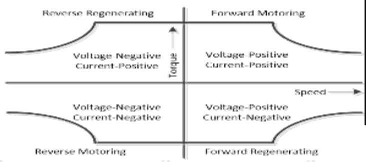
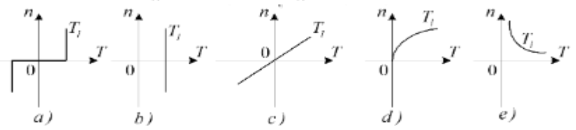
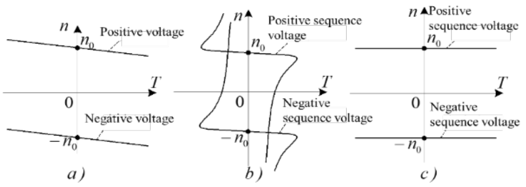


Inductively-coupled 磁耦合; bar 母线; salient 凸极; back EMF 反电势; commutation 换相, eddy 涡流





a) Excited DC motor b) Induction motor c) Synchronous motor

- Armature Losses
- Field Losses
- Iron Core Losses
- Brush Losses
- Friction and Windage Losses

RPM: Revolutions Per

HP: Horsepower

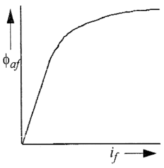
"hot" resistance:

$$\frac{rad}{s} = RPM * \frac{2\pi}{60}$$

$$W = HP * 746$$

$$R[85°C] = 1.2 \times R[25°C]$$

$$J[Kg \cdot m^2] = J[pound - feet \cdot \text{second}^2] \times 1.355$$



系统的稳定工作点在交点处满足 $\frac{dT}{dn} < \frac{dT_\ell}{dn}$

PWM 优势: 1.主电路结构简单，功率元件少。2.开关频率高，电流容易连续，谐波分量少，电机损耗和发热小。3.低速性能好，稳速精度高，调速范围宽。4.动态响应好，抗扰能力强。5.功率元件开关状态，导通损耗小，装置效率高。6.直流电源采取不控整流时，电网功率因素高

晶闸管劣势: 存在电流的谐波分量，深调速时转矩脉动大。深调速时功率因素低，限制了调速范围。平波电抗器限制了系统的快速性。

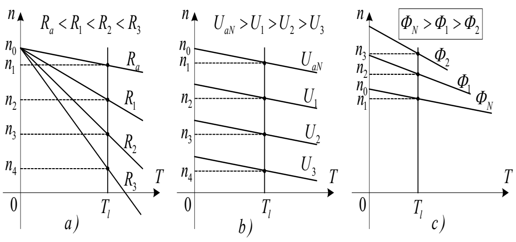
DC MOTOR

$$v_a = i_a r_a + L_a \frac{di_a}{dt} + e_a \qquad v_f = i_f r_f + L_f \frac{di_f}{dt} \qquad \alpha = \frac{\tau_i}{\tau_p}$$

$$k_t = \frac{\alpha Z}{4\pi} \qquad k_v = \frac{\alpha Z}{4\pi} \qquad T_e = k_t \phi_{af} i_a \qquad e_a = k_v \phi_{af} \omega_r$$

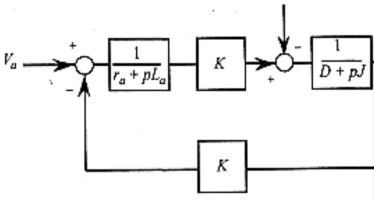
$$J\frac{d\omega_r}{dt} + D\omega_r + T_l = T_e \qquad Efficiency = \eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss-total}}$$

$$\omega_r = \frac{V_a}{K} - \frac{r_a}{K^2} T_e = \omega_{r,nl} - \frac{r_a}{K^2} T_e$$



$$\omega_r = \frac{V_a}{K} - \frac{r_a}{K^2} T_e = \omega_{r,nl} - \frac{r_a}{K^2} T_e$$

调速方法，在串电阻调速及降压调速时，整个调速范围内允许最大输出转矩不变，因此这种调速方法称为恒转矩调速。在弱磁调速时允许的输出最大转矩减小，这种调速方法称为恒功率调速。

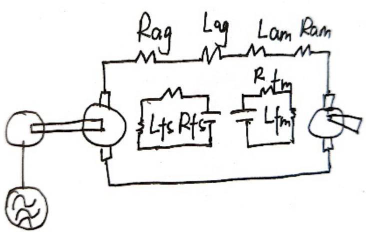


$$T_R = \frac{P_R}{w} \quad I_R = \frac{T_R}{C_T\Phi} = \frac{T_R}{K}$$

$$V_R = C_T\Phi w + I_R R_{am} = Kw + I_R R_{am}$$

$$E_{ff} = \frac{P_R(T_R w_R)}{V_R I_R + P_{winding\ loss}} \quad n_r = \frac{V_R - I(R_a + R)}{C_E \Phi}$$

Ward-Lenard/GM

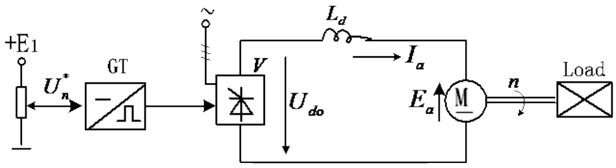


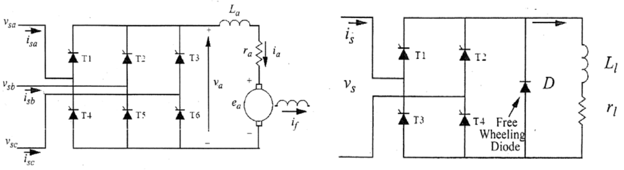
GM 电机: 启动: 1 Establish full motor field current 2 Supply DC generator field current 3 The generator EMF increase from zero 4 Increase a current flows 5 Torque & motor to accelerate 6 Rated armature voltage & speed; 减速: 1 Motor field current is increased or generator field decreased 2 Motor EMF greater than generator EMF and armature current flow reversely 3 Motor acts as a generator and slows down 换方向 1 Supply opposite generator field current 2 Generator EMF builds up with opposite polarity 3 Opposite direction of armature current & rotation Adv. 1 power supply balanced sine current 2 power small 3 field controlled power is small 4 tolerant of overloads Disadv. 1 high Power loss (low speed) 2 larger, heavier, expensive 3 large field time constants (poor transient)

Valve-Motor

VM 电机: 电机视为一大电感，电流近似不变，电流只能单向流动（两晶闸管回路有环流问题）。当α=30° ~ 150°时，将 GT&V 视为一个线性放大步骤，放大系数 Ks。

2 象限 VM（无励磁反向: 象限 12; 有: 象限 14）



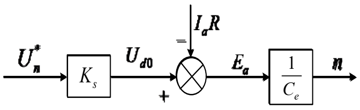


$$V_{avg} = \frac{2\sqrt{2}}{\pi} V_{rms} \cos\alpha - \frac{4}{\pi}\omega_e L_c I_{dc} = 0.9 V_{rms}\cos\alpha - 1.27\omega_e L_c I_{dc}$$

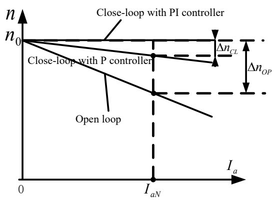
$$V_{avg} = \frac{3\sqrt{2}}{\pi} V_{l-l,rms} \cos\alpha - \frac{3}{\pi}\omega_e L_c I_{dc} = 1.35 V_{rms}\cos\alpha - 0.955\omega_e L_c I_{dc}$$

$$\text{PF} = \frac{Power}{V_{rms} I_{rms}} = \frac{I_{1,rms}\cos\theta}{I_{rms}}$$

三相: Vo 在 90°为负，6 脉波，ripple mag 小，电流谐波小，含三次（triplen）谐波，PF 在深度相控下还是很低。

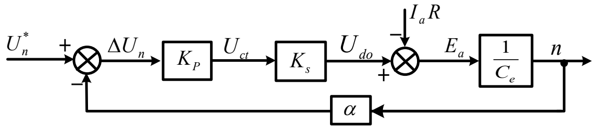


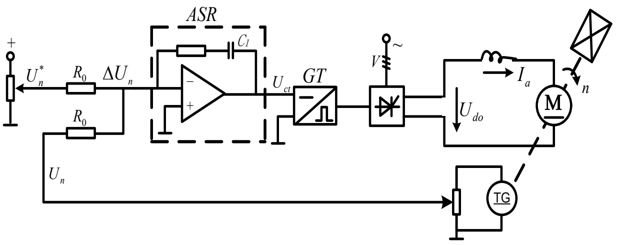
VM 开环图



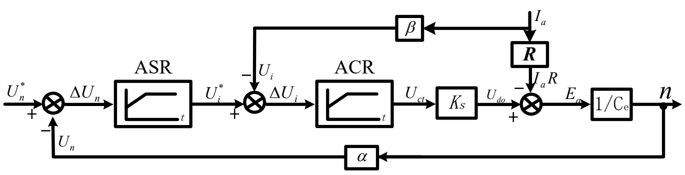
VM 速度闭环

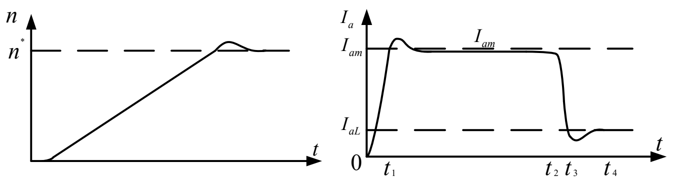
$$n = \frac{K_P K_S U_n^*}{C_e(1+K)} - \frac{R I_a}{C_e(1+K)}$$





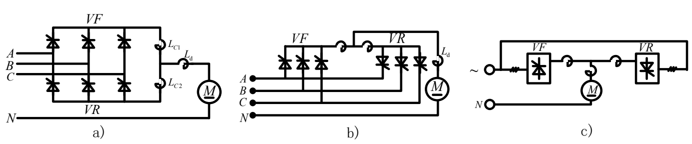
VM 双环图

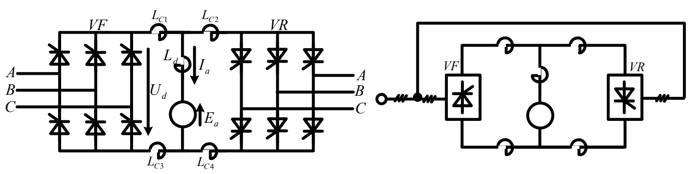




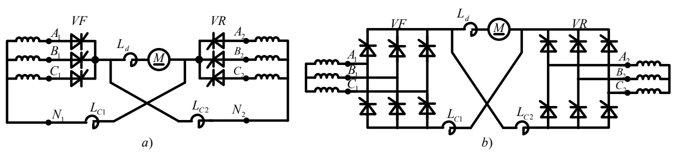
4 象限 VM

Anti-Parallel（same AC power supply）





Cross connection(two independent power sources)



Without Circulation（VF & VR 不同时工作）

Safe, reliable, no circulation and small size.

commutation dead zone, dynamic response is slow.

With Circulation（VF & VR 同时工作）

$$\Delta U_{do} = U_{doF} - (-U_{doR}) = 2U_{dom}\cos\frac{\alpha_F+\alpha_R}{2}\cos\frac{\alpha_F-\alpha_R}{2}$$

meets $\alpha_F + \alpha_R = 180°$ 环流成因：晶闸管电压瞬时值不同。抑制环流：cascade smoothing reactors

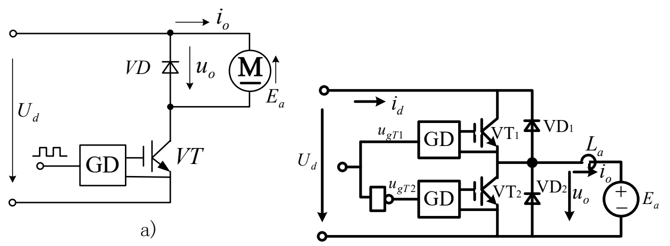
if $\alpha_F + \alpha_R < 180°$ 产生 DC Current

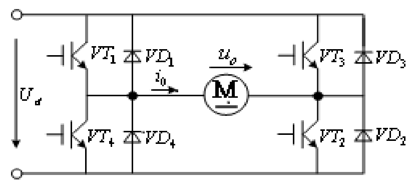
Working State of Motor		Forward Motoring	Reverse Regenerating	Reverse Motoring	Forward Regenerating
Working Quadrant		I	II	III	IV
Speed n, Back EMF E_a, Voltage U_d		+	−	−	+
Torque T, Armature Current I_a		+	+	−	−
Without Circulation	Status of VF	Rectification	Inversion	Blockade	Blockade
	Status of VR	Blockade	Blockade	Rectification	Inversion
With Circulation	Status of VF	Rectification	Inversion	Pending Inversion	Pending Rectification
	Status of VR	Pending Inversion	Pending Rectification	Rectification	Inversion

PWM-Chopper

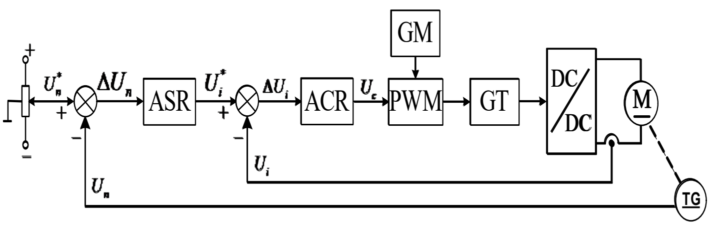
PWM 电机：制动状态可以改成双向能量流动的 DC Chopper

2 象限 Chopper（Reversible Current）

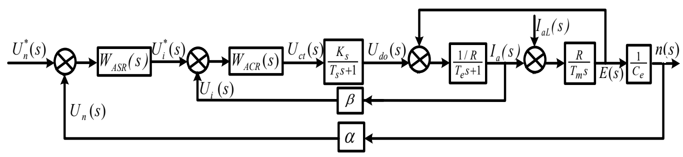




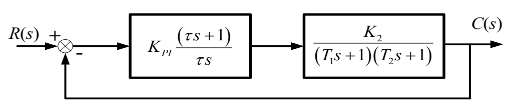
PWM 电机控制（双环）



控制 Regulator 举例

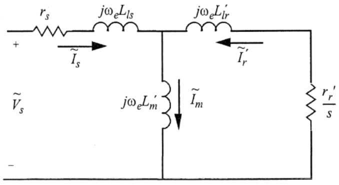


$$W_{ASR}(S) = K_{PV} + \frac{1}{T_V S} \quad W_{ACR}(S) = K_{Pi} + \frac{1}{T_i S}$$



$$W(s) = K_{PI}\frac{(\tau s+1)}{\tau s}\frac{K_2}{(T_1 s+1)(T_2 s+1)} = \frac{K}{s(T_2 s+1)}$$

Asynchronous MOTOR



负序相当于是原来是 s 的转差在负序里变成了 2-s 的转差。零序分量没有功率（为什么 SPWM 可以注入零序分量）正序 $s=1-(1-s)$ 负序 $2\text{-}s=1-(-(1-s))$

$$s=\frac{w_e-w_r}{w_e}=\frac{w_{em}-w_{rm}}{w_{esm}}$$

$$T=\frac{3pU_1^2R_2'/s}{\omega_1\left[\left(R_1+R_2'/s\right)^2+\left(x_{1\sigma}+x_{2\sigma}'\right)^2\right]}$$

$$w_e=2\pi f_e \qquad v=ri+\frac{d\lambda}{dt}$$

$$w_{em}=\frac{2\pi f_e}{P/2} \qquad \lambda_n=\sum_{k=1}^{6}L_{kn}i_i,\ n=1\ldots6$$

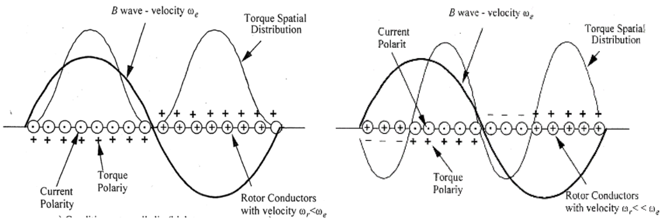
$$T_m=\pm\frac{m_1pU_1^2}{4\pi f_1\left[\pm r_1+\sqrt{r_1^2+\left(x_{1\sigma}+x_{2\sigma}'\right)^2}\right]} \qquad s_m=\pm\frac{r_2'}{\sqrt{r_1^2+(x_{1\sigma}+x_{2\sigma}')^2}}$$

$$T_{avg}=\frac{Developed\ Power}{Shaft\ Speed}=\frac{3|\tilde{I}_r|^2r_r\frac{1-s}{s}}{(1-s)w_{em}}=\frac{Air\ Gap\ Power}{Synchronous\ Speed}=\frac{3|\tilde{I}_r|^2\frac{r_r}{s}}{w_{em}}=\frac{Rotor\ Copper\ Loss}{Slip\ Speed}=\frac{3|\tilde{I}_r|^2r_r}{w_{em}s}$$

模型假设

无饱和（saturation）r、L = const（no skin、eddy）

Torque Production



S 大的时候由于空间电势和磁场有相角差，电流滞后，higher current 但 less total torque.

谐波

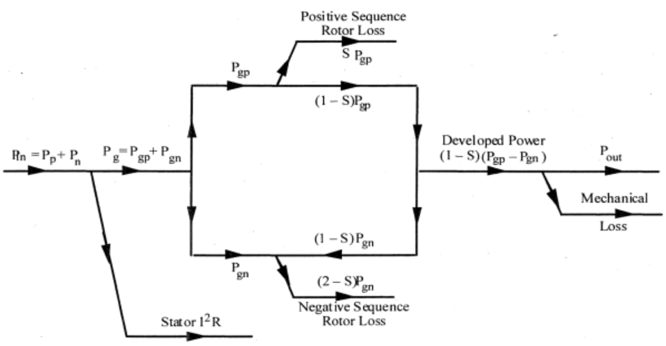
Harmonic:

$$s_h=\frac{h\omega_e\pm\omega_r}{h\omega_e}$$

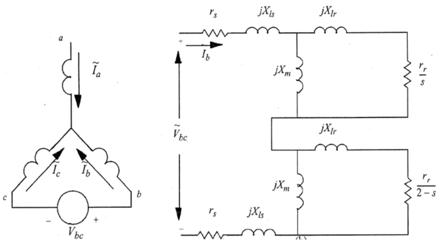
增加铜耗（趋肤效应）；扭矩脉动（谐波与基波的相互作用）。谐波电流主要由电抗决定。

相序不对称

负序：s'= 2-s 零序：等效电路只包含定子电阻和零序电抗。因为在气隙中三个 MMF 的总和为零。

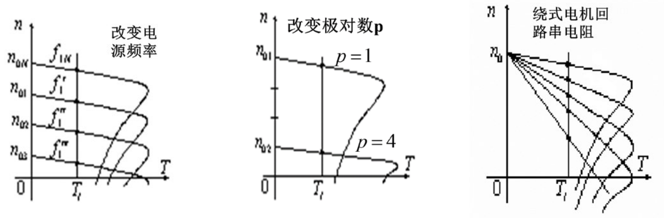


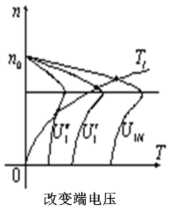
$$T=T_p-T_n, I_s^2=I_p^2+I_n^2$$

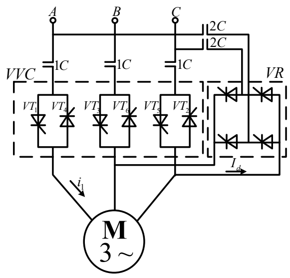


单相等效为正负序串联，进而计算电流和相关数。

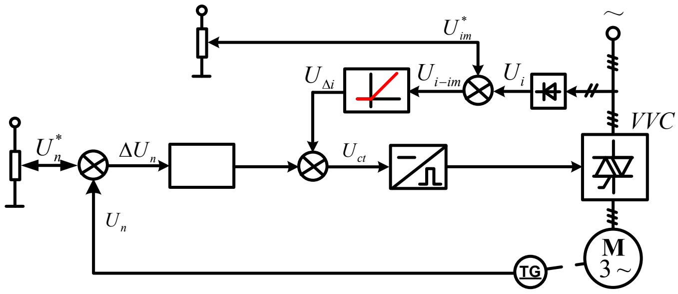
调速方法



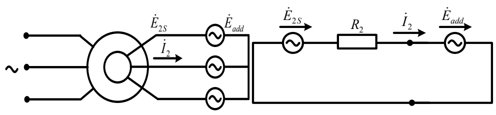




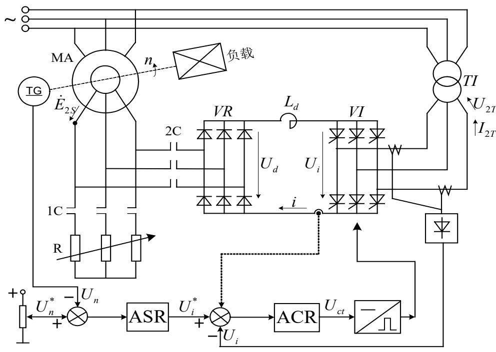
VR for Braking



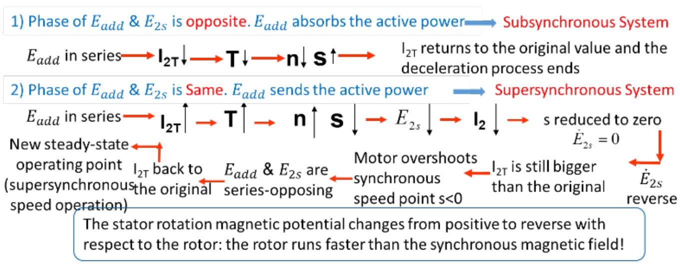
串级调速



$$\dot{I}_2=\frac{s\dot{E}_{20}\pm\dot{E}_{add}}{r_2+jsx_2}$$



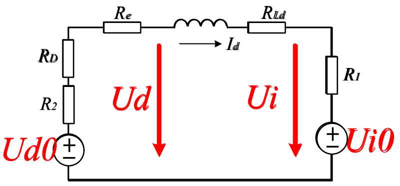
转子回路串电阻、串电势可调速。超同步和次同步。是靠调节转子电流来改变转矩叫 **Cascade Speed Regulation** 不控整流＋晶闸管构成相应回路（**次同步**）。



二极管整流加晶闸管串级调速的好处：转速范围不大，设

备的容量小；滑差功率反馈，低速时效率高。坏处：调速系统的功率因数低。（Subsynchronous Speed Cascade Speed Control System。

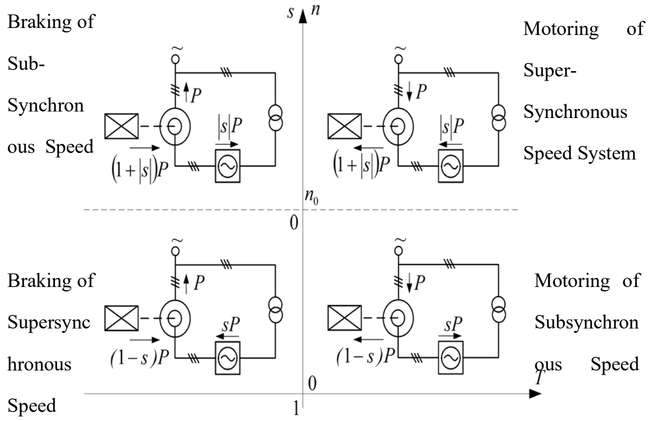
$$\left.\begin{aligned}I_d &= 0\\ U_{d0} &= U_{i0}\\ U_{d0} &= 2.34 s_0 E_{20}\\ U_{i0} &= 2.34 U_{2T}\cos\beta_1\end{aligned}\right\}$$

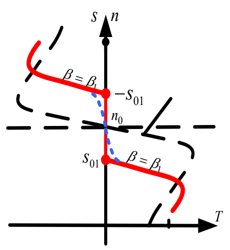


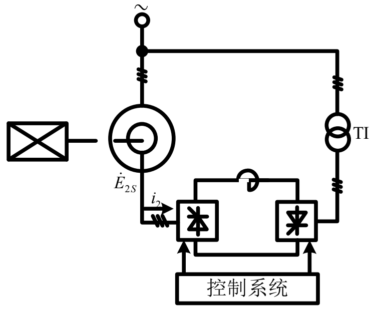
在电流为 0 的时候为最大转速位置，转差最小为设定值。因为不控整流压降存在，β=90°时与固有机械特性不一致。次同步超同步的能量关系如图所示。

$$s_0\big|_{\beta=\beta_1} = \frac{U_{2T}\cos\beta_1}{E_{20}}$$

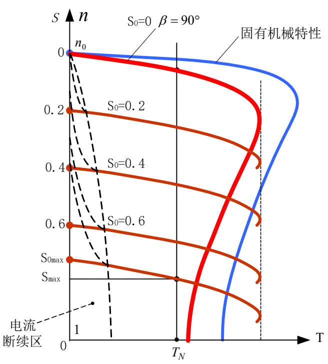
Fed 电机能量可以大于电网给的







超同步 Doubly Fed



调速相当于串一个电势，不改变电阻电感，所以机械特性是平行移动的。

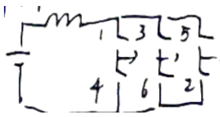
双馈型（都是晶闸管）

1 可以实现 I、II 象限任意转速下的电机和制动，2 提高系统的动态响应性能输出功率可以大于电机的额定功率，在超同步转速区可以保持恒定的转矩特性 3 设定合适的减速比，一半超同步一半次同步，设备的容量要只使用二级同步速度串联设备的一半容量。（Doubly-fed inductor motor drive）

VSI 与 CSI

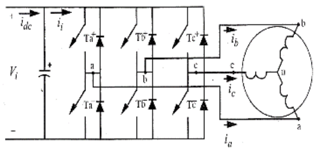
VSI PWM 整流器和 CSI PWM 整流器的区别：输入测是稳压（并电容）还是稳流（串电感），CSI 能够穿越换向故障并自然返回到正常运行，并 regenerate into the utility supply by simple reversing the polarity of the rectifier DC output voltage。

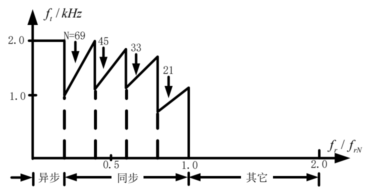
VSI Output is Constrained Voltage	CSI Output is Constrained Current
DC Bus Dominated by Shunt Capacitor	DC Bus Dominated by Series Inductance
DC Bus Current Proportional to Motor Power Factor	DC Bus Voltage Proportional to Motor Power Factor
Output Contains Voltage Harmonics Varying Inversely with Harmonic Order	Output Contains Current Harmonics Varying Inversely with Harmonic Order
Prefers Motors with Larger Leakage Reactance	Prefers Motors with Smaller Leakage Reactance
Can Handle Motors with Smaller Than Rating	Can Handle Motors Larger Than Rating
DC Bus Current Reverses in Regeneration	DC Bus Voltage Reverses in Regeneration
Immune to Open Circuits	Immune to Short Circuits
Relatively Low Load Current Losses	Relatively High Load Current Losses
Relatively High Switching Losses	Relatively Low Switching Losses
Relatively Little Efficiency Reduction Caused by Load Change	Relatively Little Efficiency Reduction Caused by Speed Change



VSI、CSI 导通，VSI：123-234-345-456-561-612，CSI：12-123-34-45-56-61，CSI60°触发一个，导通 120°，VSI60°触发，导通 180°VSI 固有问题：共模 EMI，死区

SPWM 调制方法与载波比选择





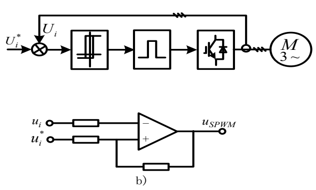
$$U_{1m} = \frac{U_{rm}}{U_{tm}}\cdot\frac{U_d}{2} = M\frac{U_d}{2}$$

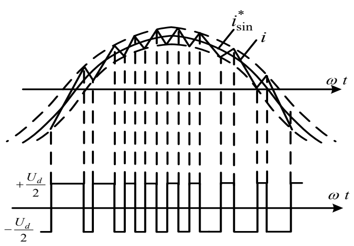
SPWM 分全桥型和半桥型。全桥可以三电平，半桥只能双电平。Synchronous & asynchronous modulation：SPWM 调制方法中载波比的选择，有 Synchronized modulation（$N = f_t/f_r$ = constant）、Asynchronous modulation（f_t constant）、Sectional modulation 三种。很显然，载波频率恒定有优点：increase the carrier wave ratio at low frequency and solve the low order harmonic problem.缺点：generally not satisfy requirement for N is a multiple of 3; larger current harmonics; difficult to maintain the symmetry between positive and negative half-wave and three-phase, especially when output of high base wave frequency.混合法集两者优点于一身。零速起动仍需串电阻。（Adv：响应好，降低谐波）

方波 $$(U_{l1})_{\max} = \frac{\sqrt{6}}{\pi}U_d = \frac{2\sqrt{3}}{\pi}U_{lin} = 1.1026U_{lin}$$

SPWM $$(U_{l1})_{\max} = \frac{\sqrt{6}}{4}U_d = \frac{\sqrt{3}}{2}U_{lin} = 0.866U_{lin}$$

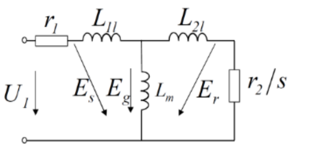
滞环 SPWM

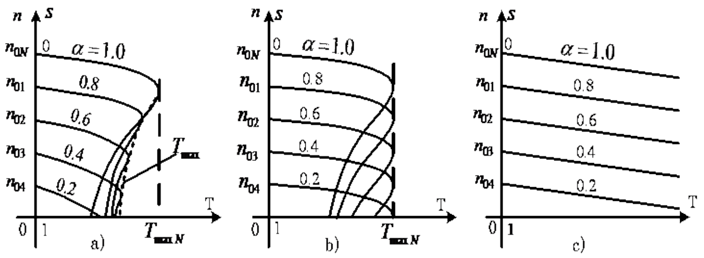




VVVF

VVVF: Variable Voltage Variable Frequency。频率变化时，若不同时改变电压， 则会使电机的磁通 Φm 大幅变化，这将使电机运行不正常甚至损坏电机，所以变频的同时必须变压，其较理想的目标是使磁通Φm 基本保持恒定。有四种 VVVF 的方法，控制端电压 $\frac{U_1}{f_1}=const$ 、电阻后电压 $\psi_s=\frac{E_s}{f_1}=const$ 、励磁电压 $\psi_g=\frac{E_g}{f_1}=const$ 、r/s 上电压 $\psi_r=\frac{E_r}{f_1}=const$ 与频正比。分为下三种图，第一个是控制端电压，第二个是控制电阻后电压、励磁电压，第三个是控制 r/s 上电压（本质：控制转子磁链恒定）。





控制端电压：

$$T=\frac{P_1}{\Omega_1}=\frac{p}{\omega_1}m_1\left(I_2'\right)^2\frac{r_2'}{s}=\frac{m_1p}{\omega_1}\cdot\frac{U_1^2r_2'/s}{\left(r_1+r_2'/s\right)^2+x_K^2}=m_1p\left(\frac{U_1}{\omega_1}\right)^2\cdot\frac{s\omega_1r_2'}{\left(sr_1+r_2'\right)^2+\left(sx_K\right)^2}$$

$$T_m=\frac{m_1p}{2\omega_1}\cdot\frac{U_1^2}{r_1+\sqrt{r_1^2+x_K^2}}\quad s_m=\frac{r_2'}{\sqrt{r_1^2+x_K^2}}$$

S 小，

$$T\approx m_1p\left(\frac{U_1}{\omega_1}\right)^2\frac{s\omega_1}{r_2'}\propto s$$

S 大，

$$T\approx m_1p\left(\frac{U_1}{\omega_1}\right)^2\frac{s\omega_1}{s\left(r_1^2+x_K^2\right)}\propto\frac{1}{s}$$

$$T_m\approx\frac{m_1p}{2}\left(\frac{U_{1N}}{\omega_{1N}}\right)^2\frac{\alpha\omega_{1N}}{r_1+\sqrt{r_1^2+\left(\alpha x_{KN}\right)^2}}$$

$$\begin{cases}f_1=\alpha f_{1N}\\ \omega_1=\alpha\omega_{1N}\\ U_1=\alpha U_{1N}\\ x_K=\alpha x_{KN}\end{cases}\quad T\approx m_1p\left(\frac{U_{1N}}{\omega_{1N}}\right)^2\frac{s\alpha\omega_{1N}r_2'}{\left(sr_1+r_2'\right)^2+\left(s\alpha x_{KN}\right)^2}$$

$$T_m\approx\frac{m_1p}{2}\left(\frac{U_{1N}}{\omega_{1N}}\right)^2\frac{\alpha\omega_{1N}}{r_1+\sqrt{r_1^2+\left(\alpha x_{KN}\right)^2}}$$

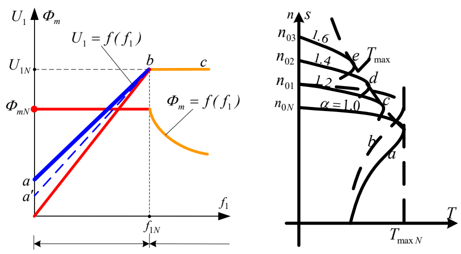
控制电阻后电压（难直接控制）：

$$T=\frac{m_1P}{\omega_1}\left(I_2'\right)^2\frac{r_2'}{s}=\frac{m_1p}{\omega_1}\frac{E_1^2\,r_2'/s}{\left(r_2'/s\right)^2+x_2'^2}=m_1p\left(\frac{E_1}{\omega_1}\right)^2\frac{s\alpha\omega_{1N}r_2'}{\left(r_2'\right)^2+\left(s\alpha x_{2N}'\right)^2}$$

$$T_{\max}=\frac{m_1p}{2}\left(\frac{E_1}{\omega_1}\right)^2\frac{\omega_1}{x_2'}=\frac{m_1p}{2}\left(\frac{E_1}{\omega_1}\right)^2\frac{\omega_{1N}}{x_{2N}'}$$

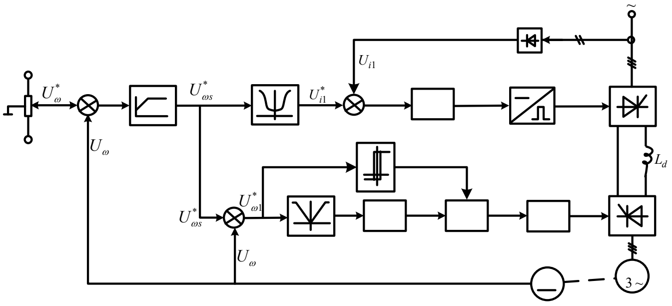
控制转子电阻电压（恒定转子磁链控制）：

$$T=\frac{m_1P}{\omega_1}\left(I_2'\right)^2\frac{r_2'}{s}=\frac{m_1p}{\omega_1}\cdot\left(\frac{E_r}{r_2'/s}\right)^2\frac{r_2'}{s}=m_1p\left(\frac{E_r}{\omega_1}\right)^2\cdot\frac{s\alpha\omega_{1N}}{r_2'}$$

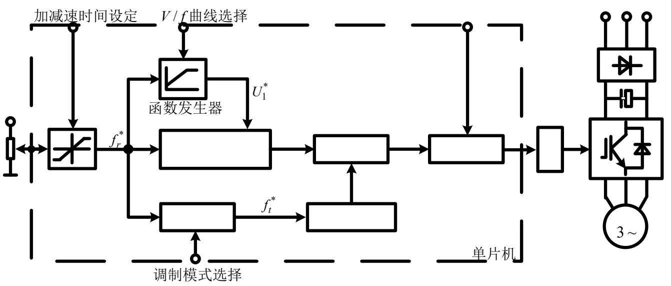


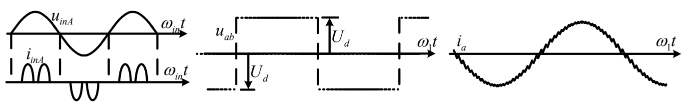
VVVF 恒转矩调速和恒功率调速，后续需要弱磁。弱磁后特性如图所示。

VV+VF ACDCAC CSI Valve Motor System



VS Type ACDCAC SPWM VVVF Speed Regulation（开环）

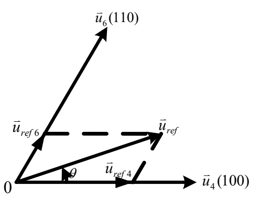


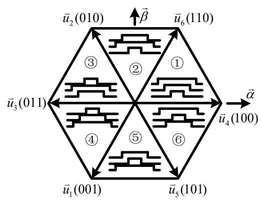


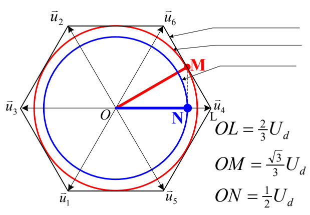
a) Input current b) Output line voltage c) Output current

SVPWM

$$\vec{u}_{ref}=\vec{u}_{ref4}+\vec{u}_{ref6}=\frac{T_4}{T}\vec{u}_4+\frac{T_0}{T}\vec{u}_0+\frac{T_6}{T}\vec{u}_6$$







The DC utilization rate of SVPWM is 15.47% higher than that of SPWM.

坐标变换

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \boldsymbol{C}_{2s/2r} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \boldsymbol{C}_{2r/2s} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

MT 坐标变换

MT 坐标系： Take d axis on the axis of the rotor's comprehensive magnetic linkage vector and called it M axis (rotor magnetic excitation axis), and the q axis ahead of 90 °is called T axis (torque shaft).定子电流决定转矩+磁链。（p 是 Laplace 微分算子 s）

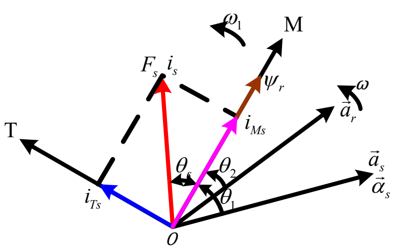
$$\begin{bmatrix} u_{Ms} \\ u_{Ts} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_1 L_s & L_m p & -\omega_1 L_m \\ \omega_1 L_s & R_s + L_s p & \omega_1 L_m & L_m p \\ L_m p & 0 & R_r + L_r p & 0 \\ \omega_s L_m & 0 & \omega_s L_r & R_r \end{bmatrix} \begin{bmatrix} i_{Ms} \\ i_{Ts} \\ i_{Mr} \\ i_{Tr} \end{bmatrix}$$

$$\begin{cases} T = n_P \dfrac{L_m}{L_r} i_{Ts} \psi_r \\ \psi_r = \dfrac{L_m}{T_r p + 1} i_{Ms} \\ \omega = \omega_1 - \omega_s \\ \omega_s = \dfrac{L_m}{T_r \psi_r} i_{Ts} \end{cases} \quad \text{vs} \quad \begin{cases} T = C_T I_a \Phi \\ \Phi = K_f I_f \\ n = n_0 - \Delta n \\ \Delta n = \dfrac{R_a}{C_e \Phi} I_a \end{cases}$$

The I_a and I_f of DC motor is separately input from the stator and rotor and can be independently controlled

The i_{Ms} and i_{Ts} of asynchronous motor are two components of the same stator current synthesis vector.

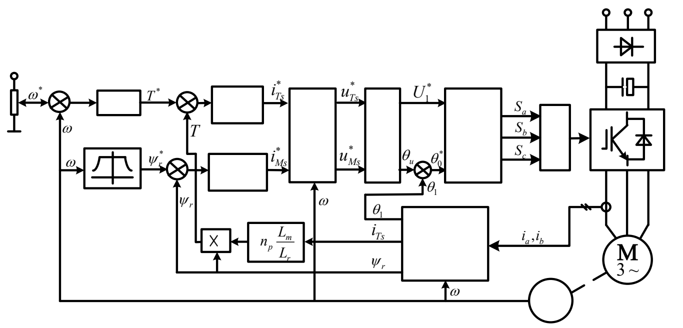
Flux Observer: Based on the above equations.



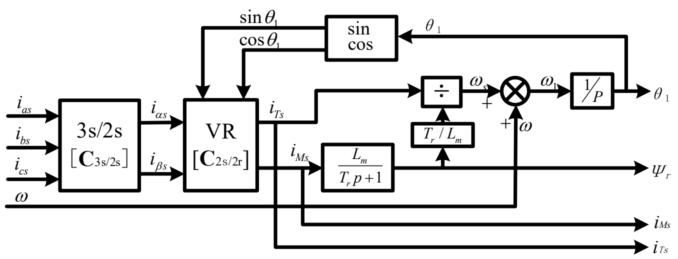
Control i_{Ms} to keep ψ_r constant. By controlling the i_{Ts}, the output torque of the motor can be controlled, so as to achieve the purpose of speed regulation.

Vector Control

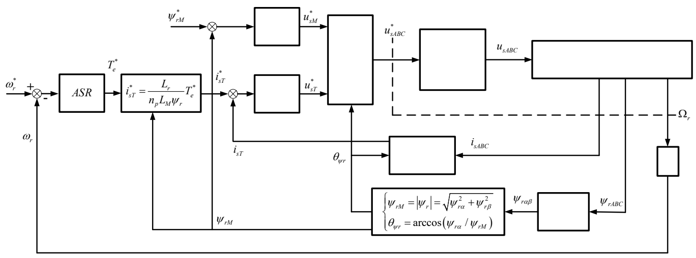
Vector control is to control the integrated current vectors. current tracking mode in voltage source inverter (eliminating harmful harmonics and increasing power utilization ratio). In order to realize the voltage control mode, the current command should be converted into the voltage command.



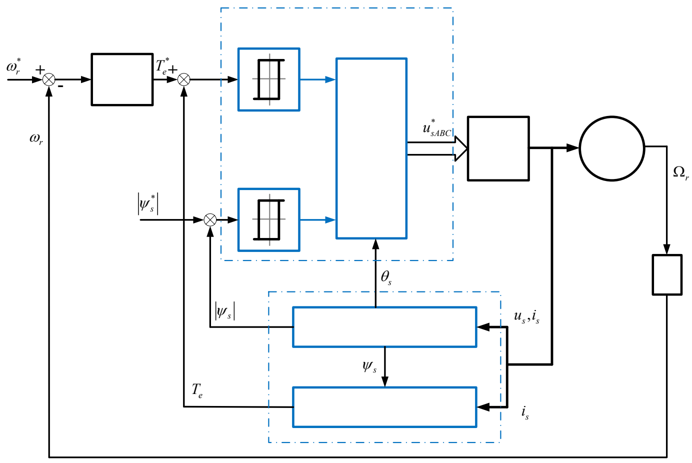
FluxObserver:（左边的公式）

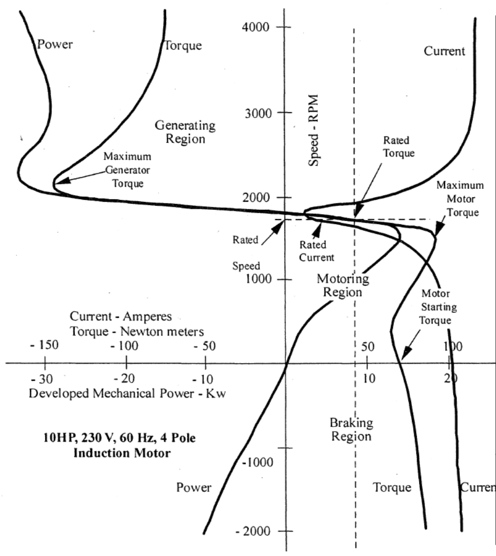


Double-loop based Vector Control

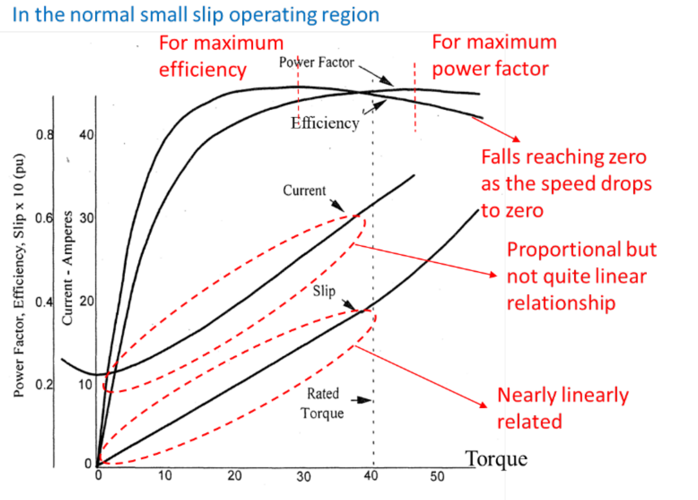


Direct Torque Control（hysterisis control）

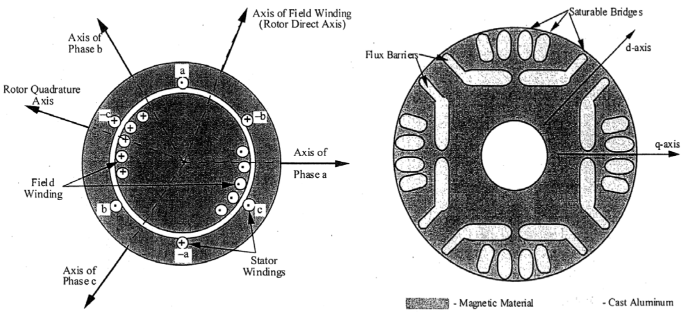




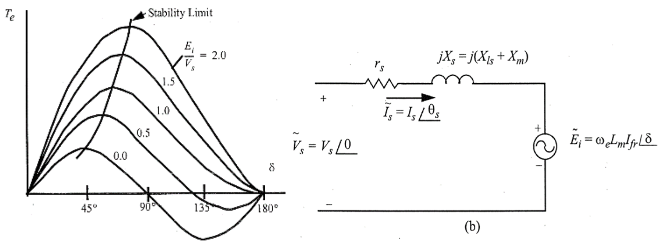
功率、转矩、电流在异步电机中的表现情况。电流一直很大，除了在s=0 附近。定子电流回升导致 Es 很大，使得定子电流磁通很大（避免）

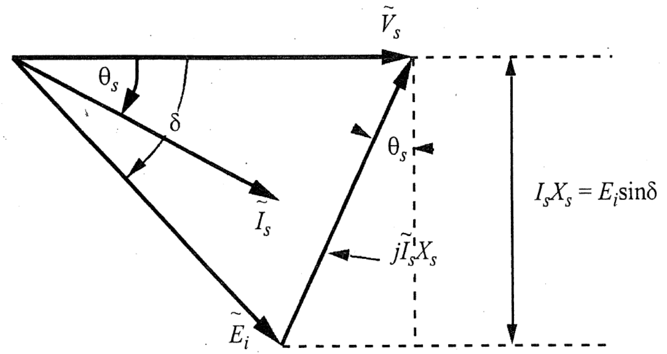


Synchronous Motor



$$T_e = -\frac{3P}{2\omega_e}\left[\frac{V_s E_i}{X_{ds}}\sin\delta + \frac{1}{2}V_s^2\left(\frac{X_{ds}-X_{qs}}{X_{ds}X_{qs}}\right)\sin 2\delta\right]$$



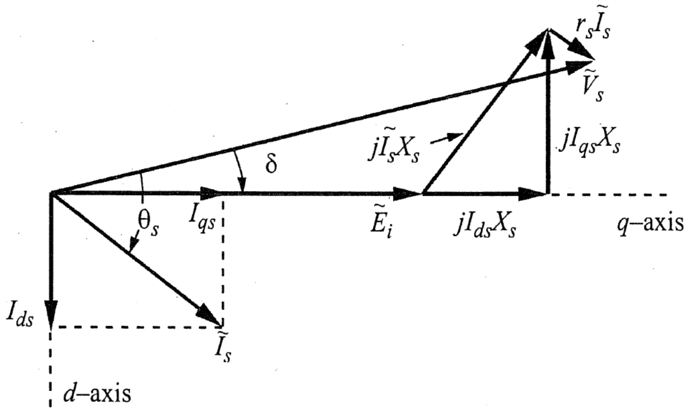


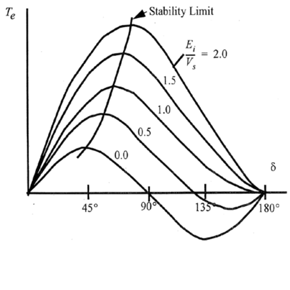
$$\tilde{I}_s = \frac{V_s e^{j0^\circ} - E_i e^{j\delta}}{jX_s} = \frac{V_s}{X_s}e^{-j90^\circ} - \frac{E_i}{X_s}e^{j(\delta-90^\circ)} \quad P_s = -3\frac{V_s E_i}{X_s}\sin\delta$$

$$I_s X_s \cos\theta_s = -E_i \sin\delta \quad P_s = 3E_i I_s \cos\gamma$$

Theta 是功角，delta 是感应电势和外电压角度，gamma 是感应电势和电流角度。(看 theta) Motor with Leading Current： overexcited 。Motor with Lagging Current (Underexcited) Generator with Leading Current (Overexcited) Generator with Lagging Current (Underexcited)

Salient-Pole Machines(凸极)





凸极励磁

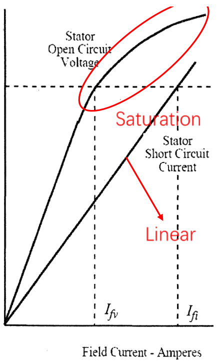
$$T_e = \frac{P_s}{\omega_e\left(\frac{P}{2}\right)} = -\frac{3P}{2\omega_e}\left[\frac{V_s E_i}{X_{ds}}\sin\delta + \frac{1}{2}V_s^2\left(\frac{X_{ds}-X_{qs}}{X_{ds}X_{qs}}\right)\sin 2\delta\right]$$

同步磁阻电机（Synchronous-Reluctance Machines）

All variants of the structure aim to obtain a high saliency ratio X_{ds}/X_{qs} Flux Barriers（q 轴加气隙）。

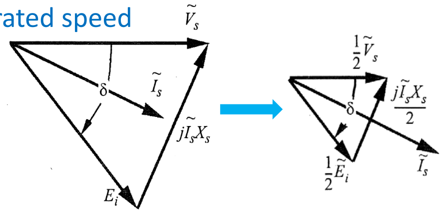
一种特殊的凸极电机，delta=45°时有最大 Torque.

Variable Frequency Operation

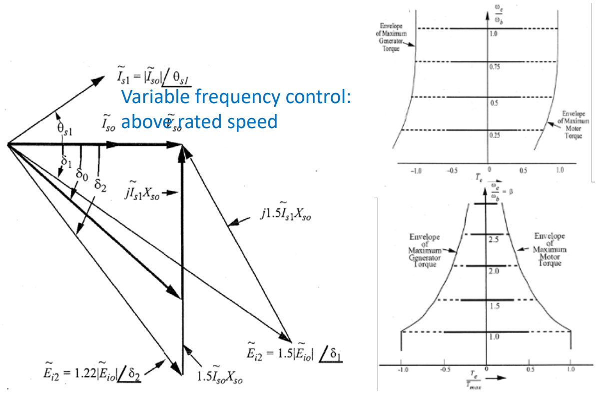


恒转矩模式（VVVF）恒功率模式（定电压 VF）

Variable frequency control: below rated speed



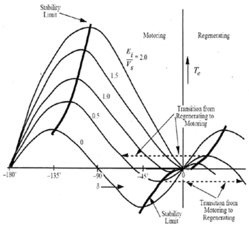
For very low frequencies, the **stator resistance** cannot be neglected and reduces the torque capability



转子回路串电阻，使得T_e=0 does not occur at δ=0

$$T_e = \left(\frac{3P}{2\omega_e}\right)\frac{1}{2}V_s^2\left(\frac{X_{ds}-X_{qs}}{X_{ds}X_{qs}}\right)[(r_s^2 - X_{ds}X_{qs})\sin 2\delta$$
$$+r_s(X_{ds}+X_{qs})\cos 2\delta - r_s(X_{ds}-X_{qs})]$$

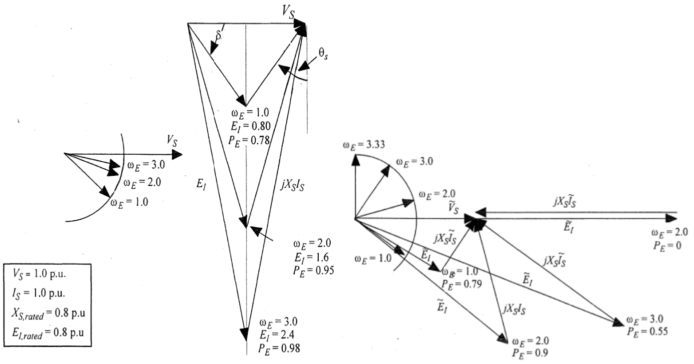
PMSM（其矢量图与凸极完全一致）或采用与异步电机等效

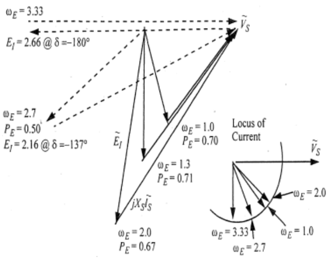


$X_{qs} > X_{ds}$ coercivity 矫顽力

The phasor diagram is the same as the salient-pole synchronous machine **with the excitation E_i constant.（constant frequency）**

对永磁电机来说其磁场为定值，感应电势与速度成正比。

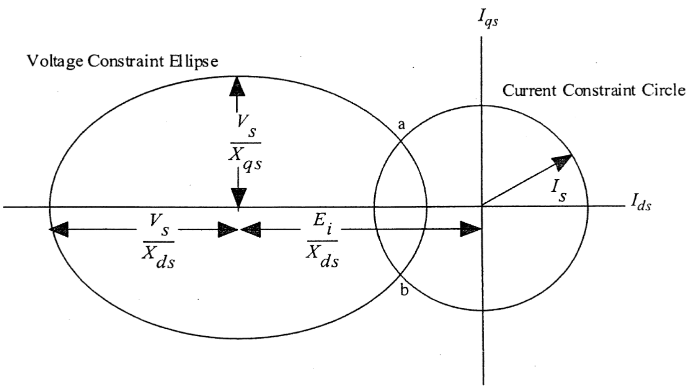




$$H_m = -\frac{l_g}{l_m}H_g \pm \frac{N_{eq}I}{2l_m}$$

同步电机可以达到的同步速——椭圆图

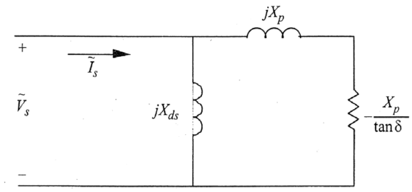
图中为固定输入电压电流幅值的变换器。对 E=IX 的电机来说，同步速可无穷。而其他两种，同步速可调范围只能到 3.33.（此处）。不能达到无穷大，具体可通过椭圆图看出。



Current and voltage constraint loci in the Iqs vs Ids plane

磁阻电机等效图

One salient but without a field(no additional potential)



$$\frac{1}{X_p} = \frac{1}{X_{qs}} - \frac{1}{X_{ds}}$$

同步电机矢量控制的两种方法

$$T = KF_sF_f\sin\theta_{sf} = KF_sF_R\sin\theta_s = KF_RF_f\sin\theta_f$$

有两种矢量控制方法，基于两种锁相方法，一种是锁相励磁磁势，一种是锁相气隙磁势。使得电流一定与他们**垂直**。进而通过控制定子电流的幅值（Fs 的幅值）可以控制转矩大小。值得注意的是，第一种需控制 Ff 不变，第二种需控制 FR 不变（需要进行加磁或弱磁）。Fs Adv Fs 与 d 轴垂直，所以 Fs 与 alpha 轴角度可以直接由传感器测得。Disadv torque 改变 is 也变，不能保持气隙磁场恒定。功率因数随功率增大而减小。Fr Adv 气隙磁场恒定，不会饱和，设计电机不用留裕度；功率因数为 1.Disadv 需要同时控制定子电流的大小，转子励磁电流的大小；需计算 Fs 的方向；控制复杂