Electric Machine Control

Chapter 9

Field Weakening Operation

Woei-Luen Chen

9.1 Introduction

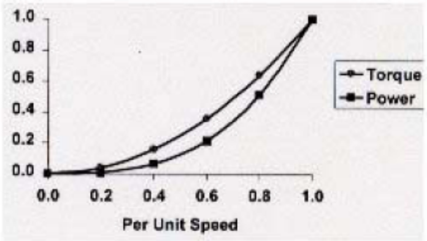
- Four categories of loads
  - 1) const speed, variable torque or const torque loads
    - Const speed pumps, fans, compressors
  - 2) adjustable speed, const torque loads
    - Elevators, fiber spinning, hoists
  - 3) adjustable speed, variable torque loads
    - Fans, pumps, compressors
  - 4) variable speed, variable torque loads
    - High performance applications: traction motors, servos

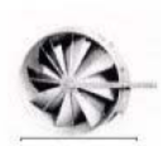
Open loop speed controller

variable :dynamic requirements ⟺ adjustable :steady state requirements

Types of Loads

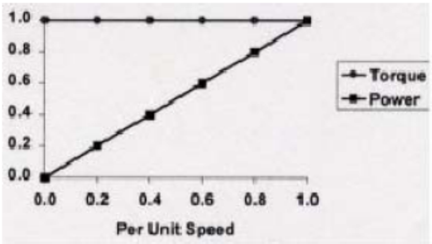
Centrifugal loads

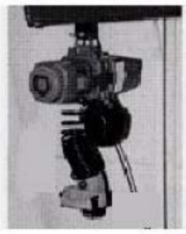




Fan

Constant Torque loads

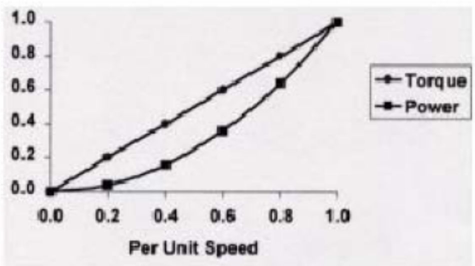


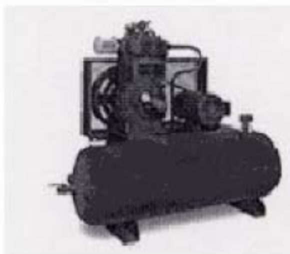


Hoist

Types of Loads

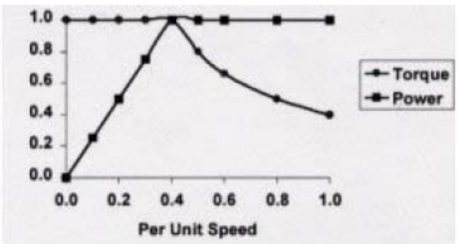
Squared power loads

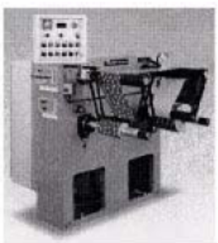




Compressor

Constant power loads





Winder

9.2 Torque Demand and Availability of High Performance Drives

- The torque available from a **dc motor** was limited by three factors:
  - The max. armature and field currents which could be safely handled by the dc motor and dc power converter
  - The max. available voltage obtainable from the dc armature power supply
  - The max. current that could be handled by the brush/ commutator mechanism at a particular speed

Torque vs. speed capability curve #1 (dc motor)

- Limit curve #1 (**constant torque limit region**):
  - **Field** and **armature currents** are set to their max. permissible values

$$T_e = \frac{P}{2}\frac{L_{af}}{L_f}\lambda_f I_a \qquad (5.2\text{–}4)$$

$$\Rightarrow \quad T_{e,\,max} = \frac{P}{2}\frac{L_{af}}{L_f}\lambda_{f,\,max} I_{a,\,max} \qquad (9.2\text{–}1)$$

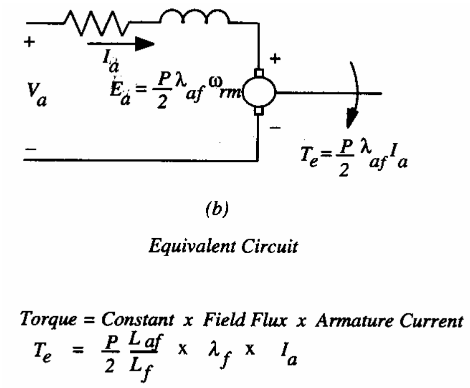
where $\lambda_{f,\,max} = L_f I_{f,\,max}$ and $I_{f,\,max}$ is the maximum field current.

Torque vs. speed capability curve #2 (dc motor)

- Limit curve #2 (**constant power limit region**):

$$E_a = \frac{P}{2}\lambda_{af}\omega_{rm} \quad (5.2\text{–}1)$$

Ia=(Va-Ea)/Ra



Strategy-i

$$w_{rm}\uparrow \Rightarrow E_a\uparrow \Rightarrow I_a\downarrow \boxed{\Rightarrow V_a\uparrow} \Rightarrow I_a\uparrow$$

$$w_{rm}\uparrow \Rightarrow E_a\uparrow \Rightarrow I_a\downarrow \boxed{\Rightarrow I_f\downarrow} \Rightarrow E_a\downarrow \Rightarrow I_a\uparrow$$

Strategy-ii

Field weakening strategy

Torque vs. speed capability curve #3 (dc motor)

- Limit curve #3 (**constant power*speed limit region**):
  - Above a certain speed the reduction of the **field current** to maintain const armature current must be curtailed
    - The armature current must begin to decrease
  - Operation along curve #3 is rarely used since commutating ability is marginal

Fig. 1

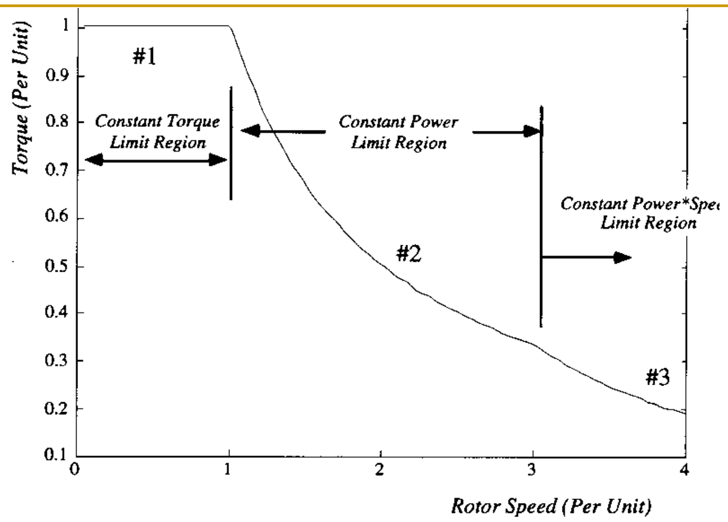
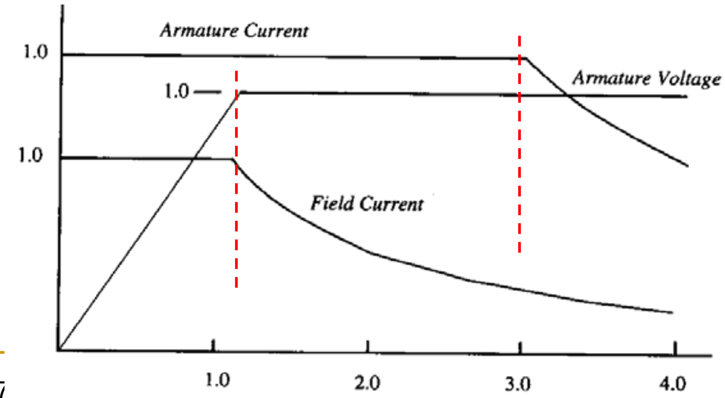


Fig. 2



9.3 IM Control Strategy for Constant Power Operation

- Max. torque requirement imposed by **curve#1** is readily satisfied in the case of a vector controlled IM
  - Ex: **when the slip is held const**

$$\left\{\begin{array}{l} j(L_m/L_r)X_m \\ (L_m/L_r)^2[r_r/(S\omega_e)]\,\omega_e \end{array}\right. \propto \text{ applied frequency}$$

$$\Rightarrow \left\{\begin{array}{l} I_{sT} \\ I_{s\phi} \end{array}\right. \text{ remains unchanged for the const stator current}$$

$$T_e = 3\frac{p}{2}\frac{E_r I_r}{\omega_e} = 3\frac{P}{2}\frac{1}{\omega_e}(\omega_e L_m I_{s\phi})\left(\frac{L_m}{L_r}I_{sT}\right) = 3\frac{p}{2}\frac{L_m^2}{L_r}I_{s\phi}I_{sT}$$

$\Rightarrow$ Torque=const

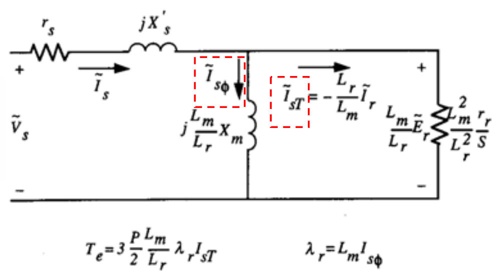


Figure 5.21 Equivalent circuit showing torque component (I_{sT}) and rotor flux component ($I_{s\phi}$) of stator current

Conventional method for the **field weakening** in the high speed range

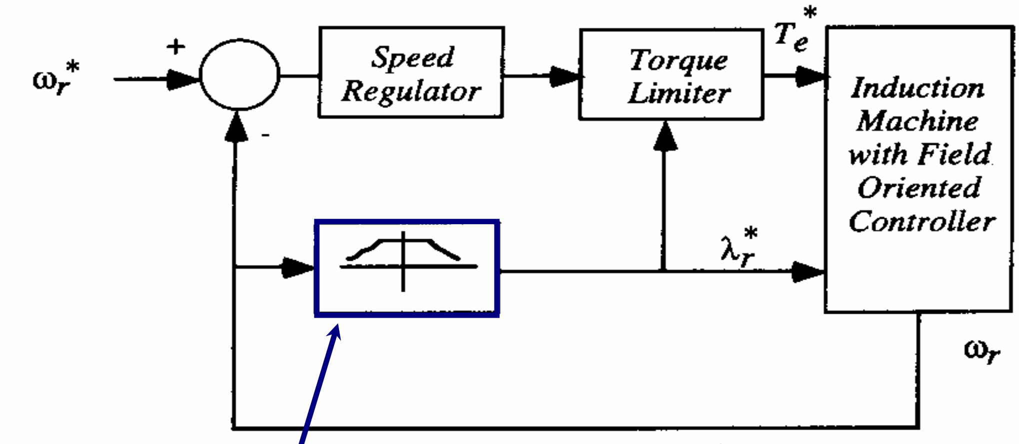


Figure 9.3 Block diagram of field weakening using rotor flux weakening

Varying the rotor flux reference in proportion to the inverse of the rotor speed

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda_{dr}^e i_{qs}^e) \quad (6.2\text{–}14)$$

Torque will decrease inversely in this phase

Although const power limit can be extended w/o limit, the **voltage must increase to counteract the increased voltage drop** across the stator leakage inductance

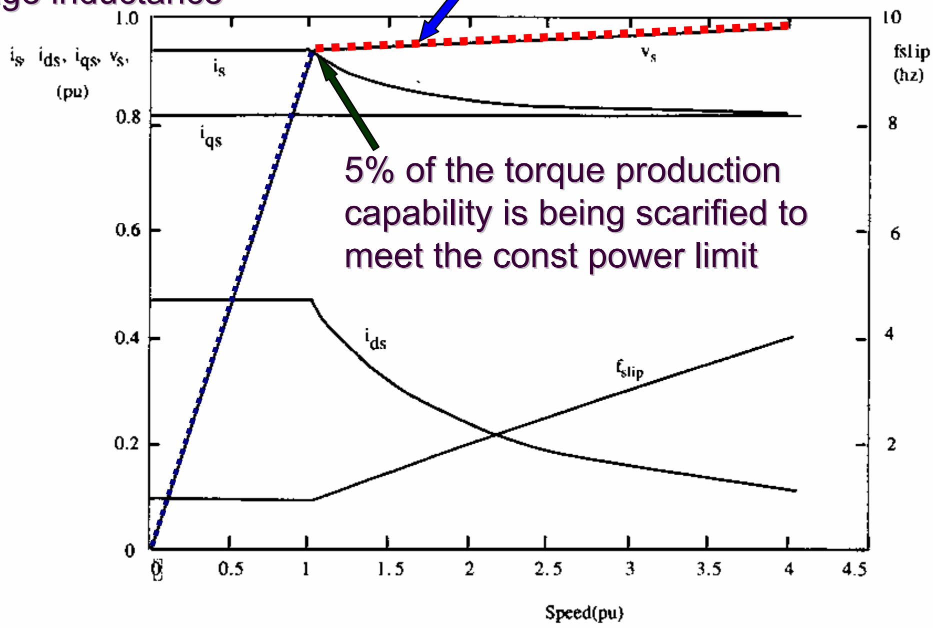
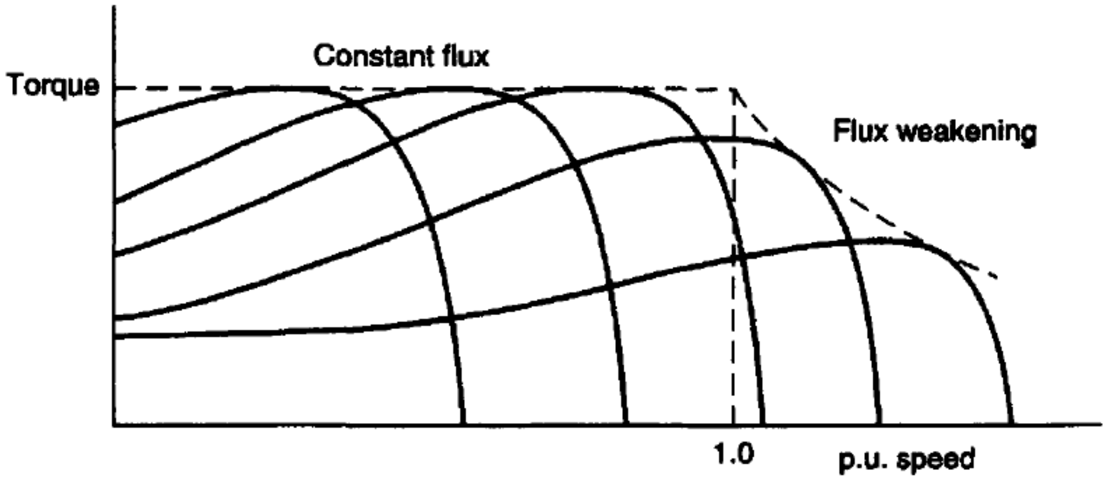


Figure 9.4 Electrical variables of induction machine satisfying the torque vs. speed requirements of Figure 9.1

IM torque/speed curves at variable frequency



9.4 Inverter Imposed Voltage and Current Limits

Motive

- The max. output torque and power developed by the machine is ultimately dependent on **inverter current rating and the max. output voltage.**

Goal

- Consider a control scheme which yield the best possible torque per ampere over the entire speed range

Strategy

- Field weakening technique

Find the current limited circle at max. inverter output voltage

- assume that the voltage reaches its limit

Dynamic equations

$$v_{qs}^e = r_s i_{qs}^e + p\lambda_{qs}^e + \omega_e \lambda_{ds}^e \qquad (9.4\text{–}1)$$

$$v_{ds}^e = r_s i_{ds}^e + p\lambda_{ds}^e - \omega_e \lambda_{qs}^e \qquad (9.4\text{–}2)$$

Field orientation

$$\begin{cases} \lambda_{ds}^e = L_s i_{ds}^e & (9.4\text{–}3) \\ \lambda_{qs}^e = L_s i_{qs}^e + L_m \boxed{i_{qr}^e} & (9.4\text{–}4) \end{cases}$$

$$i_{qr}^e = -\frac{L_m}{L_r} i_{qs}^e \qquad \lambda_{qs}^e = \left(L_s - \frac{L_m^2}{L_r}\right) i_{qs}^e$$

or $\lambda_{qs}^e = L_s' i_{qs}^e$

Steady state equations

$$V_{qs}^e = r_s I_{qs}^e + \omega_e L_s I_{ds}^e \qquad (9.4\text{–}8)$$

$$V_{ds}^e = r_s I_{ds}^e - \omega_e L_s' I_{qs}^e \qquad (9.4\text{–}9)$$

Neglecting IxR drop for high speed operation

$$\boxed{\begin{aligned} V_{qs}^e &= +\omega_e L_s I_{ds}^e \\ V_{ds}^e &= -\omega_e L_s' I_{qs}^e \end{aligned}}$$

determined by the available dc-link voltage

$$\boxed{\begin{aligned} V_{qs}^e &= +\omega_e L_s I_{ds}^e \\ V_{ds}^e &= -\omega_e L_s' I_{qs}^e \end{aligned}}$$

$$(V_{qs}^e)^2 + (V_{ds}^e)^2 \le V_{s,max}^2 \qquad (9.4\text{–}10)$$

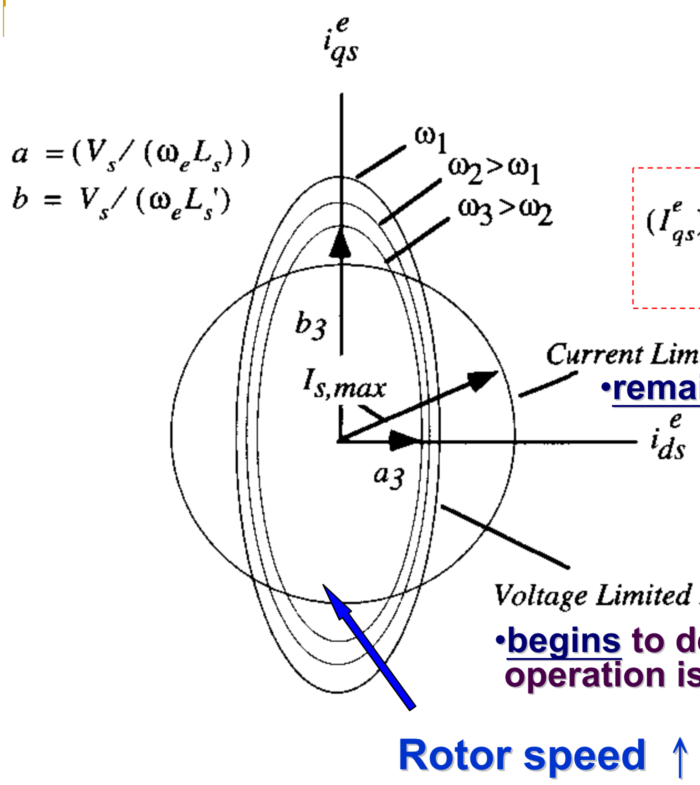
$$(\omega_e L_s I_{ds}^e)^2 + (\omega_e L_s' I_{qs}^e)^2 \le V_{s,max}^2 \qquad (9.4\text{–}11)$$

- **current limited eq. due to <u>max. inverter output voltage</u>**

$$\left(\frac{I_{ds}^e}{a}\right)^2 + \left(\frac{I_{qs}^e}{b}\right)^2 \le 1 \qquad (9.4\text{–}12)$$ where $b = V_s/(\omega_e L_s')$, $a = (V_s/(\omega_e L_s))$

- **current limited eq. due to <u>inverter current rating</u>**

$$(I_{qs}^e)^2 + (I_{ds}^e)^2 \le I_{s,max}^2 \qquad (9.4\text{–}14)$$



$$(I_{qs}^e)^2 + (I_{ds}^e)^2 \le I_{s,\,max}^2 \quad (9.4\text{–}14)$$

Current Limited Circle

•remains constant for any speed

$$\left(\frac{I_{ds}^e}{a}\right)^2 + \left(\frac{I_{qs}^e}{b}\right)^2 \le 1 \quad (9.4\text{–}12)$$

Voltage Limited Ellipse

•begins to decreases as field weakening operation is entered

9.5 Max. Torque Capability Curve Using the Conventional Method

- Rotor flux reference is varied inversely proportional to the rotor speed
  - d-axis stator current ref. is decreased so as to reduce the rotor flux linkage

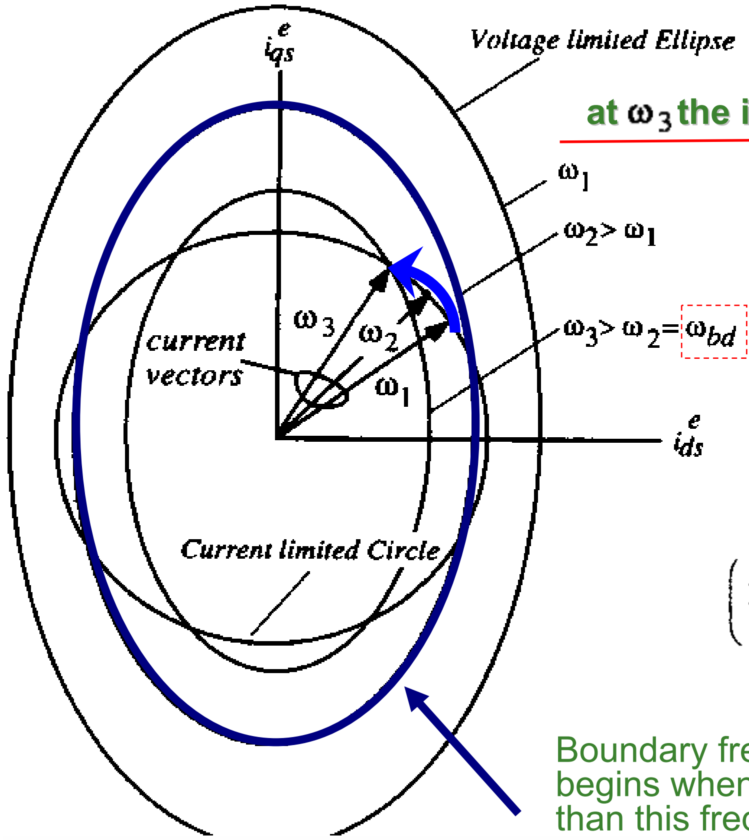
$$I_{ds}^{e*} = \frac{I_{ds,rated}}{\omega_{r(pu)}}$$

the rated d-axis current producing **rated rotor flux**

- In order to **fully utilize the current rating** of the power converter
  - q-axis stator current ref. can be increased to yield the **best possible torque per ampere** over the entire speed range

$$I_{qs}^{e*} = \sqrt{(I_{s,max})^2 - (I_{ds}^{e*})^2}$$

at ω_3 the inverter is completely saturated



$$I_{ds}^{e*} = \frac{I_{ds,rated}}{\omega_{r(pu)}} \quad (9.5\text{–}1)$$

$$I_{qs}^{e*} = \sqrt{(I_{s,max})^2 - (I_{ds}^{e*})^2} \quad (9.5\text{–}2)$$

$$\left(\frac{I_{ds,\text{rated}}}{\omega_{r(pu)}}\right)^2 + (I_{qs}^{e*})^2 = I_{s,max}^2 \quad (9.5\text{–}3)$$

Boundary frequency: field weakening begins when elec. frequency is greater than this frequency

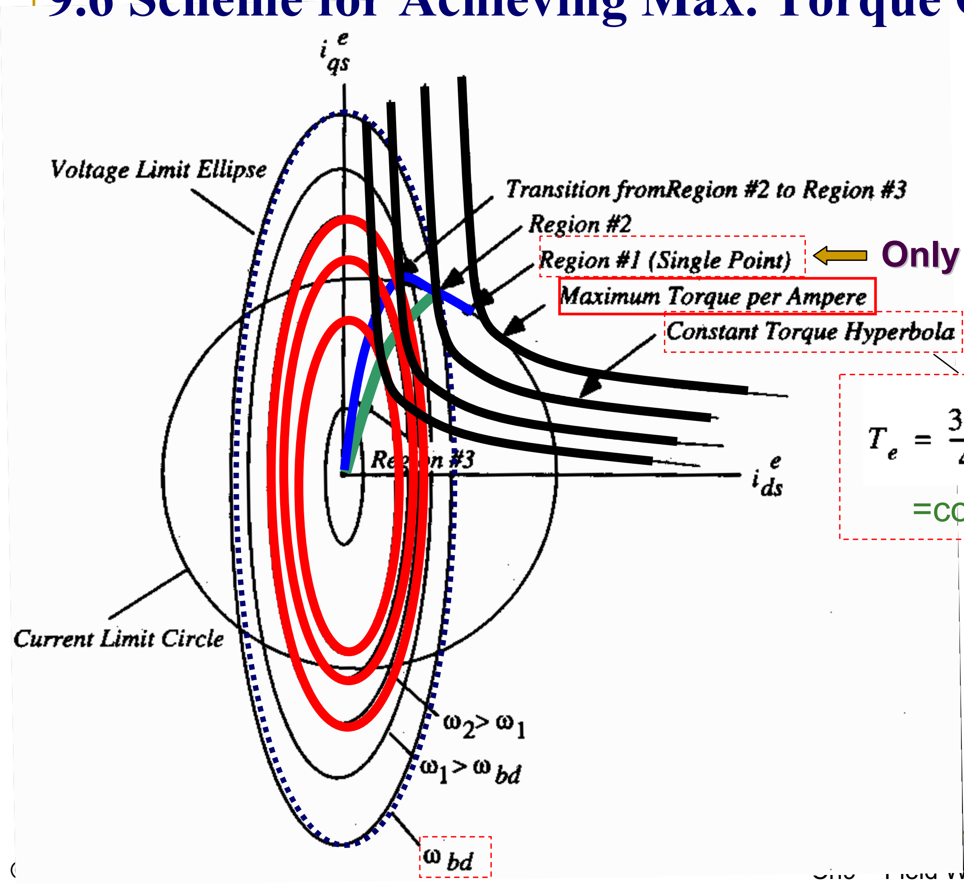
Figure 9.6 Locus of current vector for $1/\omega_r$ field weakening method showing operation reaching the voltage limit ellipse at $\omega_3 = \omega_{bd}$

The flux weakening using conventional method

- Conventional method
  - Varying the **rotor flux ref.** in proportion to the inverse of the rotor speed
  - Problem: if max. inverter voltage is reached **at one per unit speed**, the voltage margin required to regulated current is not maintained.
    - as ω_3 in Fig.9.6

      (no voltage margin is available to regulate the current)
- New method
  - Consider the **stator flux linkage**

9.6 Scheme for Achieving Max. Torque Capability



Only one OP at R#1 !!

$$T_e = \frac{3P}{4}\frac{L_m^2}{L_r} i_{ds}^e i_{qs}^e \quad (9.6\text{–}1)$$

=const at each curve

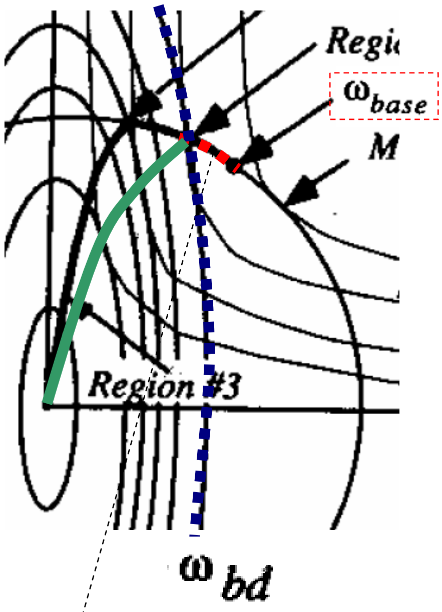
9.6.1 Transition from Constant Torque to Constant Power Operation

- **Transition frequency**

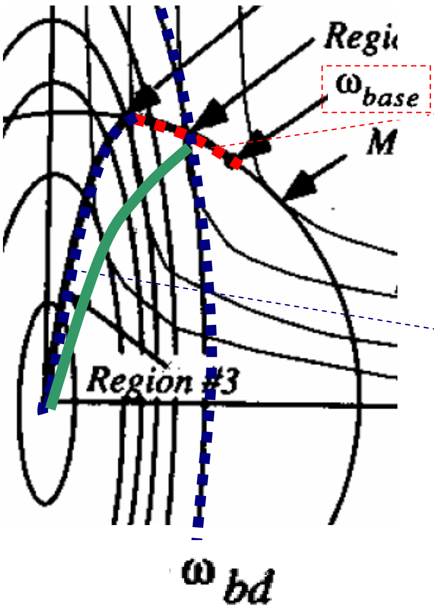
$$\begin{cases} I_{ds}^{e*} = \dfrac{I_{ds,rated}}{\omega_{r(pu)}} & (9.5\text{–}1) \\ I_{qs}^{e*} = \sqrt{(I_{s,max})^2 - (I_{ds}^{e*})^2} & (9.5\text{–}2) \\ (\omega_e L_s I_{ds}^e)^2 + (\omega_e L_s' I_{qs}^e)^2 \le V_{s,max}^2 & (9.4\text{–}11) \end{cases}$$

$$\Rightarrow \omega_{base} = \frac{V_{s,max}}{\sqrt{L_s^2 I_{ds,rated}^{e\,2} + L_s'^2 (I_{s,max}^2 - I_{ds,rated}^{e\,2})}}$$

=const



Above transition frequency:
Optimal current vector for max. torque subsequently moves along the current limit boundary



Optimal current vector for max. torque subsequently moves along the current limit boundary

As the speed continues to increase, the slip frequency increases in order to keep the stator current amplitude at its prescribed max. value.

9.6.2 Region #2 – Field Weakening with Constant Output Power (Find ω_{bd})

- In region #2:
  - q-axis stator current ↑ , d-axis stator current ↓
  - **Slip frequency** must be increased to maintain const stator current

$$S\omega_e = \frac{r_r i_{qs}^e}{L_r i_{ds}^e} \qquad (9.6\text{–}3)$$

- The OPs of Region #2 are the intersections of voltage limit ellipse and current limit circle

$$\begin{cases} (\omega_e L_s I_{ds}^e)^2 + (\omega_e L_s' I_{qs}^e)^2 \le V_{s,\,max}^2 & (9.4\text{–}11) \\ (I_{qs}^e)^2 + (I_{ds}^e)^2 \le I_{s,\,max}^2 & (9.4\text{–}14) \end{cases} \Rightarrow \begin{cases} I_{ds}^e = \sqrt{\dfrac{(V_{s,\,max}/\omega_e)^2 - (L_s' I_{s,\,max})^2}{L_s^2 - L_s'^2}} & (9.6\text{–}4) \\ I_{qs}^e = \sqrt{\dfrac{(L_s I_{s,\,max})^2 - (V_{s,\,max}/\omega_e)^2}{L_s^2 - L_s'^2}} & (9.6\text{–}5) \end{cases}$$

9.6.2 Region #2 – Field Weakening with Constant Output Power (Find ω_{bd})

$$\begin{cases} I_{ds}^e = \sqrt{\dfrac{(V_{s,max}/\omega_e)^2 - (L'_s I_{s,max})^2}{L_s^2 - L_s'^2}} & (9.6\text{–}4) \\ I_{qs}^e = \sqrt{\dfrac{(L_s I_{s,max})^2 - (V_{s,max}/\omega_e)^2}{L_s^2 - L_s'^2}} & (9.6\text{–}5) \end{cases}$$

- **Max. slip**

$$\omega_{sl,max} = \frac{L_s}{\tau_r L_s'} = \frac{1}{\sigma\tau_r} \qquad (9.6\text{–}6)$$

- **The freq. at transition of region #3**

$$\omega_{e,1} = \sqrt{\frac{L_s^2 + L_s'^2}{2L_s^2 L_s'^2}}\left(\frac{V_{s,max}}{I_{s,max}}\right) \qquad (9.6\text{–}7)$$

$$= \omega_{bd}$$

9.6.2 Region #2 – Field Weakening with Constant Output Power

- In region #3:
  - The OPs of Region #3 are the tangents of voltage limit ellipse and const torque hyperbolas

$$\begin{cases} (\omega_e L_s I_{ds}^e)^2 + (\omega_e L_s' I_{qs}^e)^2 \le V_{s,max}^2 & (9.4\text{–}11) \\ T_e = \dfrac{3P}{4}\dfrac{L_m^2}{L_r} i_{ds}^e i_{qs}^e & (9.6\text{–}1) \end{cases} \Rightarrow \begin{cases} I_{ds}^e = \dfrac{V_{s,max}}{\sqrt{2}\omega_e L_s} & (9.6\text{–}8) \\ I_{qs}^e = \dfrac{V_{s,max}}{\sqrt{2}\omega_e L_s'} & (9.6\text{–}9) \end{cases}$$

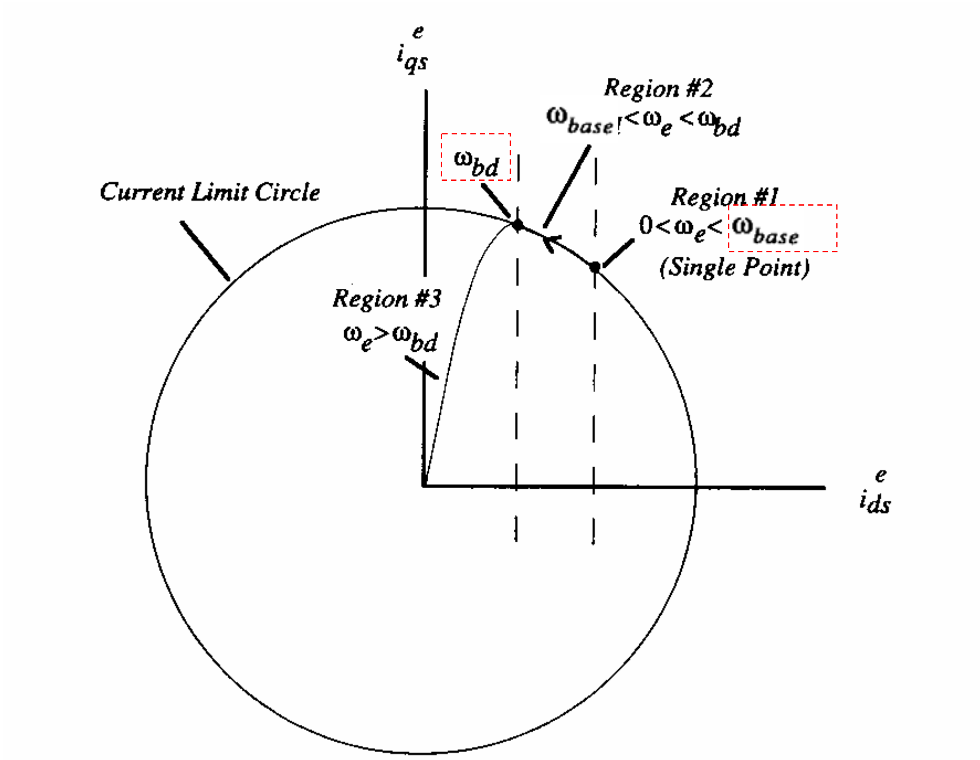


Figure 9.8 Overall trajectory of optimal stator current vector in the field weakening region

9.7 Control System Implementation

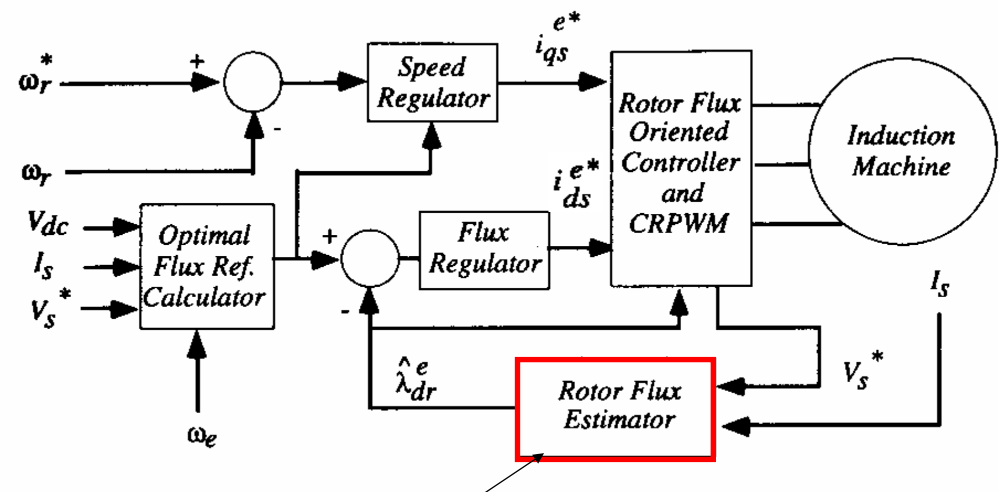


Figure 9.9 Block diagram of the overall control system for optimized operation in the field weakening range

Stator flux based rotor flux estimator

$$\hat{\underline{\lambda}}_s = \int (\underline{v}_s - r_s \underline{i}_s)\, dt$$

$$\hat{\lambda}_r = \frac{L_r}{L_m} (\hat{\lambda}_s - \sigma L_s \underline{i}_s)$$

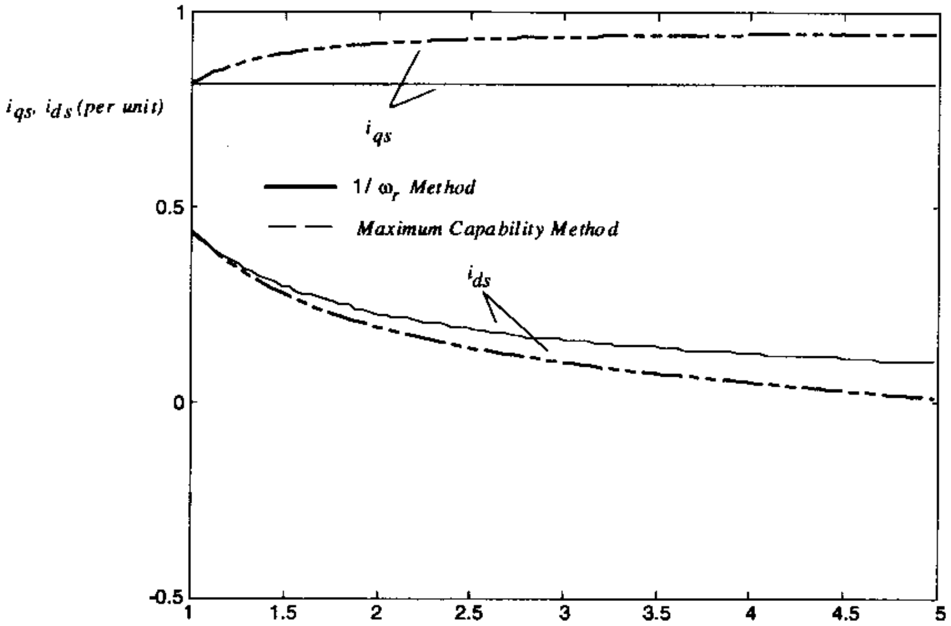


Figure 9.10 Flux reference and torque command currents vs. speed for $1/\omega_r$ method and optimized capability method