Esempio

$\lambda_m = 0$ (REL) $\qquad V_n = 180\,V$

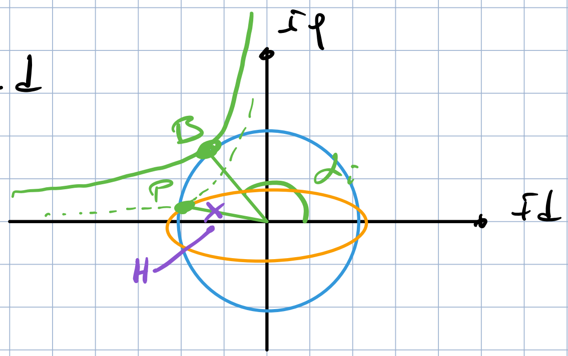
$L_d = 100\,mH \qquad I_n = 10{,}85\,A$

$L_q = 500\,mH$

$2p = 4$

a) ω_b e m_b (Determinare il punto B)

$L_q > L_d$



MTPA $\cancel{45} \Rightarrow \alpha_i = 45 + 90 = 135°$

$$\left.\begin{aligned} I_d &= -\frac{I_n}{\sqrt{2}} = -7{,}67\,A \\ I_q &= \frac{I_n}{\sqrt{2}} = 7{,}67\,A \end{aligned}\right\} \; m_B = \frac{3}{2} p (L_d - L_q)\, 7{,}67^2 (-1) = 70{,}59\,Nm$$

$$\begin{cases} \lambda_d = L_d I_d = 0{,}1(-7{,}67) = -0{,}767\,Vs \\ \lambda_q = L_q I_q = 0{,}5(7{,}67) = 3{,}835\,Vs \end{cases}$$

$$\omega_B = \frac{V_n}{\Lambda} = \frac{180}{\sqrt{0{,}767^2 + 3{,}835^2}} = 46{,}02\,\frac{rad}{s}$$

$$\omega_{Bm} = \frac{\omega_B}{p} = 23\,\frac{rad}{s} = 220\,rpm$$

b) traiettoria MTPV

$$T_{an}\alpha_{ip} = \frac{I_q}{I_d} = -\frac{1}{\xi} = -\frac{1}{5} = -0{,}2$$

$$\alpha_{ip} = 168{,}7^\circ$$

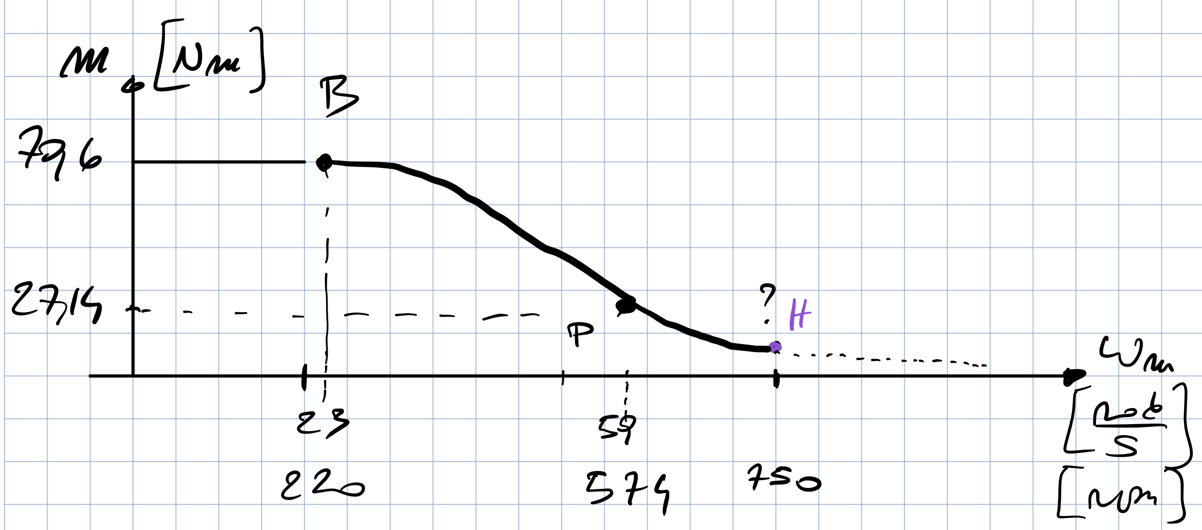
$$\begin{cases} I_{dp} = I_n \cos\alpha_{ip} = -10{,}64 \ A \\ I_{qp} = I_n \sin\alpha_{ip} = 2{,}126 \ A \end{cases}$$

$$m_p = \frac{3}{2} p (L_d - L_q) I_{dp} I_{qp} = 27{,}14 \ Nm$$

$$\lambda_d^2 + \lambda_q^2 = \frac{U_n^2}{\omega_m^2}$$

Nel punto P: $$\omega_m^e\big|_P = \frac{U_n}{\sqrt{(L_d I_{dp})^2 + (L_q I_{qp})^2}} = 119{,}7 \ \frac{rad}{s}$$

$$\omega_m\big|_P = 59{,}85 \ \frac{rad}{s} = 574 \ rpm$$



? an 750 rpm

750 rpm > 574 sono su MTPV

$$I_d = -\xi I_q = -\frac{L_q}{L_d} I_q \qquad \lambda_d^2 + \lambda_q^2 = \left(\frac{U_n}{\omega_m^e\big|_H}\right)^2$$

$$(2 L_q I_q)^2 = \left(\frac{U_n}{\omega_m^e\big|_H}\right)^2 \qquad I_q = \frac{U_n}{\omega_m^e\big|_H} \frac{1}{\sqrt{2} L_q} = 1{,}62 A$$

$$I_d = -3 I_q = -8,1\ A$$

$$I = \sqrt{I_d^2 + I_q^2} = 8,26\ A \quad < I_n = 10,85\ A$$

$$m = \frac{3}{2} p (L_d - L_q) I_d I_q = 15,75\ Nm$$

Controllo di corrente nella macchina sincrona

Corso di Azionamenti elettrici - AA 22/23

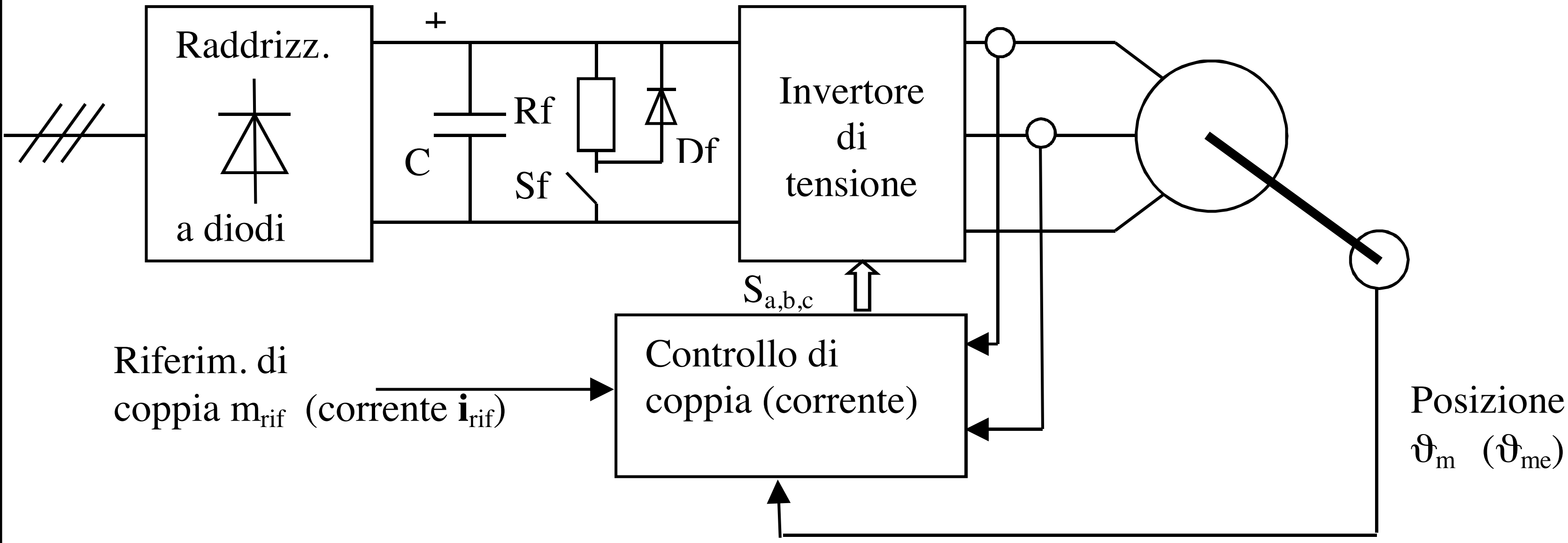


Fig. 6.1.1 – Schema di principio di azionamento brushless

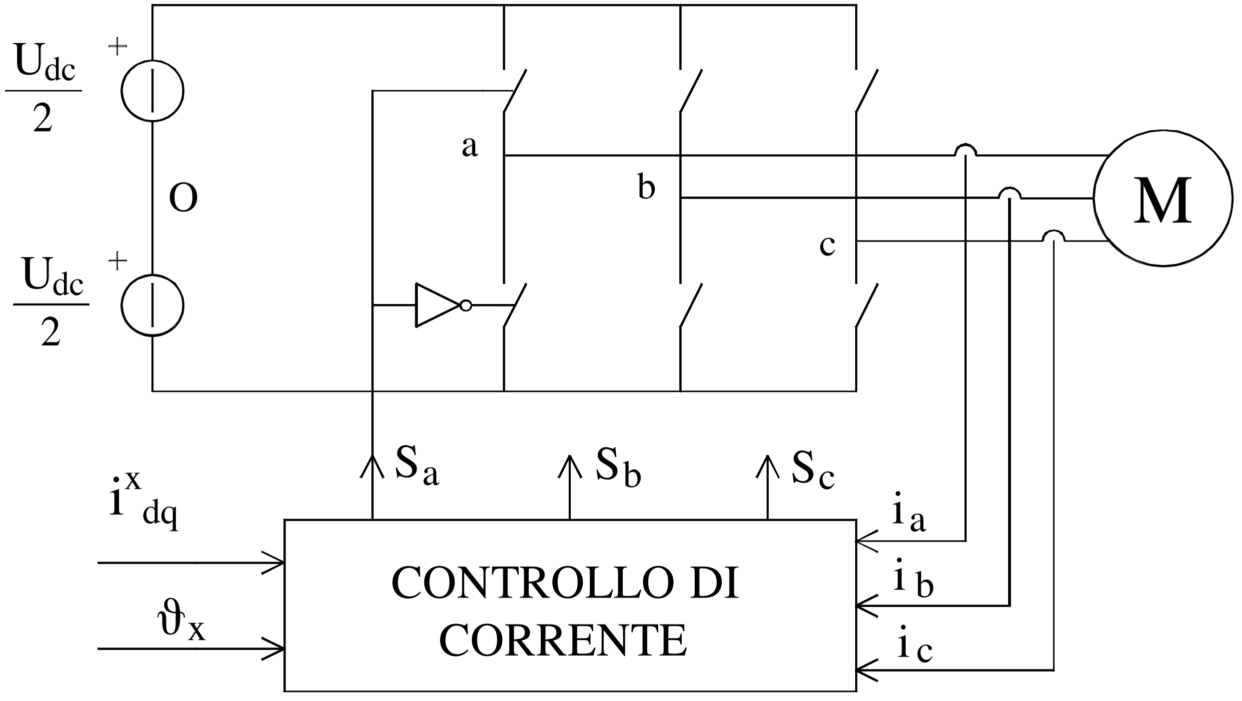


Fig.6.1.2 - Controllo di corrente di un motore in c.a. tramite inverter PWM

Tab. 6.1.1 - Classificazione dei controllori di corrente

		Tipo di comando dell’invertitore	
		Comando dell’invertitore mediante generatore PWM	Comando diretto degli stati dell’invertitore
Sistema di riferimento	Stazionario	• PID in abc • PID in $\alpha\beta$ • Predittivo in $\alpha\beta$	• Ad isteresi in abc • Ad isteresi in $\alpha\beta$
	Sincrono	• PID in d-q • Predittivo in d-q	• *Ad isteresi in d-q (non di interesse)*

6.2.1 Controllo trifase con regolatori PID - Uno schema di controllo di tipo stazionario, con controllori di corrente aventi uscite che richiedono l'uso di un generatore di PWM ha la struttura riportata in Fig.6.2.1.

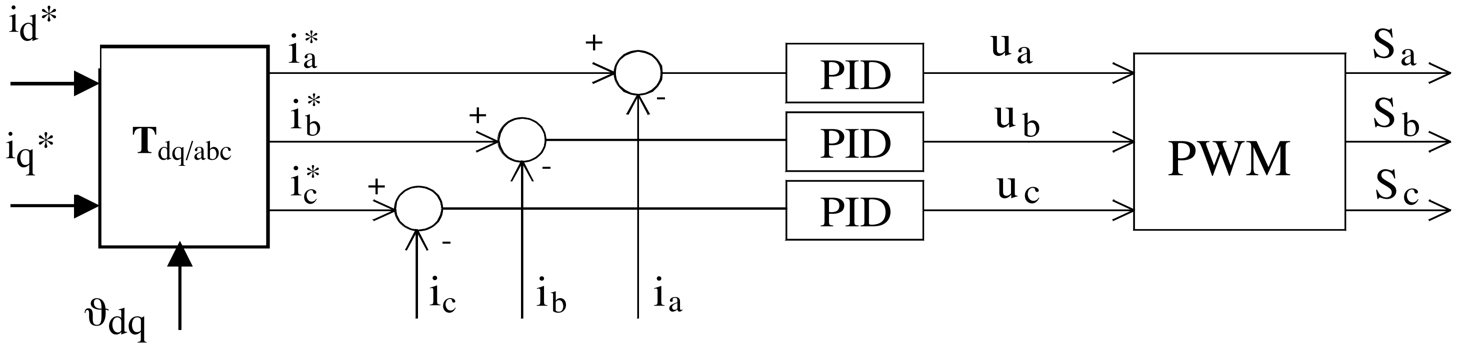


Fig.6.2.1 - Controllo di corrente stazionario, con controllori trifase PID

6.2.2 Controllo in α–β con regolatori PID - Uno schema alternativo a quello precedente è riportato in Fig.6.2.2.

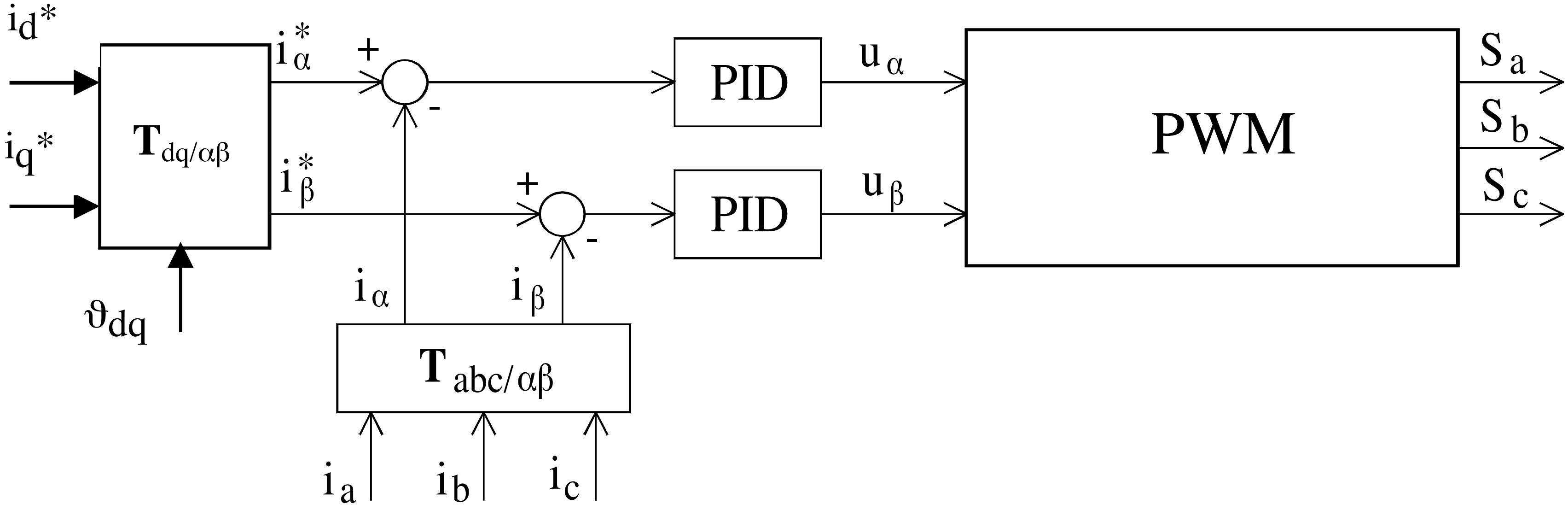
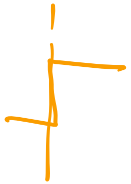
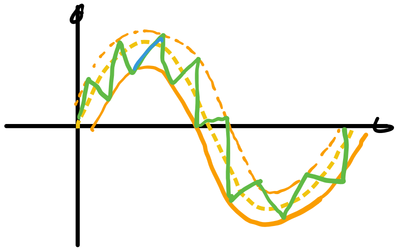


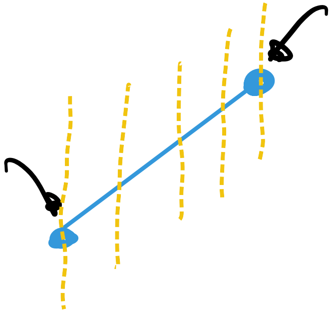
Fig.6.2.2 - Controllo di corrente in $\alpha\beta$ con PID

6.3.1 Controllo trifase a isteresi

ε







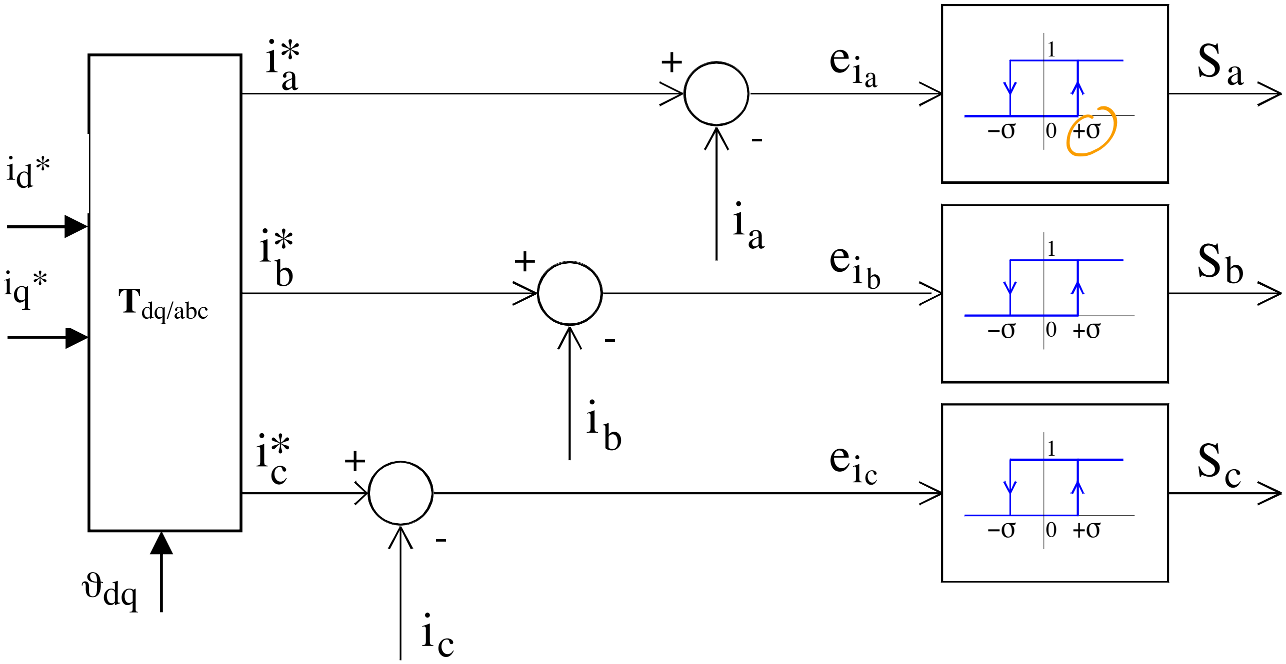


Fig.6.3.1 - Controllo di corrente trifase a isteresi

6.4.2 Controllo predittivo in d-q (con stima dei parametri del motore) - Un esempio di controllo di corrente di tipo sincrono, impiegante regolatori predittivi che richiedono l'uso di generatore di PWM è riportato in Fig.6.4.2.

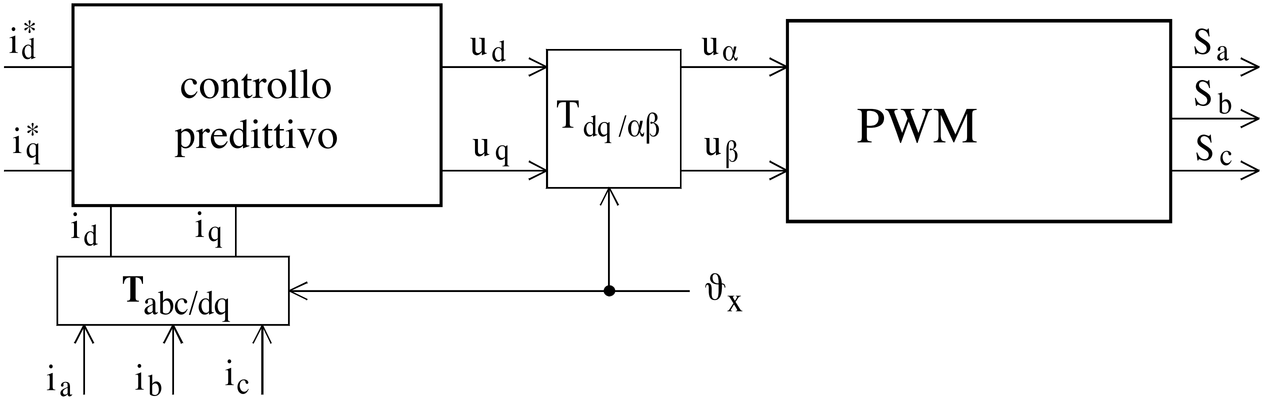


Fig.6.4.2 - Controllo di corrente sincrono, con controllori PID

6.4.1 Controllo in d-q con regolatori PID - Un esempio di controllo di corrente di tipo sincrono, impiegante regolatori che richiedono l'uso di generatori di PWM è riportato in Fig.6.4.1.

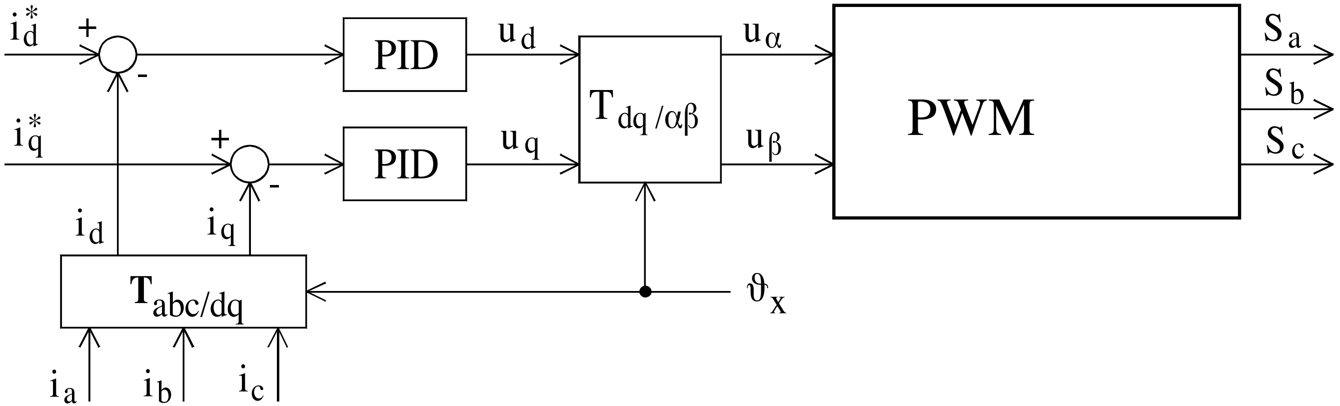
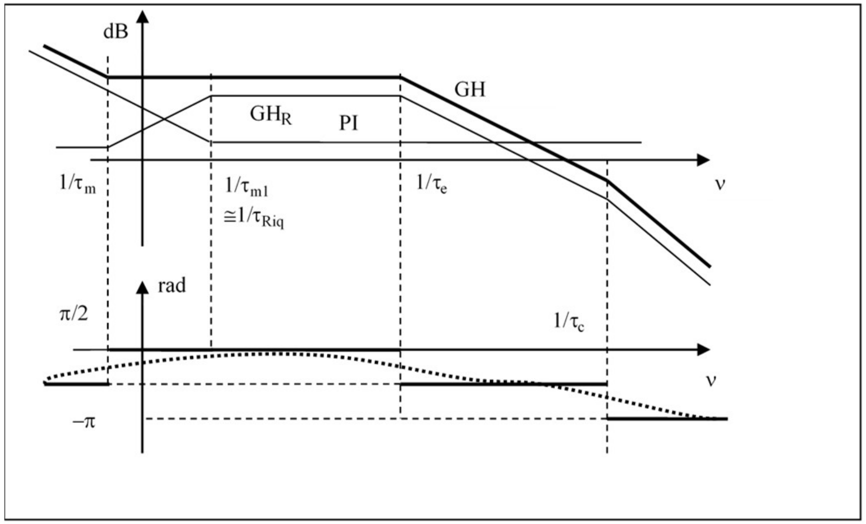


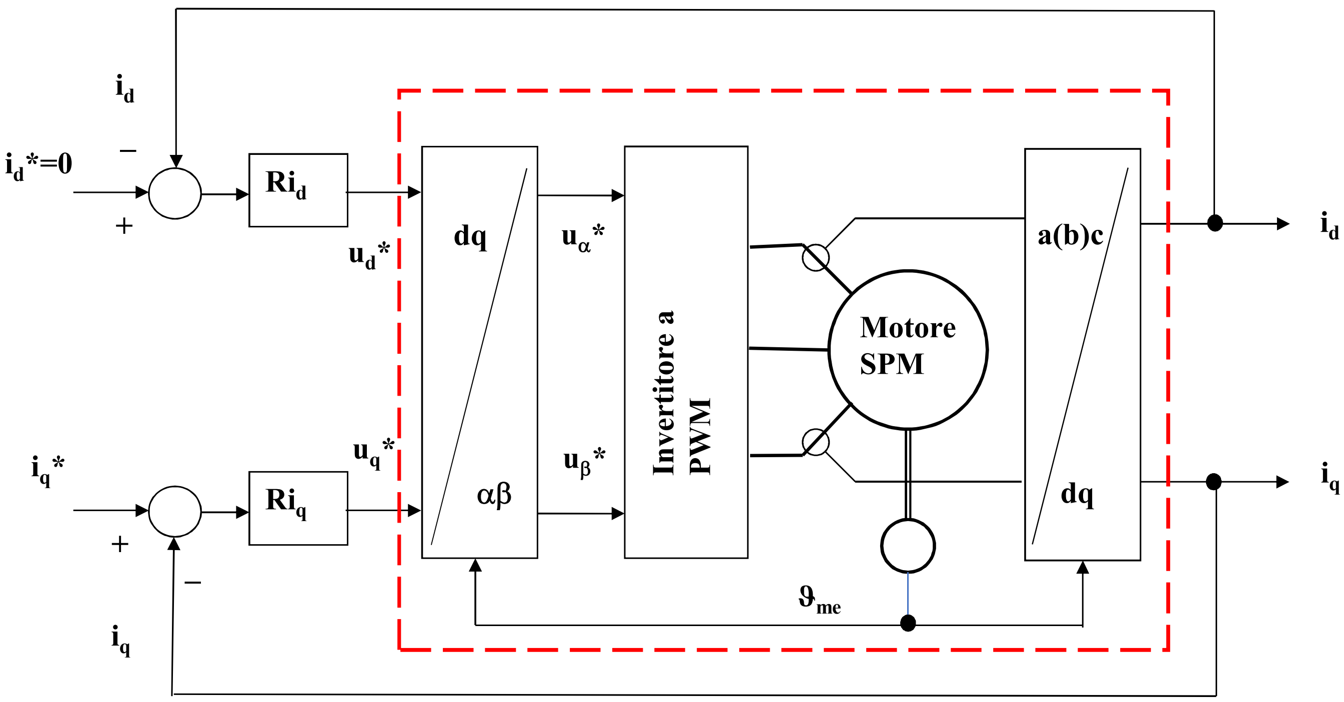
Fig.6.4.1 - Controllo di corrente sincrono, con controllori PID

PARTE III

Controllo di corrente «PID sincrono» in azionamenti con motore sincrono



Schema a blocchi del controllo di corrente dq di un motore SPM

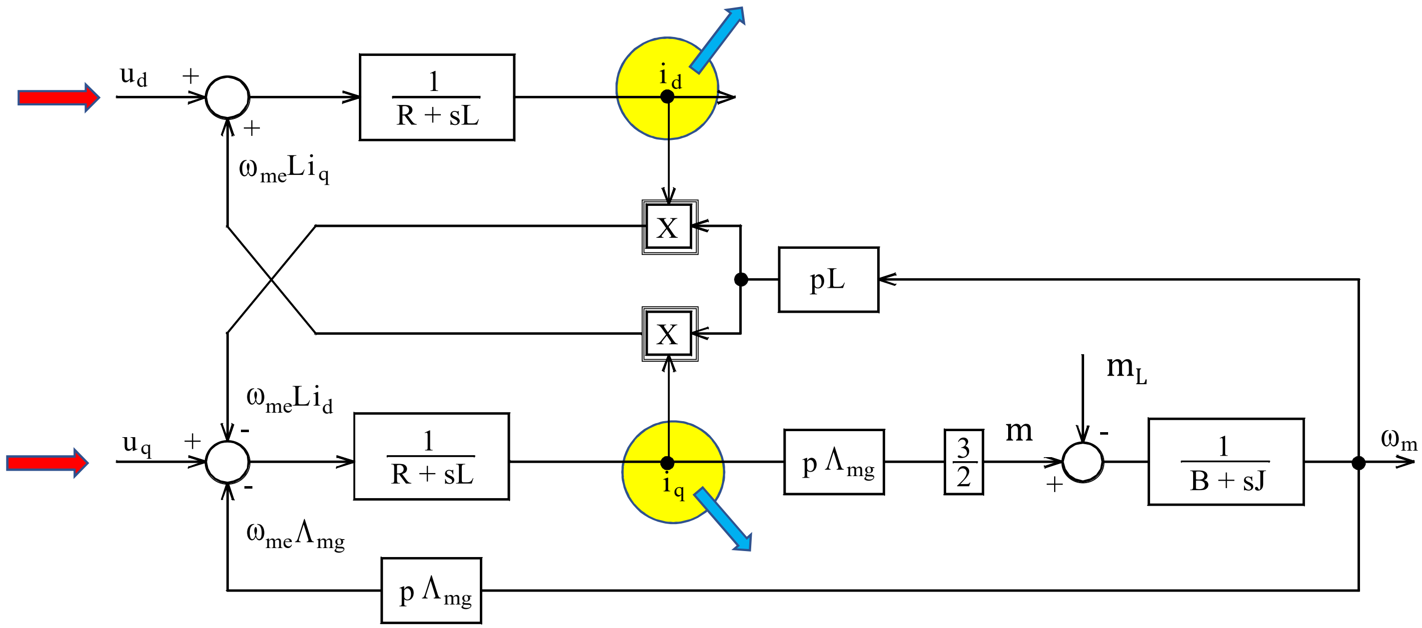


Modello in dq del sistema invertitore-motore.

Ingressi: tensioni dqdi riferimento (+coppia di disturbo)

Uscite: correnti dq

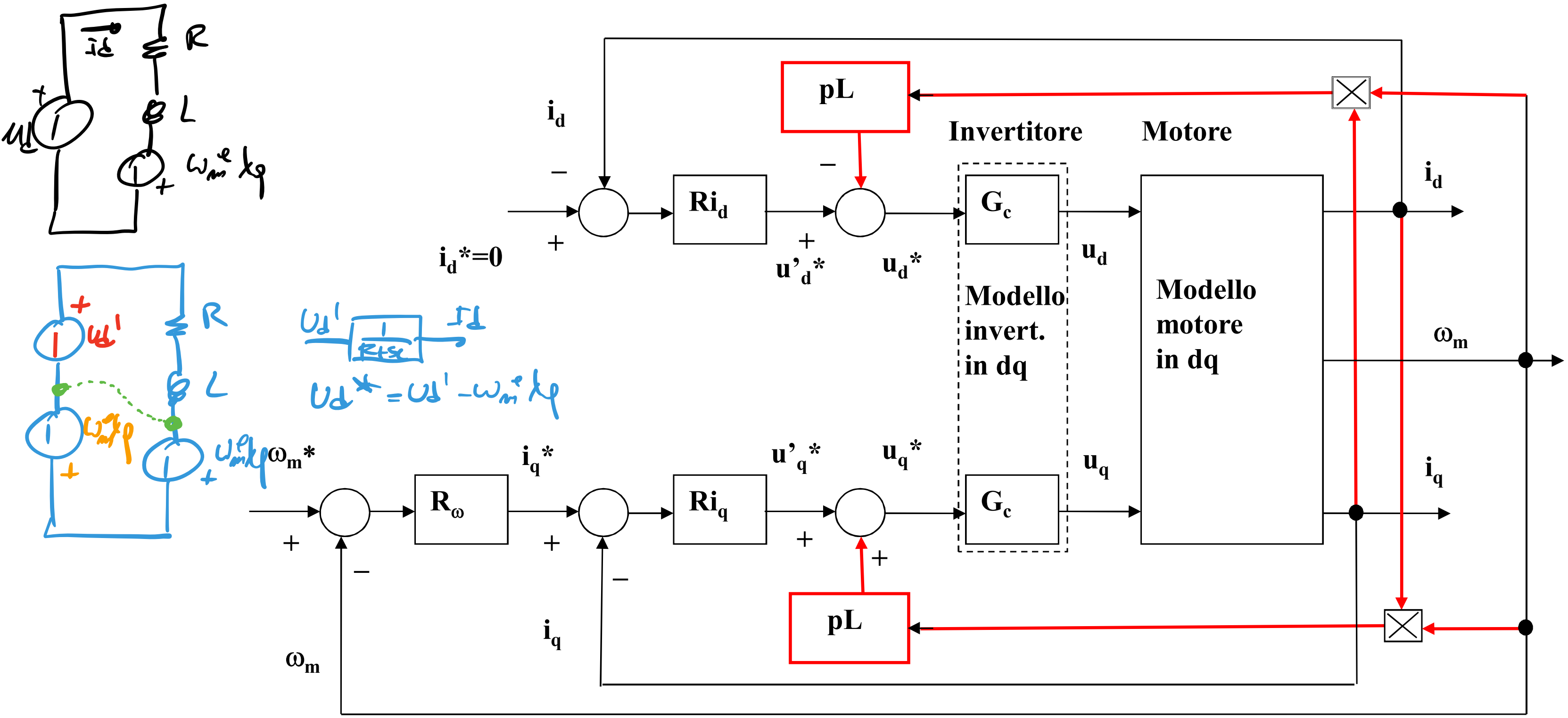
Dinamica del motore SPM (rotore isotropo)



Nel sistema di riferimento dq la dinamica tensione-corrente del motore SPM è quella di un **sistema a due ingressi e due uscite**.

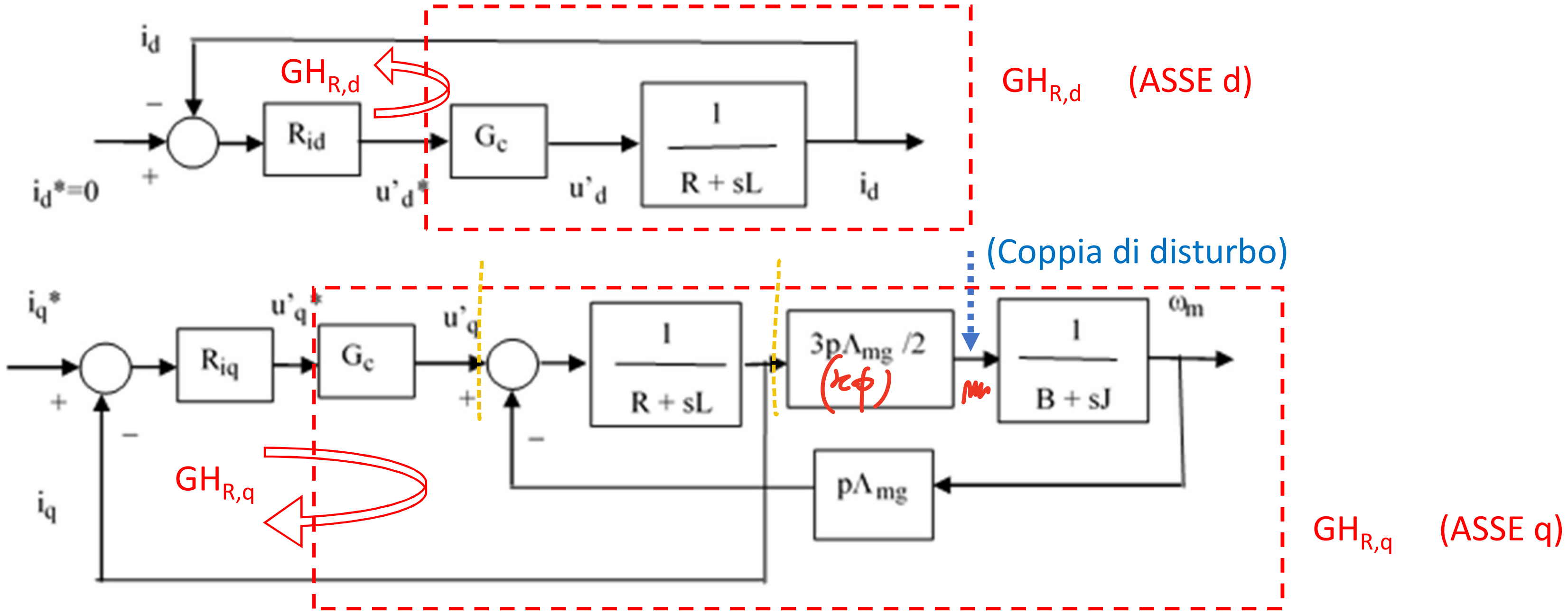
Schema a blocchi del controllo di un azionamento brushless isotropo (SPM)

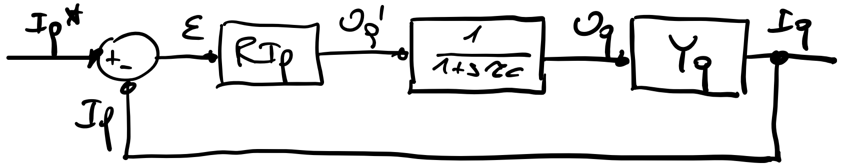
$$G_c = \frac{1}{1+s\tau_c}$$



In rosso le azioni di disaccoppiamento degli assi
per trasformare il sistema 2_IN/2_OUT in due sistemi 1_IN/1_OUT

Anelli di controllo delle correnti dq dopo disaccoppiamento degli assi



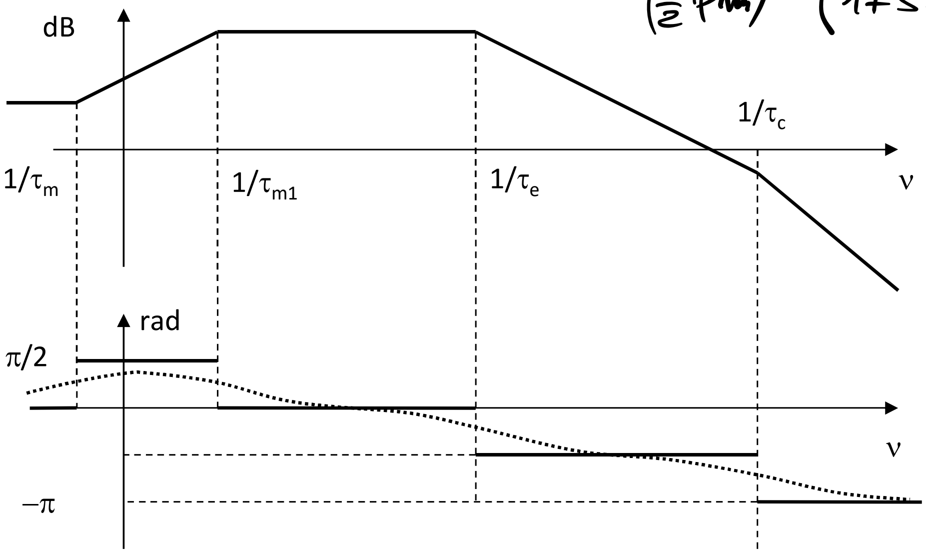


Diagrammi di Bode di $GH_{R(q)}(j\nu)$

$$GH = \frac{1}{1+s\tau_c} Y_q$$

$$= \frac{1}{1+s\tau_c} \frac{B+sJ}{\frac{3}{2}(p\Lambda_m)^2\left(1-\frac{s}{p_1}\right)\left(1-\frac{s}{p_2}\right)}$$

$$= \frac{B(1+s\tau_m)}{\left(\frac{3}{2}p\Lambda_m\right)^2(1+s\tau_c)(1+s\tau_e)(1+s\tau_{m1})}$$



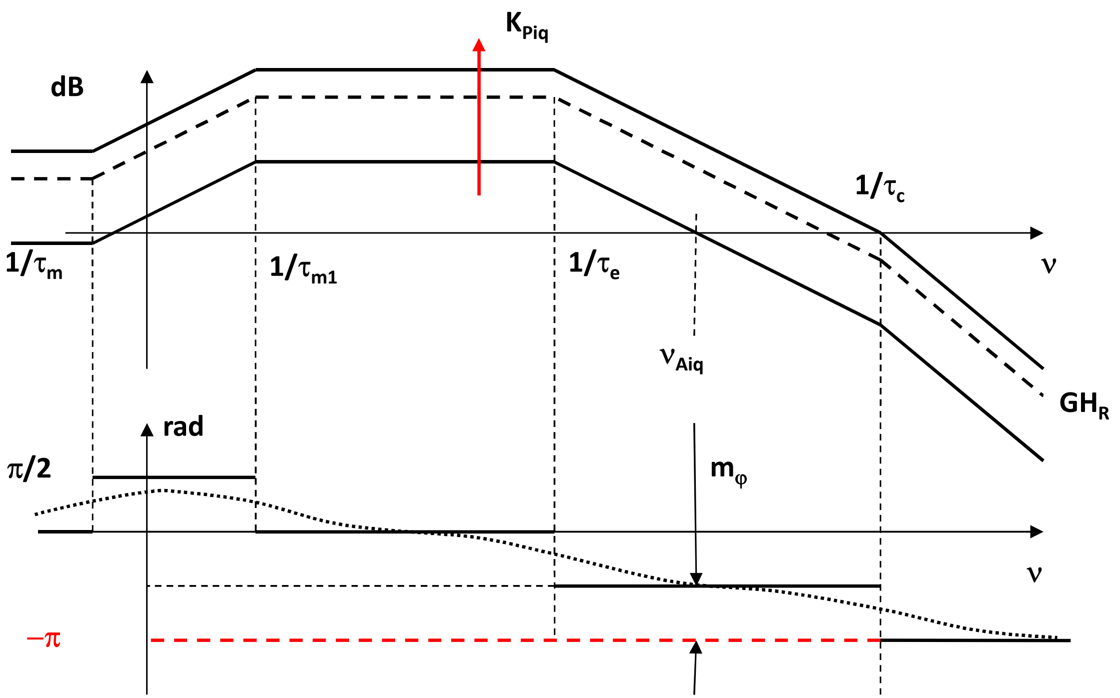
$$\tau_m = \frac{J}{B}$$

$$\tau_{m1} = \frac{RJ}{\left(\frac{3}{2}p\Lambda_m\right)^2}$$

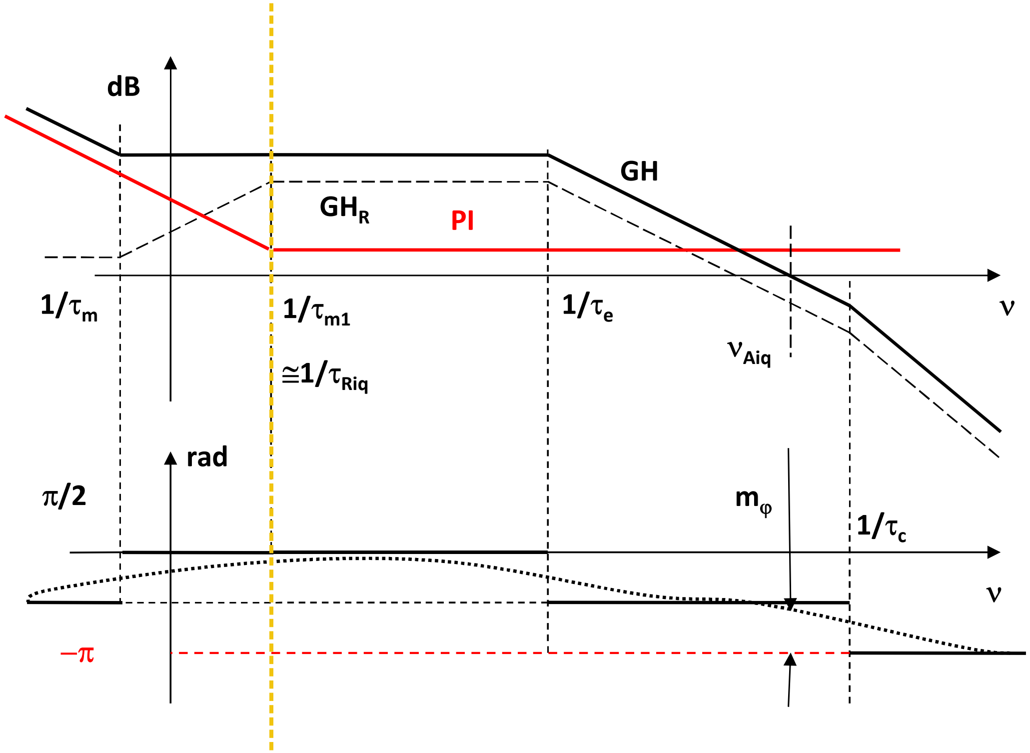
$$\tau_e = \frac{L}{R}$$

$$\tau_m > \tau_{m1} > \tau_e > \tau_c$$

Diagrammi di Bode di $GH_{(q)}(j\nu)$ con regolatore P



Diagrammi di Bode di $GH_{(q)}(j\nu)$ con regolatore PI

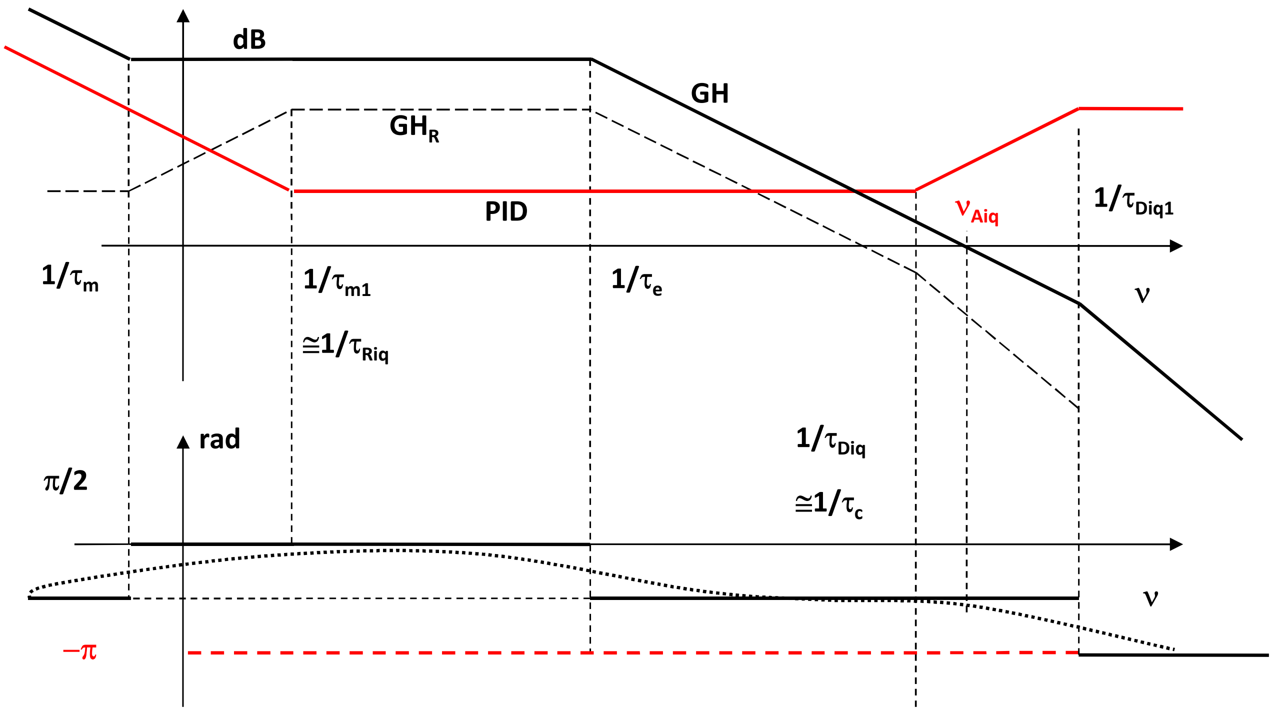


$$R_{iq} = k_p + \frac{k_I}{s}$$

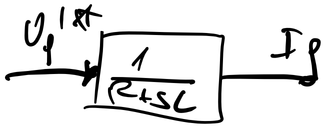
$$= k_p \frac{1+s\tau_{Riq}}{s\tau_{Riq}}$$

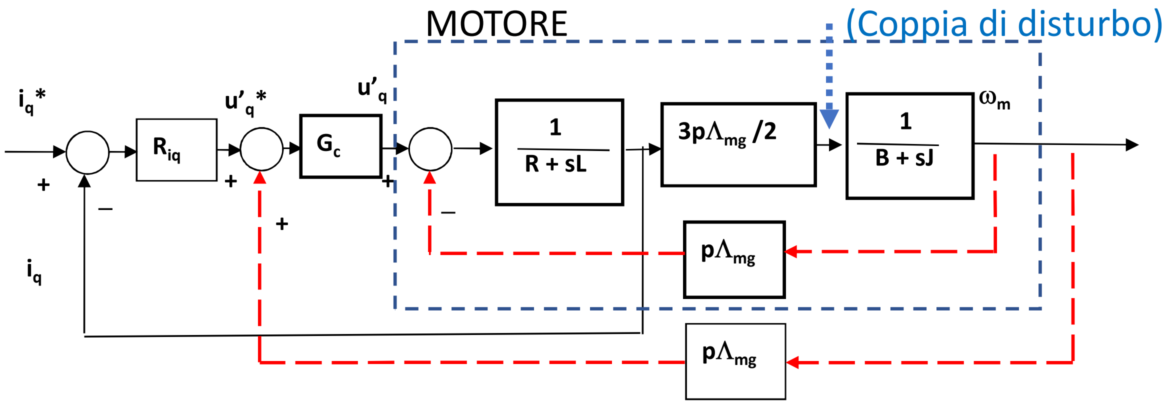
$$\tau_{Riq} = \frac{k_p}{k_I}$$

Diagrammi di Bode di $GH_{(q)}(j\nu)$ con regolatore PID



Schema a blocchi del controllo della corrente in quadratura dopo disaccoppiamento e compensazione della fem





In rosso l'azione di compensazione della fem
Le fdt dell'anello di asse q non risente del parametri meccanici e dell'effetto della coppia di disturbo.
Con motore SPM diventa identica a quella dell'asse d.

1 Block diagrams

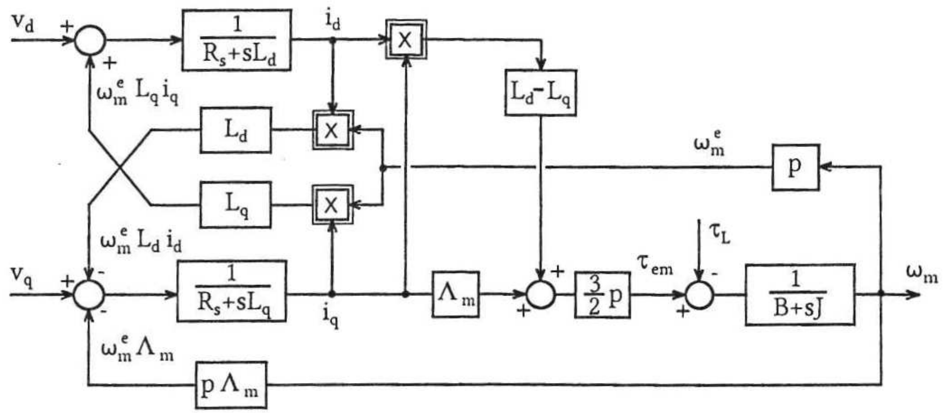
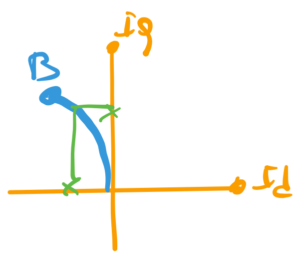


Figura 1: Scheme of the IPM motor vector control.



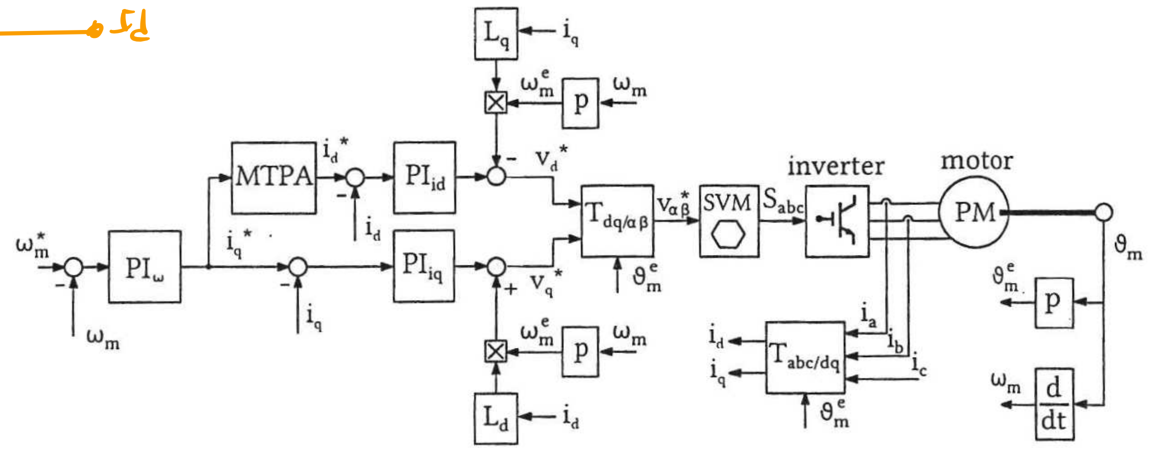
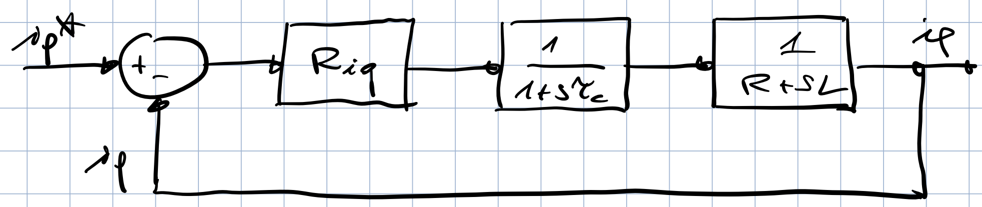
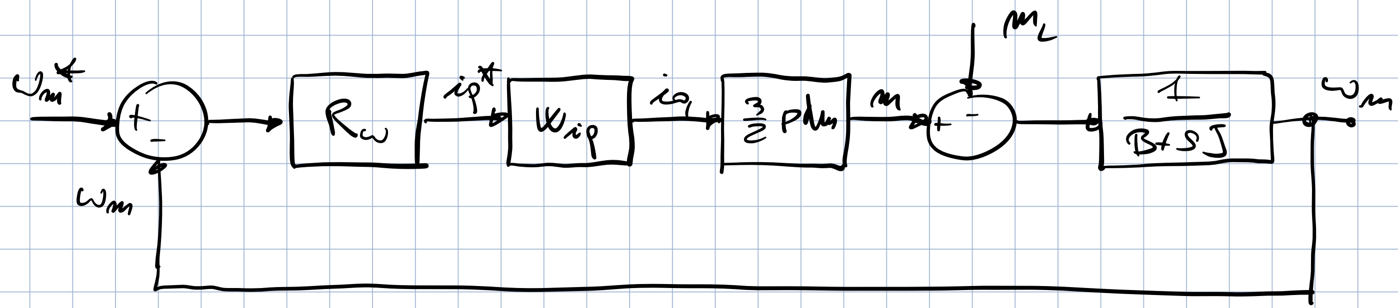


Figura 2: Scheme of the IPM motor vector control with decoupling between the two axes.

ESERCIZIO Dimensionamento anelli velocità e corrente SPM

Uso compensazione fcem ($\omega \lambda_m$) e disaccoppiamento on.





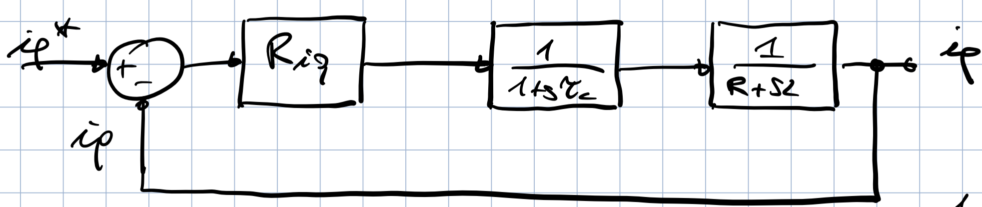
DATI:

$R = 1{,}5\ \Omega$ $\lambda_m = 0{,}067\ Vs$ $J = 0{,}29 \cdot 10^{-3}\ kg\,m^2$

$L = 5\ mH$ $2p = 8$ $B = 0{,}00192\ Nms$

$T_c = 100\ \mu s$

Anello di corrente:



$\tau_c = \frac{3}{2} T_c = 150\ \mu s$

$$\frac{1}{R+sL} = \frac{1/R}{1+s\tau_e}$$

Dimensiono R_{iq} usando cancellazione zero-polo $\tau_e = \frac{L}{R} = \frac{5}{1{,}5} \cdot 10^{-3} = 3{,}3\ ms$

$$R_{iq} = k_{pi} \frac{1+s\tau_{Ri}}{s\tau_{Ri}}$$ pongo $\tau_{Ri} = \tau_e$

$$GH(s) = k_{pi} \frac{\cancel{1+s\tau_{Ri}}}{s\tau_{Ri}} \frac{1/R}{\cancel{1+s\tau_e}} \frac{1}{1+s\tau_c} = \frac{k_{pi}}{R} \frac{1}{s\tau_{Ri}} \frac{1}{1+s\tau_c}$$

$$GH(j\vartheta) = \frac{\frac{k_{pi}}{R}}{j\vartheta\tau_e(1+j\vartheta\tau_e)}$$

$\tau_e = \tau_R$

$$\begin{cases} |GH| = \dfrac{\frac{k_{pi}}{R\tau_e}}{\vartheta\sqrt{1+(\vartheta\tau_e)^2}} \\ \arg(GH) = 0 - 90^\circ - \arctan(\vartheta\tau_e) \end{cases}$$

Impongo $M\varphi = 70^\circ = 180 + \arg(GH)$

$$20 = \arctan\left[\vartheta_{ei}\cdot 150\cdot 10^{-6}\right]$$

$$\vartheta_{e,i} = 2426\ \frac{rad}{s} \qquad \frac{1}{\tau_e} = 6666,\bar{6}\ \frac{rad}{s}$$

pulsazione di attraversamento anello di corrente

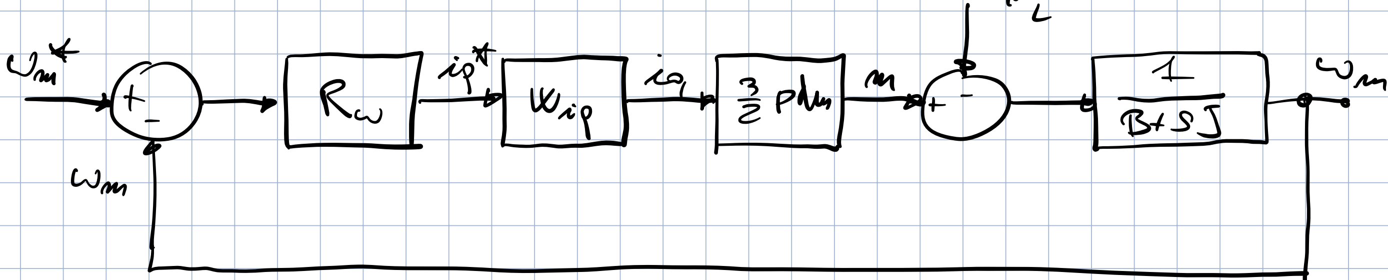
Impongo $|GH(j\vartheta_{e,i})| = 1 = \dfrac{\frac{k_{pi}}{R\tau_e}}{\vartheta_{e,i}\sqrt{1+(\vartheta_{ei}\tau_e)^2}}$

$$k_{pi} = \ldots\ldots = 12,78\ \frac{V}{A}$$

Risulta dunque

$$R_{ip} = 12,78\ \frac{1+s\,3,3\cdot 10^{-3}}{s\cdot 3,3\cdot 10^{-3}}$$

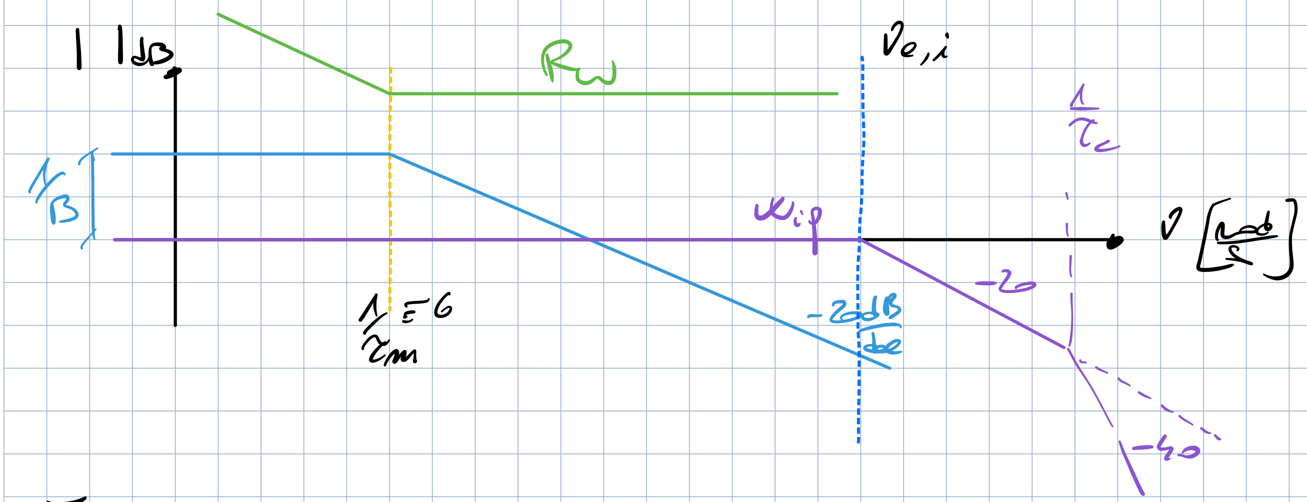
$$W_{iq} = \frac{GH}{1+GH} \cong \frac{1}{1+s\frac{1}{\vartheta_{e,i}}} = \frac{1}{1+s\tau_{ei}} = \boxed{\frac{1}{1+s\frac{1}{2426}}}$$



Dimensiono anello di velocità

$$R_\omega = K_{p\omega} \frac{1+s\tau_{R\omega}}{s\tau_{R\omega}}$$

$$\frac{1}{B+sJ} = \frac{1/B}{1+s\tau_m} \qquad \tau_m = \frac{J}{B} = \frac{0{,}29\,10^{-3}}{0{,}00192} = 0{,}15\ s$$



Fisso $\underbrace{\tau_{R\omega} = \tau_m}$ $= 0{,}15\ s$

$$GH(s) = K_{p\omega} \frac{\cancel{1+s\tau_m}}{s\tau_m} \cdot \frac{1}{1+s\frac{1}{\nu_{ei}}} \cdot \frac{1}{1+\tau_c s} \cdot \frac{\frac{3}{2} p \frac{\lambda_m}{B}}{\cancel{1+s\tau_m}}$$

$$= \frac{K_{p\omega}}{\cancel{s}\tau_m} \frac{3}{2} p \frac{\lambda_m}{B} \frac{1}{s} \frac{1}{1+s\tau_{ei}} \cdot \frac{1}{1+\tau_c s}$$

- $\tau_{ei} = 512 \cdot 10^{-6}\ s$
- $\tau_c = 150 \cdot 10^{-6}\ s$

$\tau_m = 0{,}15\ s$

$$M\phi = 70^\circ = 180 - \arg\left[GH(j\nu_{c\omega})\right]$$

$$70 - 180 = -90 - \arctan(\nu_{c\omega}\tau_{ei}) - \arctan(\nu_{c\omega}\tau_c)$$

Se trascuro il polo dell'inverter

$$20 = \arctan(\nu'_{c\omega}\tau_{ei})$$

$$\nu'_{c\omega} = \frac{\tan 20}{\tau_{ei}} = 883\ \frac{rad}{s}$$

$$f(\nu) = 20 - \arctan(\nu_{c\omega}\, 412\cdot 10^{-6}) - \arctan(\nu_{c\omega}\, 150\cdot 10^{-6})$$

ν	$f(\nu)$
883	-0,13
800	-0,089
700	-0,03
600	0,016
650	-0,01
625	0,0033
630	0,0007

Si risolve numericamente $\nu = 631$

$$\nu_{c\omega} = 631\ \frac{rad}{s}$$

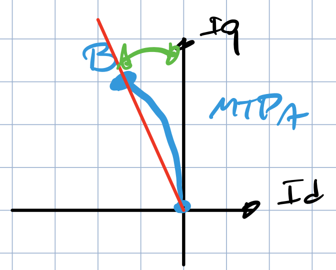
Impongo che $|GH(j\,631)| = 1$

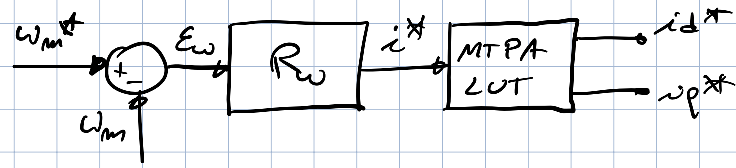
$$\overset{!}{=} \frac{k_{p\omega}\, 3 p \lambda_m}{2 B \tau_m} \frac{1}{\nu_{c\omega}} \frac{1}{\sqrt{1+(\nu_{c\omega}\tau_{ei})^2}} \frac{1}{\sqrt{1+(\nu_{c\omega}\tau_c)^2}}$$

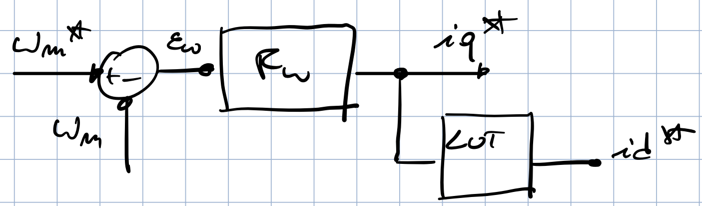
$$k_{p\omega} = 0,486\ \frac{A}{rad/s}$$

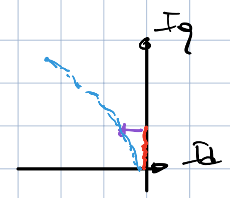
$$R_{i\omega} = k_{p\omega}\frac{1+s\tau_{R\omega}}{s\tau_{R\omega}} = 0,486\,\frac{1+s\cdot 0,15}{s\cdot 0,15}$$

BLOCCO MTPA: Come scelgo le traiettorie di controllo



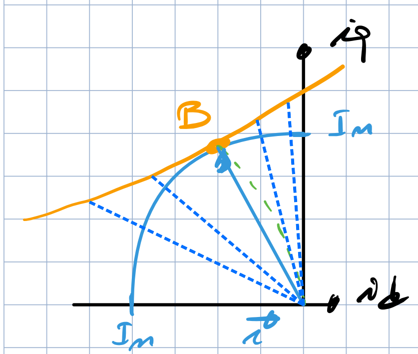


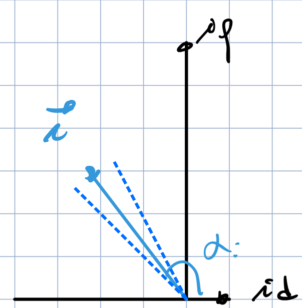


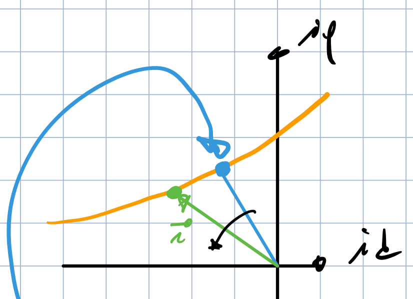


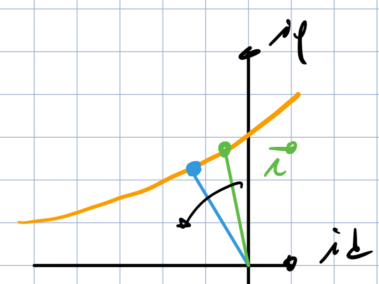
MTPA "OFFLINE"

MTPA "ONLINE"







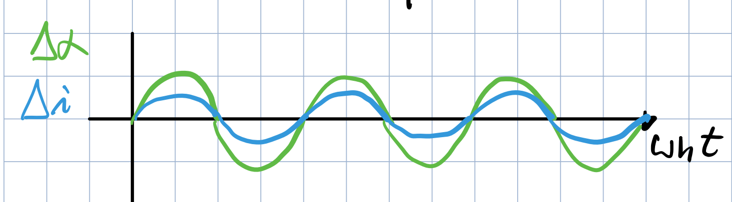


$d\alpha_i > 0 \Rightarrow |\vec{i}| \nearrow$ $\qquad$ $d\alpha_i > 0 \Rightarrow |\vec{i}| \searrow$

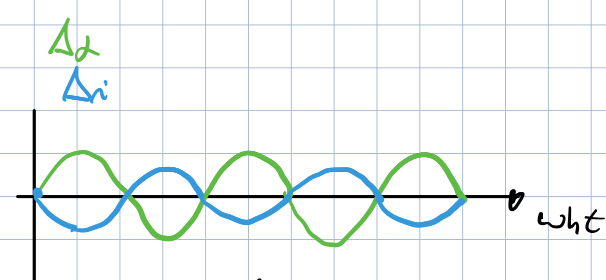
$$\vec{i} = \vec{I} + \Delta\vec{i}$$

$i_d + j\, i_q$

$\Delta\alpha = P_h \,\text{sen}(\omega_h t)$



$\Delta i = I_h \,\text{sen}(\omega_h t)$



$\Delta i = I_h \,\text{sen}(\omega_h t + \pi)$

$$\varepsilon = \Delta\alpha \, \Delta i = P_h \, sen(\omega_h t) \, I_h \, sen(\omega_h t + k'\pi) \qquad k' \begin{cases} 0 \\ 1 \end{cases}$$

$$= P_h I_h \, sen(\omega_h t) \, sen\left(\omega_h t + \frac{1-k}{2}\pi\right) \qquad k \begin{cases} 1 \\ -1 \end{cases}$$

$$= \frac{k P_h I_h}{2}\left[1 - \cos 2\omega_h t\right]$$

$$\varepsilon \longrightarrow \boxed{LPF} \longrightarrow \frac{k P_h I_h}{2} = \varepsilon_\alpha$$

Uso questo per modificare α_i