Steady State Induction Machine Field Orientation Summary:

$\lambda_{qr}^{e} = 0$

Comparison to Transient Case

1) $I_{qr}^{e} = \dfrac{-L_m}{L_r} I_{qs}^{e}$

2) $I_{dr}^{e} = 0$

3) $\lambda_{dr}^{e} = L_m I_{ds}^{e}$

4) $s\,\omega_e = \dfrac{r_r}{L_r}\dfrac{I_{qs}^{e}}{I_{ds}^{e}} = \dfrac{1}{\tau_r}\dfrac{I_{qs}^{e}}{I_{ds}^{e}}$

5) $T_e = \dfrac{3}{2}\dfrac{P}{2}\dfrac{L_m}{L_r}\lambda_{dr}^{e} I_{qs}^{e}$

$$= \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds}^{e} I_{qs}^{e}$$

Dynamic State Induction Machine Field Orientation:

$$\left[p + j(\omega_e - \omega_r)\right] \overline{\lambda}_{qdr}^{e} + r_r \overline{i}_{qdr}^{e} = 0$$

$$r_r i_{qr}^{e} + p\lambda_{qr}^{e} + (\omega_e - \omega_r)\lambda_{dr}^{e} = 0$$

$$r_r i_{dr}^{e} + p\lambda_{dr}^{e} - (\omega_e - \omega_r)\lambda_{qr}^{e} = 0$$

$$\lambda_{qr}^{e} = 0 \rightarrow \boxed{i_{qs}^{e} = \frac{-L_r}{L_m} i_{qr}^{e}}$$

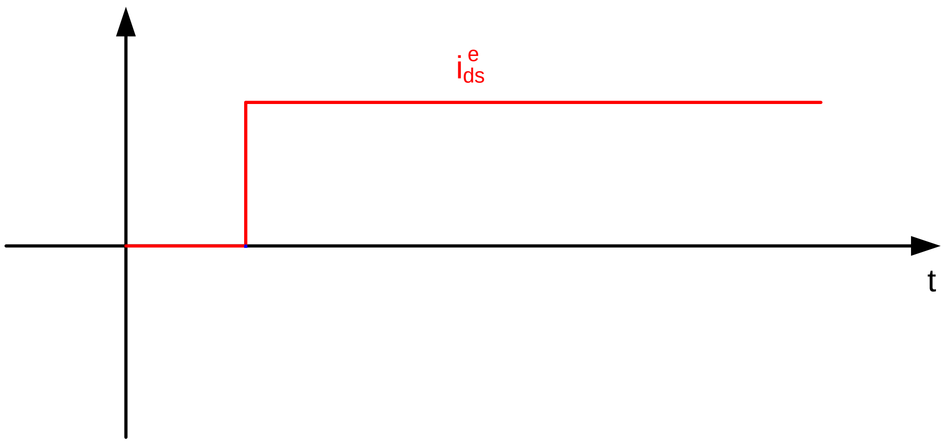
$$r_r i_{qr}^{e} + s\,\omega_e \lambda_{dr}^{e} = 0 \rightarrow \boxed{s\,\omega_e = \frac{-r_r i_{qr}^{e}}{\lambda_{dr}^{e}} = \frac{r_r}{L_r}\frac{L_m i_{qs}^{e}}{\lambda_{dr}^{e}}}$$

a) Eliminate $\lambda_{dr}^{e} = L_m i_{ds}^{e} + L_r i_{dr}^{e}$

$$r_r i_{dr}^{e} + L_m p\, i_{ds}^{e} + L_r p\, i_{dr}^{e} = 0$$

$$(r_r + L_r p)\, i_{dr}^{e} = -p L_m i_{ds}^{e}$$

$$\frac{i_{dr}^{e}}{i_{ds}^{e}} = \frac{-L_m p}{r_r + L_r p}$$

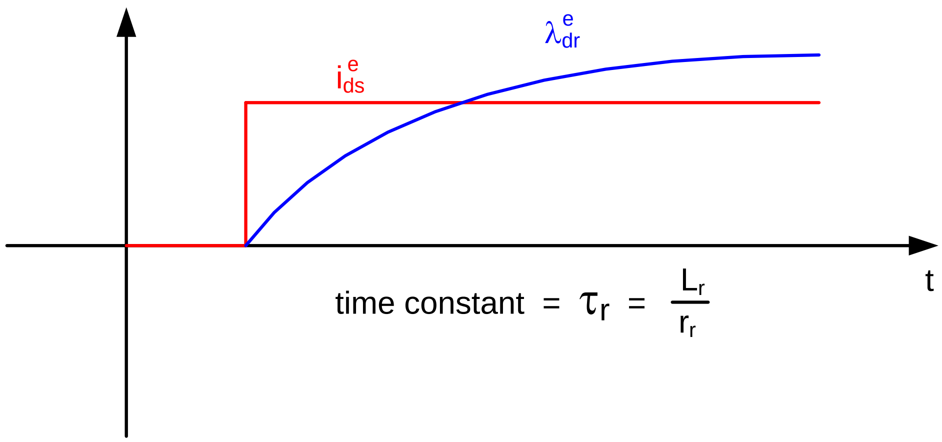


Change in Rotor d-Axis Current with a Change in Stator d-Axis Current

b) Eliminate $i_{dr}^{e} = \frac{\lambda_{dr}^{e}}{L_r} - \frac{L_m}{L_r} i_{ds}^{e}$

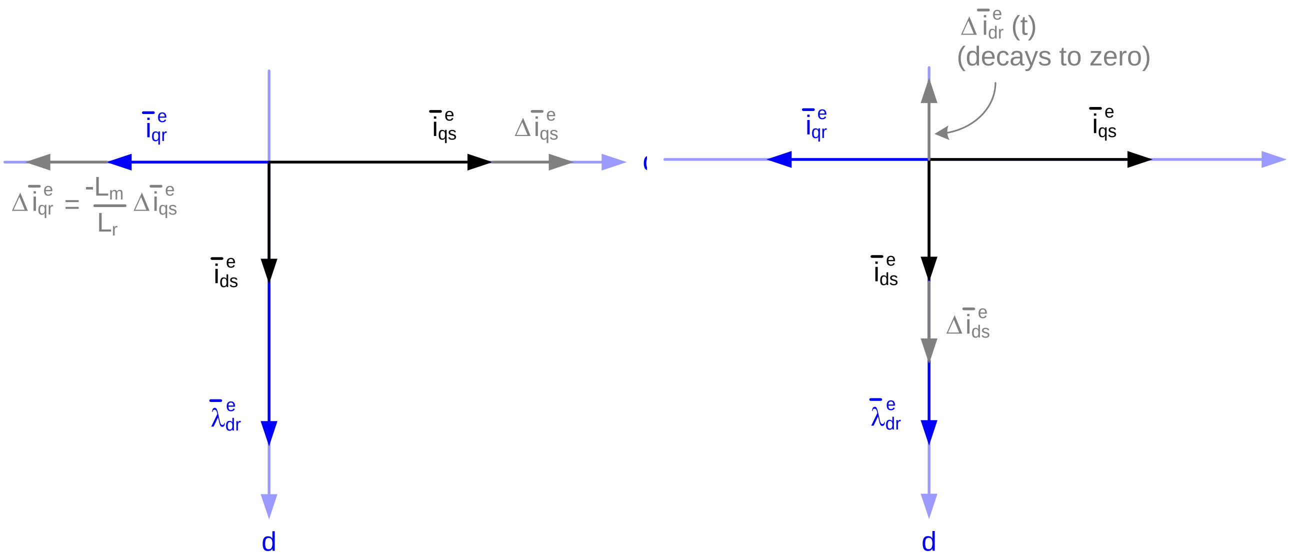
$$\frac{r_r}{L_r}\lambda_{dr}^{e} - \frac{r_r L_m}{L_r} i_{ds}^{e} + p\lambda_{dr}^{e} = 0$$

$$\left(p + \frac{r_r}{L_r}\right)\lambda_{dr}^{e} = \frac{r_r}{L_r} L_m\, i_{ds}^{e}$$



Change in Rotor Flux with a Change in Stator d-Axis Current

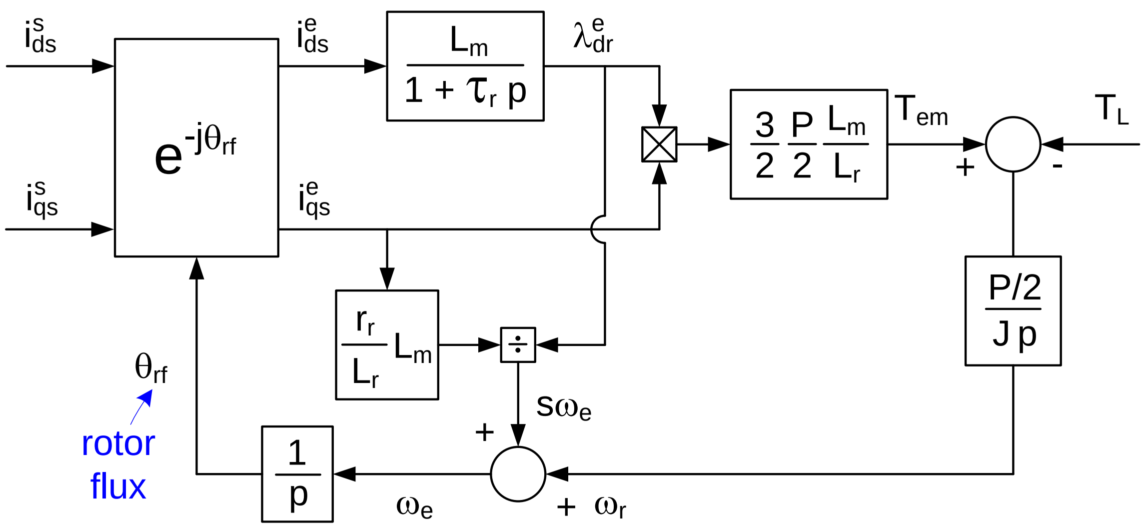
Major difference in transient case is that there can be a d-axis rotor current induced by any change in d-axis stator current that is not slip related.



Fully Transient Indirect Field Orientation of Induction Machine with i_{ds}^{e*} ***and*** i_{qs}^{e*} ***:***

$$\lambda_{dr}^{e} = \frac{L_m}{1 + p\,\tau_r} i_{ds}^{e}$$

$$\boxed{s\,\omega_e^* = \frac{\left(\dfrac{1}{\hat{\tau}_r}\right) i_{qs}^{e*}}{\left(\dfrac{1}{1 + p\,\hat{\tau}_r}\right) i_{ds}^{e*}}}$$

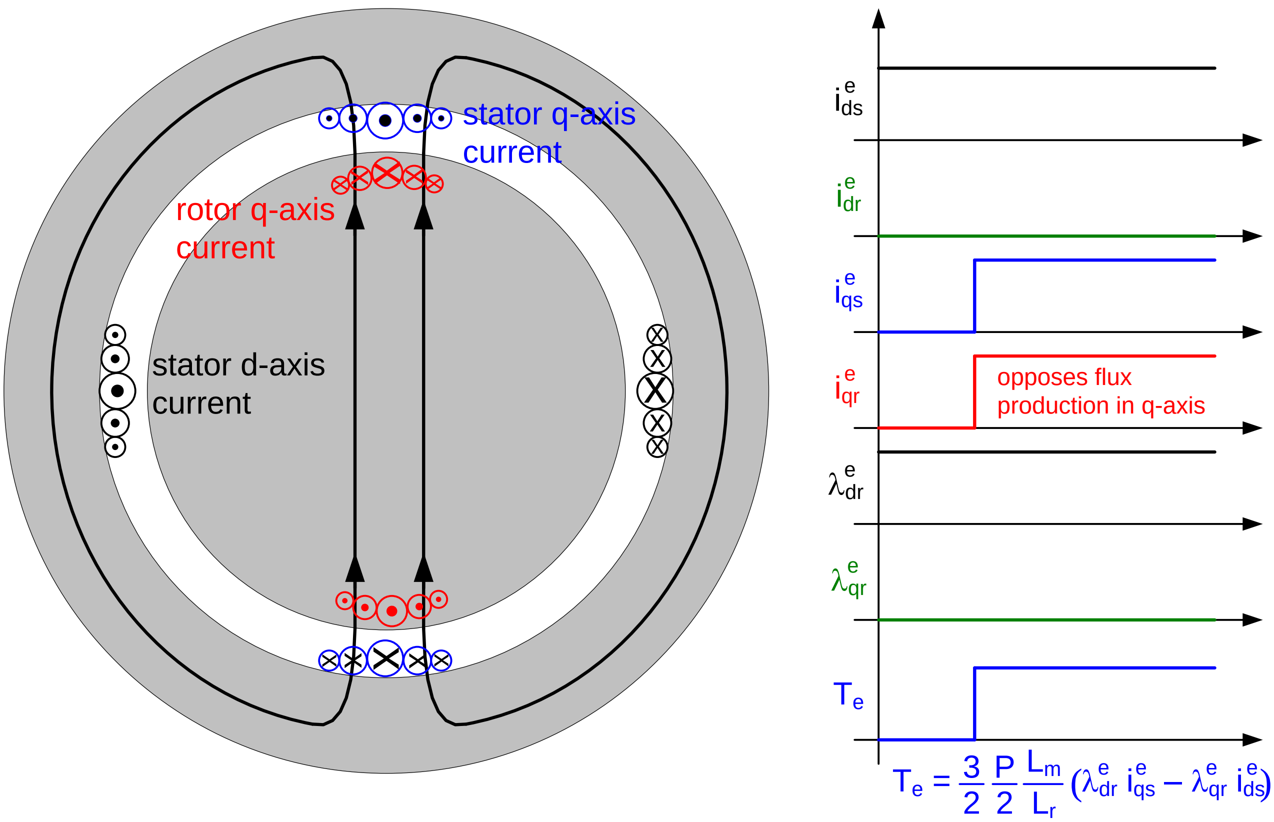


Current Fed Induction Machine in Rotor Flux Oriented Reference Frame

Indirect Field Orientation uses slip relationship to determine rotor flux

Recap: Induction Machine Field Orientation Using dq Model

A static look at Field Orientation in an Induction Machine:



Torque Production in IM with Steady State d-Axis Current and Sudden Application of q-Axis Current

So far we have discussed Indirect Field Orientation (IFO). IFO uses slip relationship to determine the spatial location of rotor flux.

"Direct" Field Orientation:

Rotor flux angle is "directly" measured (or estimated) rather than calculating it using the slip relationship. The two methods are:

a) Using air gap flux sensors (not common)

$$\bar{\lambda}^s_{qdm} = L_m\left(\bar{i}^s_{qds} + \bar{i}^s_{qdr}\right) \rightarrow$$

$$\bar{\lambda}^s_{qdr} = \bar{\lambda}^s_{qdm} + L_{lr}\,\bar{i}^s_{qdr}$$

$$=$$

$$=$$

Problems

1) Sensors in airgap
2) L_{lr} variations (w/load)

b) Use terminal voltage

$$\bar{\lambda}^s_{qds} = \frac{1}{p}\left(\bar{v}^s_{qds} - r_s\,\bar{i}^s_{qds}\right)$$ integrate stator voltage to get stator flux

$$\bar{\lambda}^s_{qdr} = L_m\,\bar{i}^s_{qds} + L_r\,\bar{i}^s_{qdr}$$

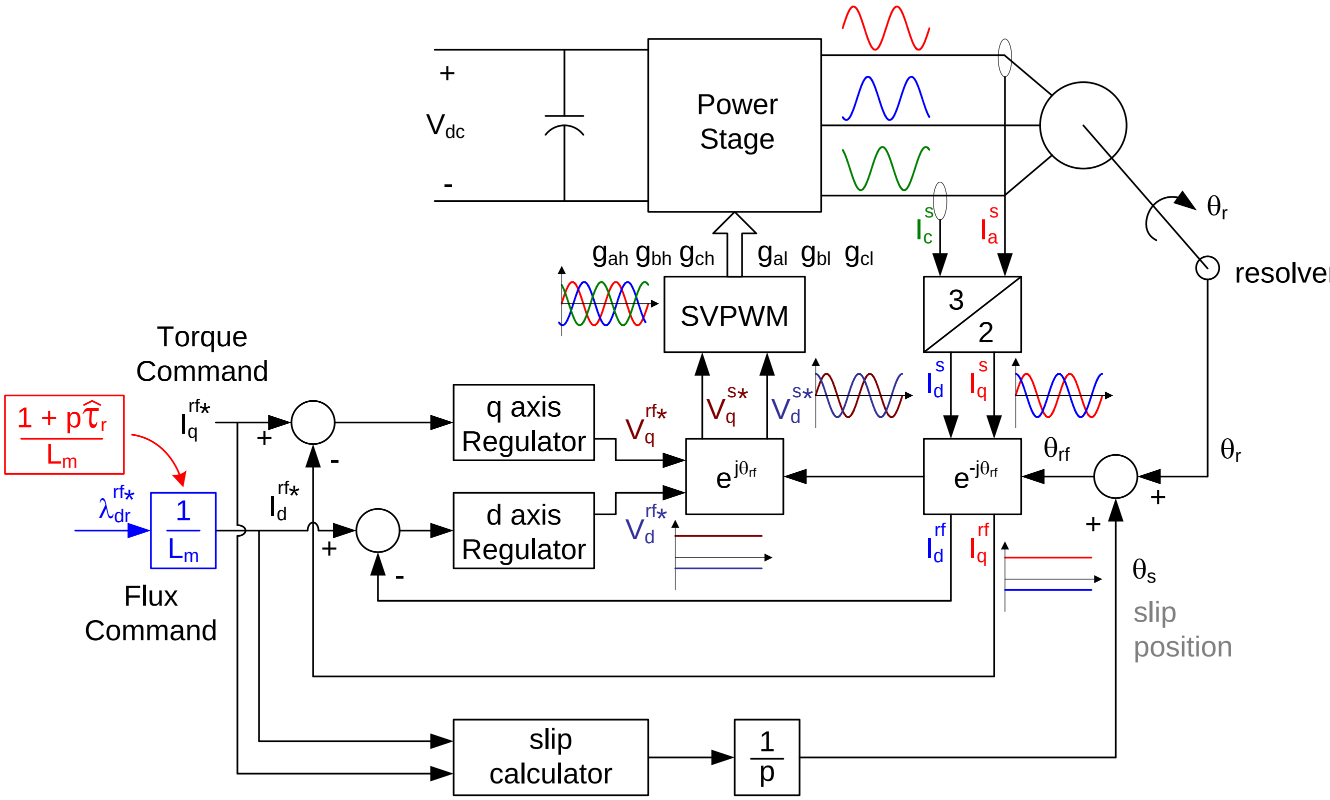
$$\bar{i}^s_{qdr} = \frac{\bar{\lambda}^s_{qds}}{L_m} - \frac{L_s}{L_m}\bar{i}^s_{qds}$$ need rotor currents to get rotor flux

$$\rightarrow \quad \bar{\lambda}^s_{qdr} = \frac{L_r}{L_m}\left(\bar{\lambda}^s_{qds} - L_s'\,\bar{i}^s_{qds}\right)$$ solve for rotor flux from stator flux and current

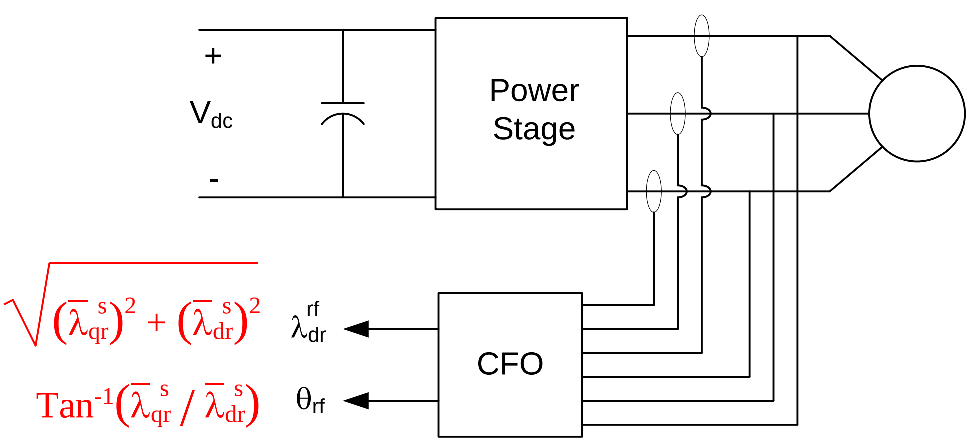
L_s' = Stator Transient Inductance

$$L_s' = L_s - \frac{L_m^2}{L_r} \approx L_{ls} + L_{lr}$$

Two Methods of Field Oriented Control (FOC) :

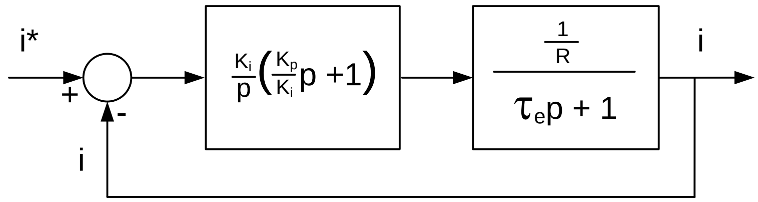


Indirect Field Orientation – Rotor Flux Orientation Induction Machine Control



Direct Field Orientation – Rotor Flux Orientation Induction Machine Control

Recap of Current Loop Controls:



Current Regulation of DC Drive (with Back EMF Decoupled)

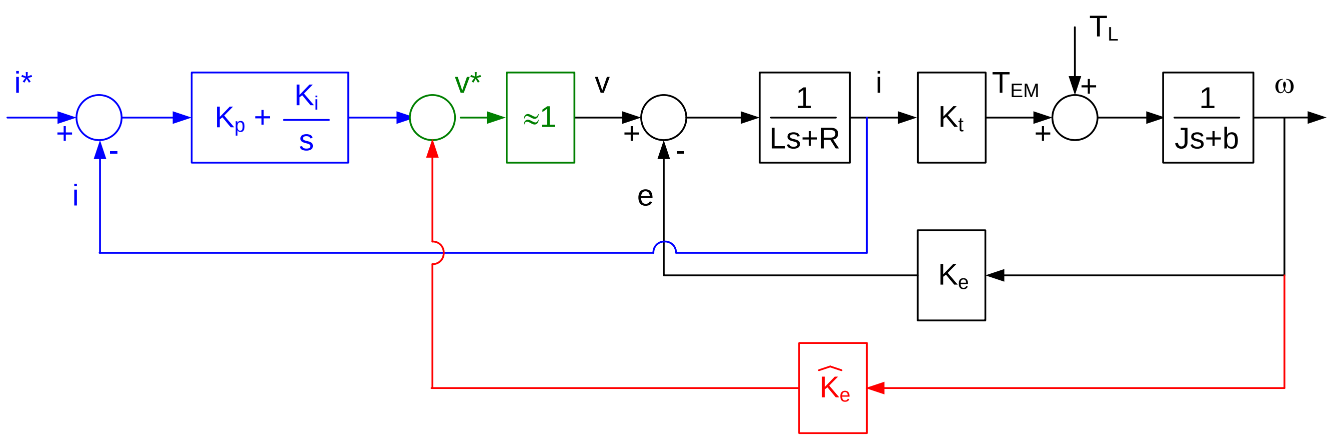
Use Proportional plus Integral (PI) Control

$$G_c = K_p + \frac{K_i}{p} = \frac{K_i}{p}\left(\frac{K_p}{K_i}p + 1\right) = \frac{K_i}{p}\left(\tau_c p + 1\right)$$

The gains to tune the current loop at locked rotor conditions are thus:

$\boxed{K_i = 2\pi f_{desired} R}$ and $\boxed{K_p = 2\pi f_{desired} L}$

Note: By using Back EMF decoupling, the desired bandwidth can be achieved at non zero speed conditions as well.



DC Motor PI Current Regulator with Back EMF Decoupling

Induction Machine Current Regulation Tuning:

We can re-write stator voltage equations as:

$$\overline{v}_{qds}^{\,e} = \left[r_s + (p + j\,\omega_e)\,\sigma L_s + \left(\frac{L_m}{L_r}\right)^2 r_r \right] \overline{i}_{qds}^{\,e} - \frac{L_m}{L_r}\, j(\omega_e - \omega_r)\,\overline{\lambda}_{qdr}^{\,e} + \frac{L_m}{L_r}\, j\,\omega_e\,\overline{\lambda}_{qdr}^{\,e} - \frac{L_m}{L_r}\frac{1}{\tau_r}{}^{e}\,\overline{\lambda}_{qdr}^{\,e}$$

$$\overline{v}_{qds}^{\,e} = \left[r_s' + (p + j\,\omega_e)\,\sigma L_s \right] \overline{i}_{qds}^{\,e} + \frac{L_m}{L_r}\,\omega_{rb}\,\overline{\lambda}_{qdr}^{\,e}$$

where

$$r_s' = \left[r_s + \left(\frac{L_m}{L_r}\right)^2 r_r \right] \qquad \omega_{rb} = \left[j\,\omega_r - \frac{1}{\tau_r} \right]$$

The scalar equations can be written as:

$$v_{qs}^{e} =$$

$$v_{ds}^{e} =$$

In the steady state,

$$\lambda_{dr}^{e} = L_m\, i_{ds}^{e}$$

So the equations can be rewritten as:

$$v_{qs}^{e} = \left(r_s' + \sigma L_s\, p \right) i_{qs}^{e} + \left(\sigma L_s\,\omega_e + \frac{L_m^2}{L_r}\,\omega_r \right) i_{ds}^{e}$$

$$v_{ds}^{e} = \left(\left[r_s + \left(\frac{L_m}{L_r}\right)^2 r_r \right] + \sigma L_s\, p \right) i_{ds}^{e} - \sigma L_s\,\omega_e\, i_{qs}^{e} - \left(\frac{L_m}{L_r}\right)^2 r_r\, i_{ds}^{e} \quad \text{or}$$

$$v_{ds}^{e} = \left(r_s + \sigma L_s\, p \right) i_{ds}^{e} - \sigma L_s\,\omega_e\, i_{qs}^{e}$$

In summary:

Transient Impedance
Synch Frame Coupling
Back EMF

$$v_{qs}^{e} = \left(r_s' + \sigma L_s p\right) i_{qs}^{e} + \left(\sigma L_s \omega_e + \frac{L_m^2}{L_r}\omega_r\right) i_{ds}^{e}$$

$$v_{ds}^{e} = \left(r_s + \sigma L_s p\right) i_{ds}^{e} - \sigma L_s \omega_e i_{qs}^{e}$$

<u>Indirect Field Oriented Control (IFOC):</u>

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left[\lambda_{dr}^{e} i_{qs}^{e} - \cancel{\lambda_{qr}^{e} i_{ds}^{e}}\right] = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr}^{e} i_{qs}^{e} = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds} I_{qs}$$

field current
torque producing current

Transient case (when changing i_{ds}^{e}):

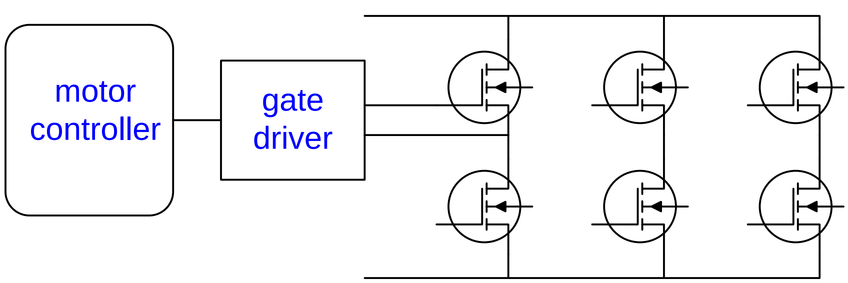
$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr}^{e} i_{qs}^{e} = K_t i_{qs}^{e} \quad \rightarrow \quad K_t = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr}^{e}$$

Steady state (not changing i_{ds}^{e}):

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds} I_{qs} = K_t i_{qs}^{e} \quad \rightarrow \quad K_t = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds}$$

<u>Voltage control of AC machines</u>

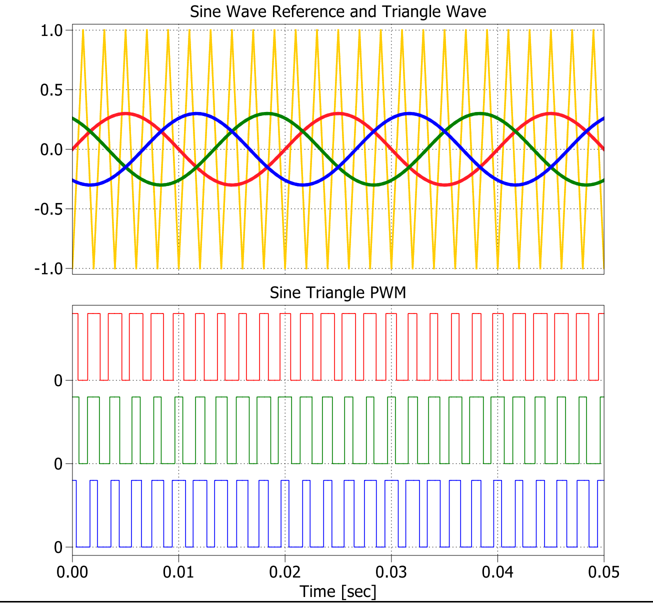
Typical inverter power levels:



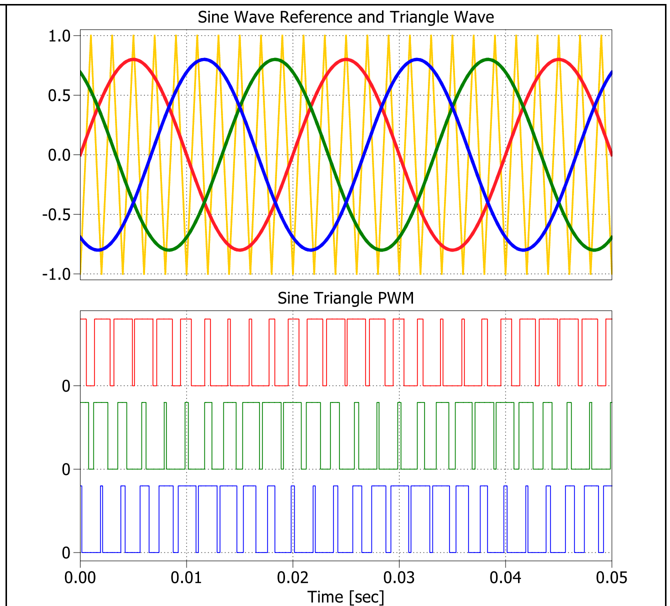
3.3V/100's mA
+15V/-5V/1-5 Apk
100's V/100's A

Typical Controller Power Sections

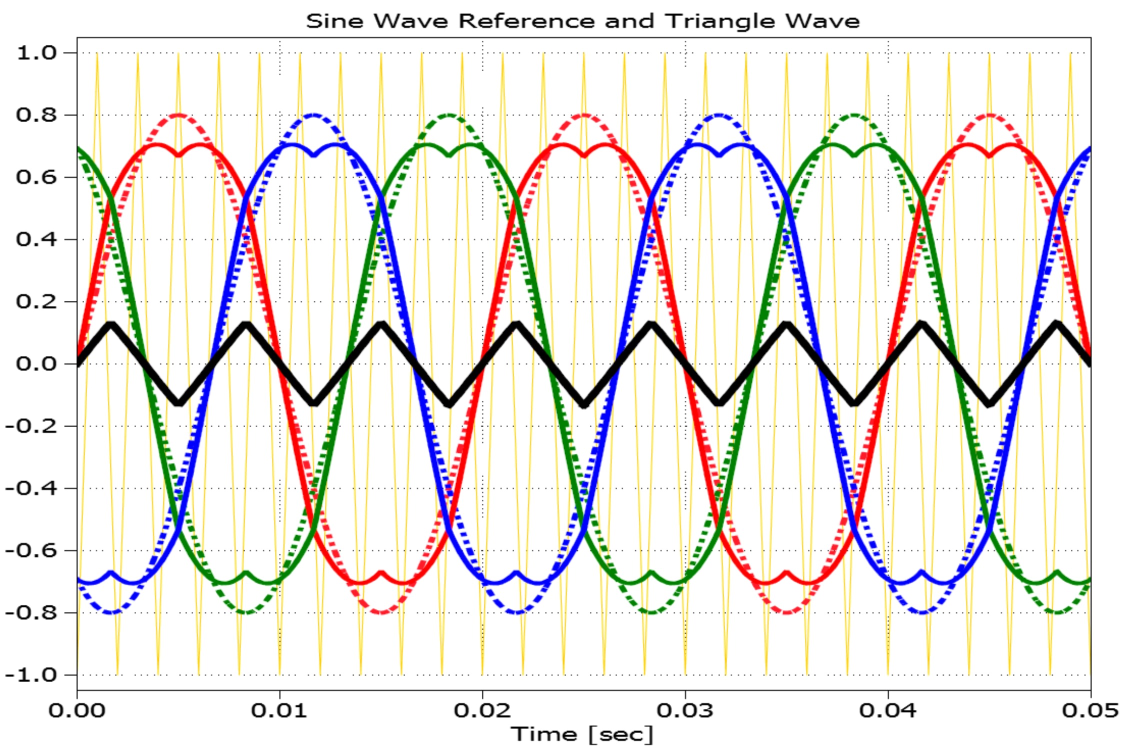
Sine Triangle PWM:



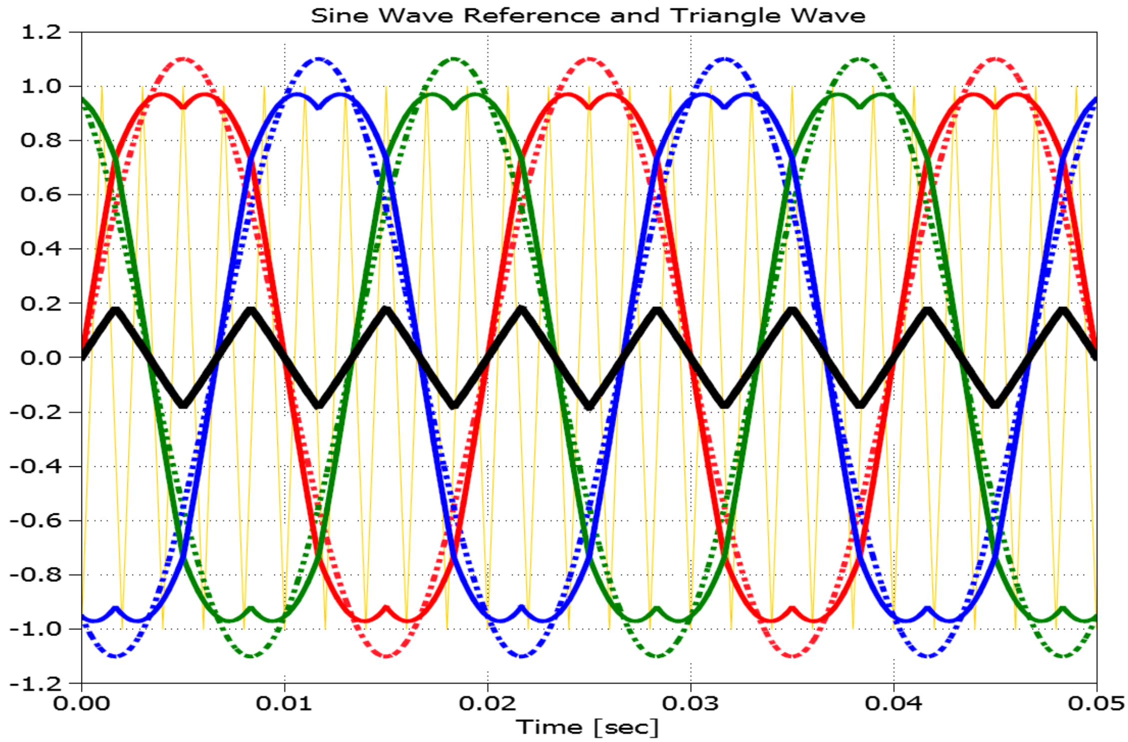
Sine Triangle PWM Waveform with m = 0.3



Sine Triangle PWM Waveform with m = 0.8

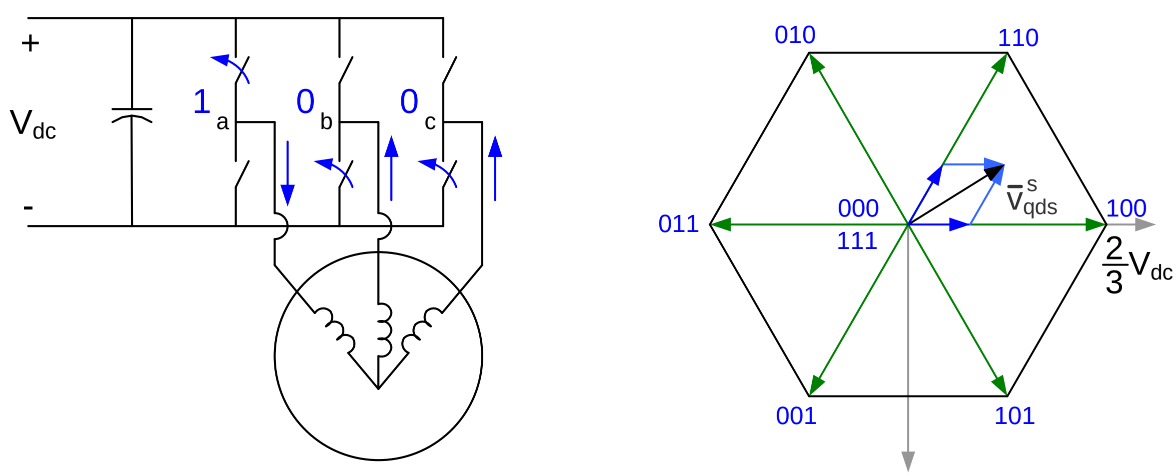


Sine Triangle and Modified Sine Triangle PWM Waveform with Zero Sequence Term with m = 0.8

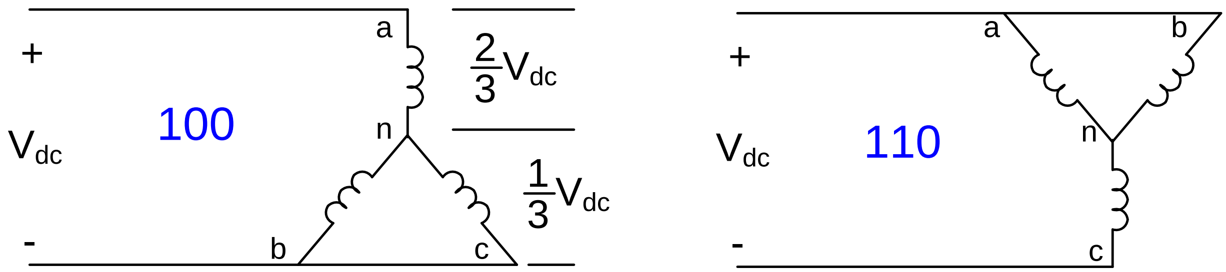


Sine Triangle and Modified Sine Triangle PWM Waveform with Zero Sequence Term with m = 1.1

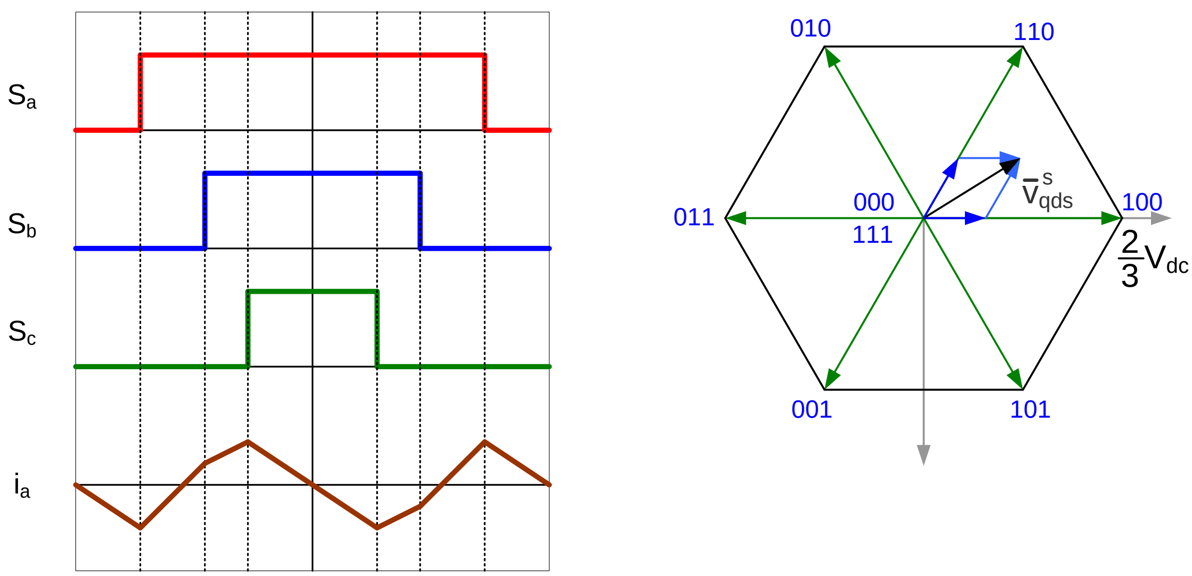
Space Vector PWM:



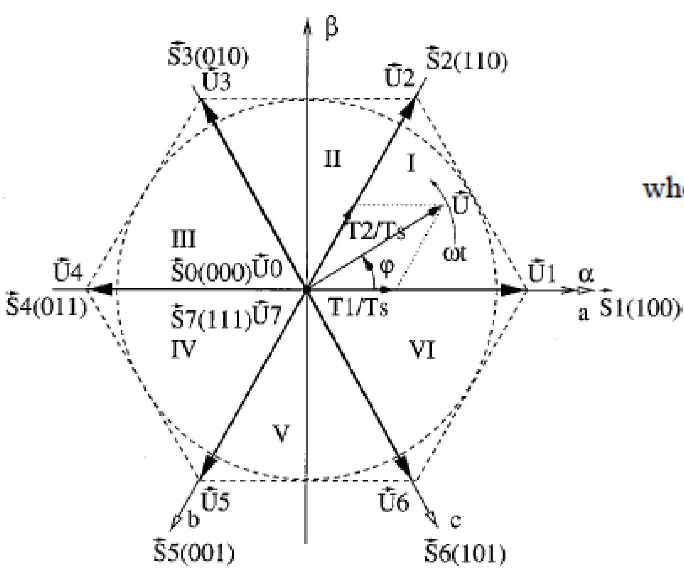
Switching States Used in Space Vector PWM



First Two States of Space Vector PWM



Switching States and Phase Current Ripple in Space Vector PWM Quadrant 1



$$\vec{U}(t) = \frac{t_0}{T_s}\vec{U}_0 + \frac{t_1}{T_s}\vec{U}_1 + \cdots + \frac{t_7}{T_s}\vec{U}_7$$

$$\vec{U} = \frac{T_1}{T_s}\vec{U}_1 + \frac{T_2}{T_s}\vec{U}_2 + \frac{T_7}{T_s}\vec{U}_7 + \frac{T_0}{T_s}\vec{U}_0$$

where $T_s - T_1 - T_2 = T_0 + T_7 \geq 0$, $T_0 \geq 0$ and $T_7 \geq 0$.

Let the length of $\vec{U}$ be m^*E, then we have

$$\frac{m^*}{\sin\frac{2\pi}{3}} = \frac{T_1}{T_s}\frac{1}{\sin(\frac{\pi}{3} - \varphi)} = \frac{T_2}{T_s}\frac{1}{\sin\varphi}. \qquad ($$

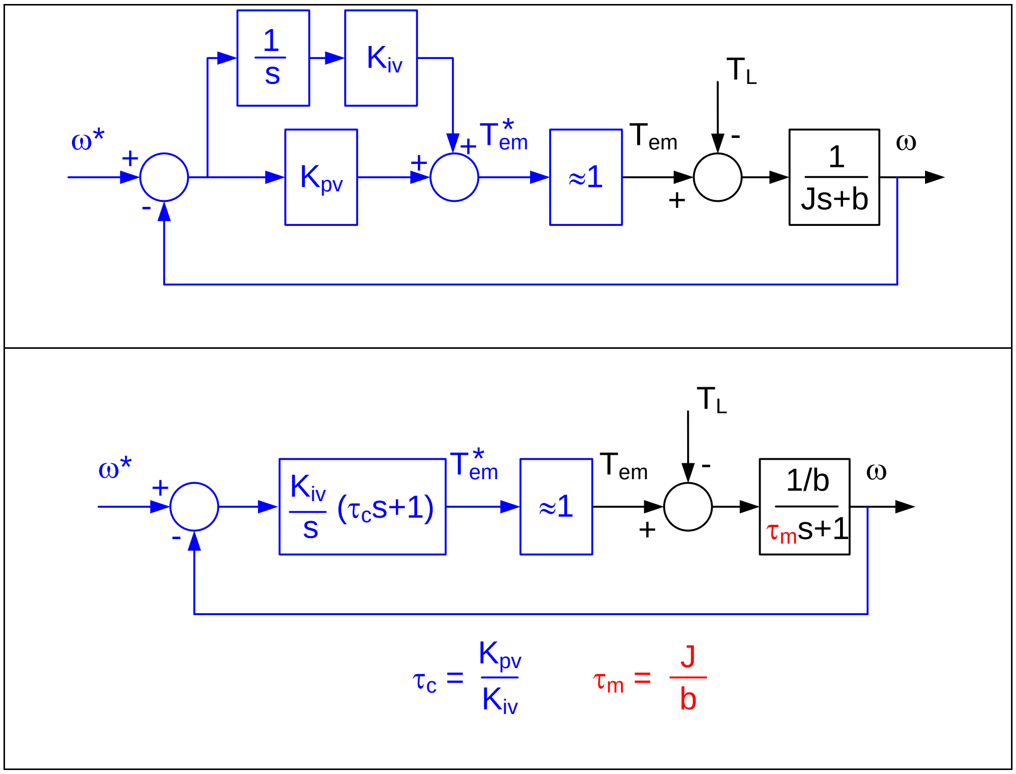
Thus,

$$\frac{T_1}{T_s} = \frac{2}{\sqrt{3}}m^*\sin(\frac{\pi}{3} - \omega t) = \frac{2}{\sqrt{3}}m^*\cos(\omega t + \frac{\pi}{6})$$

$$\frac{T_2}{T_s} = \frac{2}{\sqrt{3}}m^*\sin\omega t = \frac{2}{\sqrt{3}}m^*\cos(\omega t + \frac{3\pi}{2})$$

$$T_0 + T_7 = T_s - T_1 - T_2 \qquad ($$

Speed Control of Machines



Block Diagram of a DC Machine with Ideal Torque Regulator with a PI Speed Loop (Upper Figure)
Rewritten Using Mechanical and Controller Time Constants (Lower Figure)