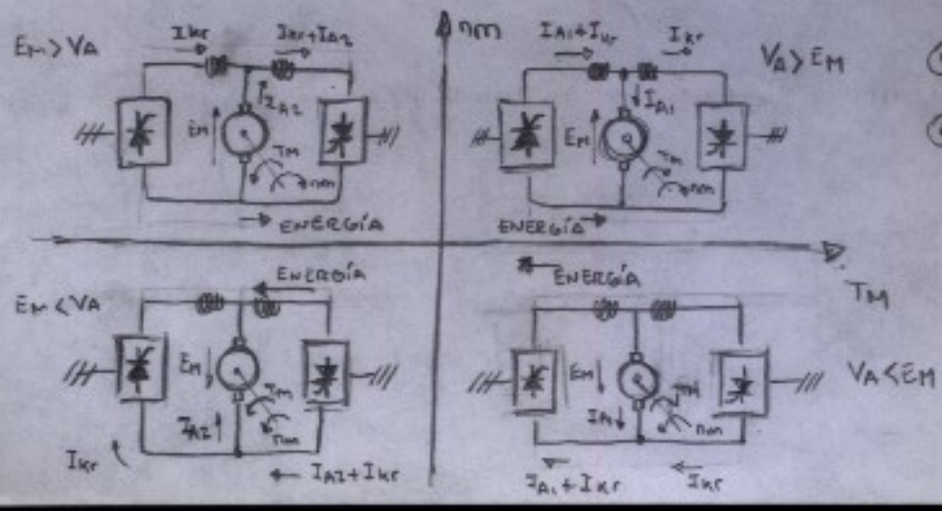
- Los convertidores conducen uno ú otro, nunca simultáneamente
- Funcionamiento:
  1) U_1 entrega I_{A1} al motor en sentido directo, U_2 bloq.
  2) U_1 se lleva del modo rectif. al límite del modo inversor ($\alpha = 90°$), $I_{A1} = \emptyset$, después de asegurarnos q'se bloqueó (tiempo muerto = 6 mseg)...
  3) Activa U_2 en límite inversor y E_{M1} actúa como generador entregando energía a la línea.



4) Montaje reversible con corriente circulante:



- Ambos convert. funcionan simultáneamente y son controlados continuamente, uno funciona como rectif. y el otro como inversor no autónomo → corriente circulante.
- Los reactores L_{r1} y L_{r2} controlan la corriente circulante.
- Libre de retardos
- En el momento que se pasa de un cuadrante al otro la $I_A = \emptyset$ y solo circula I_{kr}.



Clasificación

Motor de CA → Síncronos (Reluctancia conmutada, brushless)

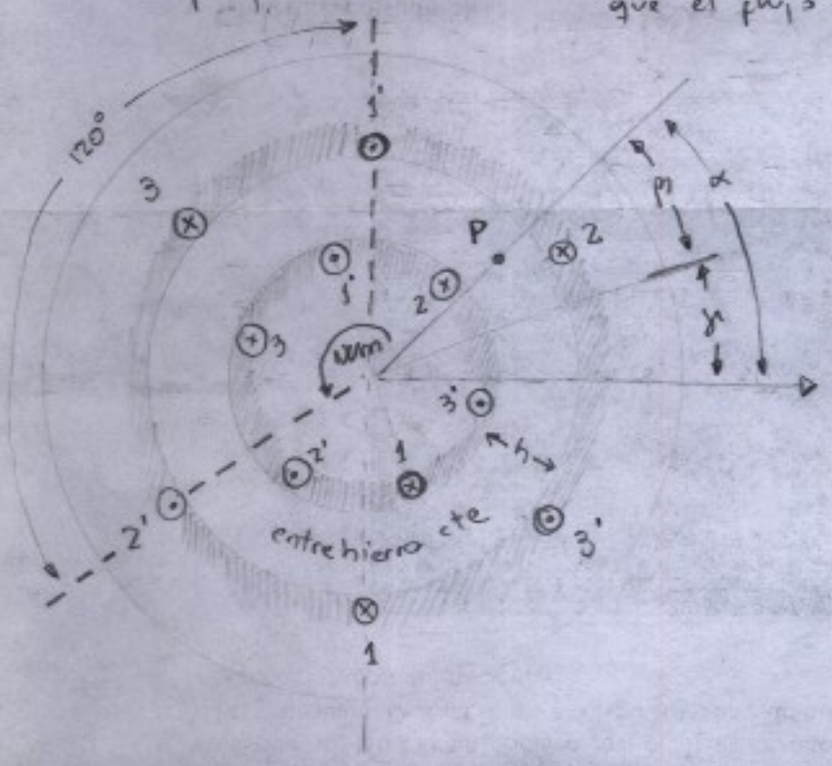
Motor de CA → Asíncronos → Rotor bobinado

Asíncronos → Jaula de ardilla

Modelo matemático de una máquina general de CA

El devanado del estator está constituido por tres arrollamientos desfasados 120° en el espacio, al introducir por ellos corrientes de una red trifásica, se produce una onda rotativa de f.m.m (amper-vuelta), que produce un flujo giratorio.

Este flujo giratorio inducirá fems en los conductores del rotor, y si está su circuito eléctrico cerrado aparecerán corrientes que reaccionarán con el flujo del estator, generando un par q' hace girar el rotor en el mismo sentido, que el flujo giratorio.



γ = ángulo de rotación del rotor respecto del estator

α = posición angular de un pto cualquiera (P) respecto del eje del devanado 1 del estator.

β = posición angular de un pto cualq. (P) respecto del eje del devanado 1 del rotor.

$$\alpha = \beta + \gamma$$

$$\omega_m(t) = \frac{d\gamma}{dt}$$

La fmm en el estator será:

$$F_S(\alpha,t) = \frac{1}{2} N_S \left[\bar{i}_S(t) \cdot e^{-j\alpha} + \bar{i}_S^*(t) \cdot e^{j\alpha} \right]$$

La fmm en el rotor será:

$$F_R(\beta,t) = \frac{1}{2} N_R \left[\bar{i}_R(t) \cdot e^{-j\beta} + \bar{i}_R^*(t) \cdot e^{j\beta} \right]$$

La onda resultante es:

$$F(\alpha,\gamma,t) = F_S(\alpha,t) + F_R(\alpha,\gamma,t)$$

La densidad de flujo en el entrehierro:

$$B_S(\alpha,\gamma,t) = \frac{\mu_0}{2h}\left[(1+\sigma_S)\,F_S(\alpha,t) + F_R(\alpha,\gamma,t)\right]$$

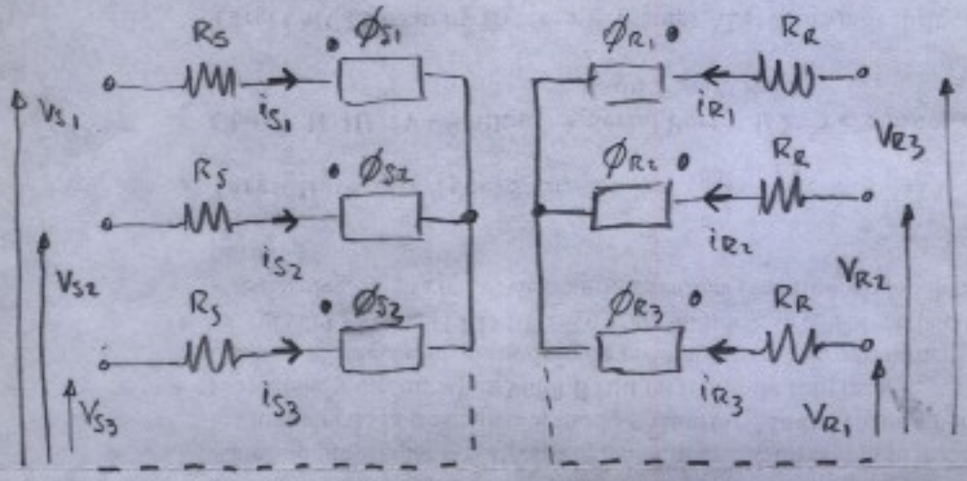
El flujo en el devanado del estator será:

$$\bar{\phi}_S(t) = L_S\,\bar{i}_S(t) + M\,\bar{i}_R(t)\,e^{j\gamma(t)}$$

El flujo en el devanado del rotor será:

$$\bar{\phi}_R(t) = L_R\,\bar{i}_R(t) + M\,\bar{i}_S(t)\,e^{-j\gamma(t)}$$

L_S, L_R : autoinduct.
M : induct. mútua.



$$\bar{V}_S(t) = \bar{i}_S(t)\cdot R_S + \frac{d\bar{\phi}_S(t)}{dt} = \bar{i}_S(t)\cdot R_S + L_S\,\frac{d\bar{i}_S(t)}{dt} + M\,\frac{d\left(\bar{i}_R(t)\,e^{j\gamma(t)}\right)}{dt}$$

$$\bar{V}_R(t) = \bar{i}_R(t)\cdot R_R + \frac{d\bar{\phi}_R(t)}{dt} = \bar{i}_R(t)\,R_R + L_R\,\frac{d\bar{i}_R(t)}{dt} + M\,\frac{d\left(\bar{i}_S(t)\,e^{-j\gamma(t)}\right)}{dt}$$

$$T_M(t) = \frac{2}{3}\,M\,\mathrm{Im}\left[\bar{i}_S(t)\cdot\left(\bar{i}_R(t)\,e^{j\gamma(t)}\right)^*\right]$$

Siendo: $L_0 = M$
$L_S = (1+\sigma_S)\,L_0$
$L_R = (1+\sigma_R)\,L_0$

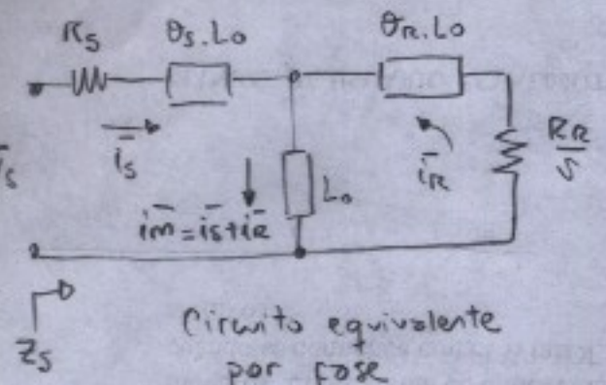
igual cantidad de vueltas en primario y secund

σ_S =
σ_R = coef de dispersión

ECUACIONES FUNDAMENTALES

$$\begin{cases} \bar{V}_S(t) = R_S\cdot\bar{i}_S(t) + L_S\,\dfrac{d\bar{i}_S(t)}{dt} + L_0\cdot\dfrac{d\left(\bar{i}_R(t)\cdot e^{j\gamma(t)}\right)}{dt} \\ \bar{V}_R(t) = R_R\,\bar{i}_R(t) + L_R\,\dfrac{d\bar{i}_R(t)}{dt} + L_0\,\dfrac{d\left(\bar{i}_S(t)\cdot e^{-j\gamma(t)}\right)}{dt} \\ J\cdot\dfrac{d\omega_m(t)}{dt} = T_M(t) - T_L(t) = \dfrac{2}{3}\,L_0\cdot\mathrm{Im}\left[\bar{i}_S(t)\cdot\left(\bar{i}_R(t)\cdot e^{j\gamma(t)}\right)^*\right] - T_L(\gamma,\omega_m,t) \\ \omega_m(t) = \dfrac{d\gamma(t)}{dt} \end{cases}$$

Motor de inducción en régimen estacionario con tensión sinusoidal simétrica



Circuito equivalente por fase

ω_1 = pulsación eléct. estator

ω_2 = pulsación eléct. rotor

ω_M = veloc. del motor

$$\omega_1 = \omega_2 + \omega_M$$

$$\frac{\omega_2}{\omega_1} = S = \text{deslizamiento}$$

$$S = \frac{\omega_1 - \omega_M}{\omega_1} = \frac{\frac{f_1 . 60}{p} - n_M}{\frac{f_1 . 60}{p}}$$

$$\omega_M = \omega_1 (1 - S)$$

Torque en régimen estacionario

$$\boxed{T_M = \frac{3}{2} \frac{1-\sigma}{\sigma} \cdot \frac{V_S^2}{\omega_1^2 \cdot L_S} \frac{2}{\frac{S}{S_{máx}} + \frac{S_{máx}}{S}}}$$

⊙ si $S = S_{máx}$ ∴ $T_M = T_P$ ⇒ par máximo

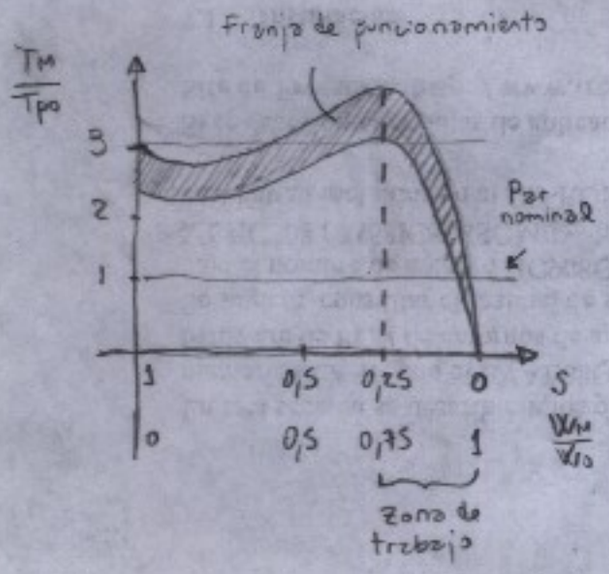
$$T_P = \frac{3}{2} \frac{1-\sigma}{\sigma} \frac{V_S^2}{\omega_1^2 L_S} \quad \therefore \quad \boxed{T_M = T_P \cdot \frac{2}{\frac{S}{S_{máx}} + \frac{S_{máx}}{S}}}$$

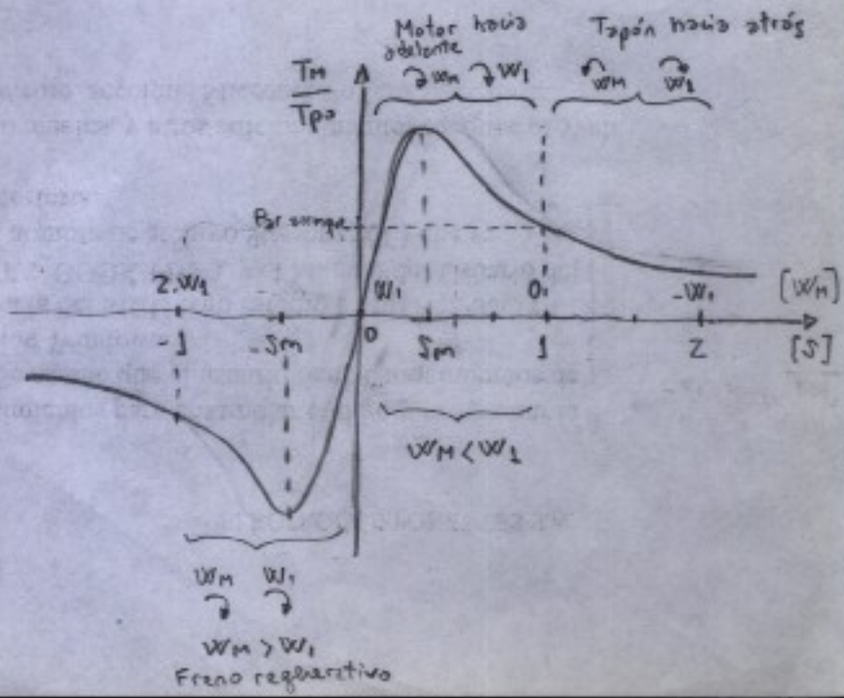
⊙ si $S = S_{máx}$ y además $V_S = V_{S0}$ ⇒ tensión nominal

$\omega_1 = \omega_0$ ⇒ frec. nominal ∴

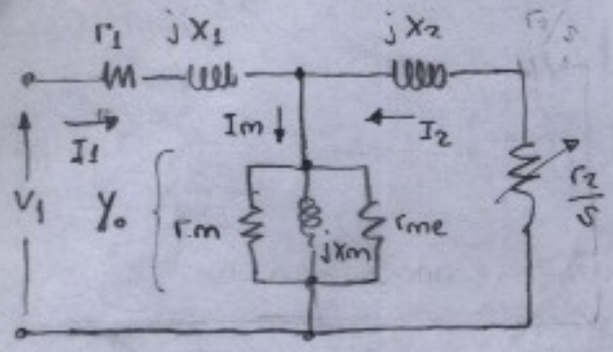
$$T_M = \frac{3}{2} \frac{1-\sigma}{\sigma} \cdot \frac{V_{S0}^2}{\omega_0^2 . L_S} = T_{P0} \Rightarrow \text{par máximo nominal}$$

$$\boxed{T_M = T_{P0} . \left(\frac{V_S / V_{S0}}{\omega_1 / \omega_0} \right)^2 \cdot \frac{2}{\frac{S}{S_{máx}} + \frac{S_{máx}}{S}}}$$





Circuito equivalente que incluye efectos adicionales (pérdidas)



r_1 = resist. por fase del estator

X_1 = reactancia de dispersión por fase del estator a la frec. de alimentación

r_2 = res. x fase del rotor referida al estator

X_2 = react. de disp. x fase del rotor a la frec. de aliment. refer. al estator.

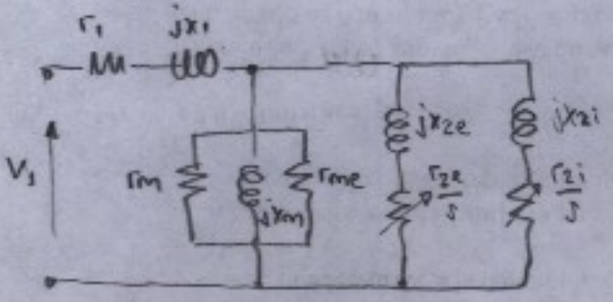
r_{me} = pérdidas mecánicas

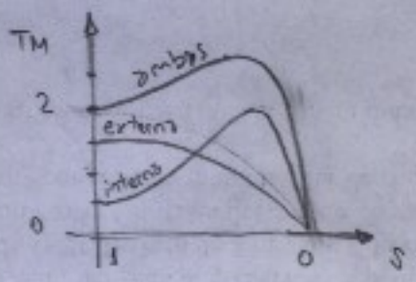
r_m = pérdidas magnéticas

X_m = reactancia de magnetización

s = deslizamiento

Motor doble jaula de ardilla:





Parámetros de rendimiento:

$P_{in} = \sqrt{3} \cdot V \cdot I \cdot \cos\varphi$ $\qquad$ P_{in} = pot. de entrada

si $s = 0 \therefore I = I_m \Rightarrow \uparrow s \rightarrow \uparrow I$

$P_{in} - P_{JS} - P_{FES} = P_\partial$

$P_{JS} = 3 I_1^2 \cdot r_1$ $\qquad$ P_{JS} = pérdidas en el cobre estator (Joule)

$P_{FES} = 3 \dfrac{V_1^2}{r_m}$ $\qquad$ P_{FES} = pérdidas en el hierro (histéresis, foucult)

P_∂ = potencia transmitida al rotor por el entrehierro.

$\left(P_\partial = 3 I_2^2 \dfrac{r_2}{s} \right)$

$P_\partial = T_M \cdot W_1$

$P_\partial - P_{JR} = P_M$ $\qquad$ P_{JR} = pérdidas en el cobre del rotor (Joule)

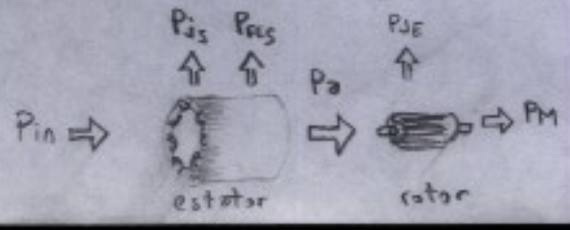
(ya que f_2 es bajo se desp. P_{FER})

$P_{JR} = 3 \cdot I_2^2 \, r_2$

$P_M = T_M \cdot W_M$ $\qquad$ P_M = pot. del rotor

$P_{pérd} = P_\partial - P_M = T_M (W_1 - W_M) = T_M \cdot s \cdot W_1$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_M - P_{sin\ carga}}{P_\partial + P_{JS} + P_{FES}} \approx \frac{P_M}{P_\partial} = \frac{T_M \cdot W_M}{T_M \cdot W_1} = \frac{W_1 (1-s)}{W_1} = \boxed{1 - s = \eta}$$

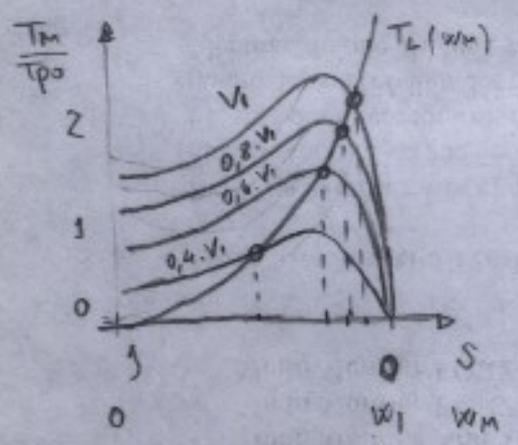


VARIACIÓN DE VELOCIDAD

$$\boxed{n_M = \frac{60 \cdot f_1}{p}(1-s)}$$

variación de velocidad
- par de polos
  - Dahlander
  - Bobinados independientes
- deslizamiento
  - tensión de estator (A)
  - resist. rotórica (B)
  - recuperación de pot. rotórica (C)
- frecuencia
  - Frecuencia del estator (D)
  - Regímenes especiales
    - tensión, frec, proporc (E)
    - debilitamiento de campo (F)
    - flujo constante (G)
    - tensión, frec, extendido (H)

Control por variación de la tensión del estator (A)



$$\boxed{T_M \propto V_1^2}$$

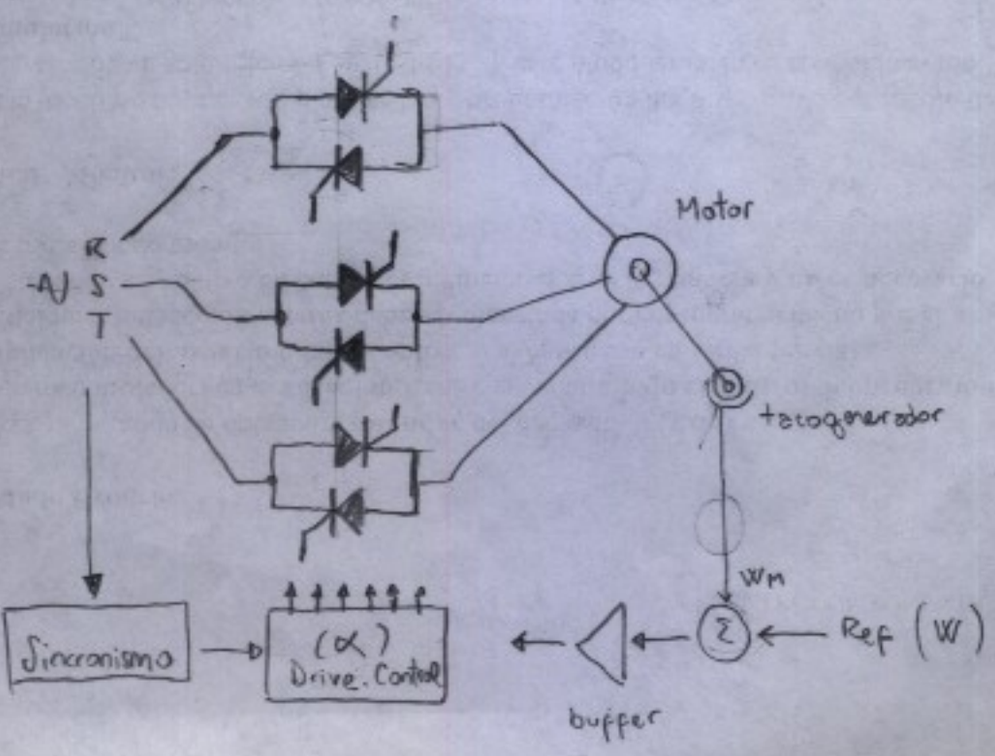
Una variación de la tensión producirá una variación de la velocidad, pero a costa de una reducción del par.

A menor tensión, disminuye la velocidad pero aumenta el deslizamiento, con lo que aumenta las pérdidas por efecto Joule.

$P_{pérd} = T_M \cdot w_1 \cdot s \rightarrow P_{pérd} \uparrow$

$\eta = 1 - s \rightarrow \eta \downarrow$

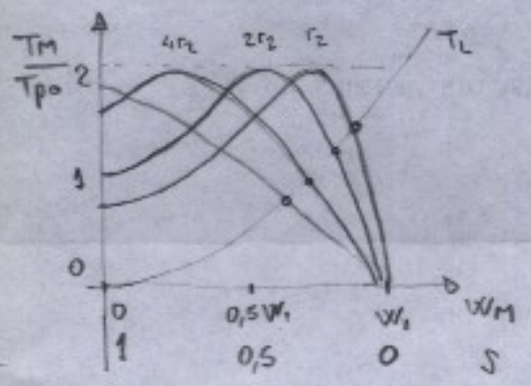
Circuito práctico (variación con tiristores)



Control por variación de la resist. rotórica (B)

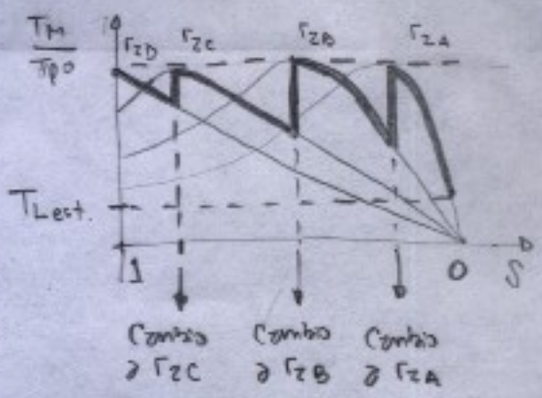
$$\left.\begin{aligned} P_\partial &= 3\, I_2^2\, \frac{r_2}{s} \\ P_{pérd} &= 3\, I_2^2 \cdot r_2 \end{aligned}\right\} \quad s = \frac{P_{pérd}}{P_\partial} \rightarrow \text{si} \uparrow r_2 \therefore \uparrow P_{pérd} \therefore \uparrow s \therefore \downarrow W_M$$

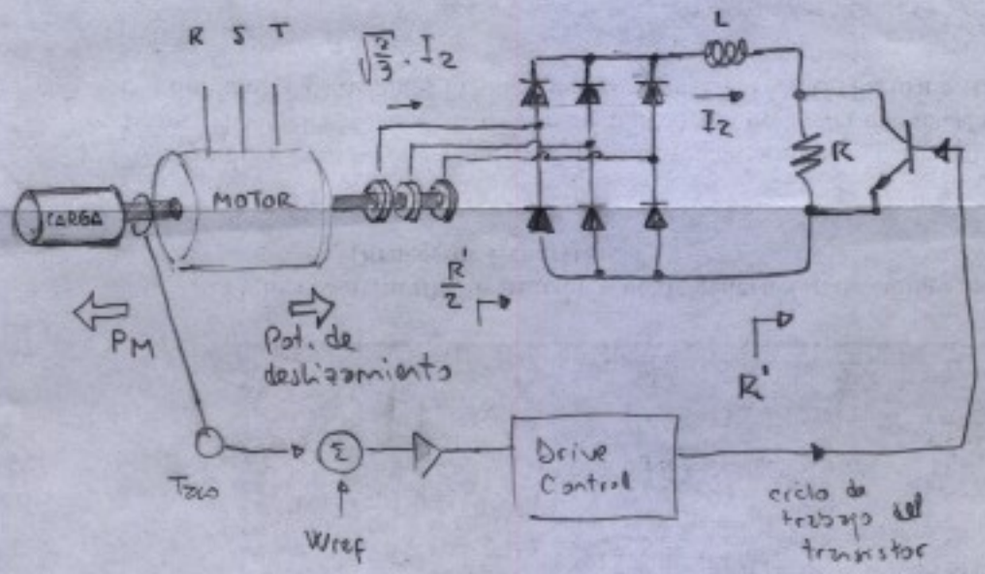
$$\left\{\begin{aligned} W_M &= W_1(1-s) \\ P_{pérd} &= T_M \cdot s \cdot W_1 \end{aligned}\right\}$$



Circuito práctico

Controlando el par de arranque mediante resistencias rotóricas



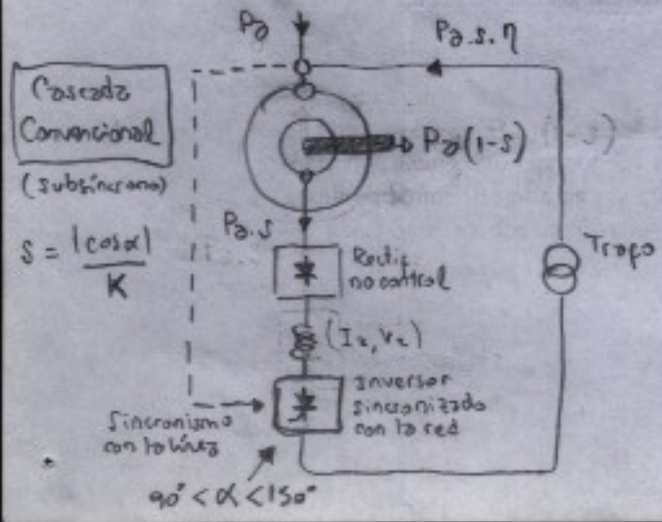


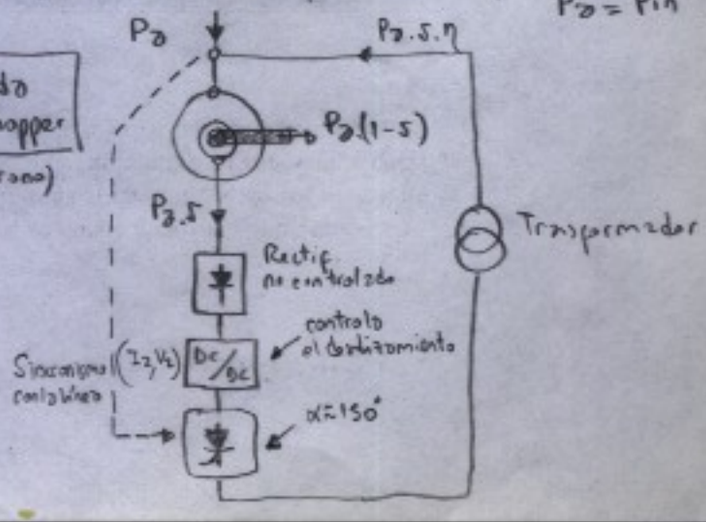
$R' = R(1-D)$

$0 < R' < R$

Control por recuperación de potencia rotórica (C)

El motor de anillos rozantes tiene en su circuito rotórico una puente de tensión activa y no un circuito pasivo de resistencias disipativo. (Consideramos $P_\partial = P_{in}$)





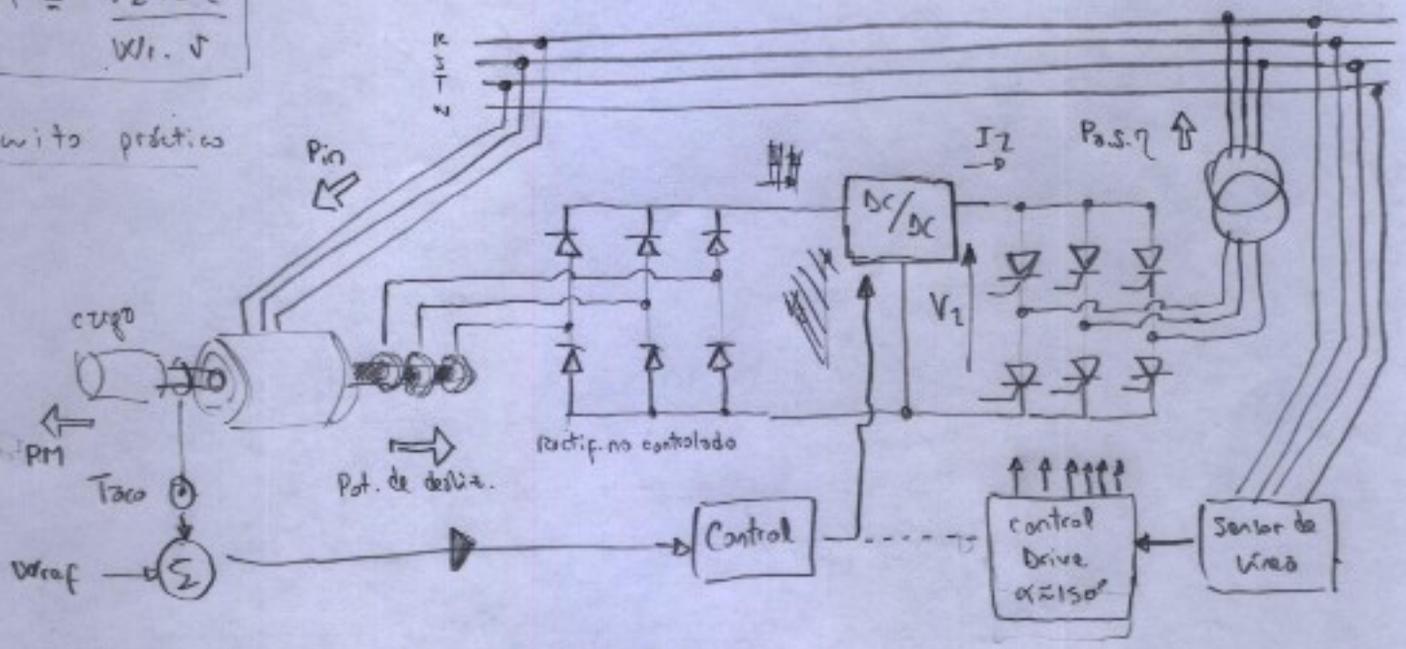
- Las tensiones entre los anillos tienen: un valor y una tensión variable (proporcionales al deslizamiento). Es necesario rectificar, para obtener una DC y luego mediante un inversor entregar la energía del rotor a la línea a la frec. adecuada y en fase.

$$S = \frac{\text{Potencia de salida del rotor}}{\text{Potencia de entrada al motor}} = \frac{P_\partial . S}{P_\partial} = S$$

$$P_M = V_2 . I_2 = P_\partial . S = T_M . W_1 . S$$

$$\boxed{T_M = \frac{V_2 . I_2}{W_1 . S}}$$

Circuito práctico



Variación de la frecuencia del estator (D)

Se utiliza:
- síncronos → $W_M = W_1$ (estrictamente ligadas)
- asíncronos → $W_M = W_1 . (1-S)$ (depende también del deslizamiento)

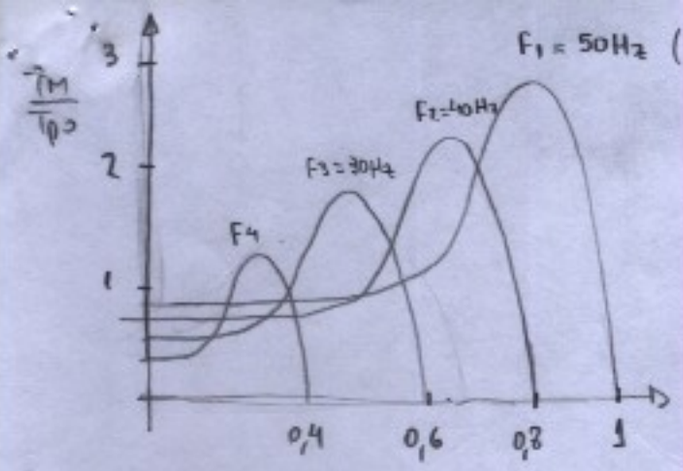
Funcionamiento con tensión/frecuencia en el estator proporcionales (E)

(voltaje/hertz)

$E_1 = 4{,}44 . K_1 . f_1 . N_1 . \phi_m$

$\phi_m = K . \left(\frac{E_1}{f_1}\right)$ → si logramos mantener la relación $\frac{E_1}{f_1} = cte$ ∴ $\phi_m = cte$ ∴ $T_M = cte$

pero nosotros controlamos $\frac{V_1}{f_1} = cte$; $V_1 = E_1 + I_1 . (r_1 + jX_1)$, a frec. altas $V_1 \approx E_1$, pero a frec. bajas el ϕ se reduce debido a que se torna significativo el efecto de la resistencia rotórica frente al de la inductancia de magnetización, y entonces $V_1 \neq E_1$.



W_0 = velocidad síncrona a la frec. nominal o base (50 Hz)

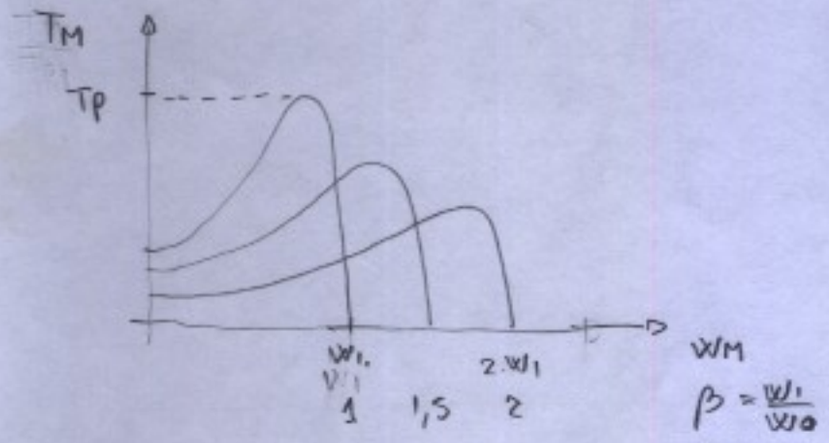
W_1 = vel. síncrona a cualq. otra frec.

$W_1 = \beta . W_0$

$$s = \frac{W_1 - W_M}{W_1} = \frac{\beta W_0 - W_M}{\beta W_0} = 1 - \frac{W_M}{\beta W_0}$$

Funcionamiento en modo debilitamiento de campo ($\beta > 1$) (F)

Si deseamos trabajar a frec. por encima de la nominal deberíamos aumentar la tensión V_1 por encima de la nominal para mantener el par cte, y ésto no es posible ya que no podemos superar la potencia máxima del motor para régimen permanente, entonces solo nos queda ↑ frec y dejar V_1 = cte con lo que disminuirá el flujo y por ende el par.

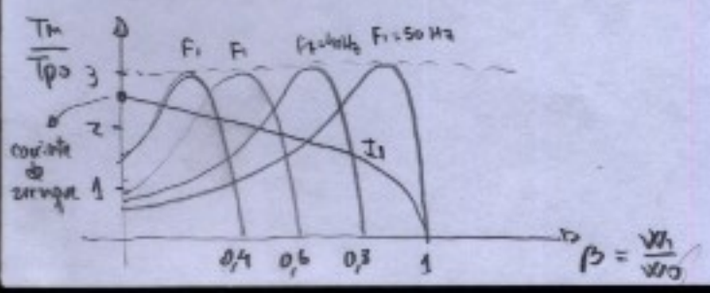


$$T_p = T_{p0} \frac{1}{\beta^2}$$

$$\frac{T_p}{T_{p0}} = \frac{1}{\beta^2} \quad \therefore \quad T_p . \beta^2 = T_{p0} = cte$$

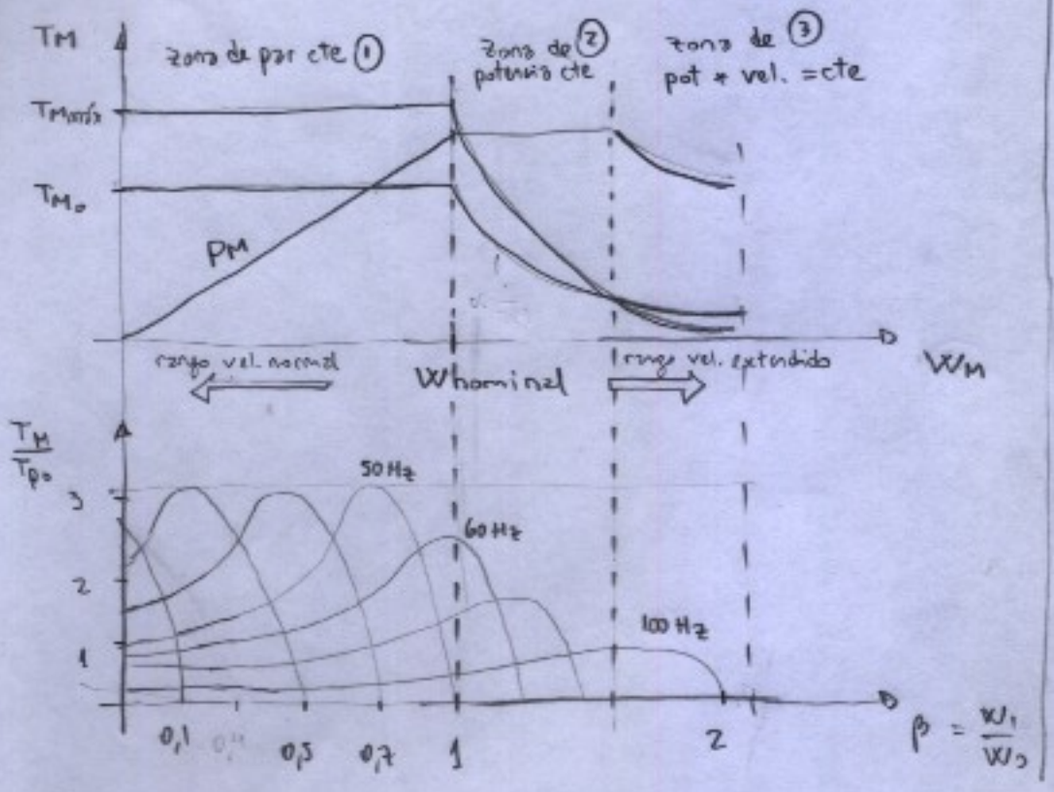
Funcionamiento a flujo constante (G)

Dijimos anteriormente que debido a que la impedancia del estator $(r_1 + jx_1)$ influye en E_1 debido a la caída de tensión que en ella ocurre. Entonces agregando un "calculador" que determine en todo momento E_1 en función de V_1 e I_1 de según: $\bar{E}_1 = \bar{V}_1 - \bar{I}_1 . (r_1 + jx_1)$ podemos lograr ϕ_m = cte y T_M = cte



Variación por método tensión/frecuencia extendido (H)

Para → $\beta < 1$ → motor a flujo cte
→ $\beta > 1$ → motor a debilitamiento de campo



(1) $T_m = cte = \frac{P_M}{W_M}$

(2) $P_M = cte = T_m \cdot W_m$

$\therefore T_M = \frac{P_M}{W_M}$

$T_M \propto \frac{1}{W_M}$

$T_{Mmáx} \propto \frac{1}{W_M^2}$

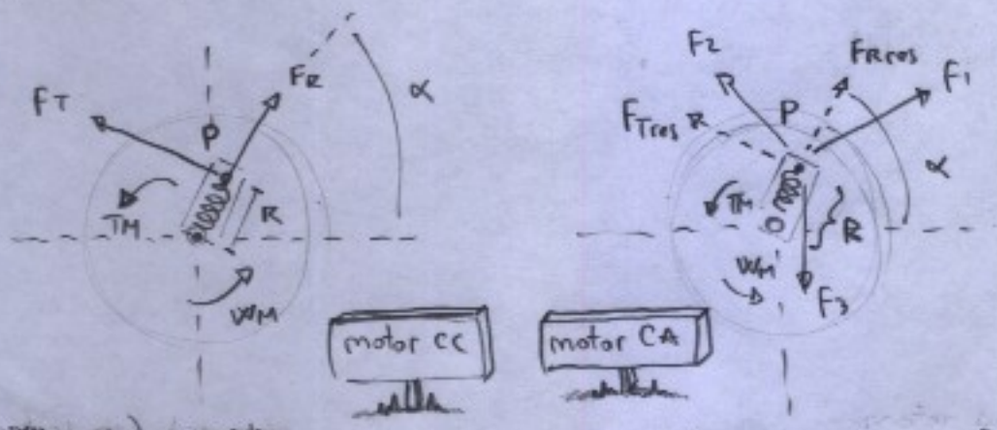
(3) $P_M * W_M = cte$

incremento de velocidad →

CONTROL DE MOTORES DE INDUCCIÓN

Analogía mecánica

Las diferencias en "las dinámicas del control" dentre un motor de CC y uno AC se pueden explicar con modelos mecánicos:



1) $F_R \propto$ tensión campo
2) $R \propto$ flujo principal
3) $F_T \propto$ corriente de armad
4) $F_T \cdot R \propto$ torque eléctrico
5) $F_T \cdot R \cdot W_M \propto$ potencia eléctrica
6) $R \cdot W_M \propto$ tensión inducida (e_M)

(T_M, W_M y α) → pueden ser completamente controlados si (F_T) y (F_R) pueden elegirse independientemente.

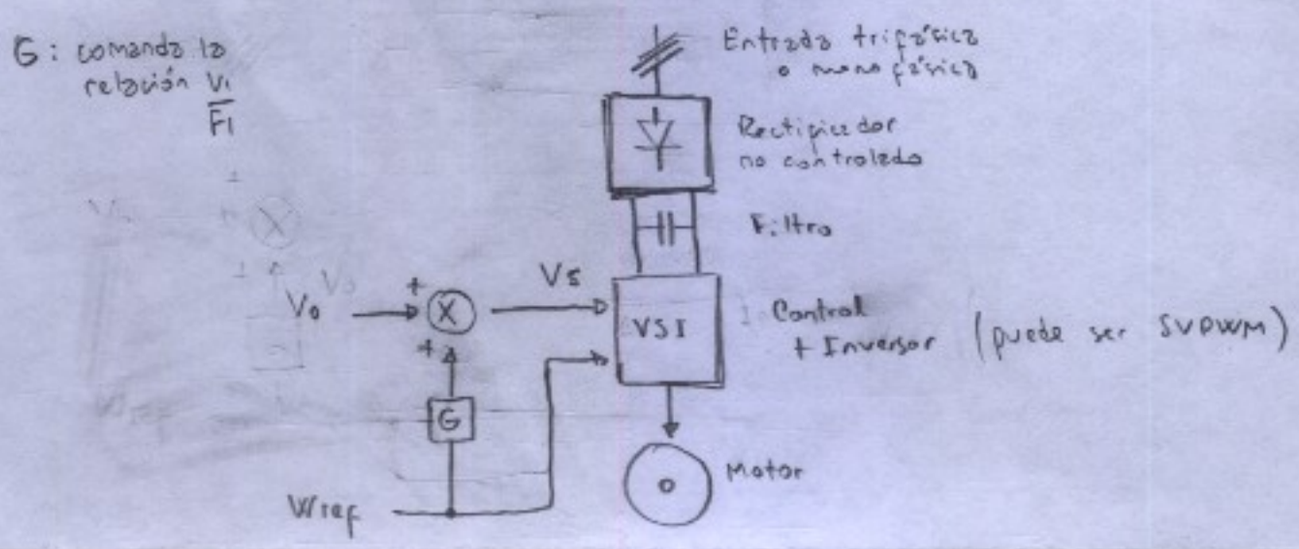
El pin (P) es manejado por (F_1, F_2, F_3) aplicados a 120° c/u, se requiere una coordinación del set de fuerzas para lograr $F_{T\,result}$ y F_R resultantes.

• Control Escalar (Volts/Hertz)

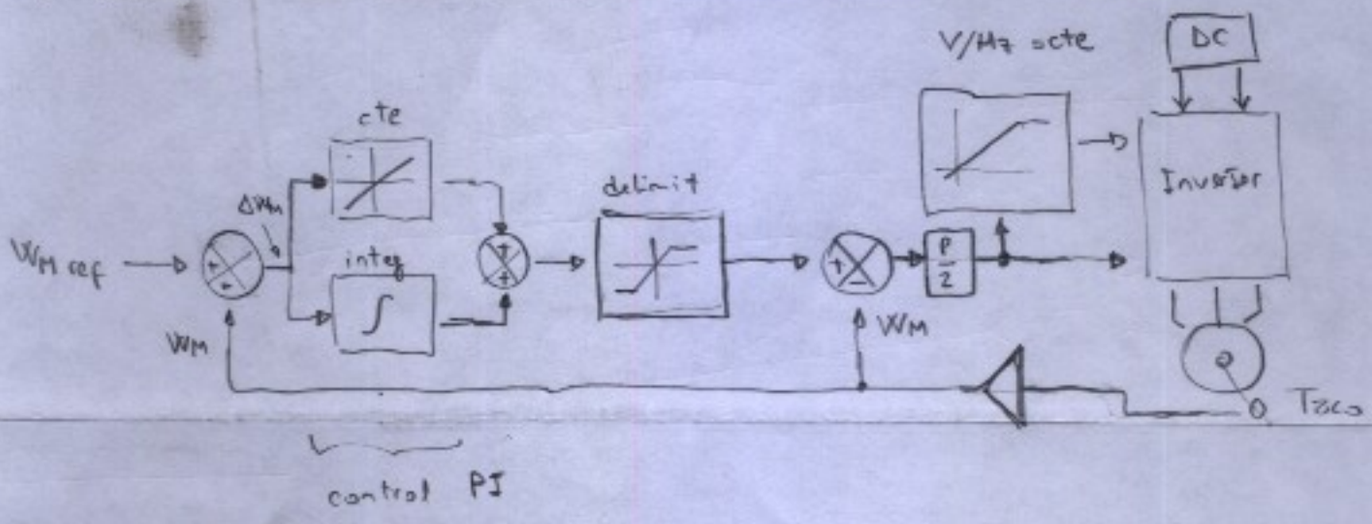
El control escalar desprecia el efecto de acoplamiento entre las variables de control. Se trabaja con flujo aprox. constante. Para aprovechar al máximo el motor se trata de que el flujo sea lo más cercano al nominal. Para lograr el flujo const. es necesario que a bajas frec. la tensión sea más elevada que la ley de proporcionalidad $V_1/F_1 = cte$.

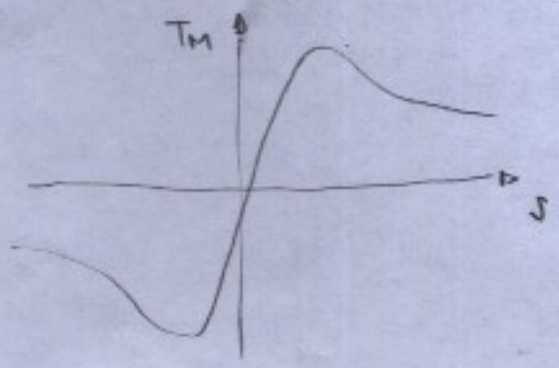
(No tiene una resp. dinámica satisfactoria)

A) Control Volts/Hertz lazo abierto:



B) Control Volts/Hertz en lazo cerrado con regulación de deslizamiento:





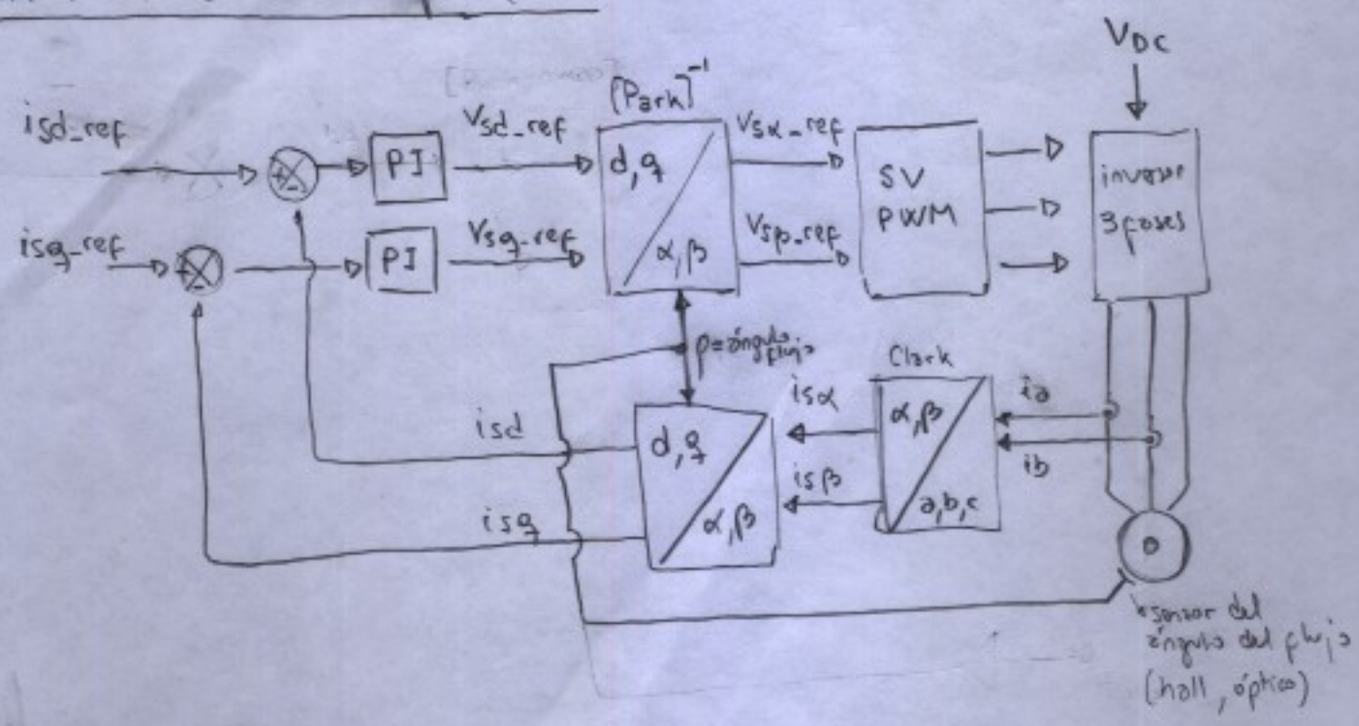
El torque depende solo del deslizamiento ya que $\frac{V_1}{F_1} = cte$

Control Vectorial

- **FOC**: Field oriented control. Se aplica el método de "dos vectores", a través de separar la corriente del estator en dos componentes. Una comp. es la que produce el flujo, y la otra componente ortogonal es la que produce el par. La clave de éste método es conocer el "ángulo" del vector de flujo del rotor con respecto al estator.
  "De esta manera se provee el mismo control desacoplado de flujo y torque el cual es inherentemente posible en un motor de DC"

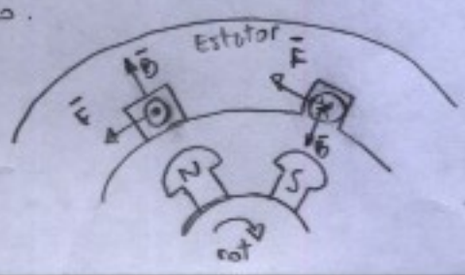
- **DTC**: direct. torque Control. (sensorless) No es necesario la transformación al sistema de ejes "d" y "q". El torque electromagnético y el flujo del estator son estimados y controlados directamente con la aplicación del vector tensión del estator apropiado.

Control orientado al campo (FOC)

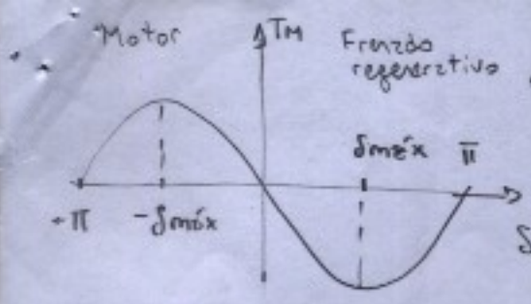


MOTOR SÍNCRONO

$W_m = W_1 \rightarrow$ La velocidad del motor permanecerá cte a menos que la máquina pierda el sincronismo por haberse aplicado el eje un par resistente superior al máximo.



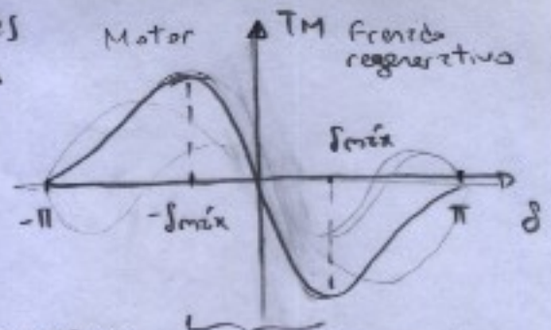
$$n_m = \frac{60\, f_1}{p}$$



rotor cilíndrico

(con bobinado rotórico)

polos salientes

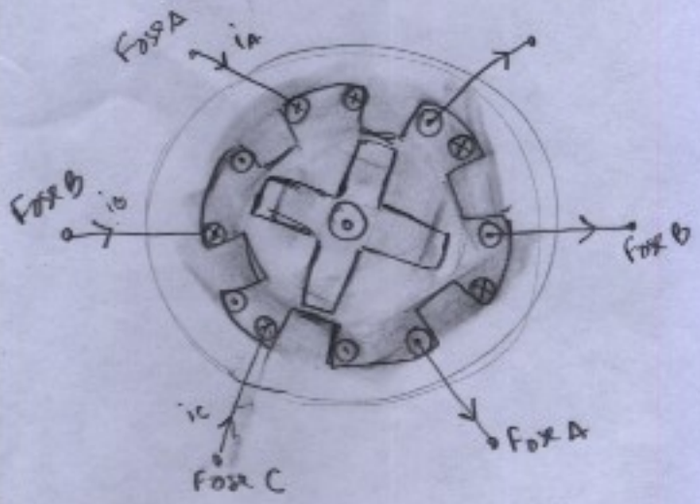


zona de trabajo = $-\frac{\pi}{2} \leq \delta \leq \frac{\pi}{2}$

ESTABILIDAD

$-\delta_{máx} < \delta < \delta_{máx}$ = zona de trabajo

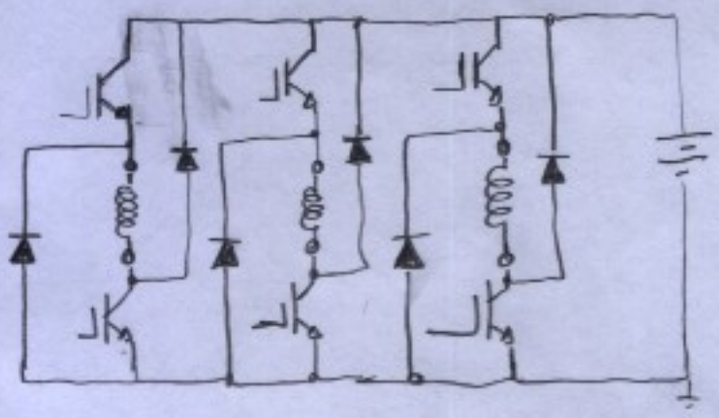
Motor síncrono de reluctancia conmutada



Cada bobinado del estator está colocado entre los dientes opuestos diametralmente

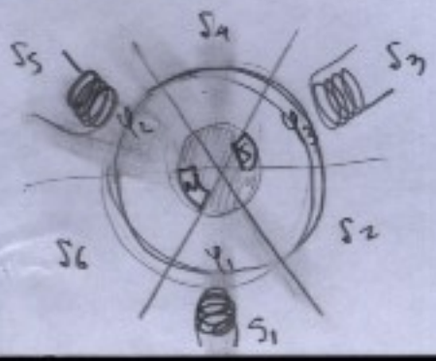
N_1 = dientes del estator
N_2 = dientes del rotor
q = nº de fases

$$N_2 = N_1 \pm \frac{N_1}{q}$$



Motor síncrono autopilotado

Los motores brushless o "sin escobillas" son básicamente motores síncronos en autocontrol, cuya conmutación está gobernada por un encoder. La frec. de la alimentación se modifica en proporción con la posición angular del motor proporcionado por el encoder, y se conmutan las distintas fases en los momentos oportunos de posición relativa de los fasores espaciales que representan a los flujos del estator y del rotor. De este modo, se mantiene en todo momento el par por la interacción de los campos.

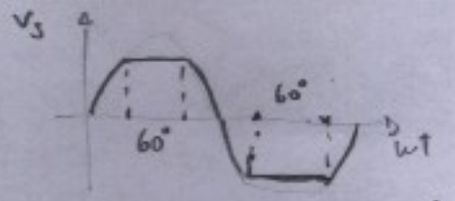


Posición	Gira antihorario			Gira horario		
	φ_1	φ_2	φ_3	φ_1	φ_2	φ_3
S_1	Ø	N	S	Ø	S	N
S_2	N	Ø	S	S	Ø	N
S_3	N	S	Ø	S	N	Ø
S_4	Ø	S	N	Ø	N	S
S_5	S	Ø	N	N	Ø	S
S_6	S	N	Ø	N	S	Ø

← Me dice cómo debe ser la conmutación para salir de la posición actual en el siguiente.

• Motor trapezoidal:

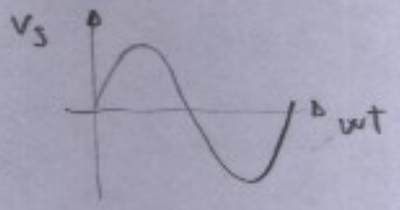
Se ha manipulado el diseño del motor de manera que la alimentación del estator debe ser una señal senoidal "achatada", digamos trapezoidal. Se logra así el efecto de una "patada suave" en los ptos de conmutación.



tensión trapezoidal

• Motor senoidal:

Pueden ser manejados como un motor síncrono de CA, aplicándole corrientes sinusoidales a los arrollamientos del motor, desfasadas 120° entre ellas. Se necesita un resolver (en vez de un simple encoder) o un encoder óptico de alta resolución, de esta manera, es posible mantener un ángulo de torque de 90° muy exacto, resultando un ripple de torque despreciable y una rotación muy uniforme a bajas frecuencias.

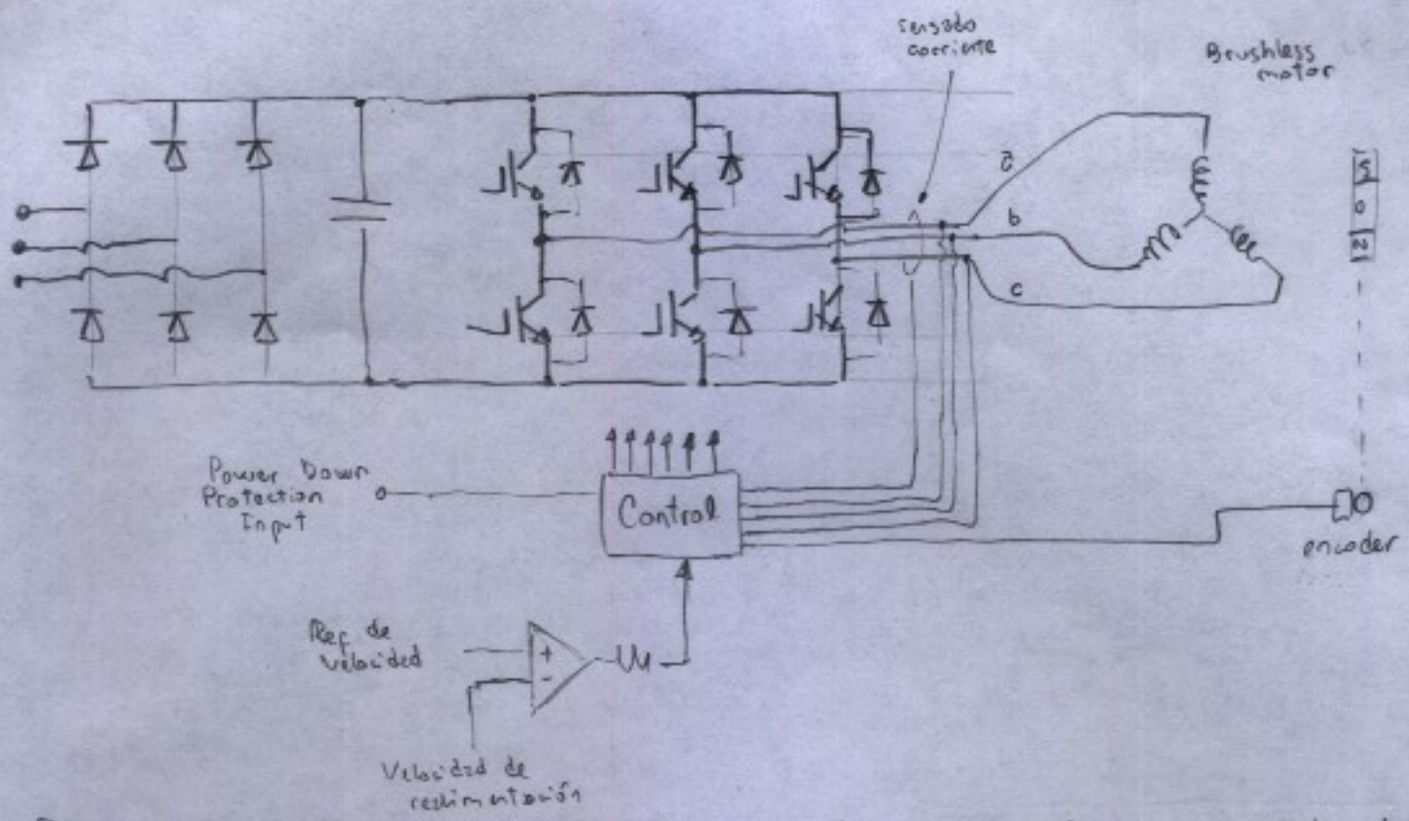


Control del motor síncrono autopilotado

Para lograr el autopilotado se puede aplicar el "control de la orientación" del campo (control vectorial), lo que requiere capacidades poderosas de procesamiento aritmético, para calcular el flujo del rotor y ejecutar las transformaciones de coordenadas necesarias.

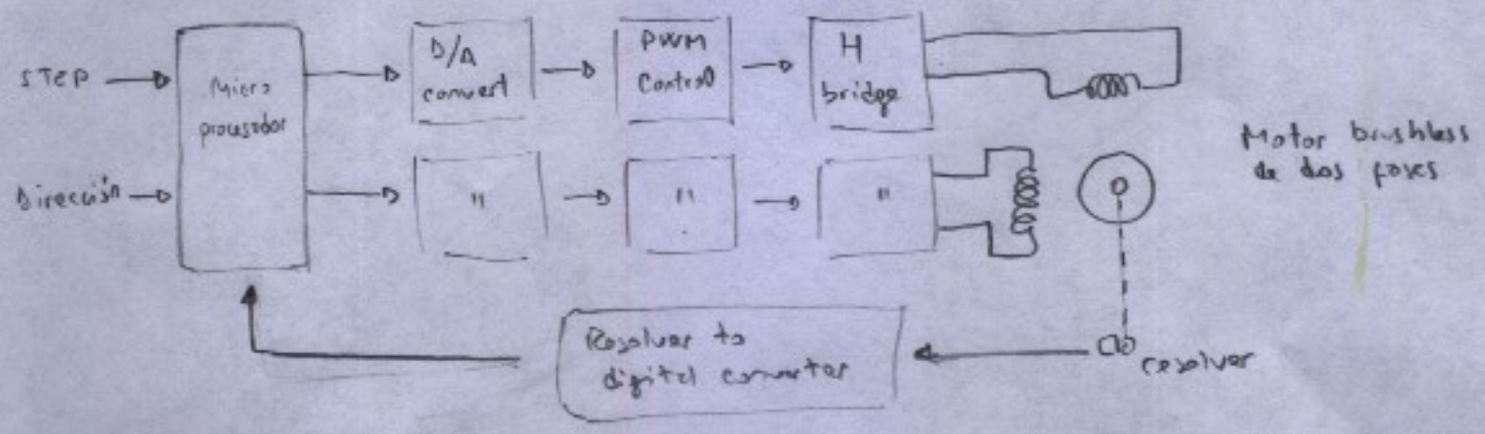
Los controles sin sensores son otro aspecto que requiere intensivos cálculos matemáticos de un D.S.P. → se basa en las operaciones matemáticas que calculan velocidad y posición en tiempo real, en base a vectores de corrientes y tensiones conocidas.

El drive trapezoidal:



Solamente se encienden 2 tx a la vez. La circulación de corriente dependerá de la posición del rotor y del sentido de rotación, por lo que los tx del puente completo son seleccionados por un manejo lógico basado en la información que provee el encoder de conmutación. Un PWM controla la corriente de circulación.
La información de la corriente de realimentación se obtiene del sensado de las ramas que van al motor

El drive senoidal:



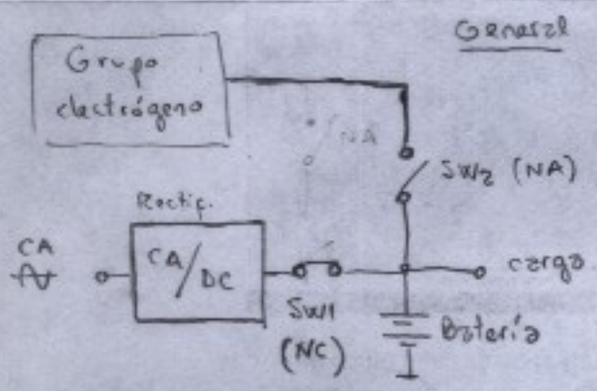
El microprocesador lee entradas de "STEP" y "dirección", las corrientes en los dos arrollamientos deben ser seno y coseno. El resolver indica la posición del eje mediante un valor que debe ser comparado con una tabla de referencia para determinar el valor de la corriente instantánea para cada posición particular del eje., el procesador deberá multiplicar el valor de seno y coseno por la demanda de torque para obtener el valor final de la corriente de cada fase.

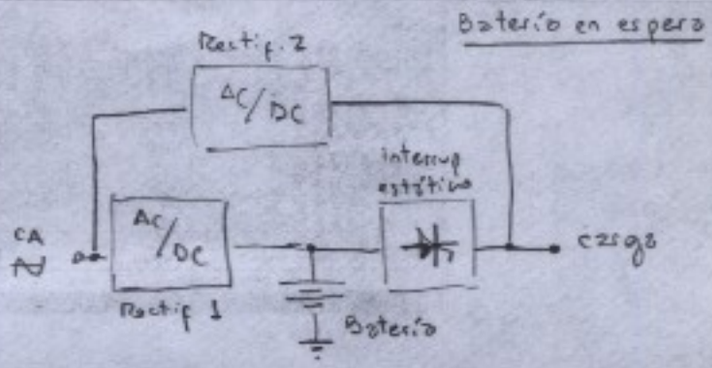
UPS

Su función es mantener la alimentación de la carga limpia de "ruidos", "microcortes" e "ininterrumpida" (por un tiempo suficiente hasta que se pueda desconectar la carga).

Topologías → DC
→ AC → on line
→ off line
→ interactivo con la línea

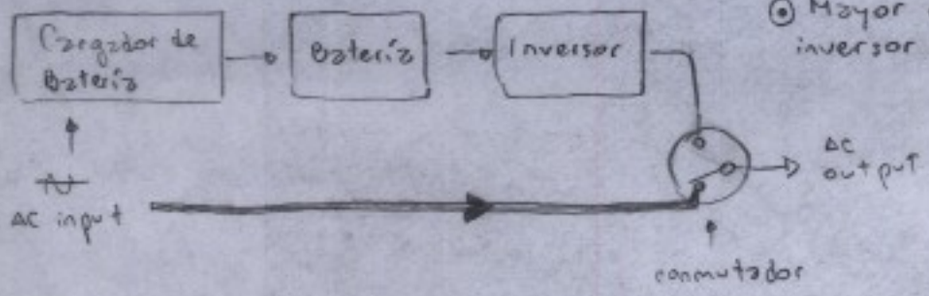
UPS de DC





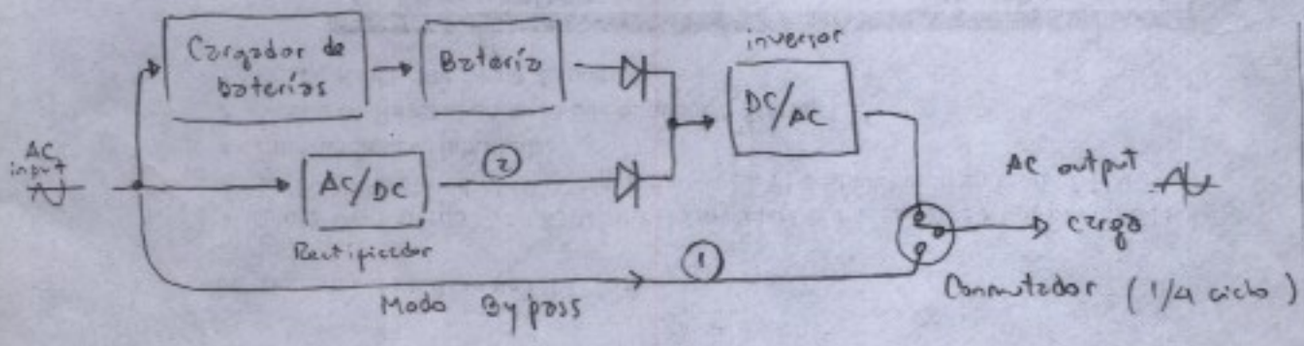
UPS de AC

OFF LINE



- El inversor está generalmente desconectado entre la línea de aliment y la carga
- Mayor rendim → en operación normal el inversor no tiene carga
- Más propenso a fallos ya que existe un "tiempo de conmutación" de la red al inversor → debe ser menor a 1/4 ciclo.
- Utiliza → cargas no críticas.

ON LINE

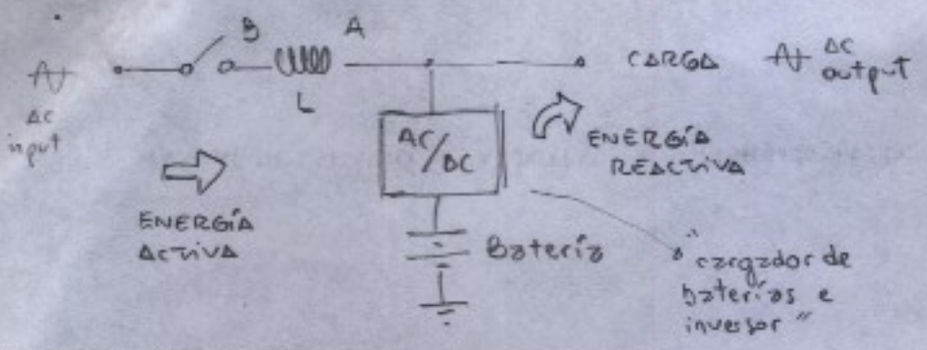


Si falla el inversor en modo normal se puede pasar a modo by pass si la red está buena.

- El inversor está continuamente conectado en línea
- Cargas críticas

1. Modo By-pass: en el arranque, hasta que "inversor" rég. permanente
2. Modo Normal: una vez sincronizado con línea de entrada el inversor.
3. Modo Backup: falla la red se conecta sist. de baterías.

INTERACTIVO CON LA LÍNEA



- Controlando la dif. de fase entre los puntos A y B se puede hacer que la red provea toda la energía activa y el inversor la reactiva.
- UPS → compensador de factor de potencia

UPS on line. Modos de operación

Diagrama en bloques. Aislado en la entrada (100 KVA)

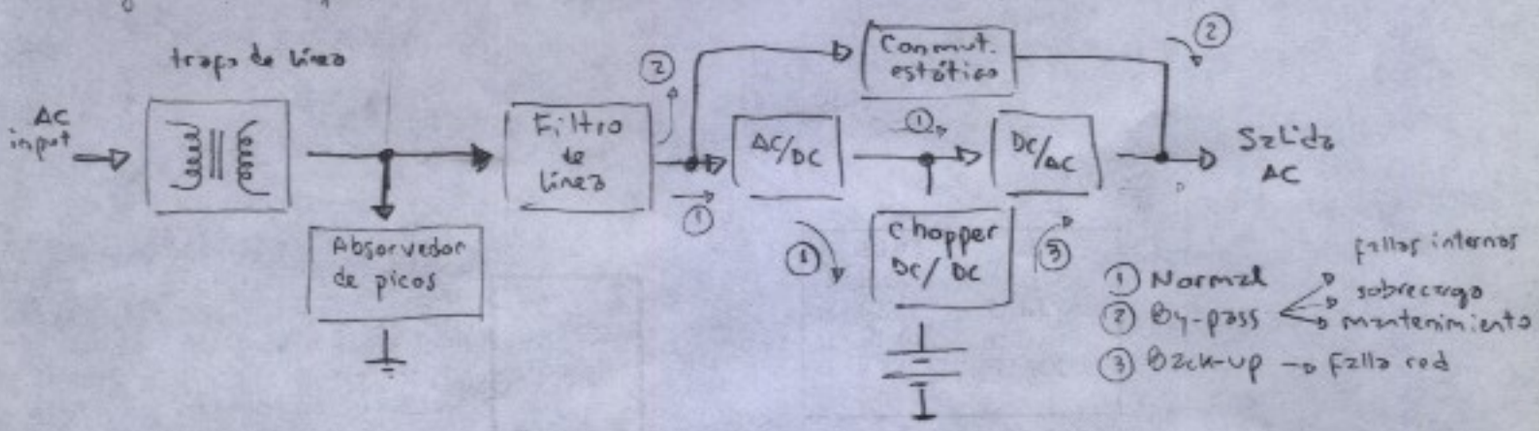
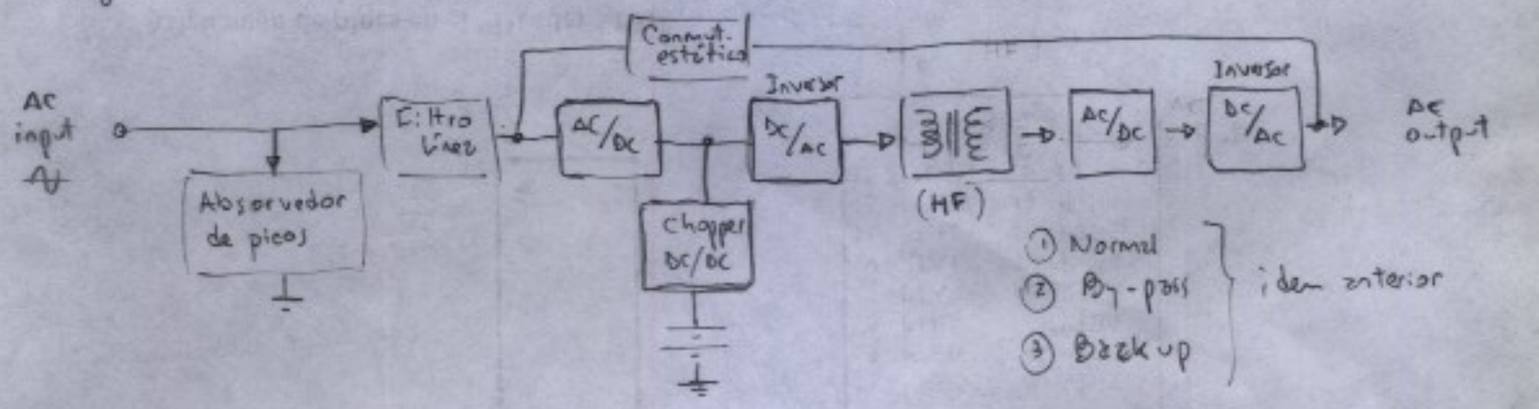
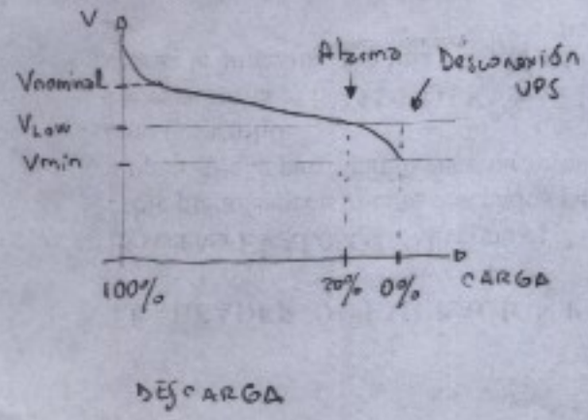
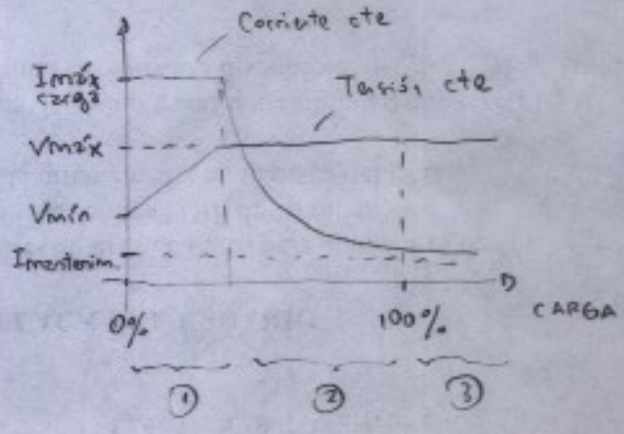


Diagrama en bloques. Aislado en la salida (20 KVA)



BATERÍAS, CARGA Y DESCARGA





CARACT. DE LOS UPS:

De manual:

* Input
* Output
* Batería
* Entorno trabajo

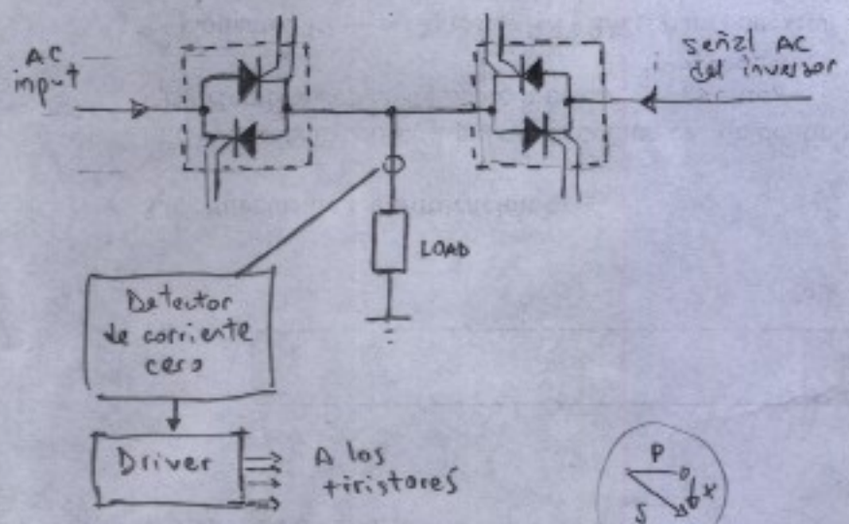
Otras:

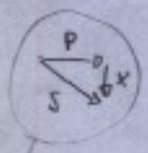
* Autonomía
* Estabilización
* Forma de onda de salida → carga crít: senoidal; carga no crít: cuadrada
* Aislación eléctrica (seguridad) → Baja frec. (entrada: 50 Hz); Alta frec (salida) menos peso, volumen, etc
* Paralelismo.

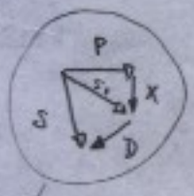
↓

Amplia potencia, autonomía ó confiabilidad:
(condiciones: igual magnitud, frec y fase)

LLAVE ESTÁTICA O BY-PASS:





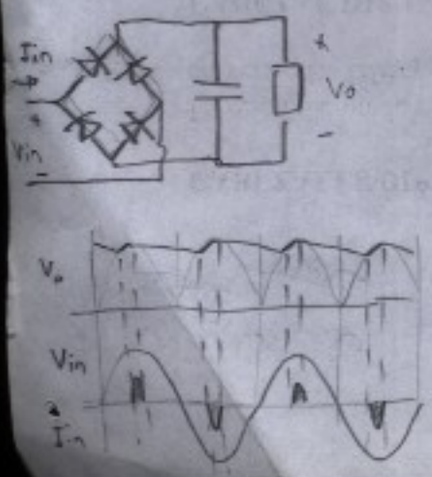


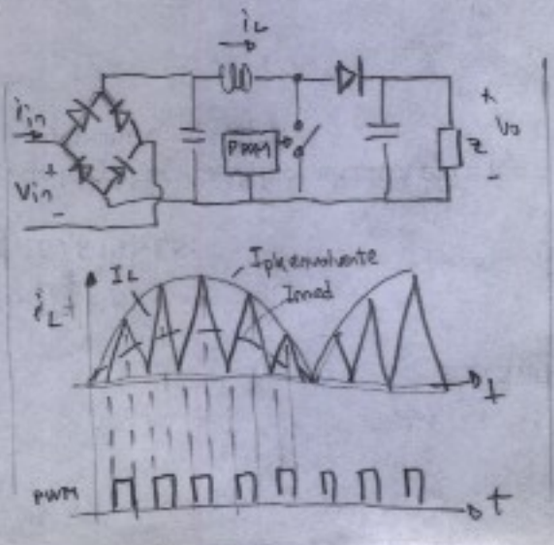
FACTOR DE POTENCIA: ($PF = \cos\varphi$; $PF = I_{1\text{-}rms} \cos\varphi / I_{rms}$; $PF = P/S$)

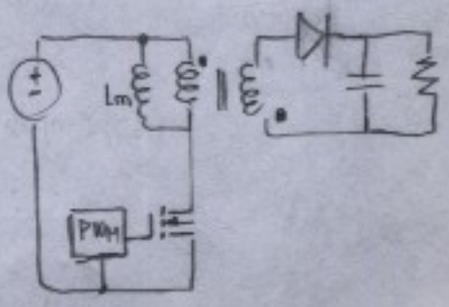
Se puede mejorar el factor de potencia con cualquier topología de conmutación.

Lo más recomendado → BOOST → pocos componentes; L minimiza el ruido de entrada; driver simple

→ Fly-back (aislación)







PRÁCTICO: "RECTIFICADORES DE POTENCIA"

A.1) Diseño completo de un rectificador, aplicado a motor de C.C. con control de los 4 cuadrantes. Vin = 380 rms
Tres fases con neutro con corriente circulante

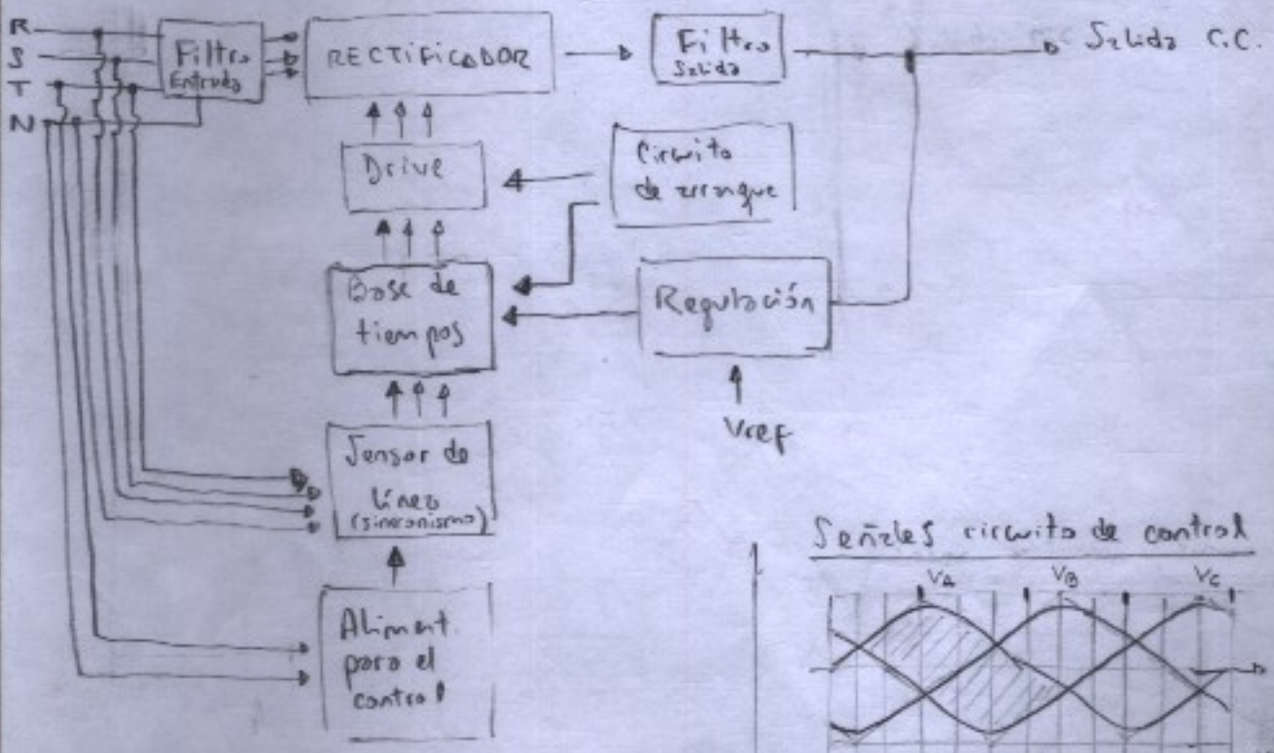
A.2) Selección y cálculo de los dispositivos de potencia

A.3) Diseñar filtro de entrada de línea para eliminar los armónicos generados a la red por el rectificador.

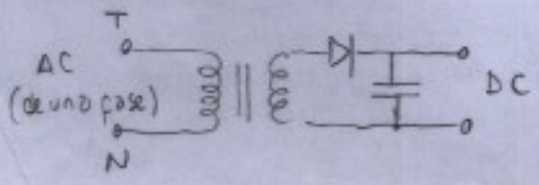
A.4) Red de ayuda SNUBBER

A.5) Drive de compuerta del tiristor, arranque suave y protección de sobrecorriente → ¿habrá querido decir sobretensión?

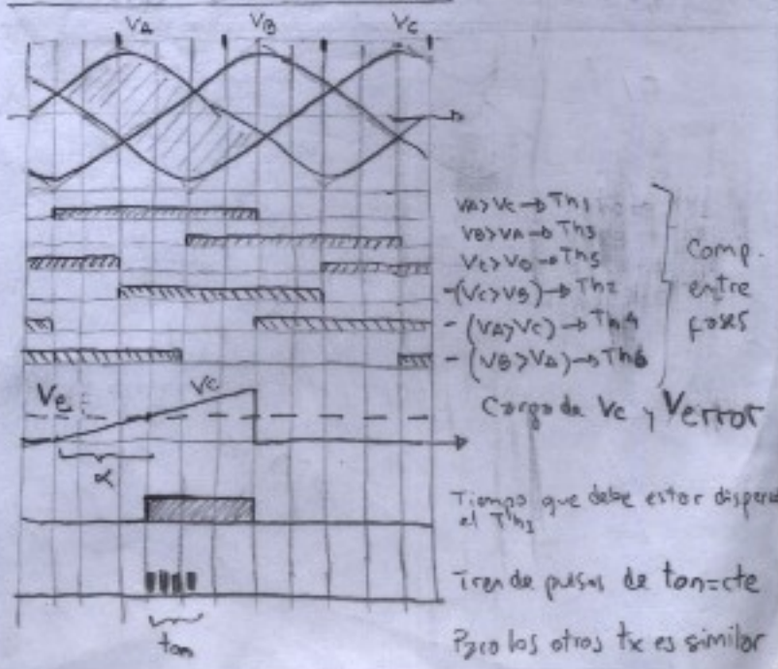
A.1) Esquema general (A.1.1)



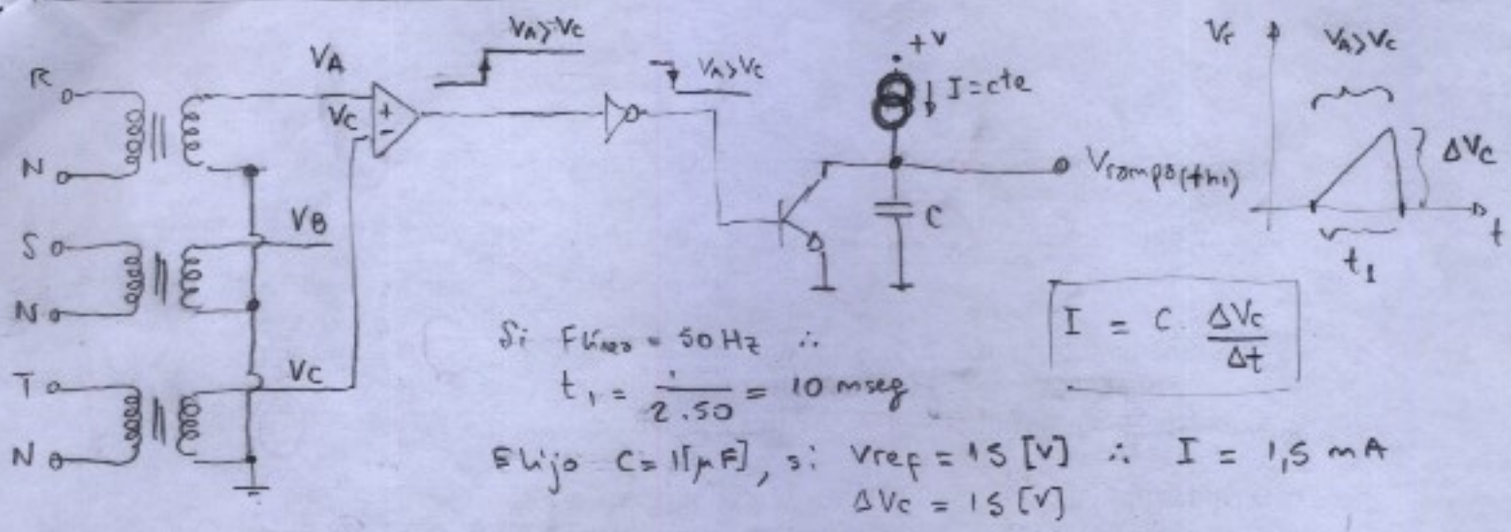
Aliment para el control (A.1.2)



Señales circuito de control (A.1.3)



Sensor de línea (sincronismo de fase) (A.1.4)



$$I = C \cdot \frac{\Delta V_c}{\Delta t}$$

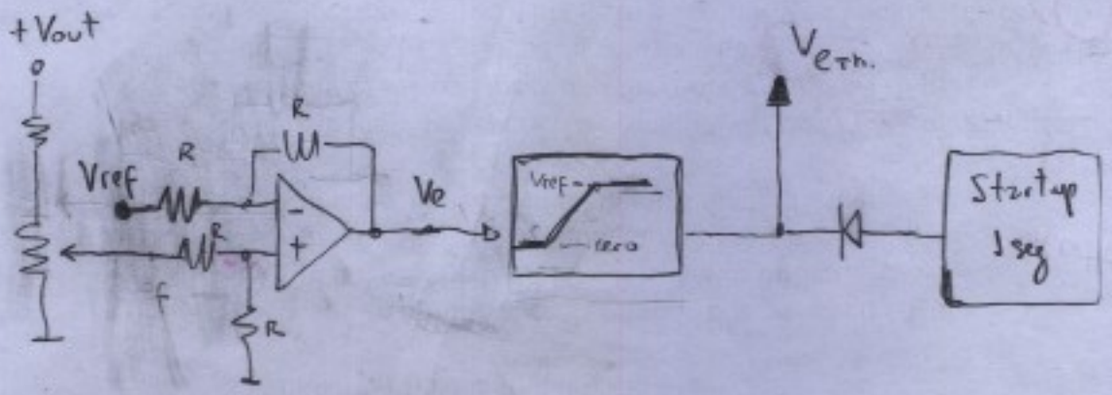
Si $F_{línea} = 50\,Hz$ ∴

$$t_1 = \frac{1}{2 \cdot 50} = 10\ mseg$$

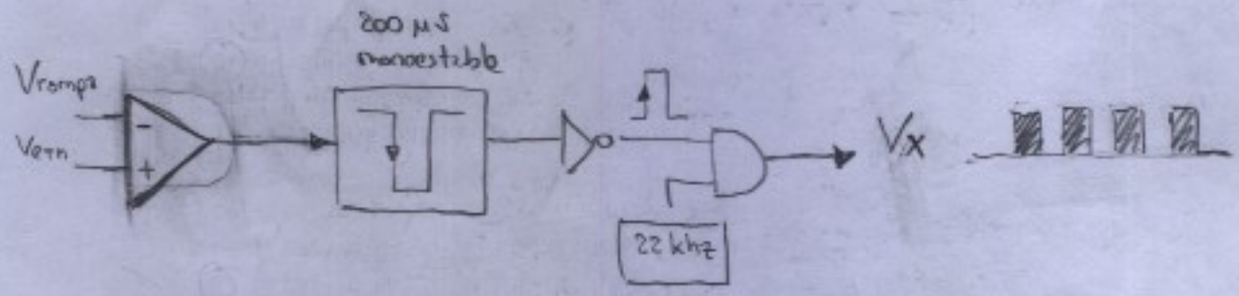
Elijo $C = 1[\mu F]$, si $V_{ref} = 15\,[V]$ ∴ $I = 1{,}5\ mA$

$\Delta V_c = 15\,[V]$

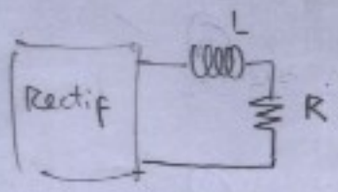
Regulación y circuito de arranque (A.1.5)



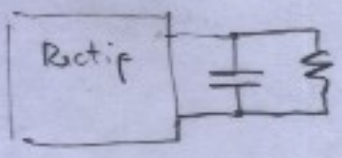
Base de tiempos (A.1.6)



Filtro de salida (A.1.7)

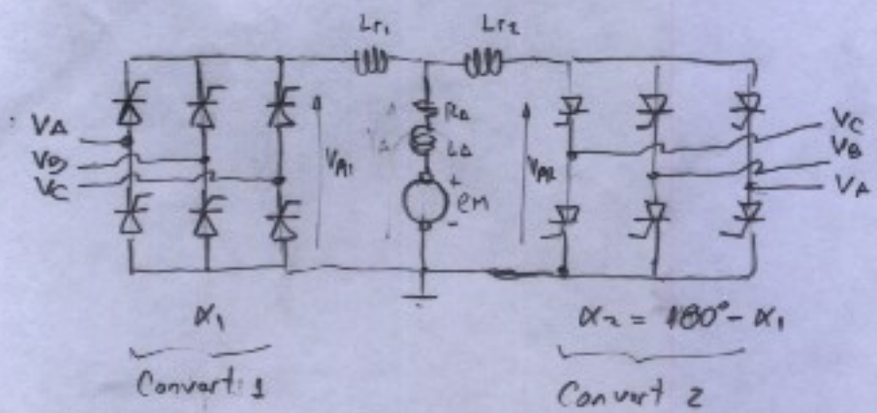


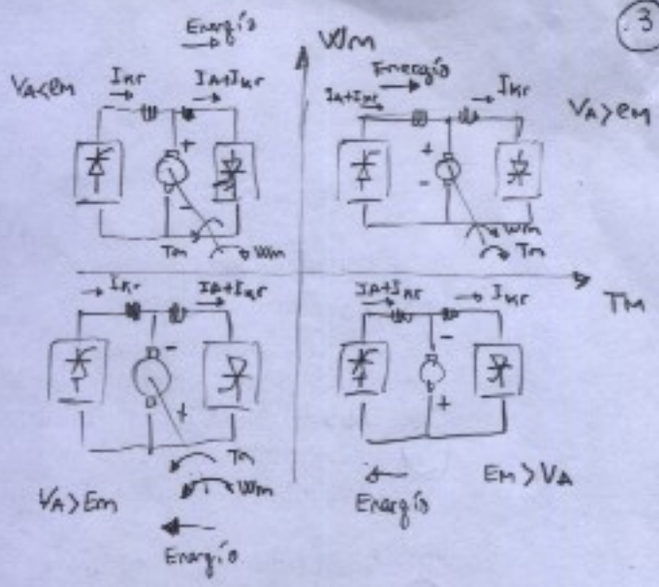
aplicac. alta potencia (mejora el factor de forma)



aplic. baja pot. (mejora el ripple de salida)

Rectificador Dual (A.1.8)





A.2)

$V_{LL_rms} = 380$ V

$V_{LN_rms} = 220$ V

$I_r = 10\% \cdot I_A = 10\% \cdot I_{omáx}$

$I_{Th_AV} = \dfrac{I_{o_máx}}{3} = \dfrac{I_o}{3}$

$I_{Th_rms} = \dfrac{I_{o_máx}}{\sqrt{3}}$

$V_{R_máx} = 2 \cdot V_{máx} \cos\left(\dfrac{\pi}{2q}\right)$

$V_{máx_PD} = \sqrt{3} \cdot V_{LN_máx}$

$V_{máx} = \sqrt{3} \cdot 311 = 538{,}66$ V

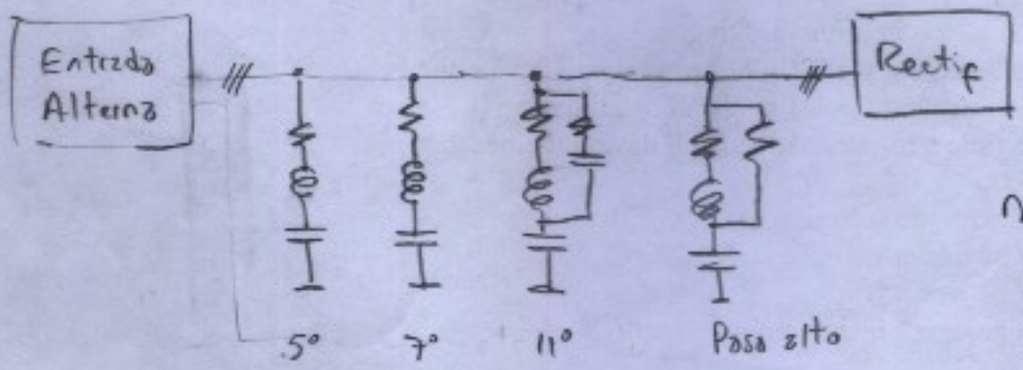
$V_{R_máx} = 2 \cdot 538{,}66 \cdot \underbrace{\cos\left(\dfrac{\pi}{6}\right)}_{\sqrt{3}/2} = 932{,}98$ [V]

Si $V_{AV} = 100$ [V], no es dato, suponemos

$V_{AV} = \dfrac{3\sqrt{3}\, V_{máx_{LN}}}{\pi} \cos\alpha = \dfrac{3\sqrt{3} \cdot 311}{\pi} \cdot \cos\alpha = 514{,}39 \cos\alpha = 100$

$\alpha = \arccos\left(\dfrac{100}{514{,}39}\right) = \arccos(0{,}1944) = 78{,}79°$

A.3)



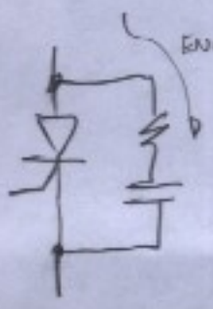
$n = k \cdot p \pm 1$

$k = 1, 2, 3, \ldots$

$p = 3$

$n = 5, 7, 11, 13, \ldots$

A.4)



snubber red

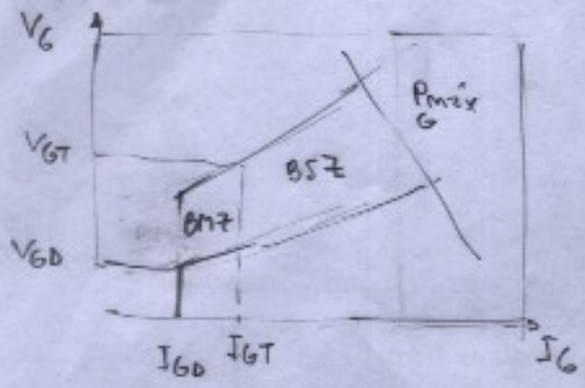
controla la $\dfrac{dv}{dt}$

$R = 470\ \Omega$

$C = 0{,}1\ \mu F$

de la vida real

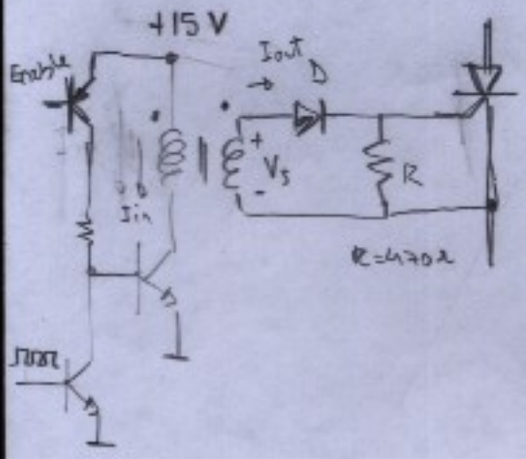
A.5) Drive del tiristor : (A.5.1)

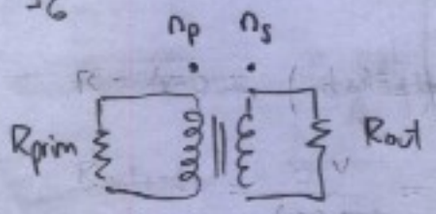


$I_G \rightarrow$ 3 a 5 veces I_{GT}

$I_{GT} \approx 150$ mA $\rightarrow I_G = 600$ mA

$V_{GT} \approx 3V$





$$R_{out} = \frac{0,7+3}{0,6} = 6,17\,\Omega$$

$$R_{prim} = \left(\frac{n_p}{n_s}\right)^2 \cdot 6,17\,\Omega$$

$$P_{out} = 3,7 \cdot 0,6 = 2,22\ W$$

$$\eta = 0,8 \therefore P_{in} = \frac{2,22}{0,8} = 2,775\ W$$

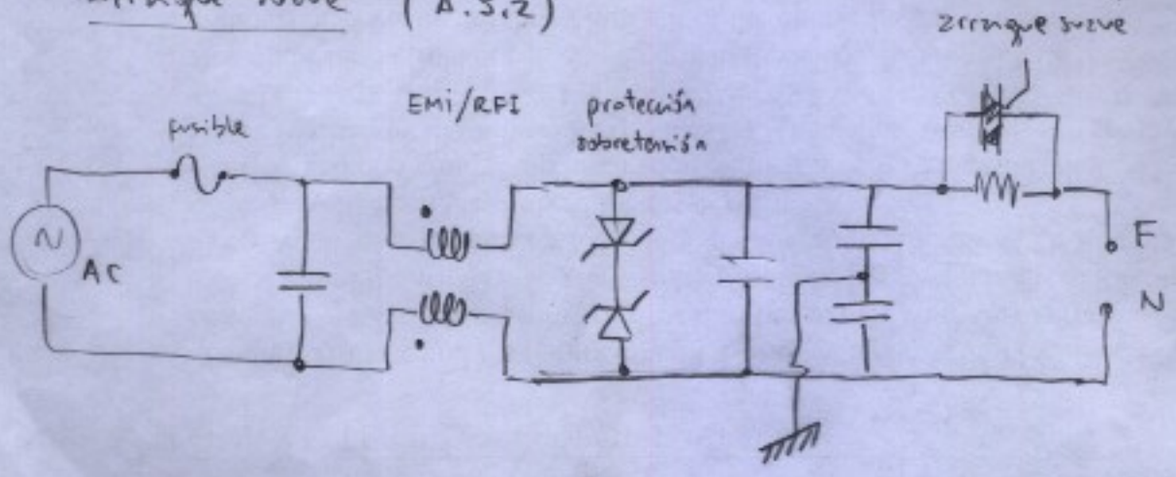
$$I_{in} = \frac{2,775}{15-0,2} = 0,187\ A$$

$$\frac{V_p}{n_p} = \frac{V_s}{n_s}$$

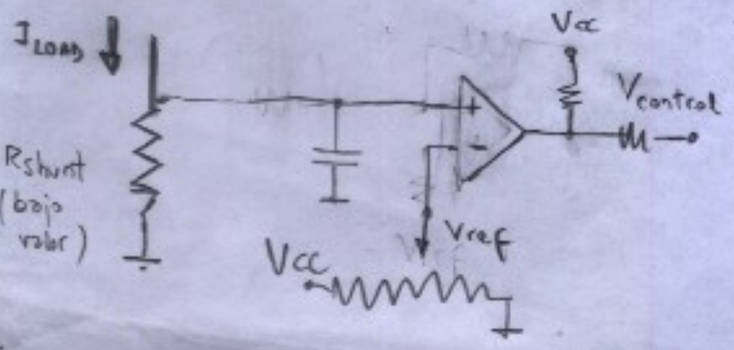
$$\frac{n_p}{n_s} = \frac{14,8}{3,7} = 4$$

$$R_{prim} = 98,72\,\Omega$$

Arranque suave (A.5.2)



Protección sobrecorriente (A.5.3)



B.1) Diseño de un rectificador semicontrolado PD3

B.2) Diseño del circuito de control

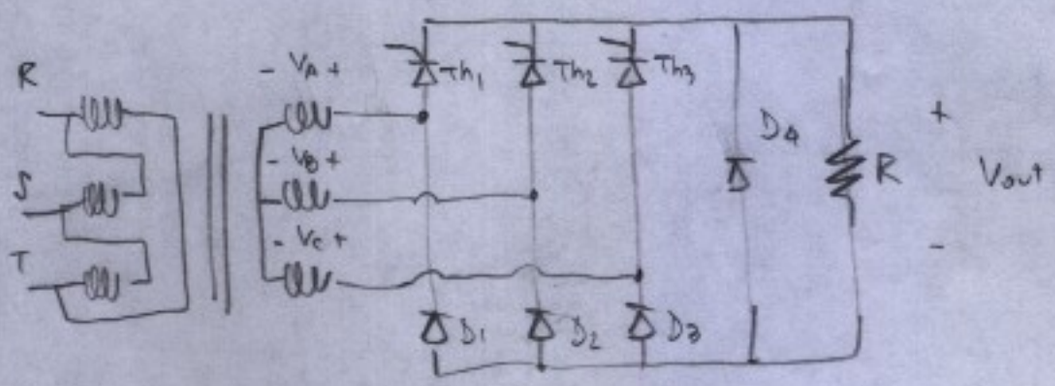
B.3) Circuito sincronismo de fase

B.4) Etapa de potencia

Datos: I_o (máx) = 100 A
Carga resistiva
V_{out} = 100 V a V_{out} máx posible
V_{in} = 380 V, 50 Hz, con neutro
V_{ref} = 0 a 15 V

B.1) Esquema general idem pto. (A.1) excepto pto. (A.1.8)

Rectif. Semicontrolado (B.1.1)



B.2) Idem ptos (A.1.3) (A.1.2) (A.1.5)

B.3) Idem ptos (A.1.4) (A.1.6)

B.4) $I_{AV(diodos/Ths)} = \frac{I_{omáx}}{q} = \frac{100\ A}{3} = 33\ A$

$I_{rms} = \frac{I_o}{\sqrt{q}} = \frac{100}{\sqrt{3}} = 57{,}73\ A$

$V_{R_máx} = 2 \cdot V_{máx} \cdot \cos\left(\frac{\pi}{2q}\right) = 2 \cdot$

$V_{máx} = 2 \cdot 930 \cdot \frac{\sqrt{3}}{2} = 1610$ [Volts]

Si en cambio consideramos $V_{máx} = 311$ ∴

$V_{R_máx} = \sqrt{3} \cdot 311 = 538{,}66$ V

Si los 380 V son $V_{in_{LL-rms}}$ entonces debido a Δ→λ tenemos:

$V_{FN_rms_sec} = 380$ V

$V_{FN_máx_sec} = \sqrt{2} \cdot 380 = 537{,}4$

$V_{LL_máx} = \sqrt{3} \cdot 537{,}4 = 930{,}8$

Cálculo de α para $V_{out} = 100$ V ($V_{out\,mín}$):

$$V_{AV} = \frac{3\sqrt{3}\cdot V_{máx}}{2\pi}(1+\cos\alpha) = 257{,}195\,(1+\cos\alpha) = 100$$

$$\alpha = \cos^{-1}\left(\frac{100}{257{,}195} - 1\right) = 127{,}67^\circ$$

Rango de α $\longrightarrow$ $0^\circ \leq \alpha \leq 127{,}67$

PRÁCTICO: "FUENTES CONMUTADAS"

C) Diseño de una fuente conmutada aislada bidireccional para ser aplicada a un equipo de soldadura por arco

$V_{in} = 380$ Vrms (3 fases con neutro)

$V_{out} = 20$ a 30 V

$I_{out} = 200$ A (máximo)

$F_{sw} = 50$ khz

C.1) Seleccionar el convertidor más adecuado para esta aplicación

C.2) Seleccionar el PWM y su alimentación

C.3) Utilizar el transistor más adecuado. Justificar

C.4) Diseño del trafo de aislación. Fórmulas más importantes para esta aplicación.

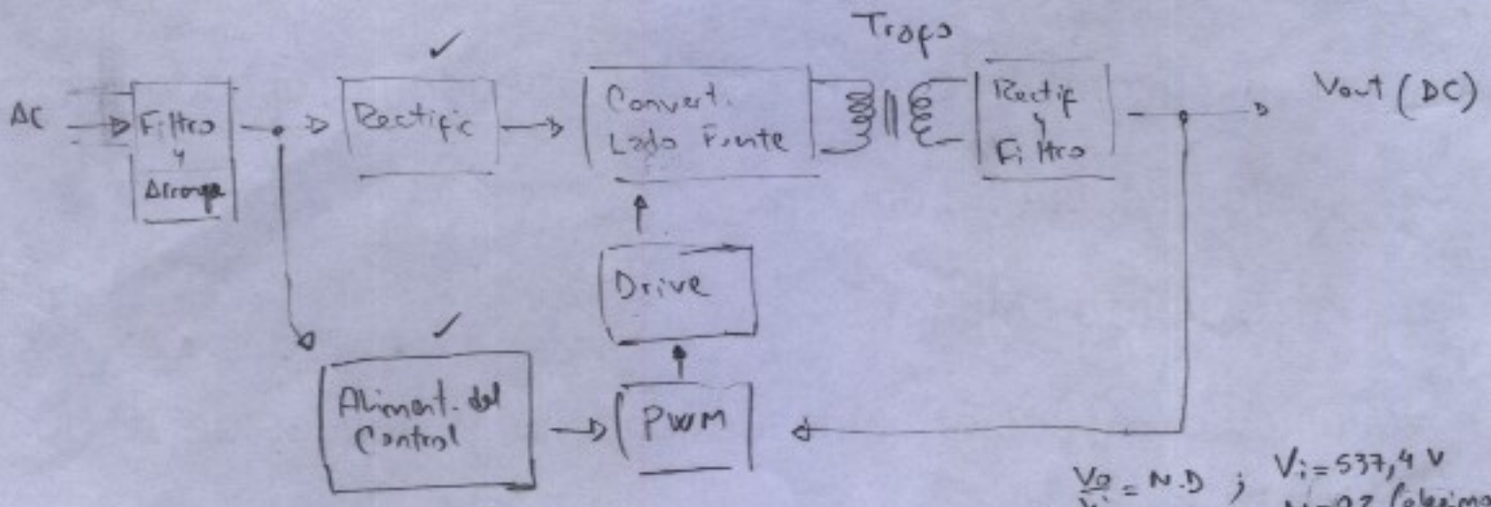
C.5) Red de ayuda a la conmutación. (snubber). Si es aplicable.

C.6) SOA y driver de base

C.7) Arranque suave y protección de sobrecorriente

C.8) Incluir filtro EMI-RFI.

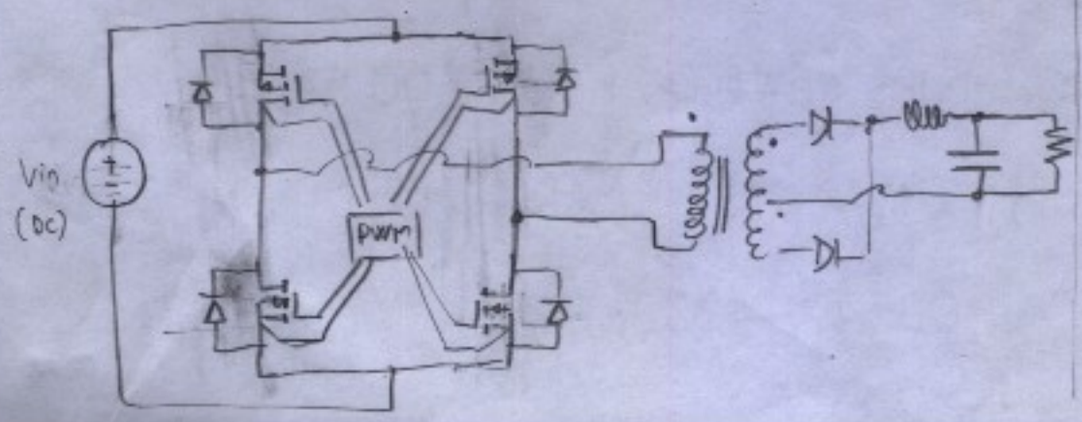
C.1) $P_{out} = V_{out} \cdot I_{out} = 30 \cdot 200 = 6000\ W = 6\ kW \rightarrow$ Fullbridge



$\frac{V_o}{V_i} = N \cdot D$; $V_i = 537{,}4$ V
$N = 0{,}2$ (elegimos)

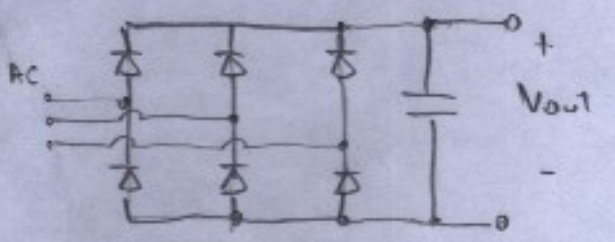
Para $V_o = 30$ V $\rightarrow D_1 = 0{,}279$

Para $V_o = 20$ V $\rightarrow D_2 = 0{,}186$



Rectificador (C.1.1)

Usamos un PD3



$V_{out} = V_{LL-máx} = 380 \cdot \sqrt{2} = 537{,}4\,[V]$

• Selección Tx para Fullbridge ⇒ $V_{amáx} > V_{inmáx}$

$V_{amáx} > 537{,}4\,V$

$I_{amáx} > N \cdot I_{out}$

$I_{amáx} > 40\,[A]$

• Elección Dx para PD3

⇓

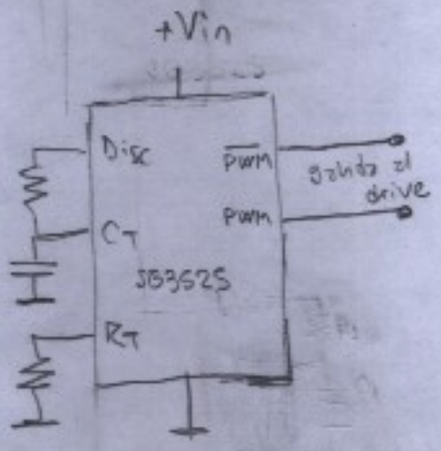
$V_{R(máx)} = \sqrt{3} \cdot V_{máx_{LL}} =$

$V_{R(máx)} = \sqrt{3} \cdot 537{,}4 = 930{,}8\,[V]$

$$\begin{cases} I_{Dmáx} = I_o \\ I_{Dmed} = \dfrac{I_o}{3} \\ I_{Drms} = \dfrac{I_o}{\sqrt{3}} \end{cases}$$

Aliment. del control: idem (A.1.2)

C.2) PWM



R_1 entre CT y Disch → controla tiempo muerto.

CT, RT → Controlan la frec. de oscilación.

Para 50 kHz $R_T = 3{,}6\,k\Omega$ aprox

$C_T = 0{,}01\,\mu F$ aprox.

C.3) Elegimos igbt

→ No puede ser mosfet ya que la V_{DSS} debería ser de 537,4 V y es mucho para un mosfet. Un igbt sí puede manejar es V_{CEV}

(Controlado por tensión) → Drive fácil

Bajas pérdidas en conducción

Inmunidad contra el autoencendido.

Si bien no tiene tan buenas características de conmutación como el MOSFET pero sí está muy cerca (mejores q' el BJT)

Puede manejar la corriente necesaria con alguna.

C.4) a) Especificaciones (datos)

b) Dimensiones del núcleo

c) Evaluación de la densidad del flujo de AC máximo:

si $B_{dc} \neq 0 \therefore B_{AC_máx} + B_{dc} < B_{sat}$.

d) Determinación de la cantidad de vueltas

e) Determinación sección del alambre

f) Verificar los cálculos → (inductancia de magnetización, corriente pico de magnetización, resist de los devanados)

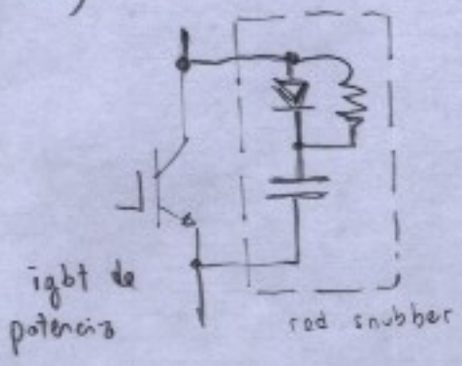
g) Ley de Faraday

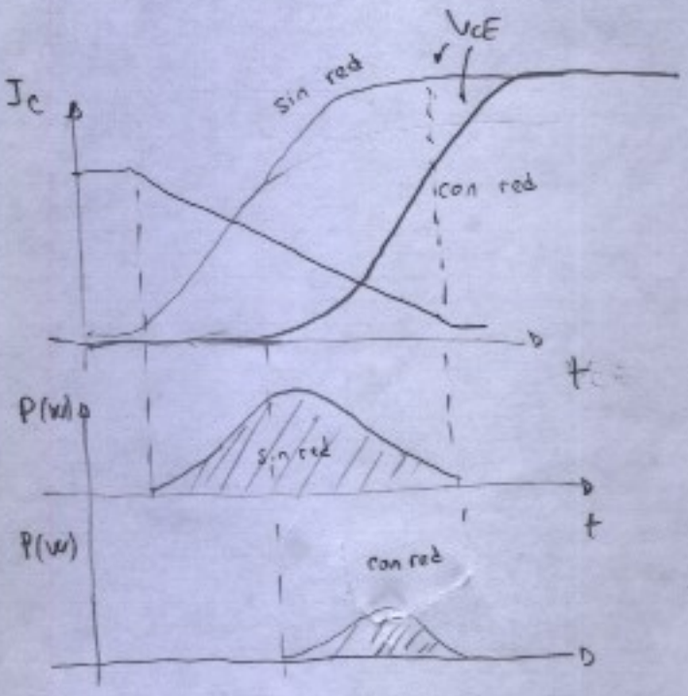
$$v(t) = N \cdot A_c \cdot \frac{dB(t)}{dt}$$

Ley de Ampere

$$H(t) \cdot l_m = N \cdot i(t)$$

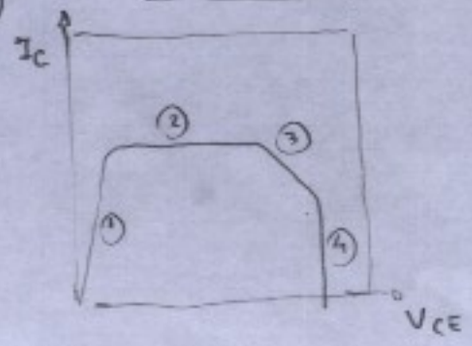
C.5)





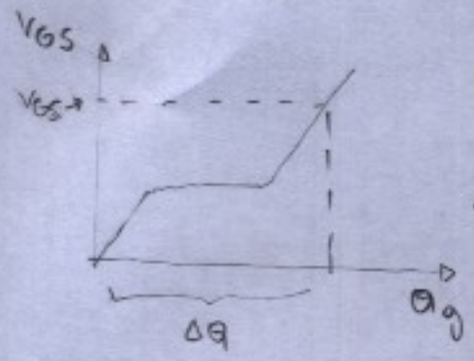
C.6)

SOA (IGBT) (C.6.1)



1. Límite impuesto por la resist. de saturación
2. " " por la $I_{CMÁX}$
3. " " " " $P_{MÁX}$ (CE)
4. " " " " $V_{CEMÁX}$)

Drive de base (C.6.2)



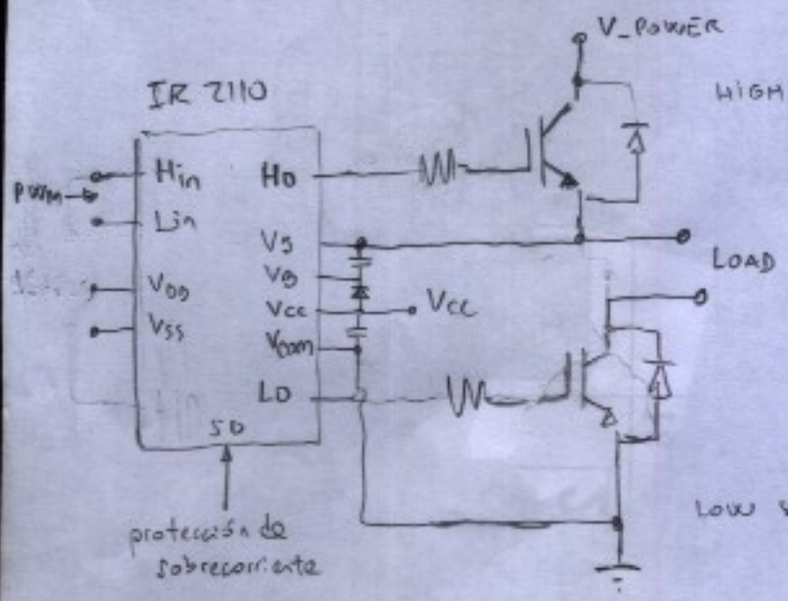
"carga de compuerta"

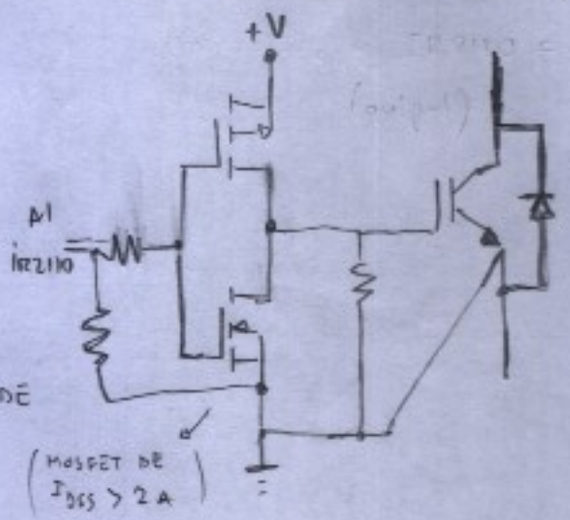
← (datasheet)

$$\frac{\Delta Q}{t_{conm}} = I_G$$

$I_{omáx}$ (IR2110) = ±2 A

Si hace falta más ↓





C.7) ¡idem ptos (A.5.2) y (A.5.3)

C.8) ¡idem pto (A.5.2)

PRÁCTICO: "INVERSORES"

D) Diseño de un inversor trifásico para poder ser aplicado en un control escalar para un motor asíncrono por la técnica V/f con las siguientes características:

V_{in} = 380 Vrms 3 fases con neutro

V_o = 380 Vrms 3 fases sin neutro

f_o = 0 a 100 Hz / 50 Hz nominal

D.1) Diagrama en bloques y circuito completo

D.2) Modulación SVPWM

D.3) Usar IGBT

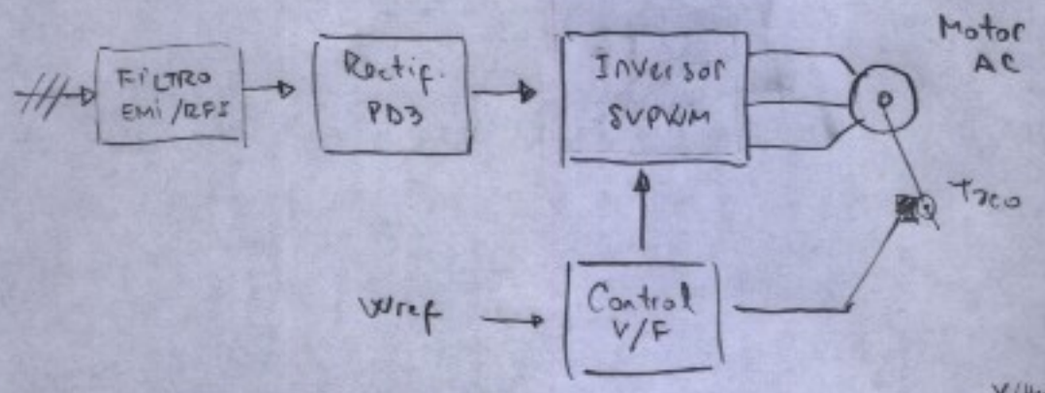
D.4) Selección de los dispositivos de potencia

D.5) Si es aplicable red snubber

D.6) SOA y driver de base del transistor

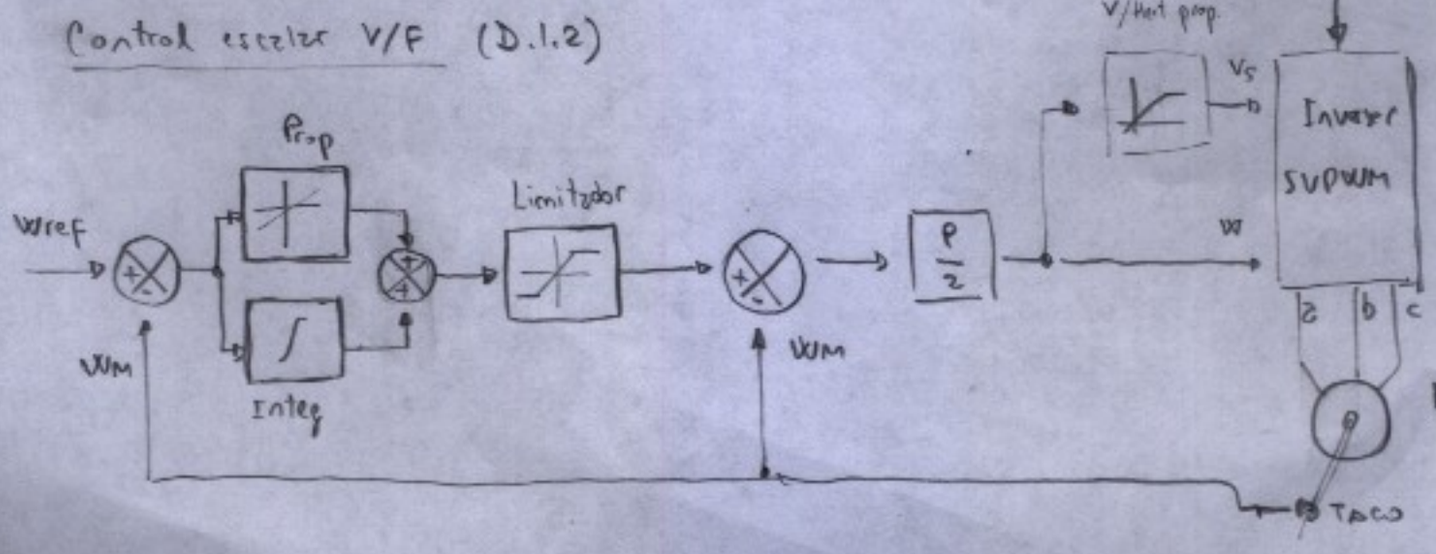
D.7) Incluir filtro EMI/RFI

D.1) Diagrama en bloques (D.1.1)



No especifica si el control debe ser a lazo abierto o cerrado, elegimos a lazo cerrado (con realimentación) para tener error en estado estac. igual a cero

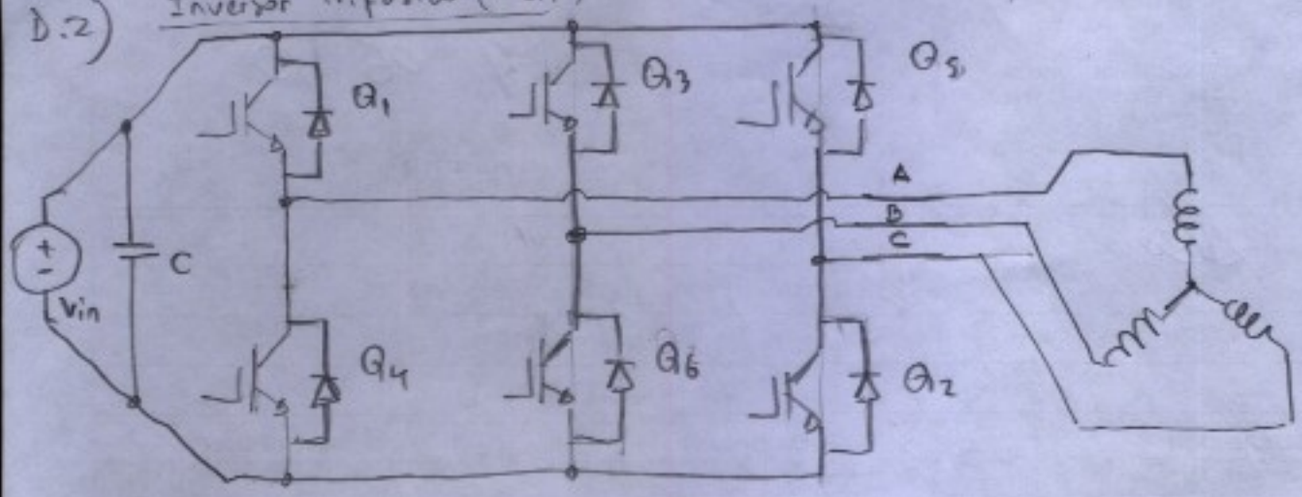
Control escalar V/F (D.1.2)



Filtro EMI/RFI: idem (A.5.2) + armónicos (A.3) por c/fase

Rectificador PD3: idem (C.1.1)

D.2) Inversor trifásico (D.2.1)



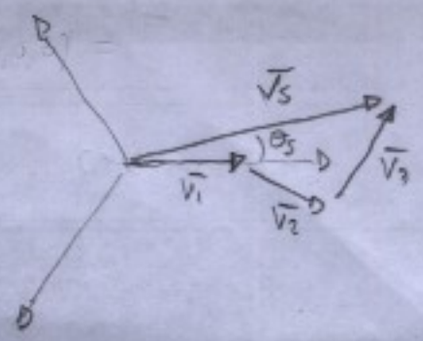
Modulación SVPWM (D.2.2)

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = V_{in} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad ; \quad \begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{in}}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

a	b	c	V_{AB}	V_{BC}	V_{CA}	V_{AN}	V_{BN}	V_{CN}
0	0	0	0	0	0	0	0	0
0	0	1	-1/3	-1/3	2/3	0	-1	1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	0	1/3	1/3	-2/3	0	1	-1
1	1	1	0	0	0	0	0	0

$$\bar{V}_S(t) = V_a(t) \cdot e^{j\phi} + V_b(t) \cdot e^{j\frac{2\pi}{3}} + V_c(t) \cdot e^{j\frac{4\pi}{3}}$$

$$\bar{V}_S(t) = \bar{V}_1(t) + \bar{V}_2(t) + \bar{V}_3(t) = \hat{V}_S \cdot e^{j\theta_S}$$



$\bar{V}_S(0,0,0) = \bar{V}_0 = \emptyset$

$\bar{V}_S(0,0,1) = \bar{V}_1 = V_{in} \cdot e^{j4\pi/3}$

$\bar{V}_S(0,1,0) = \bar{V}_2 = V_{in} \cdot e^{j2\pi/3}$

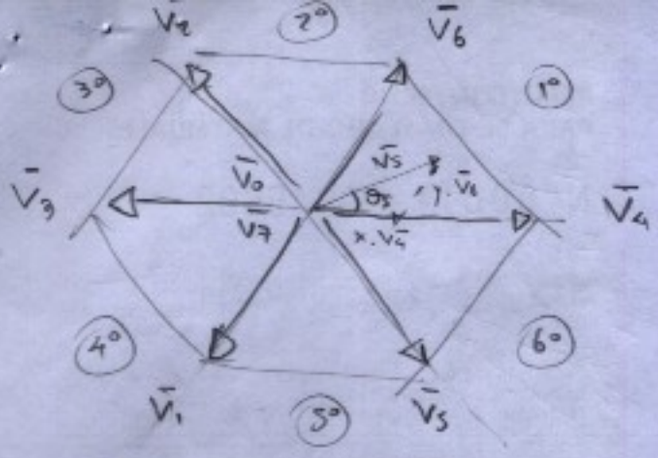
$\bar{V}_S(0,1,1) = \bar{V}_3 = V_{in} \cdot e^{j\pi}$

$\bar{V}_S(1,0,0) = \bar{V}_4 = V_{in} \cdot e^{j\phi}$

$\bar{V}_S(1,0,1) = \bar{V}_5 = V_{in} \cdot e^{j5\pi/6}$

$\bar{V}_S(1,1,0) = \bar{V}_6 = V_{in} \cdot e^{j\pi/3}$

$\bar{V}_S(1,1,1) = \bar{V}_7 = \emptyset$



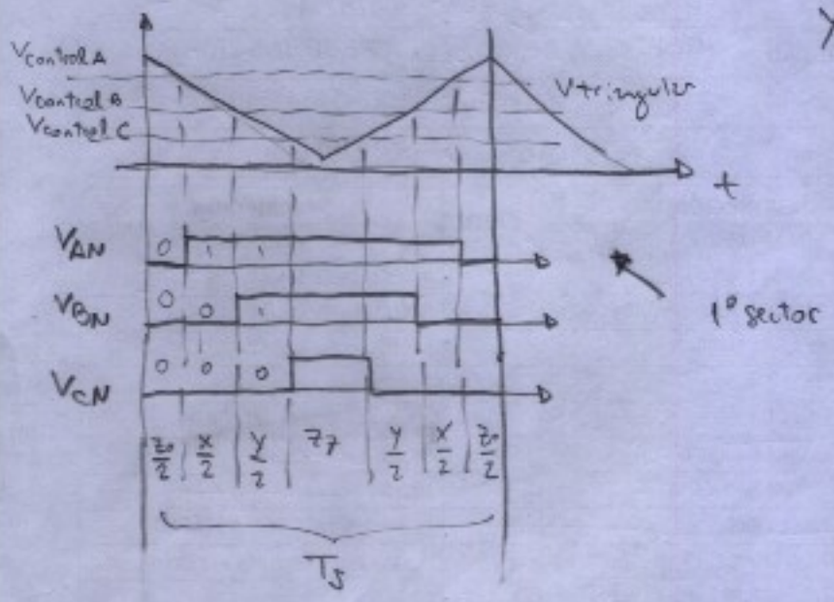
$$\bar{V}_s = \hat{V}_s \cdot e^{j\theta_s} = \frac{1}{T_s}\left(x.T_s.\bar{V}_4 + y.T_s.\bar{V}_6 + z.T_s.\bar{0}\right) \quad (13)$$

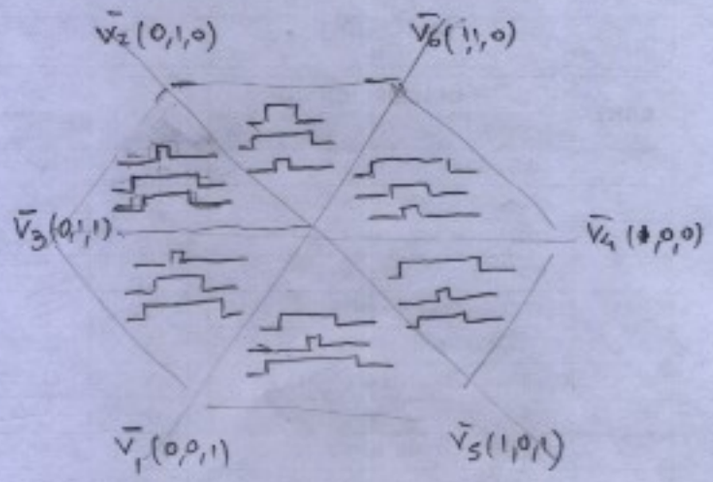
$$\bar{V}_s = x.\bar{V}_4 + y.\bar{V}_6$$

$$x + y + z = 1$$

$$x = \frac{\hat{V}_s}{V_4}\left(\cos\theta_s - \frac{\operatorname{sen}\theta_s}{\sqrt{3}}\right)$$

$$y = \frac{2.\hat{V}_s}{\sqrt{3}.V_6}.\operatorname{sen}\theta_s$$





D.3) Usamos IGBT. idem pto (C.3)

D.4) V_{CES} ó $V_{(BR)CES} > V_{in_max}$

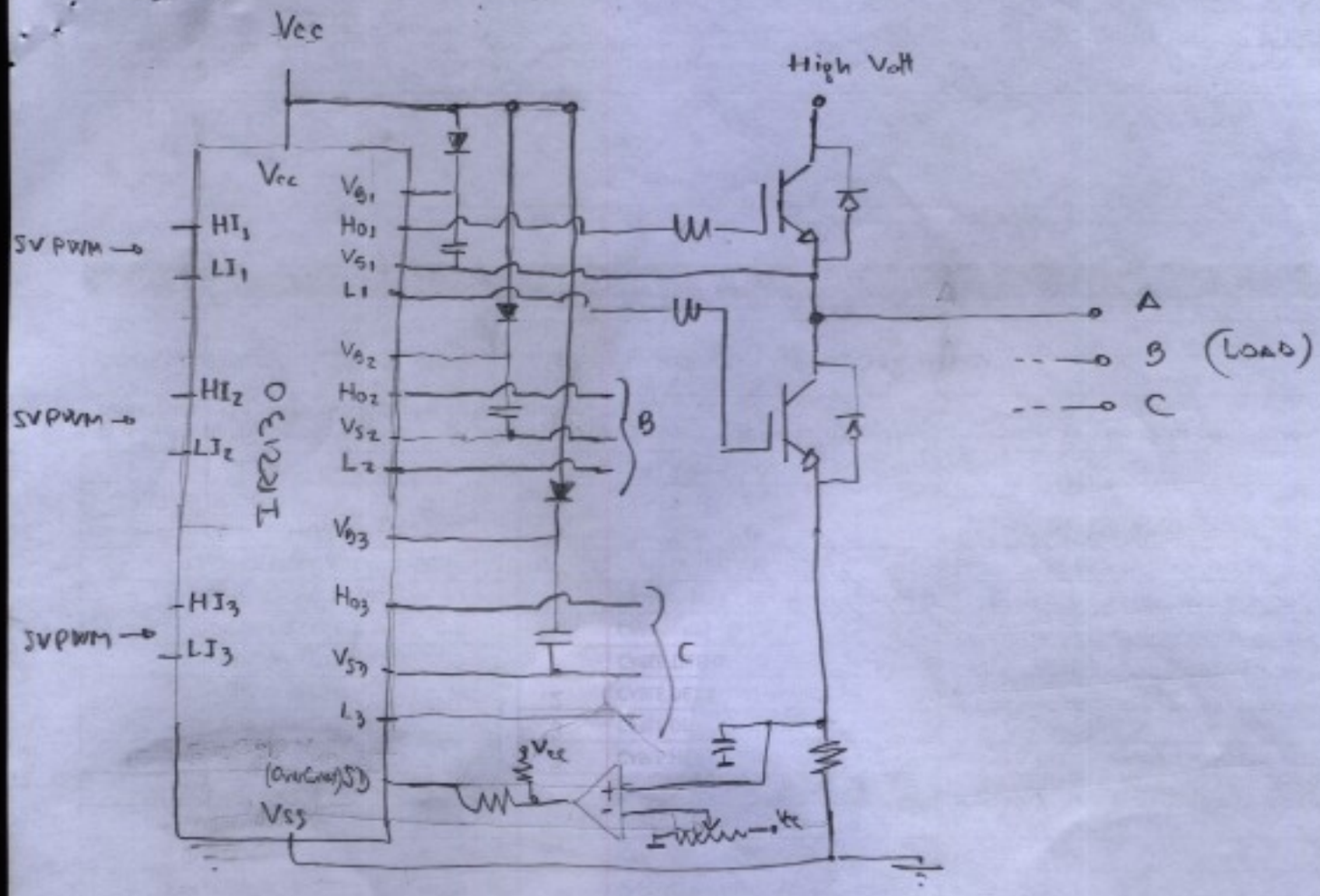
$V_{CES} > 537{,}4\ [V]$ ← Salida del PD3 con capacitor filtro.

$I_{CE(máx)} > I_0$

D.5) No es aplicable red snubber

D.6) <u>SOA y drive de base (D.6.1)</u>: idem (C.6) + ...

Usamos el IR2130, que tiene capacidad para manejar tres canales (ALTO y BAJO) independientes. $I_{omáx} \approx 250$ mA → se puede llegar a necesitar un buffer extra si la $I_G > 250$ mA (es lo más probable).



Si $I_G > 250$ mA → circuito (C.6.2)

D.7) Filtro EMI/RFI: idem (A.5.2)

PRÁCTICO: "MOTORES DE CC"

E.1) Diseño de un control de velocidad para un motor de cc. clase C

E.2) Circuito de aplicación

E.3) Lazo cerrado de control de velocidad

E.4) Utilizar técnica de conmutación adecuada y justificar.

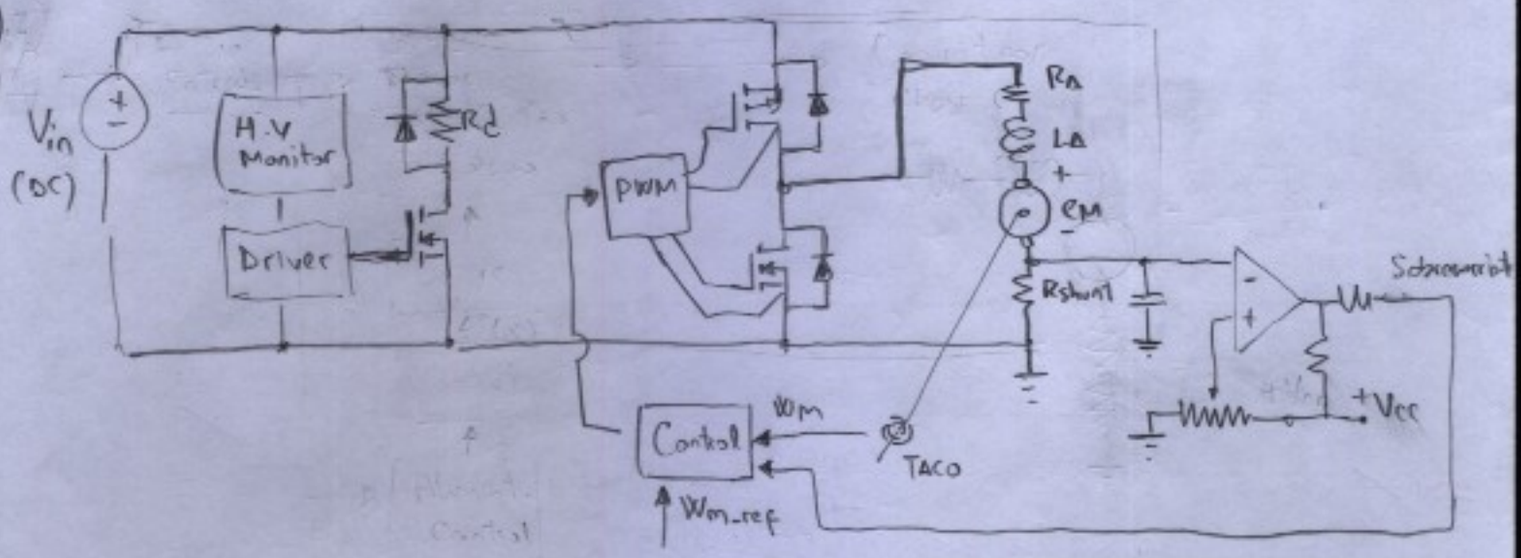
E.5) Utilizar transistores más apropiados y justificar

E.6) Si es aplicable red snubber

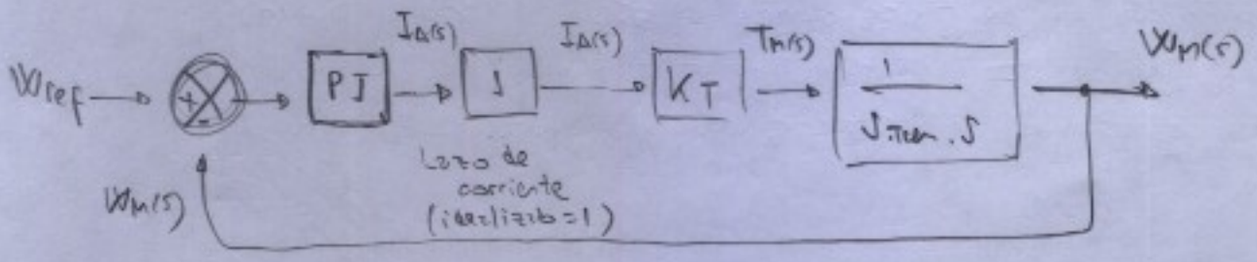
E.7) Driver de base . SOA

E.8) Protección sobrecorriente

E.1)
E.2)



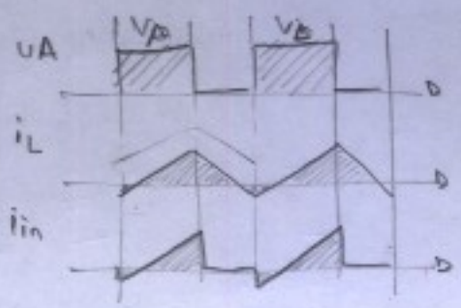
E.3) Lazo control de velocidad



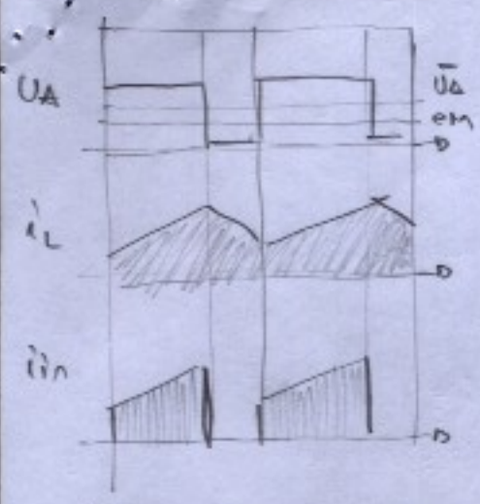
$$G_{\Omega(ol)} = \frac{K_{i\Omega} \cdot K_T}{J_{Tm}} \cdot \frac{1}{s^2}\left(1 + \frac{s}{k_{i\Omega}/k_{p\Omega}}\right)$$

Ancho de banda aprox = 100Hz

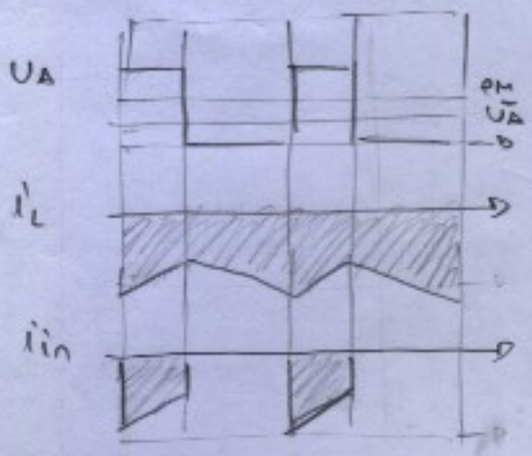
E.4) Usamos CCM para no perder torque



cuadrantes en 1° y 2° cuadrante



1° cuadrante (motor)



2° cuadrante (freno)

E.5) Utilizamos mosfet.

- Rápida conmutación
- Fácil driver (controlado por tensión) → requiere poca pot. de entrada, pocos comp.
- Maneja corriente de motores de mediana potencia

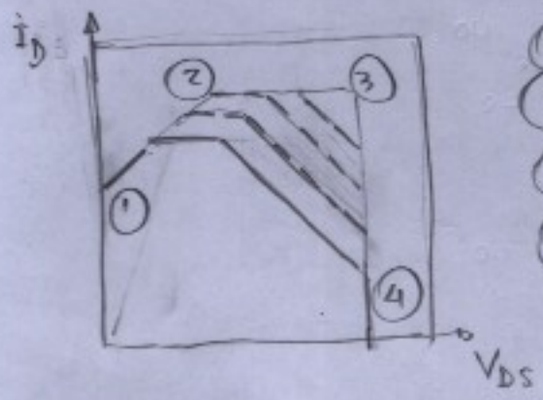
$$V_{DS_máx} > V_{in\,máx}$$

$$I_{DS_máx} > \frac{V_A - e_M}{R_A} + \left[I_{L\,mín} - \frac{V_A - e_M}{R_A} \right] \cdot e^{-t_{on}/\tau_{el\,A}}$$

E.6) No es aplicable red snubber

E.7) Drive de base idem (C.6.2)

SOA

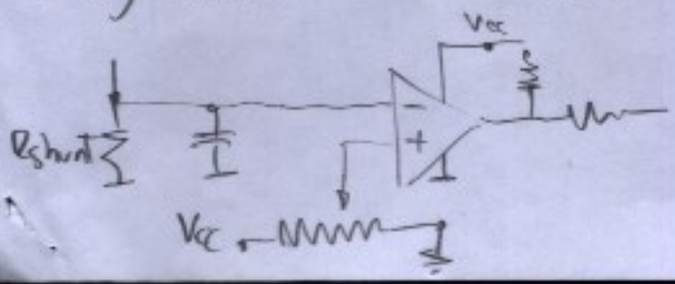


1. $R_{DS(ON)}$
2. $I_{D\,máx}$
3. Pot. máx

} función de D

4. $V_{DS\,máx} = V_{(BR)DS}$

E.8) Protección sobrecorriente

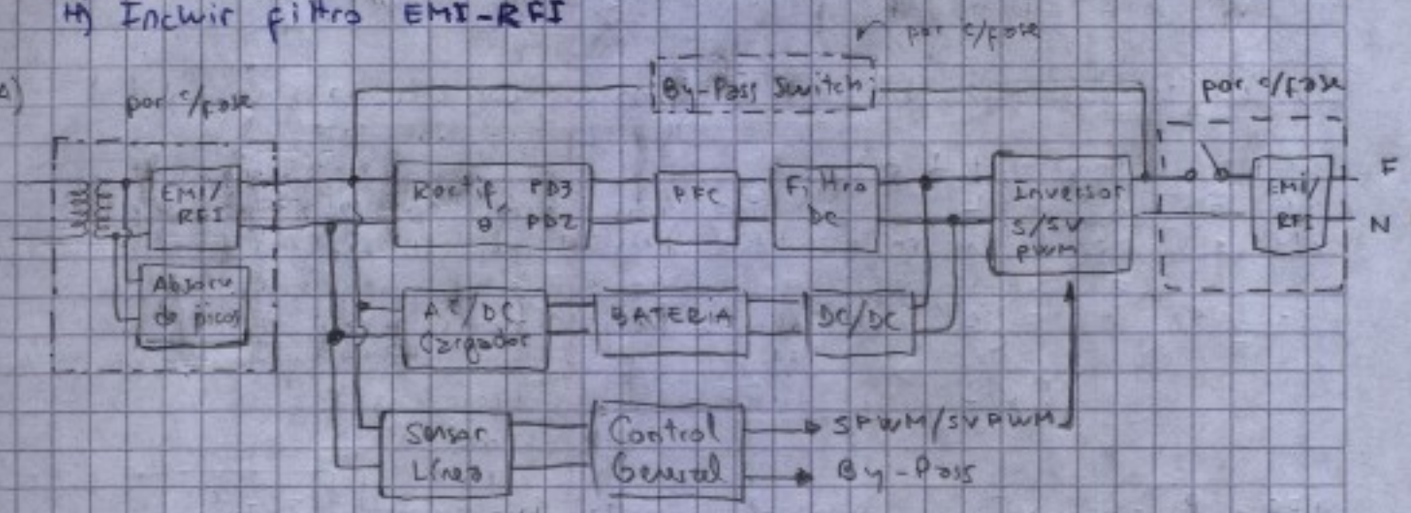


5) DISEÑAR UN INVERSOR PARA UN UPS ON-LINE

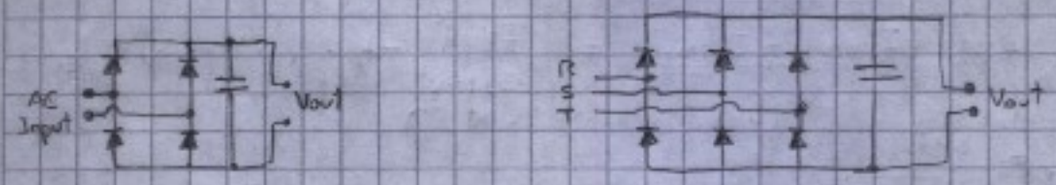
$V_{in} = 380$ rms c/neutro
$V_{out} = 220$ rms
$I_{out} \Rightarrow$ 50 Hz nominal enganchado con la red.

A) Diagrama en bloques del circuito completo
B) Circuito de control, análisis en c/etapa.
C) Usar SPWM
D) Propuesta de una lógica de funcionamiento en bloques
E) Usar IGBT
F) Selección de los dispositivos de potencia
G) SOA - Driver de base
H) Incluir filtro EMI-RFI

A)



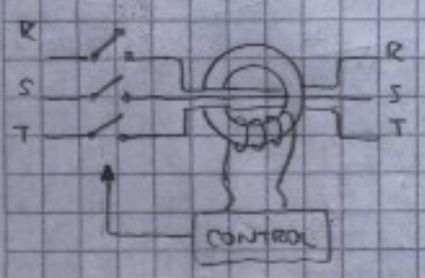
By D) PD2 PD3



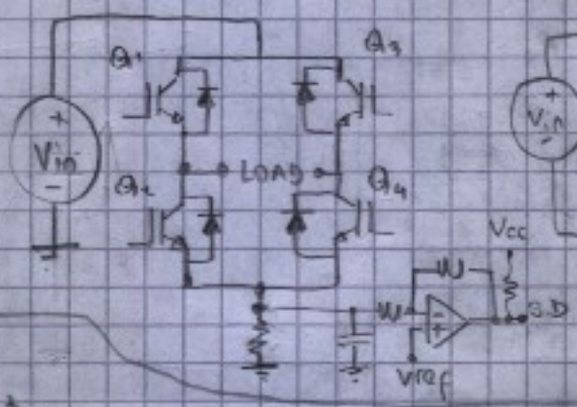
$V_{out} = \hat{V}_{in} = \sqrt{2} \cdot 220 = 311$ V
ó $V_{out} = \hat{V}_{in} = \sqrt{2} \cdot 380 = 537{,}4$ V

$V_{out} = \hat{V}_{in} = V_{L\,rms} \cdot \sqrt{2} = 380 \cdot \sqrt{2} = 537{,}4$ V

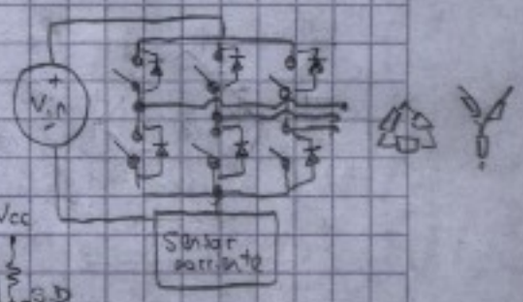
Sensor de línea



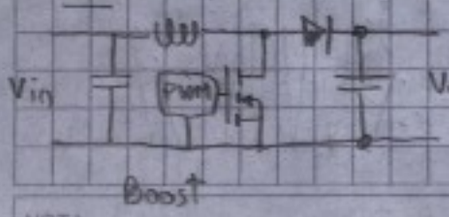
Inversor Monofásico



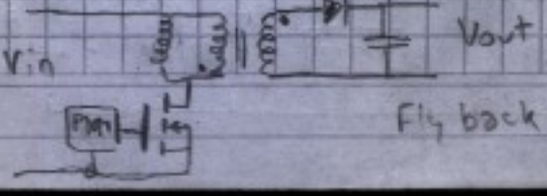
Inversor Trifásico



PFC



Boost



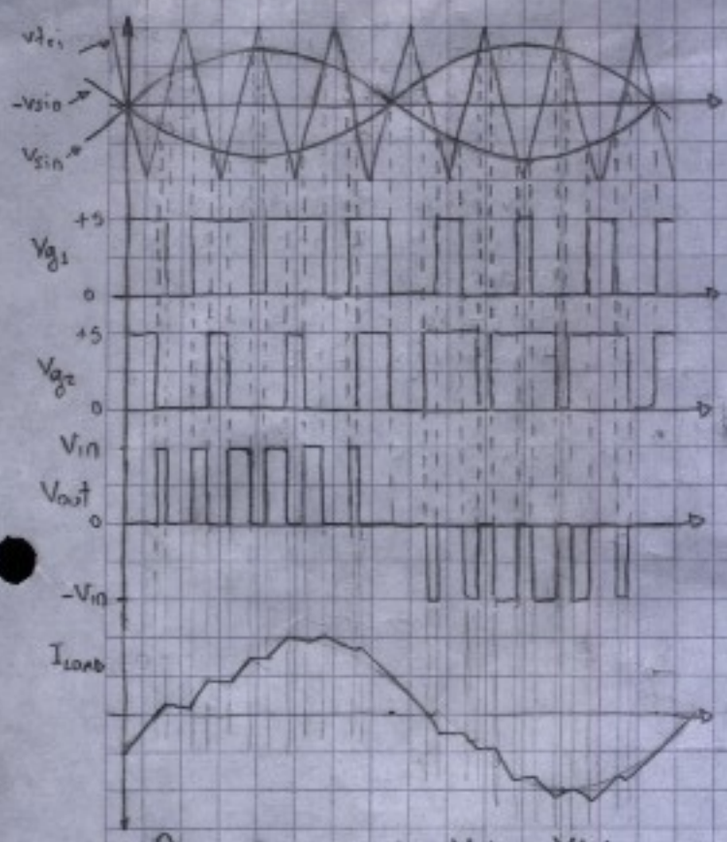
Fly back

NOTA

HOJA N°

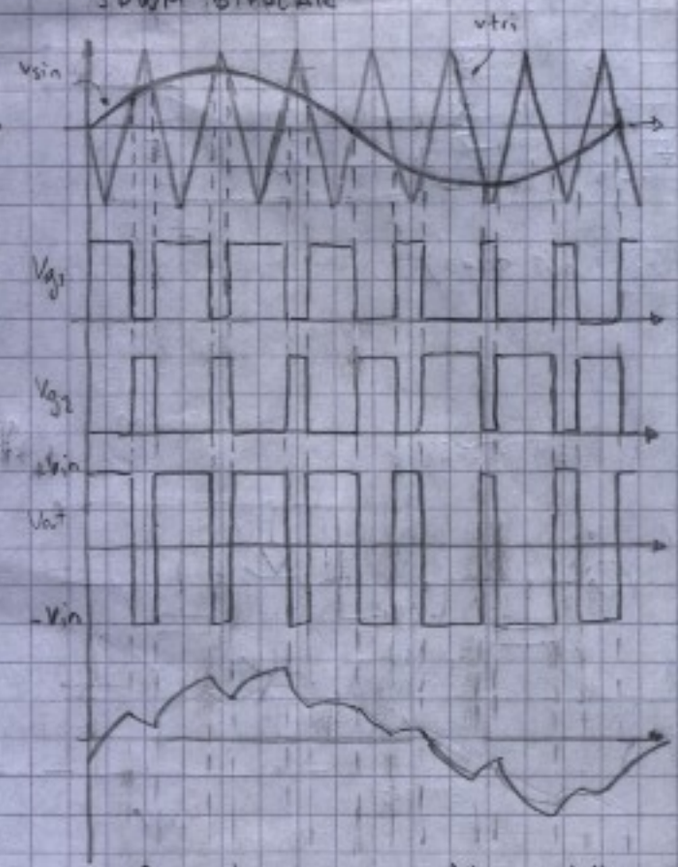
FECHA

C) SPWM UNIPOLAR

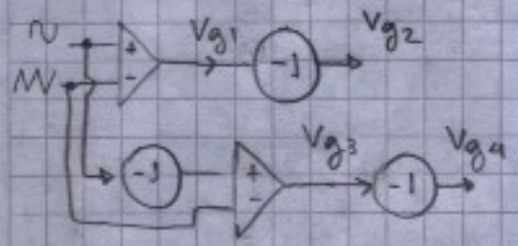


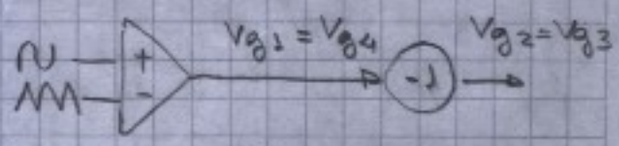
Q_1 conduce cuando $V_{sin} > V_{tri}$
Q_2 " " $-V_{sin} < V_{tri}$
Q_3 " " $-V_{sin} > V_{tri}$
Q_4 " " $-V_{sin} < V_{tri}$

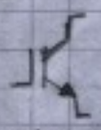
SPWM BIPOLAR



Q_1 conduce cuando $V_{sin} > V_{tri}$
Q_2 " " $V_{sin} < V_{tri}$
Q_3 " " $V_{sin} < V_{tri}$
Q_4 " " $V_{sin} > V_{tri}$



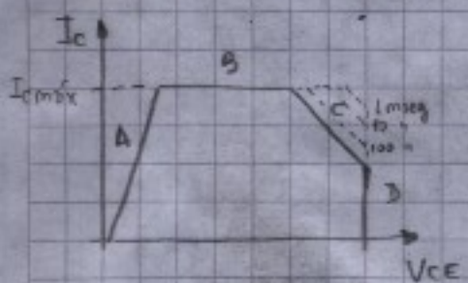


E, F) Igbt  $V_{CES} \geq V_{in\,máx}$

$V_{in\,máx} = \sqrt{2} \cdot V_{rms} = \sqrt{2}\ 220 = 311\ V$
ó $V_{in\,máx} = \sqrt{2} \cdot 380 = 537{,}4\ V$

Valores típicos V_{CES} ó $V_{(BR)CES} = 1200\ V$

G) FBSOA (forward biased safe operation area) } SOA
SSOA (switching " " ")



A. Debido a $R_{DS(ON)}$ (ley de Ohm)

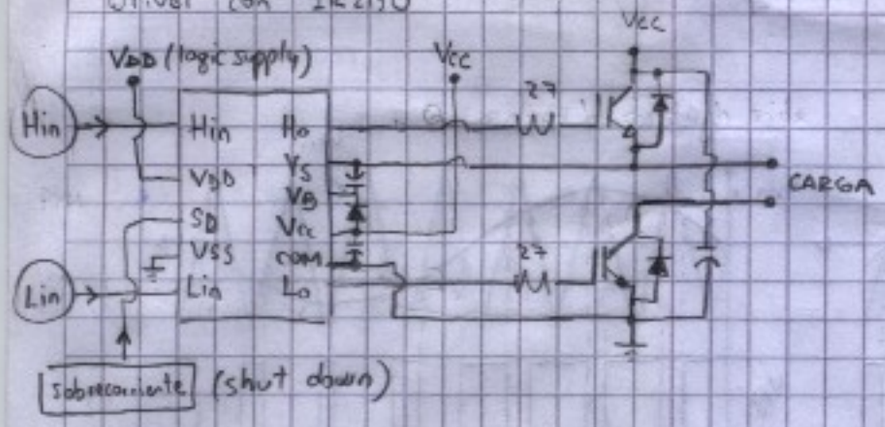
B. $I_{cmáx}$

C. Máx. temperatura (límite de potencia)

D. Debido a V_{CES} ó $V_{(BR)CES} = V_{CEmáx}$

NOTA

Driver con IR2110



Si usamos PWM bipolar necesitamos dos configuraciones idénticas donde:

$Hin_1 = Vg_1$; $Lin_1 = Vg_2$

$Hin_2 = Vg_3$; $Lin_4 = Vg_4$

pero $Vg_1 = Vg_4$ ∴ $Hin_1 = Lin_4$

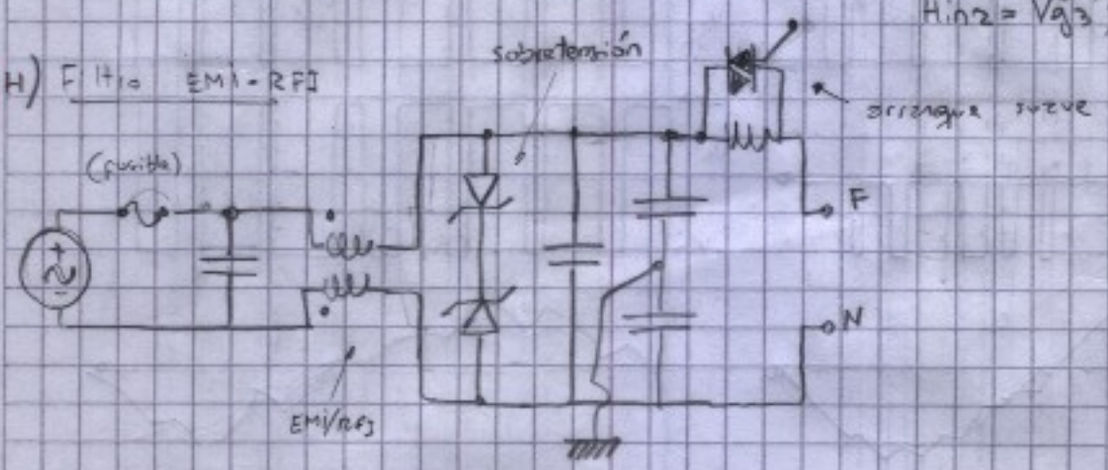
$Vg_2 = Vg_3$ ∴ $Lin_1 = Hin_2$

Si usamos PWM unipolar necesitamos 2 config. idénticas donde:

$Hin_1 = Vg_1$; $Lin_1 = Vg_2$

$Hin_2 = Vg_3$; $Lin_2 = Vg_4$

H) Filtro EMI-RFI

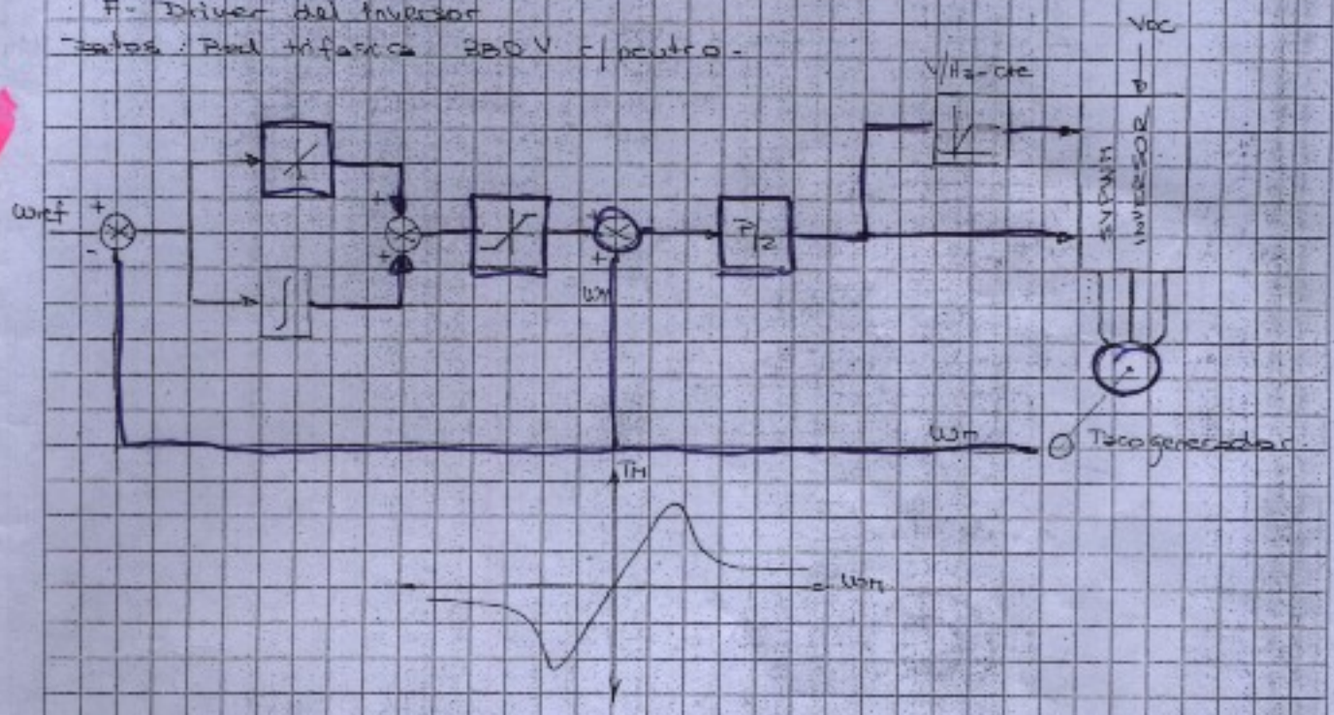


NOTA

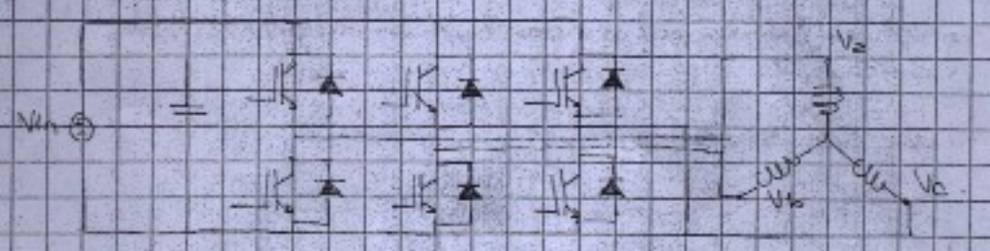
PRACTICO MOTOR CA

2.

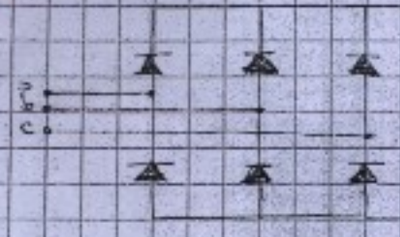
- Circuito de control escalar V/Hz por SVPWM de un motor de inducción
  - A- SOA
  - B- Sobrecorriente
  - C- Protección de falla de alimentación
  - D- Ventajas de este control
  - E- Si es aplicable snubber
  - F- Driver del inversor
- Datos: Red trifasica 380 V c/neutro -



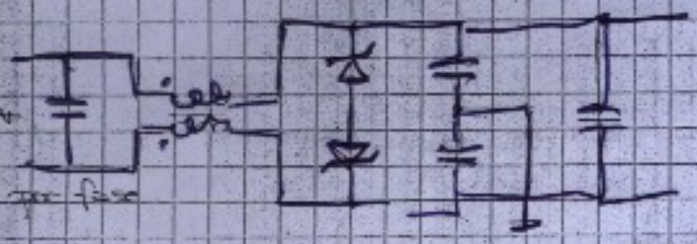
Circuito inversor



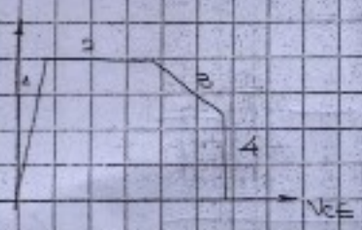
Rectificador



EMI | RF

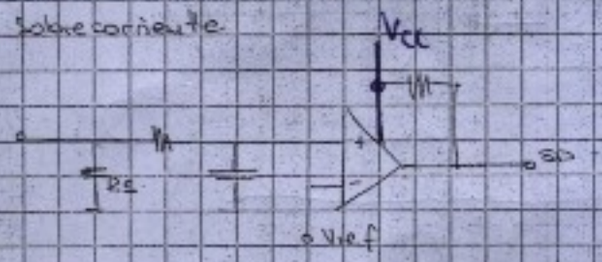


B- SOA

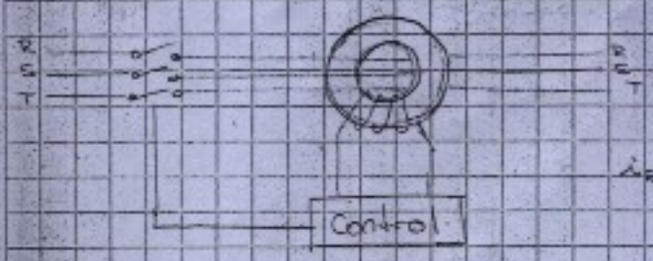


1- Pérdidas (on)
2- Ic(máx)
3- Térmico (ancho de pulso)
4- VCES (máx)

C- Sobrecorriente



D- Protección falla de línea

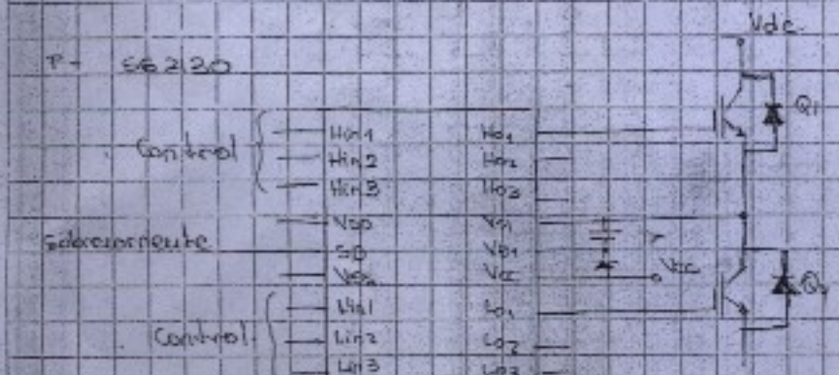


$i_R(t) + i_S(t) + i_T(t) = 0$

a- Este control es bueno en régimen estacionario pero no tan bueno en régimen dinámico

E- No es aplicable para snubber

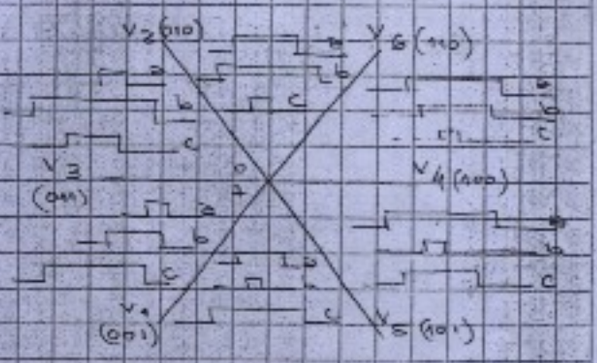
F- SG2130



Modulación SVPWM

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{in} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$



$V_0 = 0$

$V_1 = V_{in}\, e^{j\frac{\pi}{3}}$

$V_2 = V_{in}\, e^{j\frac{2\pi}{3}}$

$V_3 = V_{in}\, e^{j\pi}$

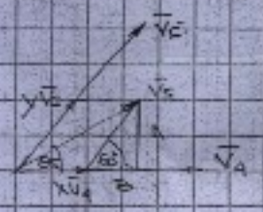
$V_4 = V_{in}\, e^{j0}$

$V_5 = V_{in}\, e^{j\frac{5\pi}{3}}$

$V_6 = V_{in}\, e^{j\frac{\pi}{3}}$

$V_7 = 0$

Cualquier vector $\bar{V}_s$ se puede sintetizar a partir de los vectores básicos de c/ sector



$$\bar{V}_s e^{j\theta_s} = x V_{in} e^{j0} + y V_{in} e^{j\frac{\pi}{3}}$$

$$\bar{V}_s = \frac{1}{T_s}\left(x T_s \bar{V}_a + y T_s \bar{V}_b + z_0 T_s \bar{V}_7\right)$$

$$x T_s + y T_s + z_0 T_s = T_s \Longrightarrow x + y + z_0 = 1$$

$$x \bar{V}_a = V_s \cos\theta_s - B$$

$$A = V_s \operatorname{sen}\theta_s \qquad \frac{A}{B} = \operatorname{tg} 60° = \sqrt{3} \longrightarrow B = \frac{A}{\sqrt{3}} = \frac{V_s \operatorname{sen}\theta_s}{\sqrt{3}}$$

$$\boxed{x = \frac{V_s}{V_a}\left[\cos\theta_s - \frac{\operatorname{sen}\theta_s}{\sqrt{3}}\right]}$$

$$y \bar{V}_b = \frac{B}{\cos 60°} = 2B \qquad y \bar{V}_b = \frac{2}{\sqrt{3}} V_s \operatorname{sen}\theta_s$$

$$\boxed{y = \frac{2}{\sqrt{3}} \frac{V_s}{V_b} \operatorname{sen}\theta_s}$$