

Elettronica di potenza e di controllo

Modulo su batterie e driver motori

07. Driver motori

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EPC: Modulo motor driver

Motor driver per BLDC e PMSM (R. Roncella)

(Power Electronics and motor drive systems,
Stefanos Manias, Elsevier 2017; pp 938-956.

AC Motor Control and Electric Vehicle Applications,
Kwang Hee Nam, CRC press 2010; cap 10)

Parte 1

Motori sincroni a magneti permanenti

Motori sincroni a magneti permanenti

- Alta densità di potenza
 - Compattezza e semplicità del rotore
 - Basso momento di inerzia
- Alta efficienza
 - Assenza di perdite negli avvolgimenti rotorici
- Alta affidabilità
 - Semplicità costruttiva
 - Assenza di contatti striscianti

Configurazioni rotoriche

- Magneti superficiali, statore liscio
 - Traferro elevato, salienza ridotta
- Magneti interni, poli salienti
 - Flusso sinusoidale
 - Distribuzione sinusoidale degli avvolgimenti statorici
 - Flusso trapezoidale (BLDC)
 - Avvolgimenti concentrati

Modello di un PMSM

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix}$$

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{aa}(\theta_e) & M_{ab}(\theta_e) & M_{ac}(\theta_e) \\ M_{ab}(\theta_e) & L_{bb}(\theta_e) & M_{bc}(\theta_e) \\ M_{ac}(\theta_e) & M_{bc}(\theta_e) & L_{cc}(\theta_e) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \psi_{ma}(\theta_e) \\ \psi_{mb}(\theta_e) \\ \psi_{mc}(\theta_e) \end{bmatrix}$$

Frame abc (terna diretta)

v_a, v_b, v_c tensioni di fase

i_a, i_b, i_c correnti di fase

R_a, R_b, R_c resistenze di fase

ψ_a, ψ_b, ψ_c flusso di fase

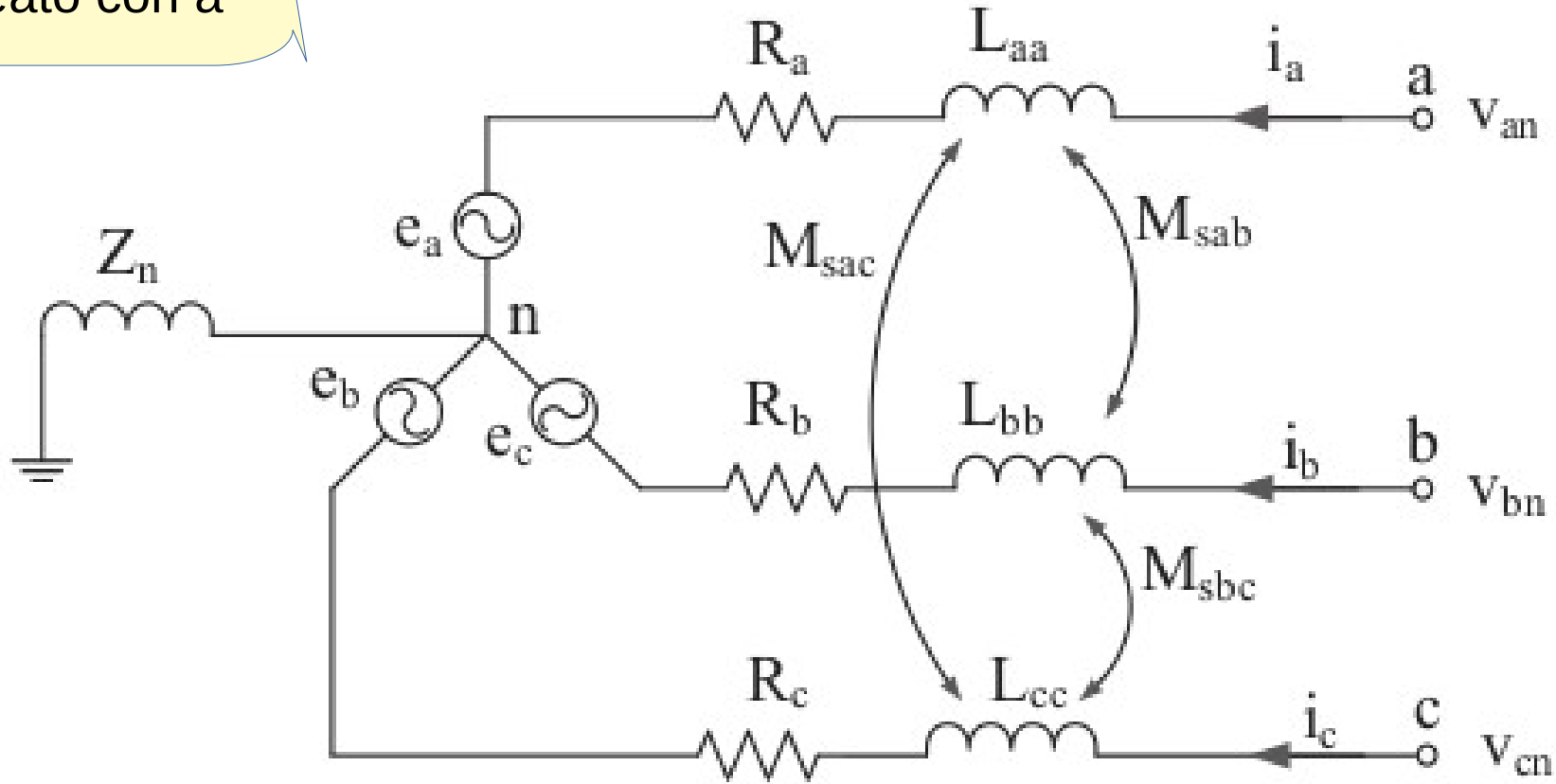
$\psi_{ma}, \psi_{mb}, \psi_{mc}$ magneti permanenti

θ_e angolo elettrico

Circuito equivalente

$\theta_e = 0$ flusso
allineato con a

P: poli
P/2: coppie di poli



$$\theta_e = \theta_r = \frac{P\theta_m}{2}$$

$$\omega_e = \frac{P\omega_m}{2}$$

Assunzioni

- Avvolgimenti statorici distribuiti in modo sinusoidale
 - Generano FMM sinusoidale
- Trascurabili gli effetti della geometria
 - dei denti e delle cave statoriche
- Flusso magnetico prodotto dai magneti permanenti sinusoidale
- Flusso magnetico associato alla reazione di armatura statorica significativo solo per la componente principale
 - Dovuto alla corrente fatta circolare dalle tensioni indotte
- Si trascura la saturazione

Andamento delle induttanze

Andamento che si ripete
2 volte uguale nel periodo
elettrico

Massima con "a"
allineato al
nord/sud del rotore

$$\begin{bmatrix} L_{aa}(\theta_e) \\ L_{bb}(\theta_e) \\ L_{cc}(\theta_e) \end{bmatrix} = L_0 + L_2 \begin{bmatrix} \cos(2\theta_e) \\ \cos(2\theta_e - 2\pi/3) \\ \cos(2\theta_e + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} M_{ab}(\theta_e) \\ M_{ac}(\theta_e) \\ M_{bc}(\theta_e) \end{bmatrix} = M_0 + M_2 \begin{bmatrix} \cos(2\theta_e + 2\pi/3) \\ \cos(2\theta_e - 2\pi/3) \\ \cos(2\theta_e) \end{bmatrix}$$

Mutua "ab" massima con "c"
allineato al nord/sud del rotore

Mutua "ac" massima con "b"
allineato al nord/sud del rotore

Mutua "bc" massima con "a"
allineato al nord/sud del rotore

Flusso prodotto dal rotore

$$\begin{bmatrix} \psi_{ma}(\theta_e) \\ \psi_{mb}(\theta_e) \\ \psi_{mc}(\theta_e) \end{bmatrix} = \psi_m \begin{bmatrix} \cos(\theta_e) \\ \cos(\theta_e - 2\pi/3) \\ \cos(\theta_e + 2\pi/3) \end{bmatrix}$$

Rotore allineato con a,
poi dopo $2\pi/3$ con b e
infine con c

Tensioni indotte

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} V_a^{i=0} \\ V_b^{i=0} \\ V_c^{i=0} \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} \psi_{ma} \\ \psi_{mb} \\ \psi_{mc} \end{bmatrix} = \psi_m \cdot \frac{d\theta}{dt} \cdot \frac{d}{d\theta} \begin{bmatrix} \cos(\theta_e) \\ \cos(\theta_e - 2\pi/3) \\ \cos(\theta_e + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = -\psi_m \omega_m \begin{bmatrix} \sin(\theta_e) \\ \sin(\theta_e - 2\pi/3) \\ \sin(\theta_e + 2\pi/3) \end{bmatrix}$$

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m}$$

Coppia risultante dal bilancio di potenza

Trasformate di Clarke e Park

Il fattore $2/3$ rende la lunghezza di $x_\alpha + jx_\beta$ pari al picco della grandezza trifase.

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

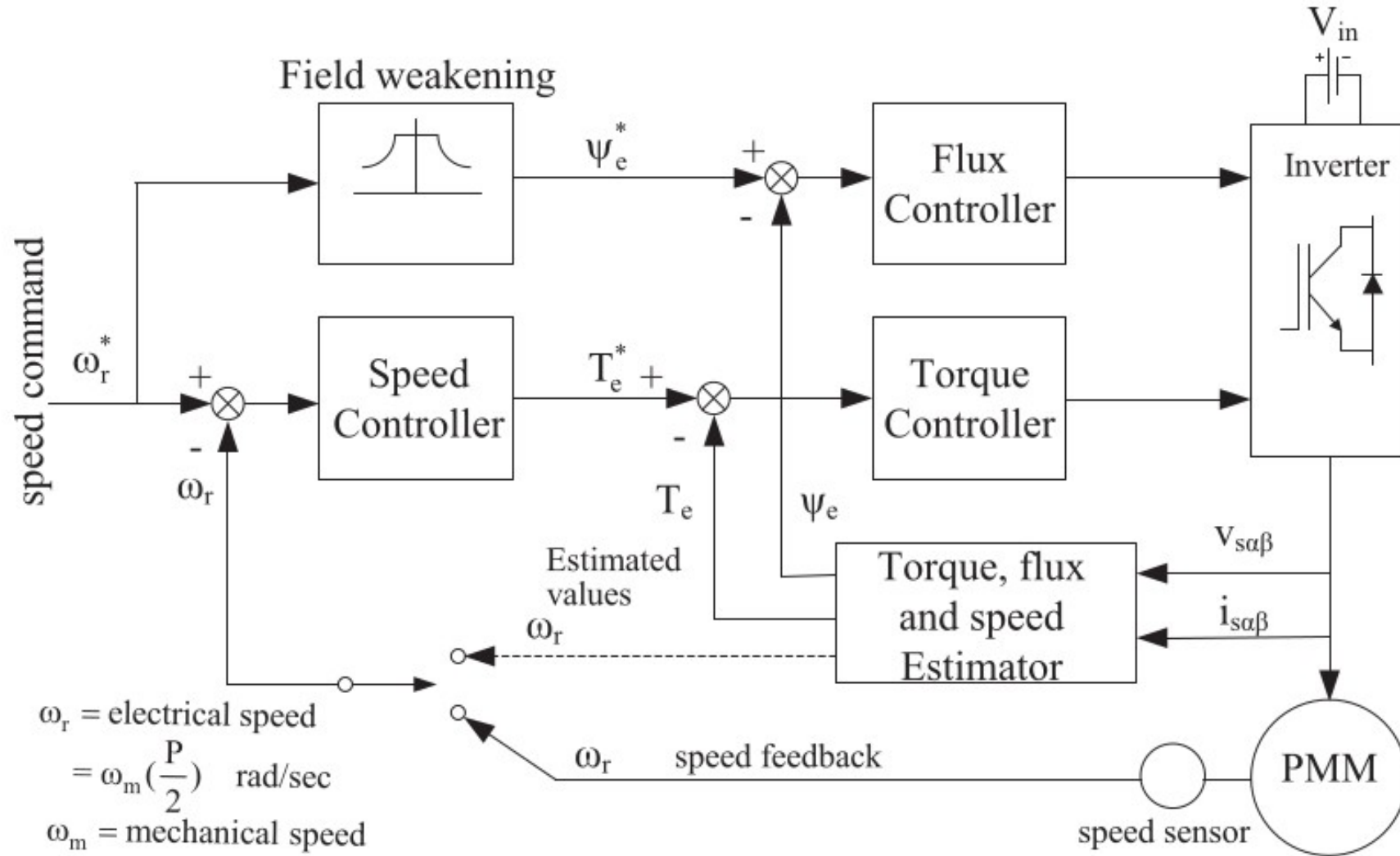
Da grandezze trifasi a fasore con componente in fase e quadratura. Riferimento statico.

For the inverse transformation, the inverse matrix is utilized:

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \cdot \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix}$$

Clarke: $\theta=0$
Park: $\theta=\theta_e$

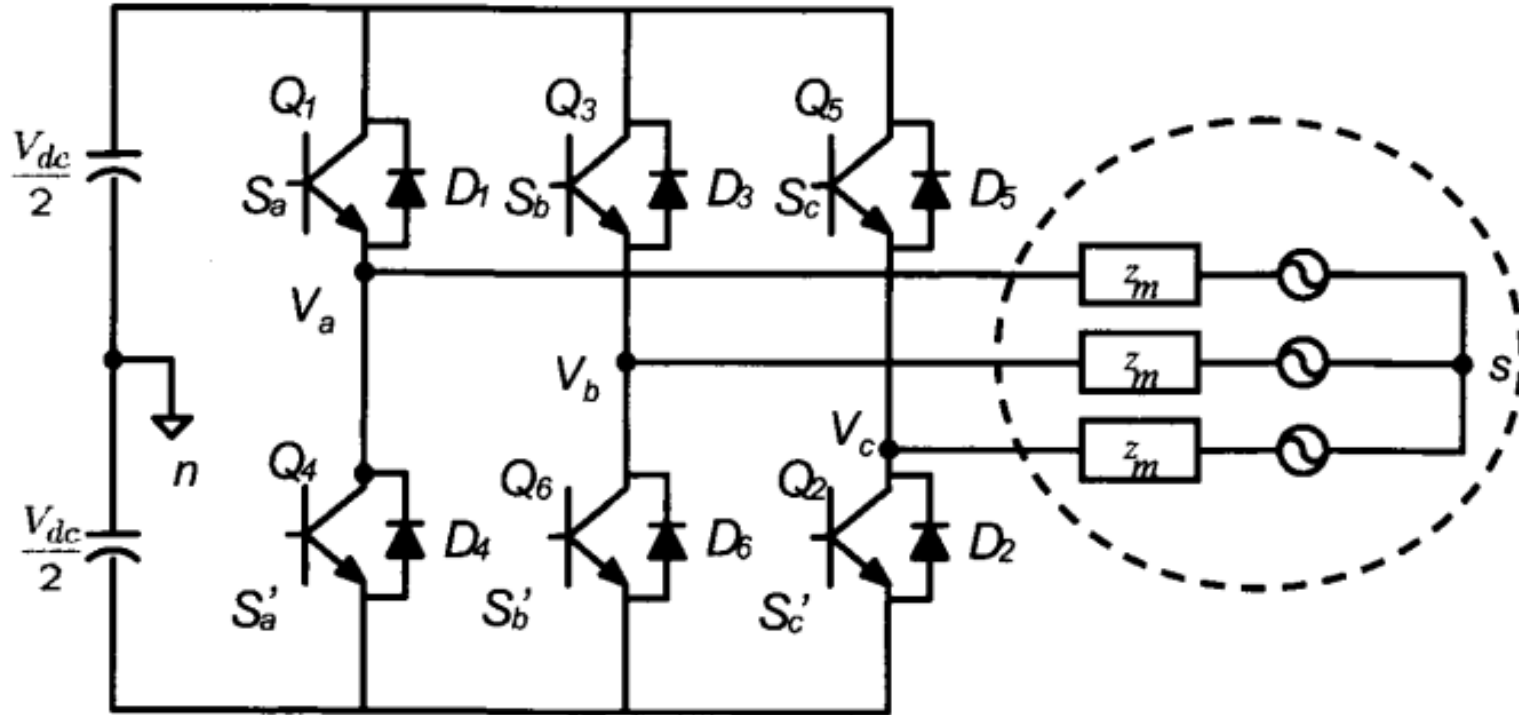
Schema generico di un controllore



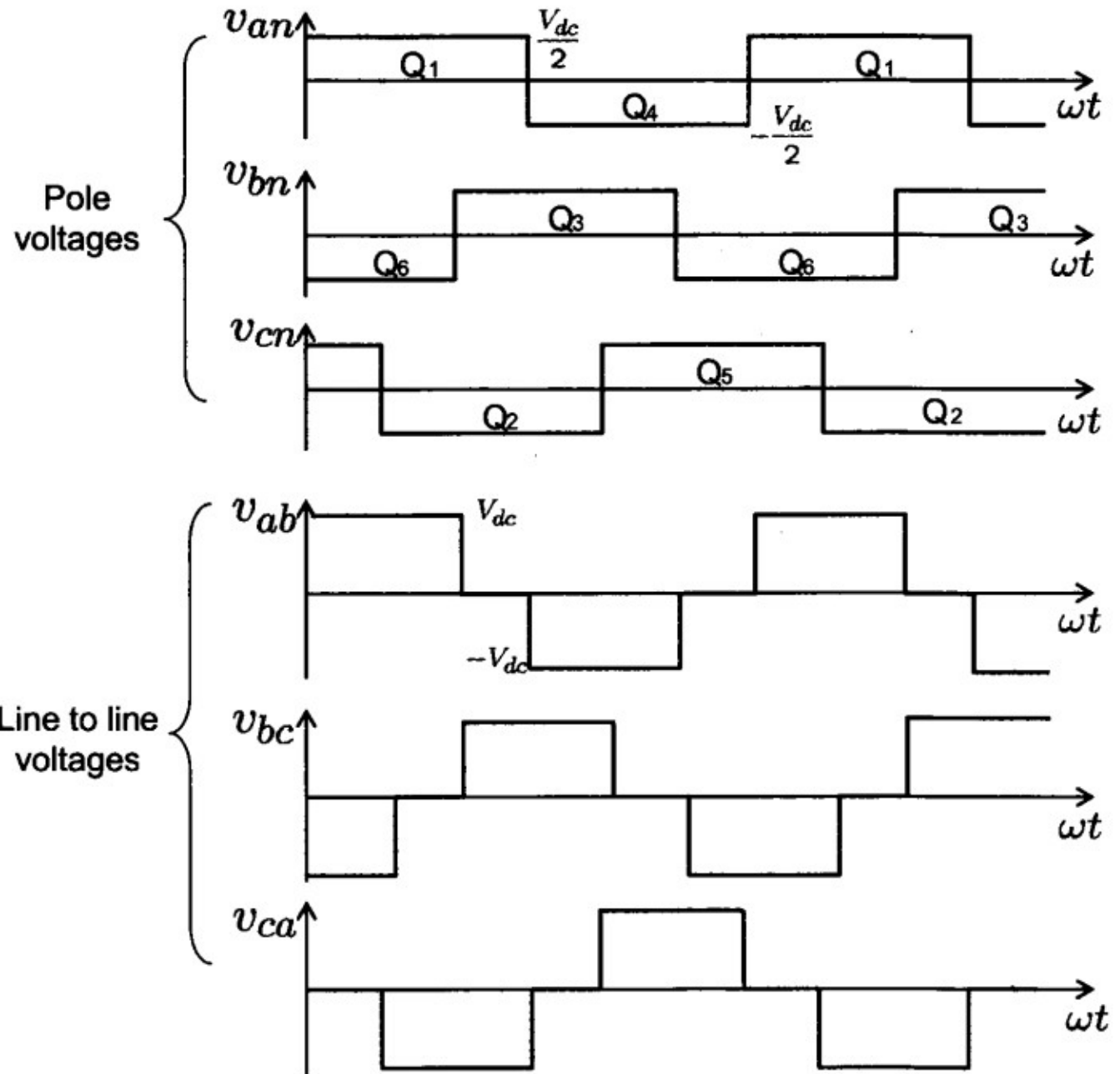
Parte 2

Inverter trifase

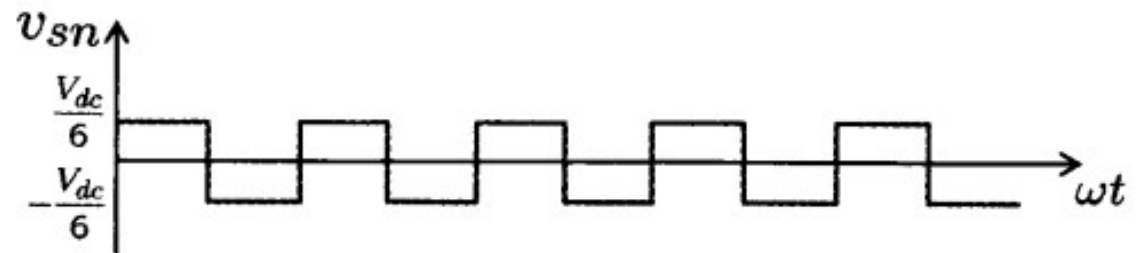
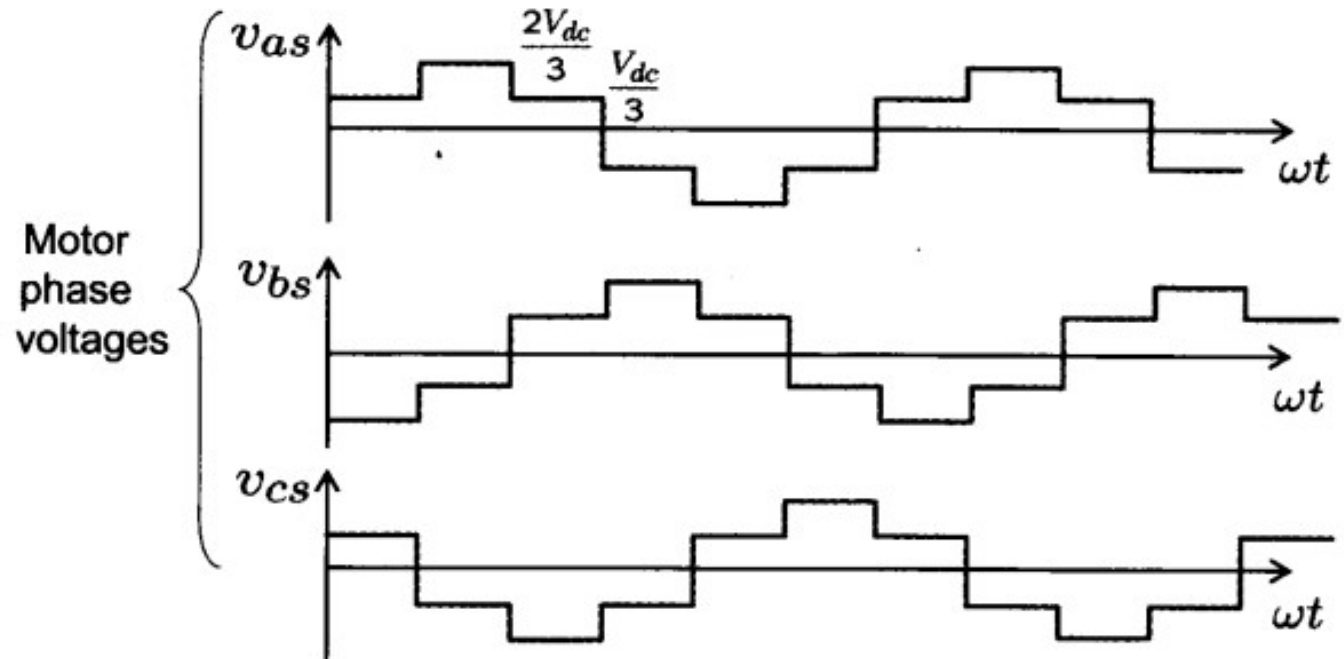
Inverter per tensioni trifasi



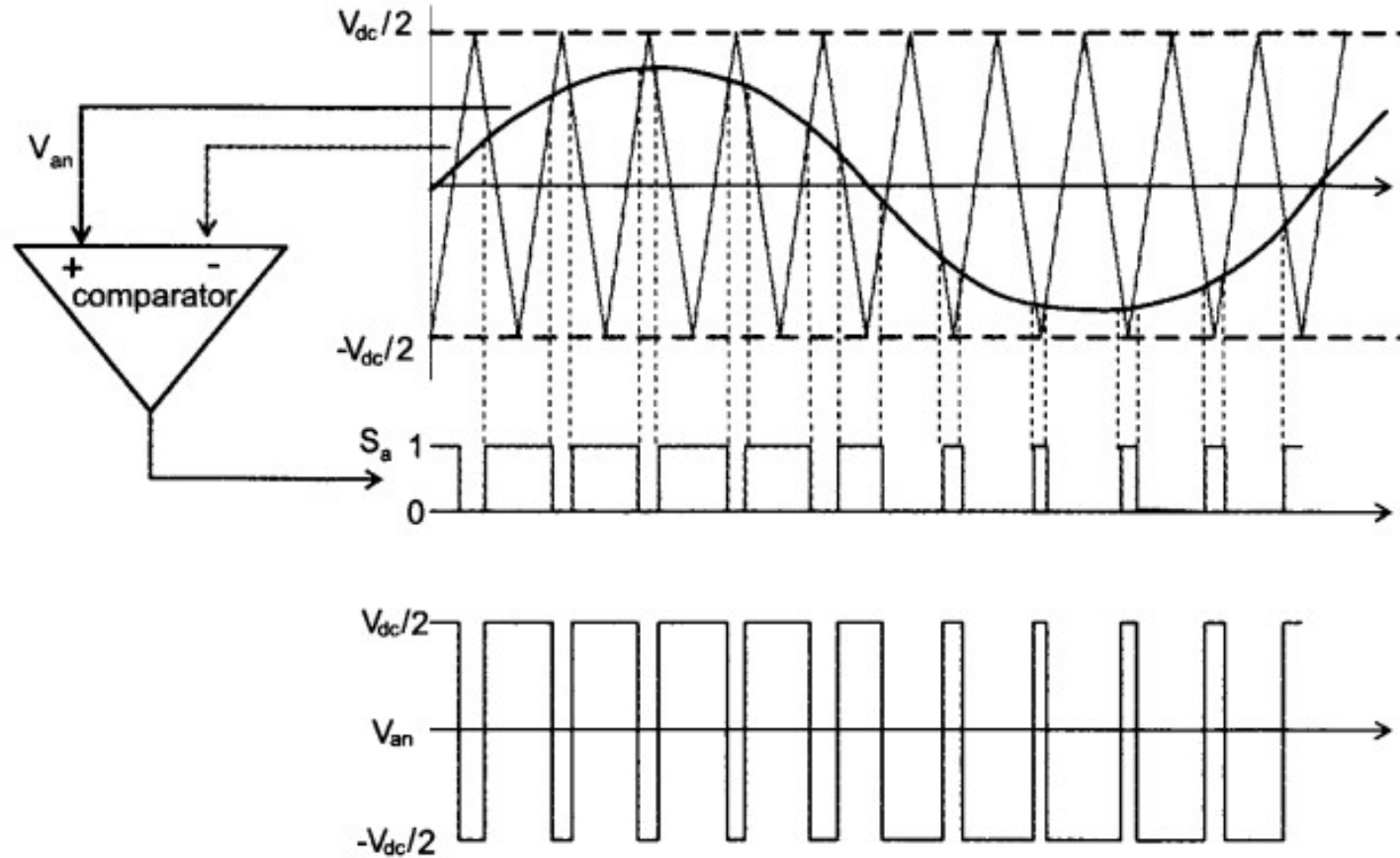
Six steps



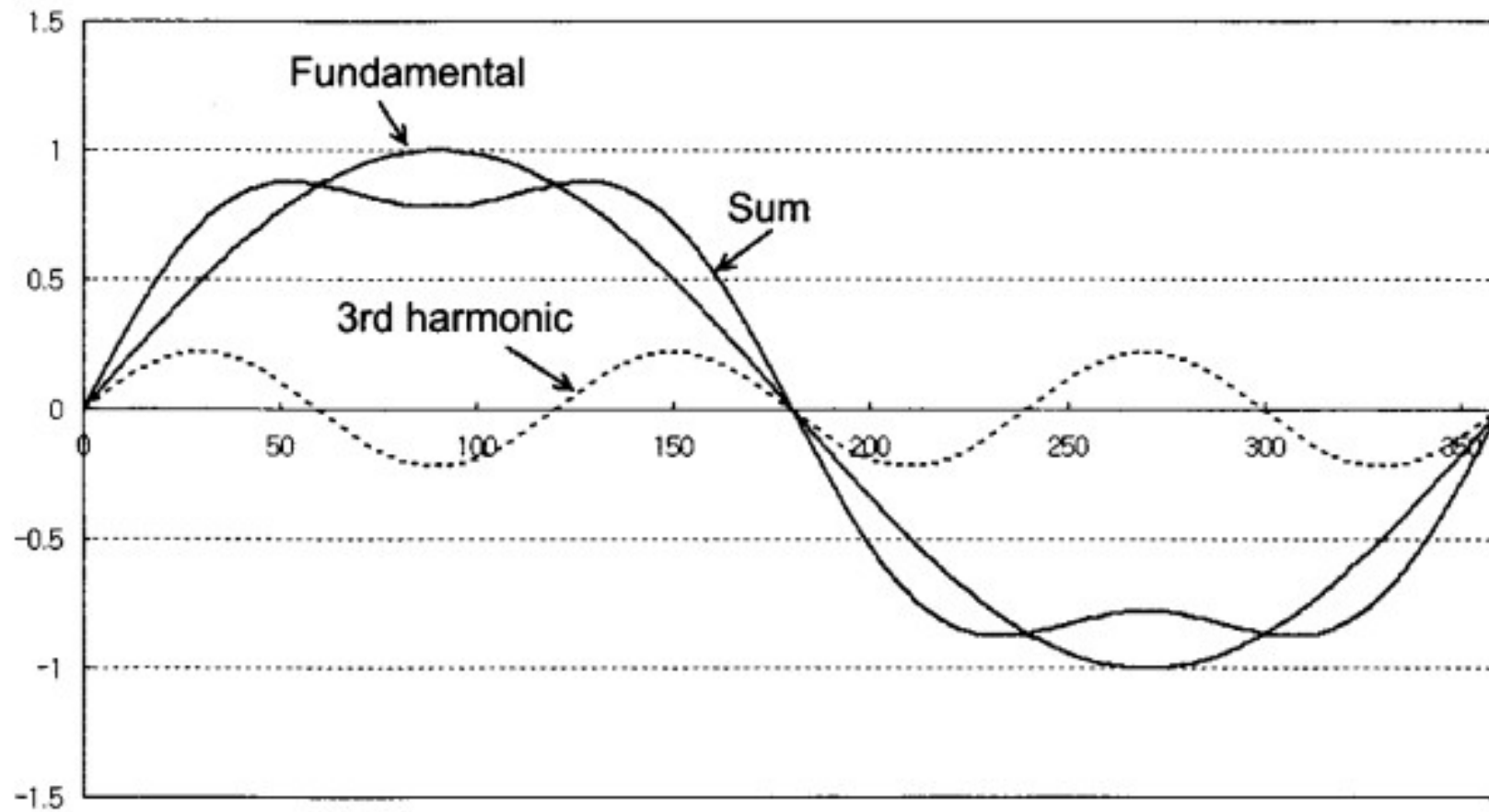
Six steps



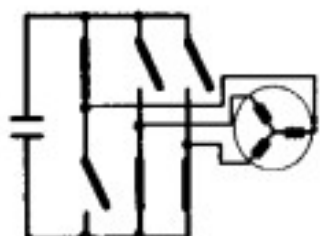
PWM sinusoidale



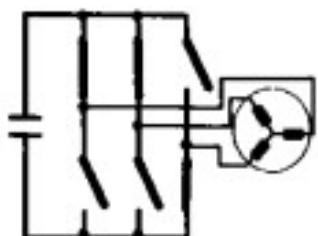
Aggiunta di 3^a armonica



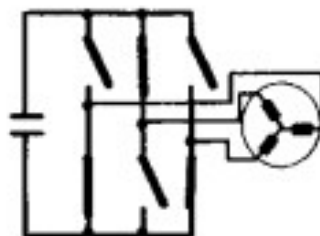
Space Vector PWM



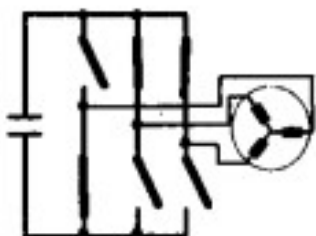
$V_1 (1,0,0)$



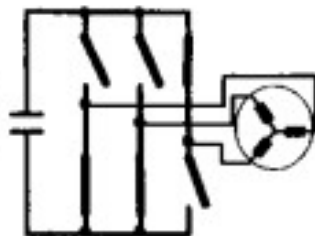
$V_2 (1,1,0)$



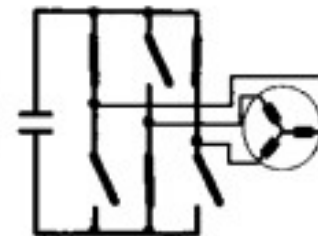
$V_3 (0,1,0)$



$V_4 (0,1,1)$



$V_5 (0,0,1)$



$V_6 (1,0,1)$

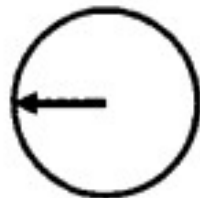
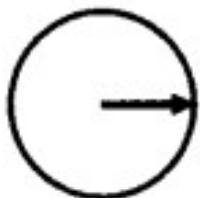
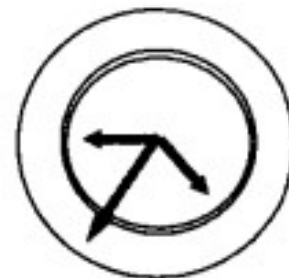
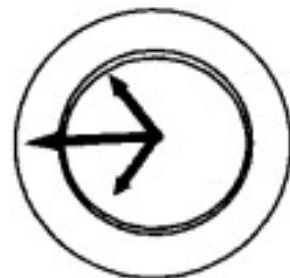
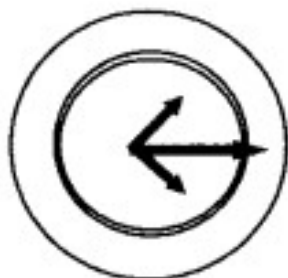
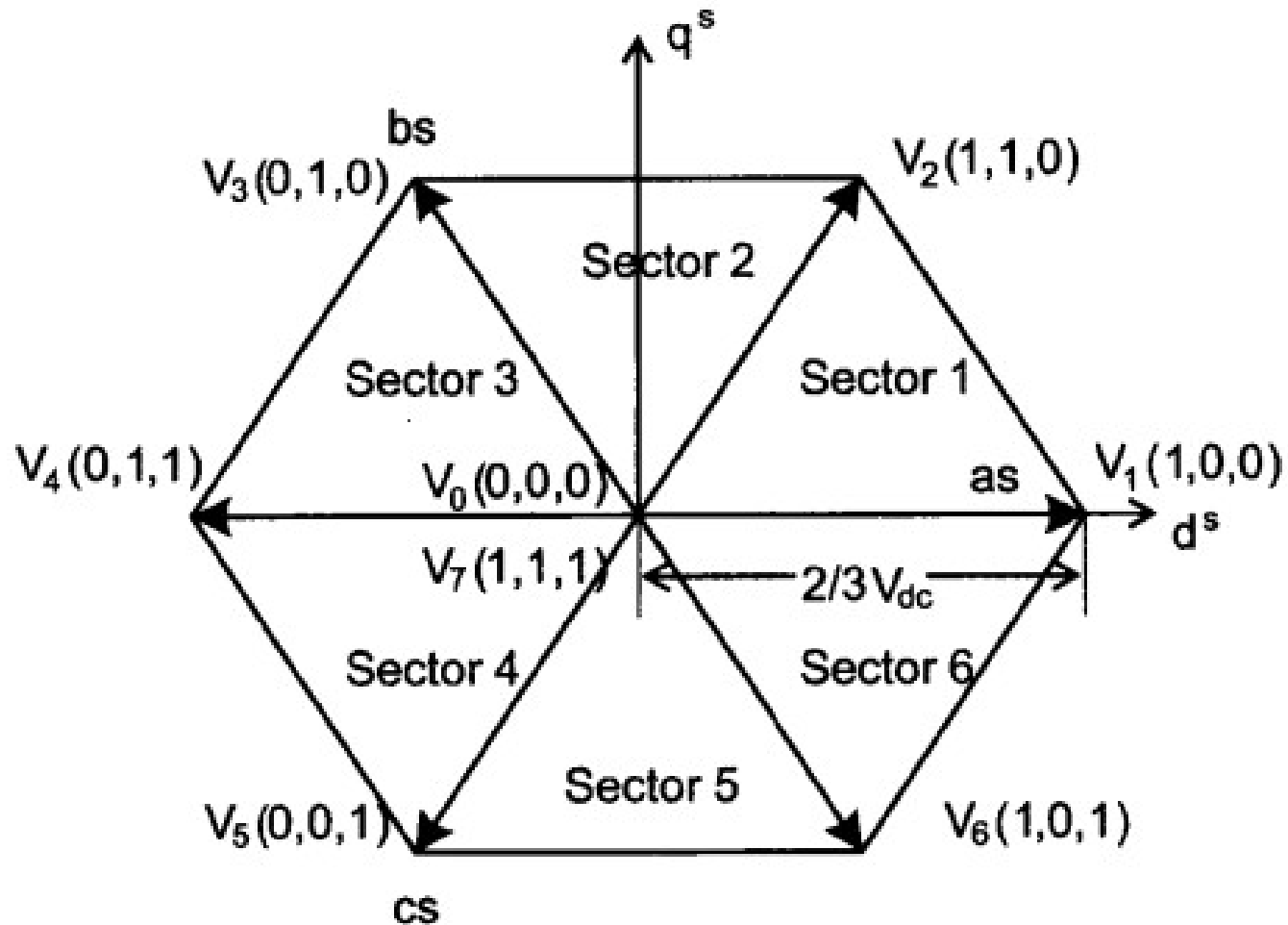
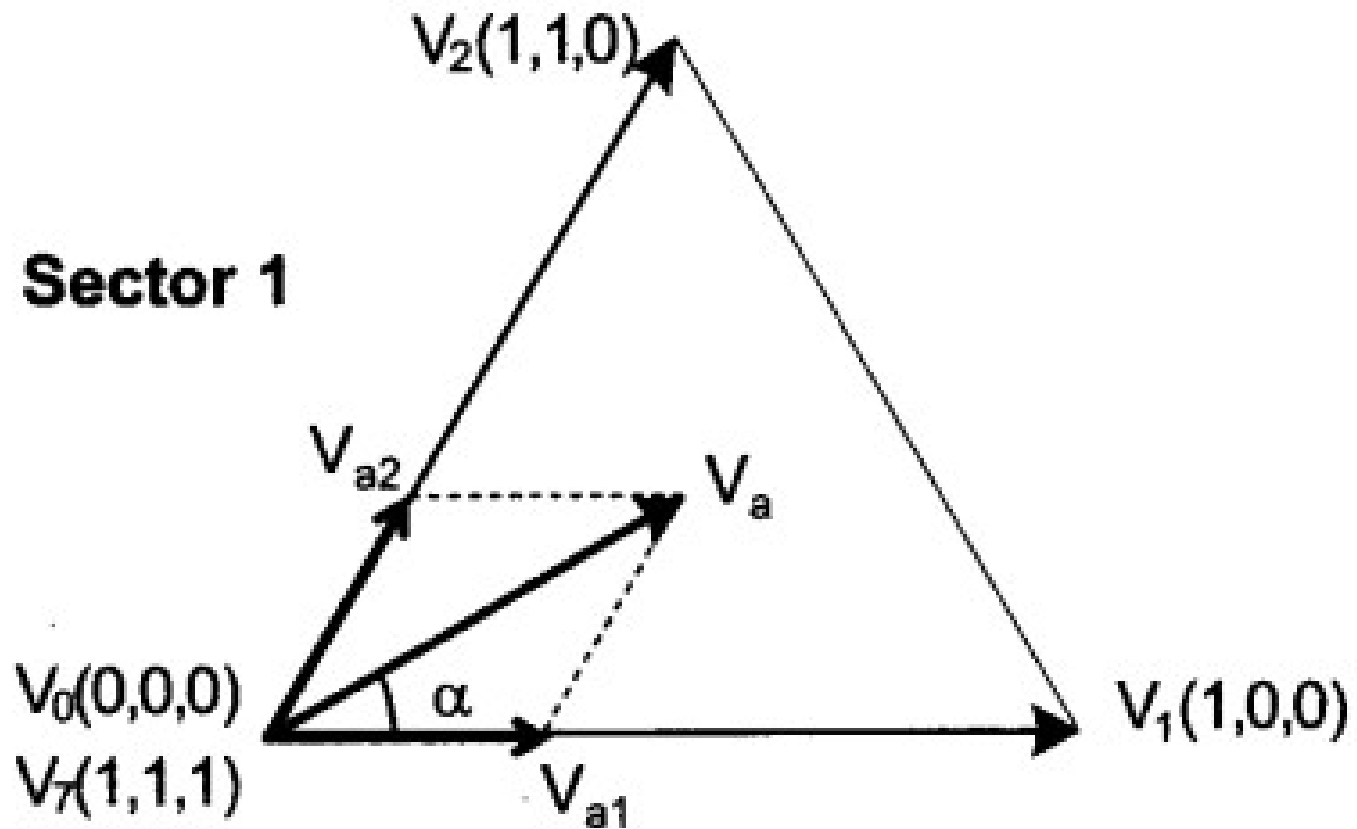


Diagramma dei vettori (SV)



Calcolo dei tempi per V_a



Calcolo dei tempi nel periodo

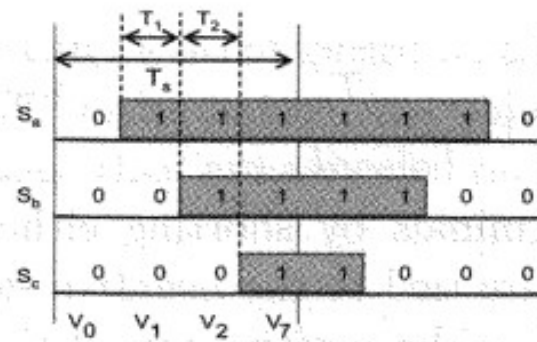
$$\begin{aligned} \begin{bmatrix} v_d^s \\ v_q^s \end{bmatrix} &\equiv V_a \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = \frac{T_1}{T_s} \frac{2}{3} V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \frac{T_2}{T_s} \frac{2}{3} V_{dc} \begin{bmatrix} \cos \frac{\pi}{3} \\ \sin \frac{\pi}{3} \end{bmatrix} \\ &= \frac{2}{3} \frac{V_{dc}}{T_s} \begin{bmatrix} 1 & \cos \frac{\pi}{3} \\ 0 & \sin \frac{\pi}{3} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}. \end{aligned}$$

$$\begin{aligned} \frac{V_{a1}}{(2/3)V_{dc}} &= \frac{T_1}{T_s}, \\ \frac{V_{a2}}{(2/3)V_{dc}} &= \frac{T_2}{T_s}. \end{aligned}$$

$$T_1 = \frac{\sqrt{3}T_s}{V_{dc}} \left[\sin\left(\frac{\pi}{3}m\right)v_d^s - \cos\left(\frac{\pi}{3}m\right)v_q^s \right],$$

$$T_2 = \frac{\sqrt{3}T_s}{V_{dc}} \left[-\sin\left(\frac{\pi}{3}(m-1)\right)v_d^s + \cos\left(\frac{\pi}{3}(m-1)\right)v_q^s \right],$$

Sector 1

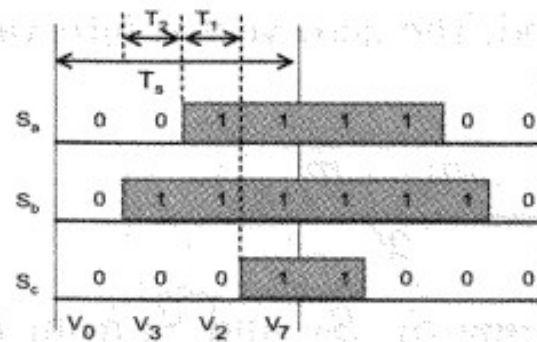


$$S_a = T_1 + T_2 + (T_s - T_1 - T_2)/2$$

$$S_b = T_2 + (T_s - T_1 - T_2)/2$$

$$S_c = (T_s - T_1 - T_2)/2$$

Sector 2

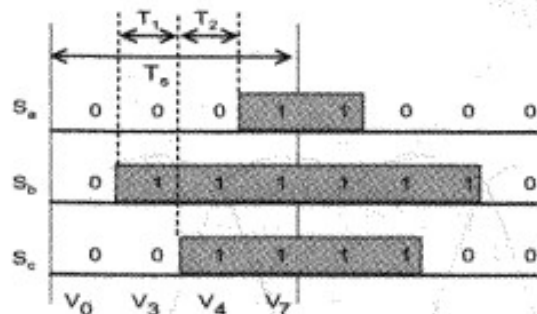


$$S_a = T_1 + (T_s - T_1 - T_2)/2$$

$$S_b = T_2 + T_1 + (T_s - T_1 - T_2)/2$$

$$S_c = (T_s - T_1 - T_2)/2$$

Sector 3

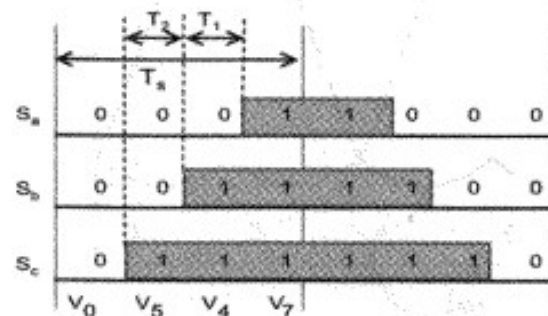


$$S_a = (T_s - T_1 - T_2)/2$$

$$S_b = T_1 + T_2 + (T_s - T_1 - T_2)/2$$

$$S_c = T_2 + (T_s - T_1 - T_2)/2$$

Sector 4

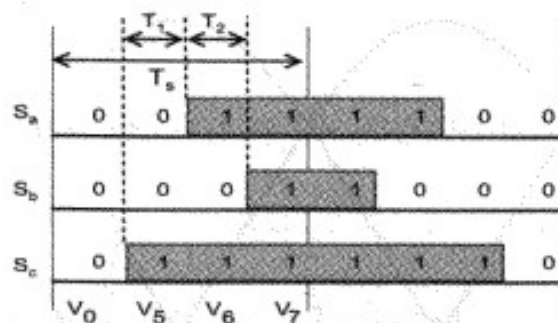


$$S_a = (T_s - T_1 - T_2)/2$$

$$S_b = T_1 + (T_s - T_1 - T_2)/2$$

$$S_c = T_2 + T_1 + (T_s - T_1 - T_2)/2$$

Sector 5

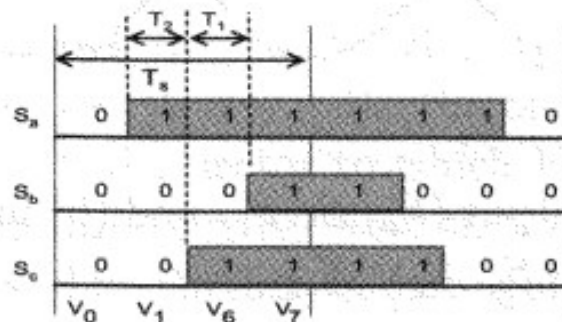


$$S_a = T_2 + (T_s - T_1 - T_2)/2$$

$$S_b = (T_s - T_1 - T_2)/2$$

$$S_c = T_1 + T_2 + (T_s - T_1 - T_2)/2$$

Sector 6

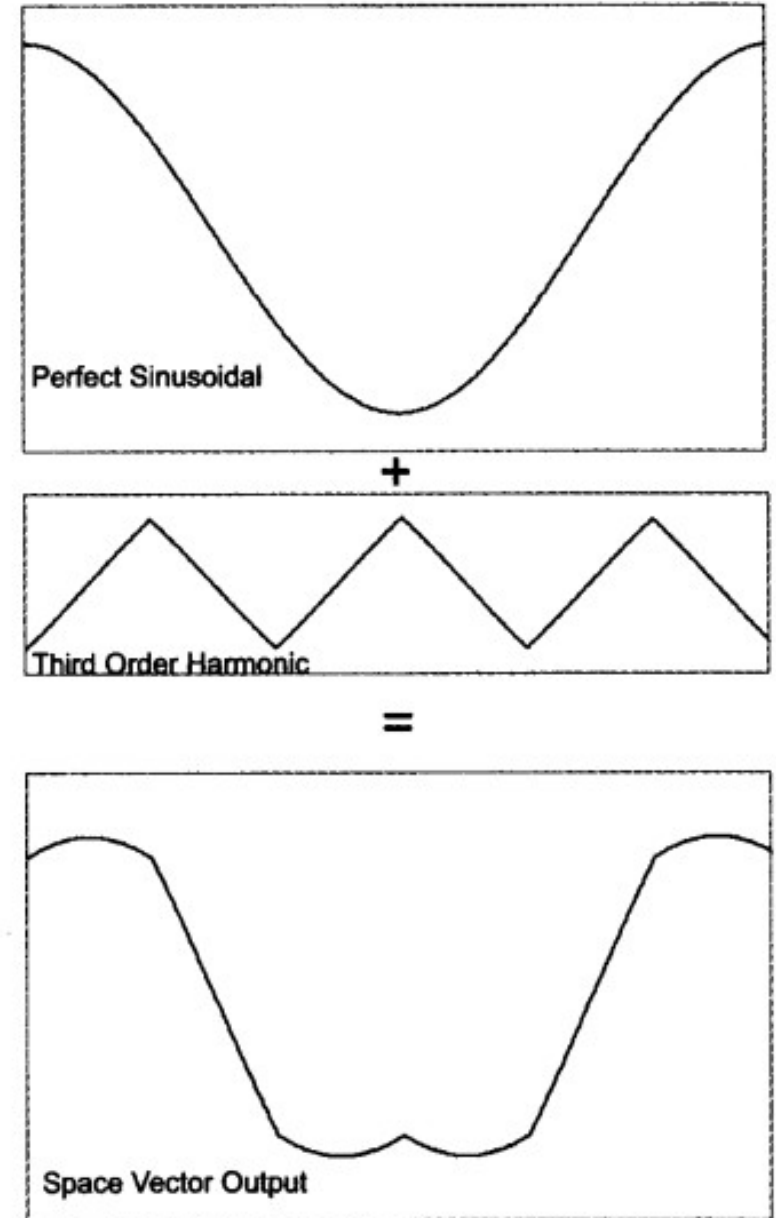


$$S_a = T_2 + T_1 + (T_s - T_1 - T_2)/2$$

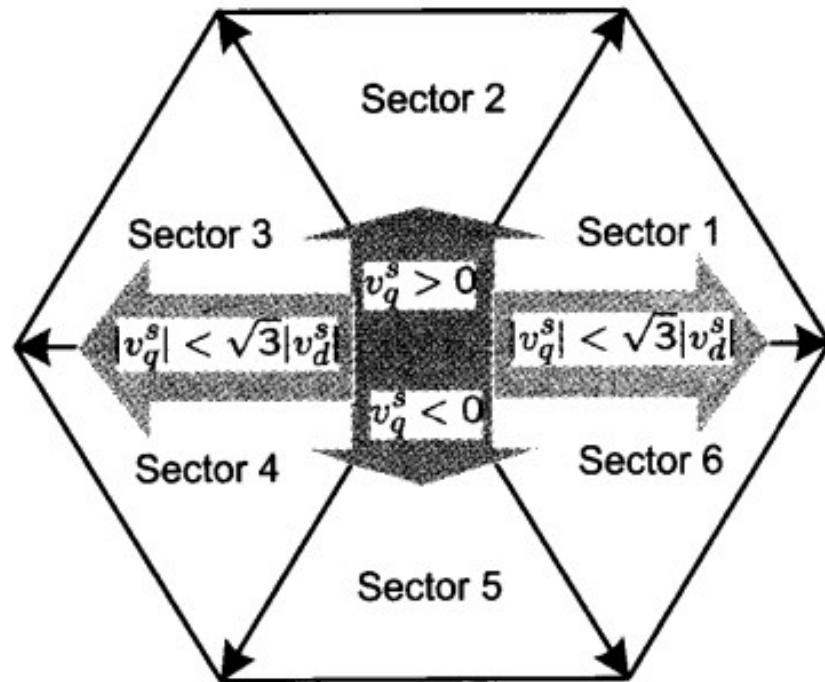
$$S_b = (T_s - T_1 - T_2)/2$$

$$S_c = T_1 + (T_s - T_1 - T_2)/2$$

Scomposizione della SVM



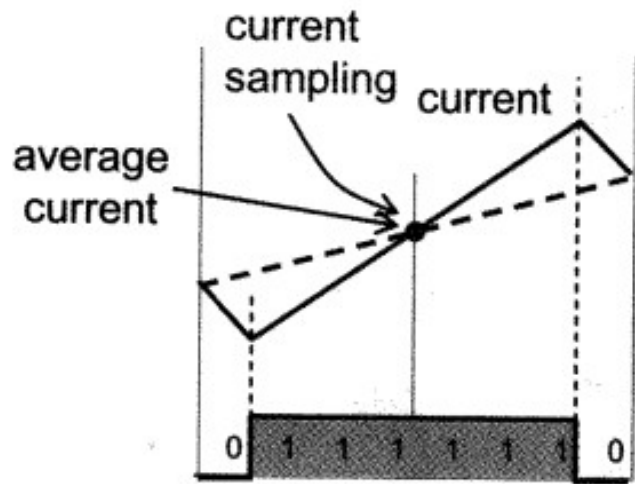
Determinazione del settore



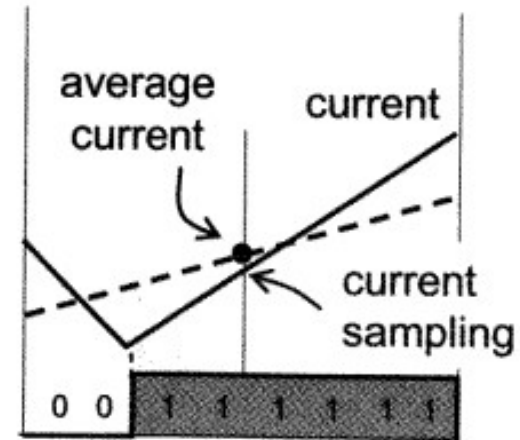
Sovramodulazione

Confronto PWM sinusoidale/SVM

Campionamento della corrente

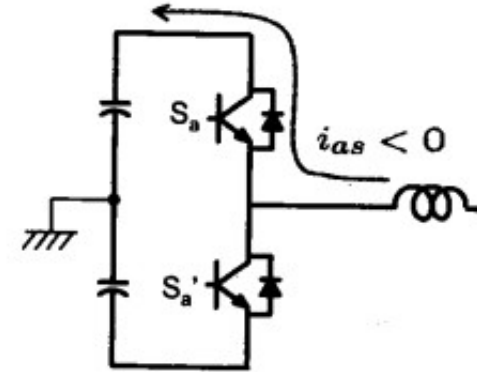
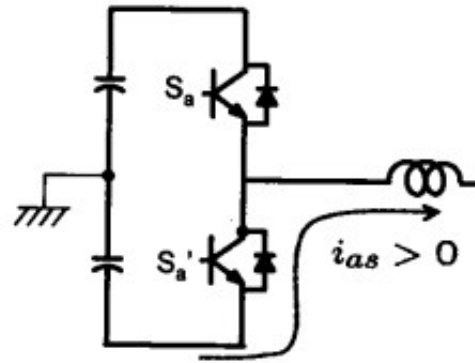


PWM simmetrica

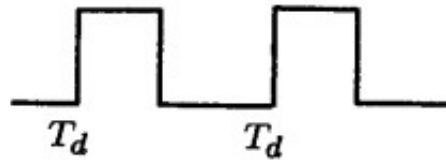


PWM asimmetrica

Il problema del tempo morto



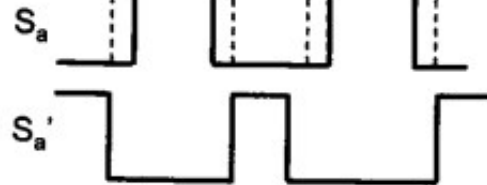
Original PWM



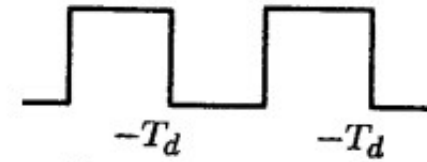
With dead time compensation



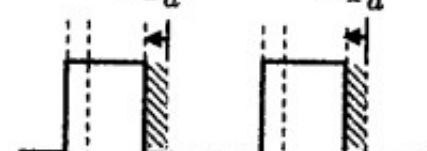
Gate signal after providing dead time



Original PWM



With dead time compensation



Gate signal after providing dead time

