



BLDC控制原理 及MPS集成化控制方案

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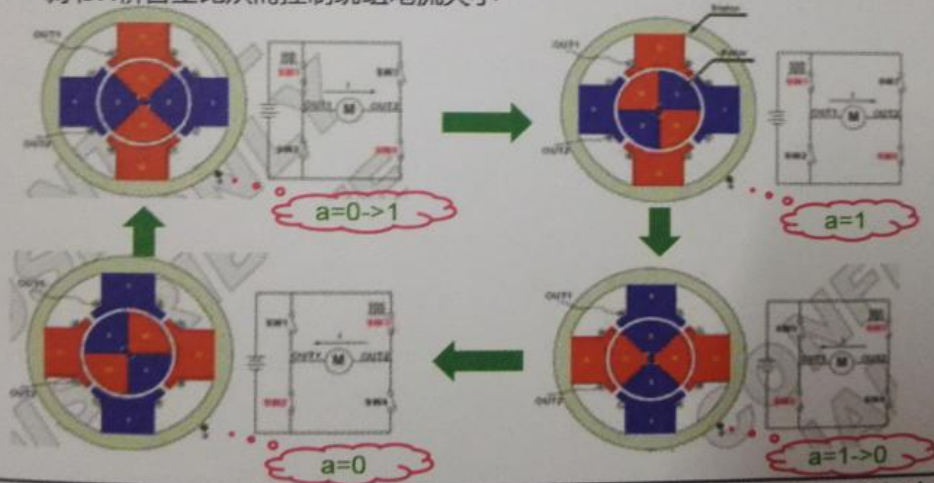


内容简介

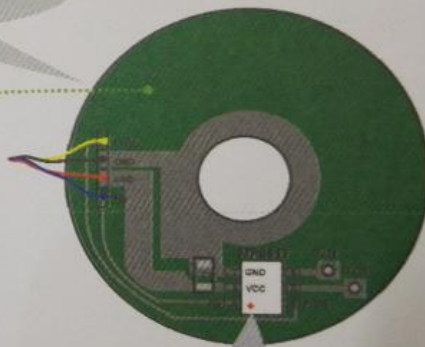
- 单相BLDC电机驱动原理及MPS高度集成控制方案
- 三相BLDC电机、步进电机和PMSM电机优缺点
- PMSM FOC控制原理
- SVPWM 控制原理
- 基于FOC方案的MPS高度集成控制方案及应用

单相直流无刷电机原理

- 需要检测转子磁场位置
- 根据位置信息决定通电顺序，以产生持续旋转的磁场
- 调节H桥占空比从而控制绕组电流大小



1ps 1uF/0603 cap!
Up to 600mA@single-layer!



Straight Lead TSOT23-6

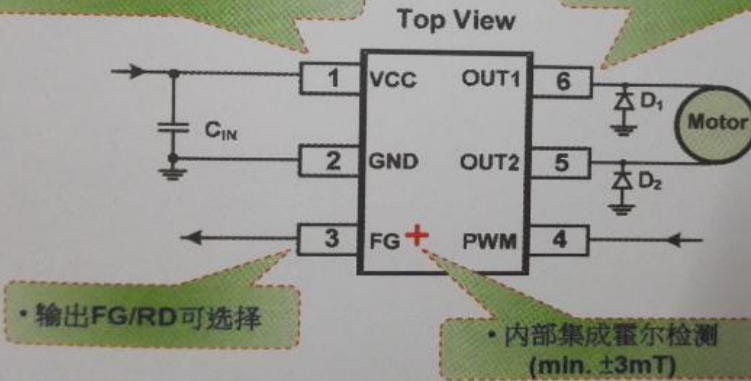
PCB PCB

Rotor Magnet

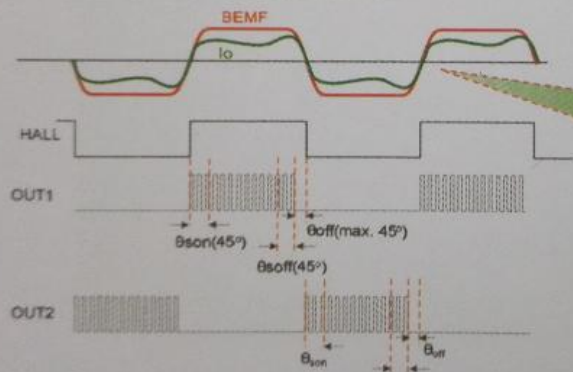
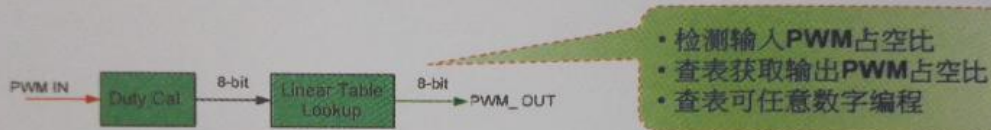
• 单相直流应用实例：(MP9518为例)

- 3V to 18V 输入，21V过压保护
- 输入防插反

- 软换相抑制电流过冲和噪声
- BEMF和电流自动锁相提高效率



• 单相直流无刷电机控制技术实例：(MP9518)



- 软换相抑制电流过冲和噪声
- BEMF和电流自动锁相提高效率

• 三相BLDC电机优缺点

- 转子磁场梯形波充磁
- 控制简单(两两导通三相六状态控制方式)
- 每60deg换向一次，换向存在转矩波动
- 效率一般
- 电机成本低

- ❖ 根据三相霍尔位置决定导通相，以产生旋转的定子磁场
- ❖ 每60°有两相导通，另外一相悬空
- ❖ 每相电流导通240°



• 步进电机优缺点

- 转子磁场正弦波充磁
- 控制简单(电流开环控制方式)
- 步进角取决于电机设计和控制方式
- 效率低
- 电机成本最高

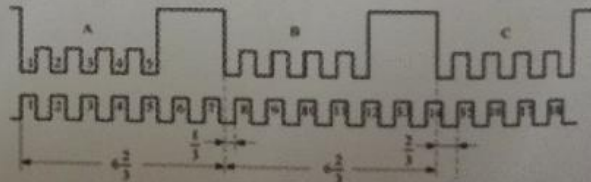
- ❖ 相邻相磁极轴线与转子齿数的关系：
Zr为转子齿数，p为极对数，为m相数，K为正整数

$$\frac{Zr}{2pm} = K \pm \frac{1}{m}$$

- ❖ 电周期的通电拍数与步进角的关系
(N拍转一个齿距)：

$$\theta_s = \frac{360^\circ}{NZ_r}$$

$$N = Cm$$



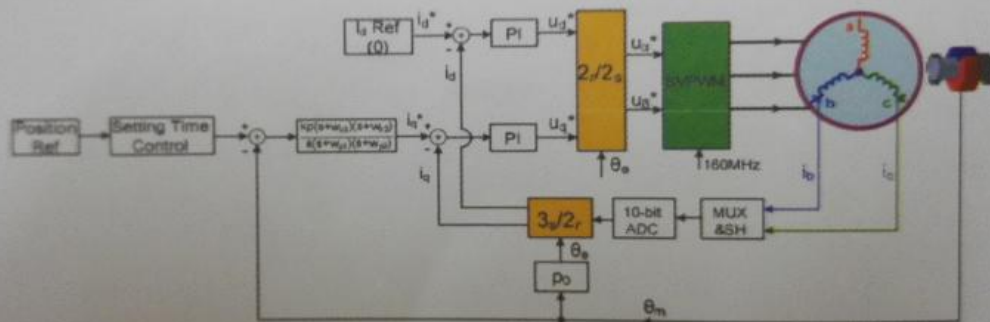
A相对齐时 (3相步进电机为例)

• PMSM电机优缺点

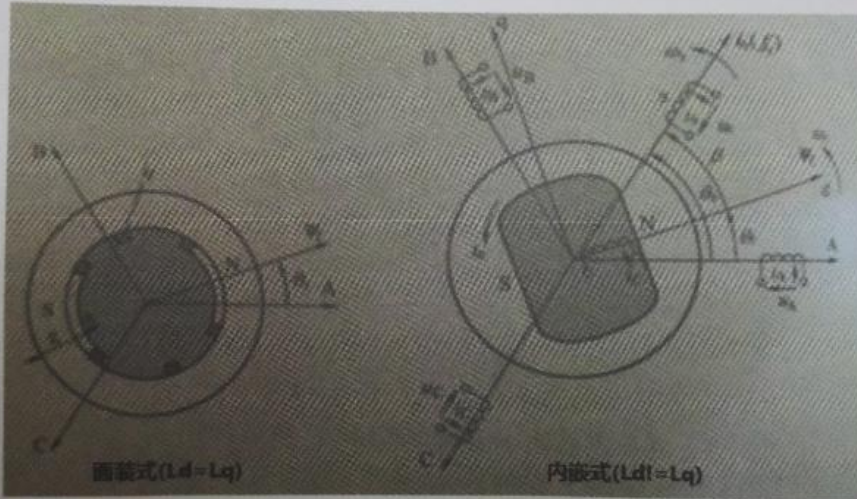
- 转子磁场正弦波充磁
- 控制复杂（磁场定向矢量控制方式）
- 不存在换向波动
- 控制精度高，效率高，
- 电机成本居中

• PMSM 基于转子磁场定向FOC 矢量控制系统框图

- $3s/2r$ 及 $2r/2s$ 旋转变换
- SVPWM的产生



• 三相坐标下电机模型



• 三相坐标下电机模型

- 电压方程：

$$\begin{aligned} u_a &= R_s i_a + \frac{d\psi_a}{dt} \\ u_b &= R_s i_b + \frac{d\psi_b}{dt} \\ u_c &= R_s i_c + \frac{d\psi_c}{dt} \end{aligned}$$

- 磁链方程：

$$\begin{pmatrix} \psi_a \\ \psi_b \\ \psi_c \end{pmatrix} = \begin{pmatrix} L_{m1} + L_{m\sigma} & -\frac{1}{2}L_{m\sigma} & -\frac{1}{2}L_{m\sigma} \\ -\frac{1}{2}L_{m\sigma} & L_{m1} + L_{m\sigma} & -\frac{1}{2}L_{m\sigma} \\ -\frac{1}{2}L_{m\sigma} & -\frac{1}{2}L_{m\sigma} & L_{m1} + L_{m\sigma} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} \psi_{r1} \\ \psi_{r2} \\ \psi_{r3} \end{pmatrix} \rightarrow \begin{pmatrix} \psi_a \\ \psi_b \\ \psi_c \end{pmatrix} = (L_{m1} + L_{m\sigma}) \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} \psi_{r1} \\ \psi_{r2} \\ \psi_{r3} \end{pmatrix}$$

- 电流约束方程：

$$i_a + i_b + i_c = 0;$$

Lm1: 每相绕组的自感；

Lm: 3/2*Lm1

Lmσ: 每相绕组自感；

ψA/ψB/ψC: 定子每相总磁链；

ψr1/ψr2/ψr3: 转子每相磁链；

为什么寻求矢量变换

- 三相交流电量 (a/b/c) 变换到两相直流电量(d/q)
- 采用传统直流电机经典控制控制方法

三相电量到矢量/ud,uq平面转换原理

- 等功率变换原则 (ua*ia+ub*ib+uc*ic=ud*id+uq*iq)

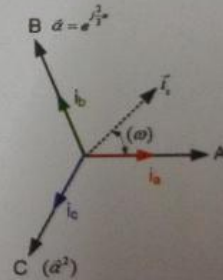
$$\bar{i}_s = \sqrt{\frac{2}{3}}(i_a + \bar{\alpha} \cdot i_b + \bar{\alpha}^2 \cdot i_c)$$

$$\bar{u}_s = \sqrt{\frac{2}{3}}(u_a + \bar{\alpha} \cdot u_b + \bar{\alpha}^2 \cdot u_c)$$

$$\bar{\psi}_s = \sqrt{\frac{2}{3}}(\psi_a + \bar{\alpha} \cdot \psi_b + \bar{\alpha}^2 \cdot \psi_c)$$

$$\bar{\psi}_f = \sqrt{\frac{2}{3}}(\psi_{fa} + \bar{\alpha} \cdot \psi_{fb} + \bar{\alpha}^2 \cdot \psi_{fc})$$

$$\begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos \theta r & -\sin \theta r & 0 \\ \cos(\theta r - \frac{2}{3}\pi) & -\sin(\theta r - \frac{2}{3}\pi) & 0 \\ \cos(\theta r - \frac{4}{3}\pi) & -\sin(\theta r - \frac{4}{3}\pi) & 0 \end{pmatrix} \begin{pmatrix} x_d \\ x_q \\ 0 \end{pmatrix}$$



基于转子磁场定向(u,q)平面下PMSM电机模型

- 电压方程：

$$\bar{u}_s^{dq} = R_s \bar{i}_s^{dq} + \frac{d\bar{\psi}_s^{dq}}{dt} + j\omega_r \bar{\psi}_s^{dq}$$

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r (L_d i_d + \psi_f)$$

- 磁链方程：

$$\bar{\psi}_s^{dq} = L_d i_d + \psi_f + jL_q i_q$$

$$\psi_d = L_d i_d + \psi_f$$

$$\psi_q = L_q i_q$$

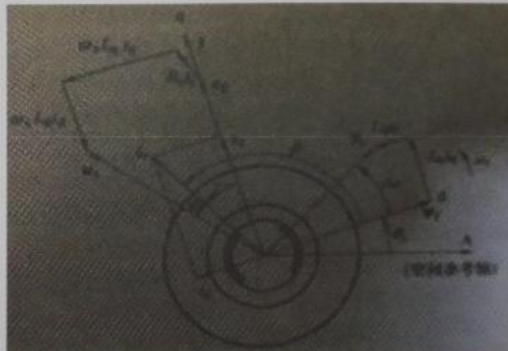
- 转矩方程：

$$T_e = p_0 \bar{\psi}_s \times \bar{i}_s = p_0 (\psi_d + j\psi_q) \times (i_d + j i_q)$$

$$T_e = p_0 [\psi_f i_q + (L_d - L_q) i_d i_q]$$

- 功率方程：

$$T_e = T_e \cdot \Omega_m = p \cdot T_e \cdot \omega_r$$



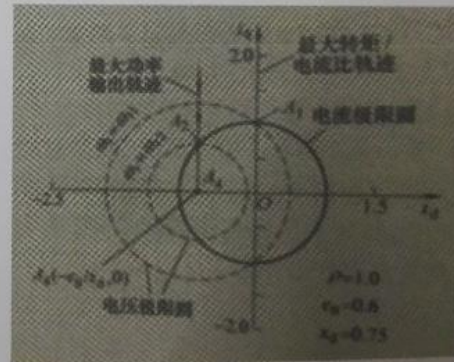
• 最优控制策略 (Ld=Lq)

- OA段：采用最大转矩电流比(te/is)控制
 - ❖ id=0,
 - ❖ 转矩正比于iq
- A1A2段：弱磁控制（遵循电压极限圆）
 - ❖ Id<0,
 - ❖ 转矩减小，功率继续增加
- A2A4段：采用最大功率控制
 - ❖ Id=恒定,
 - ❖ 转矩减小，功率保持最大功率
 - ❖ |id|<=ψr/Ld

电压极限圆： $(L_q i_q)^2 + (L_d i_d + \psi_f)^2 \leq (\frac{U_{lim}}{\omega_s})^2$

电流极限圆： $i_q^2 + i_d^2 \leq i_{lim}^2$

$u_{lim} = \frac{V_{DC}}{\sqrt{2}}$; i_{lim} 取决于逆变器和电机容量



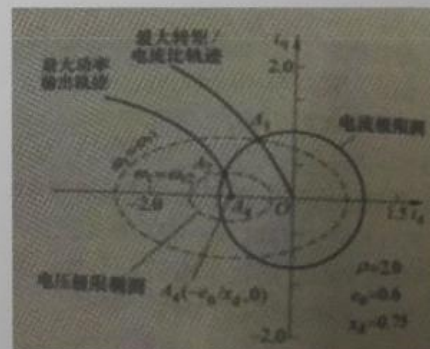
• 最优控制策略 (Ld ≠ Lq)

- OA段：采用最大转矩电流比(te/is)控制
 - ❖ 转矩增加，功率增加
- A1A2段：弱磁控制（遵循电压极限椭圆）
 - ❖ Id<0,
 - ❖ 转矩减小，功率继续增加
- A2A4段：采用最大功率控制
 - ❖ 转矩减小，功率保持最大功率
 - ❖ |id|<=ψr/Ld

电压极限圆： $(L_q i_q)^2 + (L_d i_d + \psi_f)^2 \leq (\frac{U_{lim}}{\omega_s})^2$

电流极限圆： $i_q^2 + i_d^2 \leq i_{lim}^2$

$u_{lim} = \frac{V_{DC}}{\sqrt{2}}$; i_{lim} 取决于逆变器和电机容量

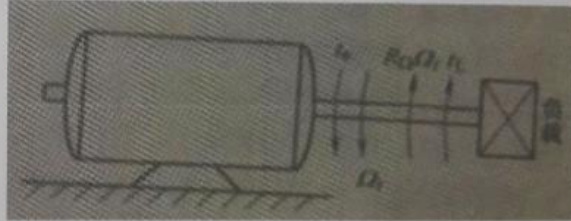


- 电机机械系统等效控制模型
 - 系统等效模型

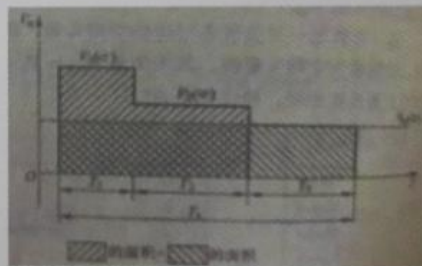
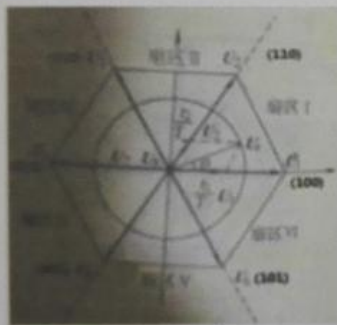
$$\left(\begin{aligned} t_e &= J \frac{d\Omega_m}{dt} + F \cdot \Omega_m + t_L \\ \Omega_m &= \frac{d\theta_m}{dt} \end{aligned} \right)$$

⇒

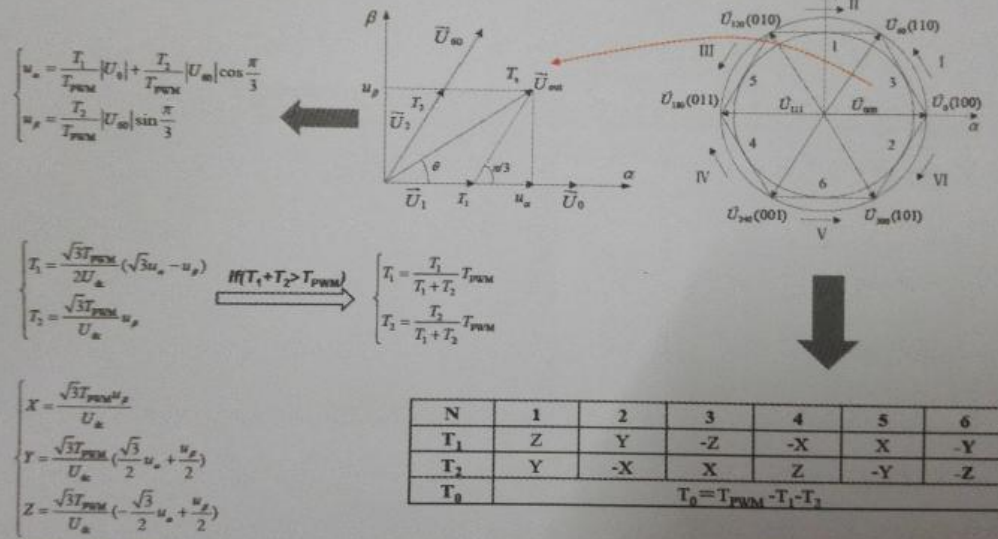
$$\left(\begin{aligned} \frac{\Omega_m(s)}{t_e(s)} &= \frac{1}{J \cdot s + F} \\ \frac{\theta_m(s)}{t_e(s)} &= \frac{1}{s \cdot (J \cdot s + F)} \end{aligned} \right)$$



- 面积等效原理
 - 旋转矢量由两相邻基本矢量面积等效而成。
 - 最大化电压利用率



• 面积等效原理



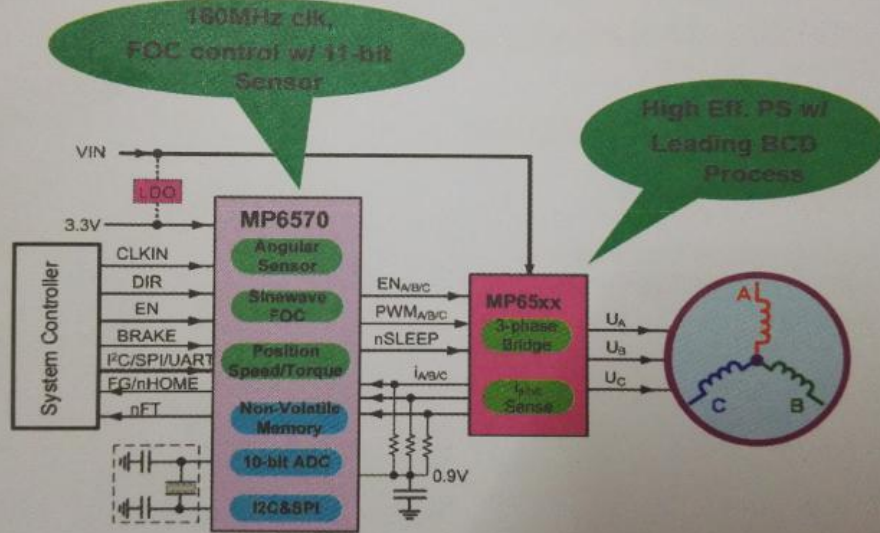
• 系统结构



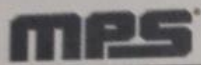


基于FOC方案的MPS高度集成控制方案及应用

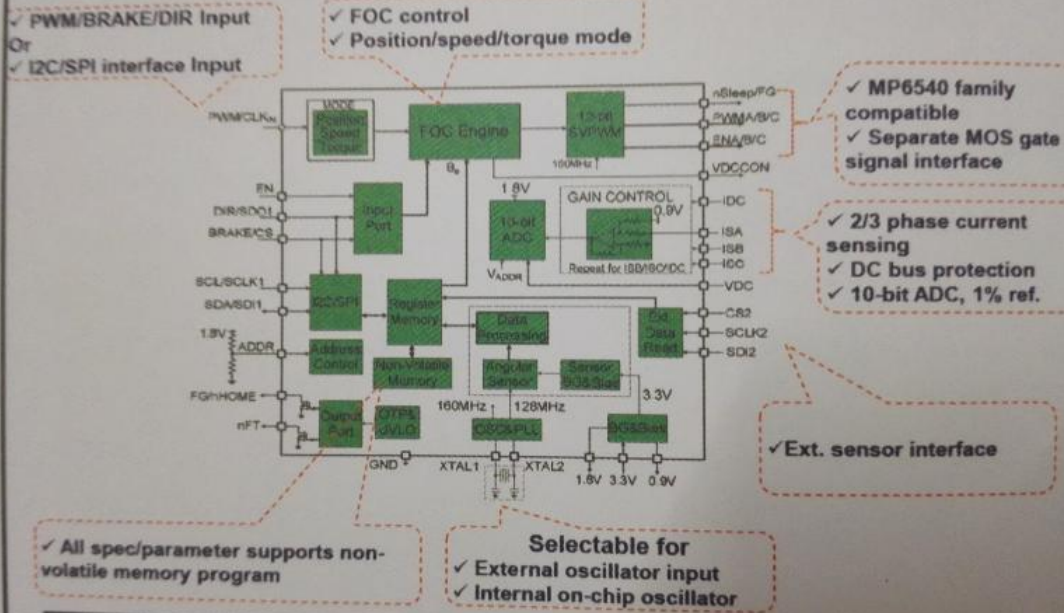
应用原理图



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基于FOC方案的MPS高度集成控制方案及应用



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基于FOC方案的MPS高度集成控制方案及应用

- 所有控制参数可烧写于非易失存储器

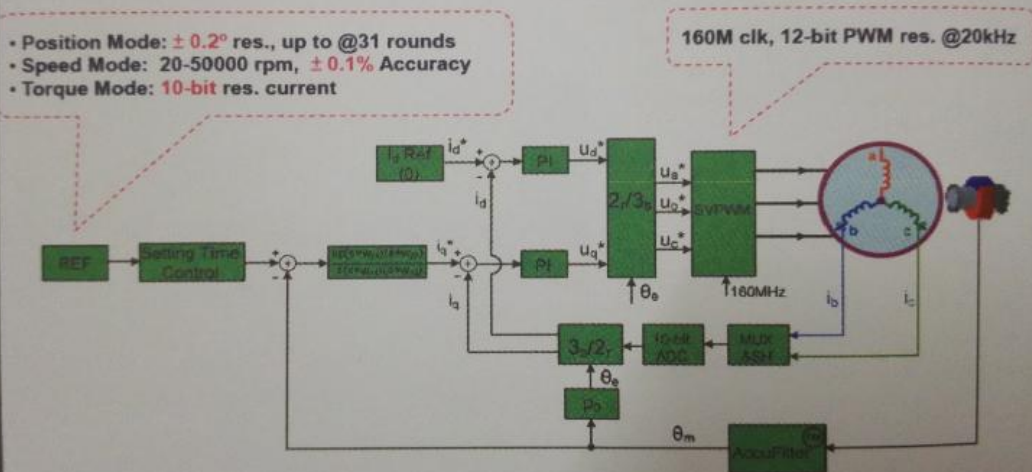
Motor	Control	Protection
L_d : d axis inductance	mode: Position/Speed/Torque select	loop: current limit
L_q : q axis inductance	$k_{p,i}, k_{i,i}$: torque loop spec	t_{dec}/t_{lock} : lock timer
ψ_r : rotor flux	$k_{p,w}, k_{i,w}$: speed/position loop spec	t_{dec} : lock detection time
p_0 : stator pole-pair	period: switching frequency	brk_iq: brake current
spd_min: min. speed	pos_step/spd_step: ref slope	lin_max/vin_max: max. Vin/lin
speed_cmd: speed ref	com_mod: interface select	t_retry: Fault retry timer
theta_cmd: position ref	exang: sensor source select	i_max: max. torque current
id_ref/iq_ref: torque ref	ad_mod/ad_gain: AD control	brk_mod: brake mode
theta_bias: initial position	bct/kalman/resolution: sensor filter ctr.	
	data_comp: Accufilter 32 data set	
	pwm_mod: PWM output mode	
	sam_mod: 1/2/3 phase current ctr.	

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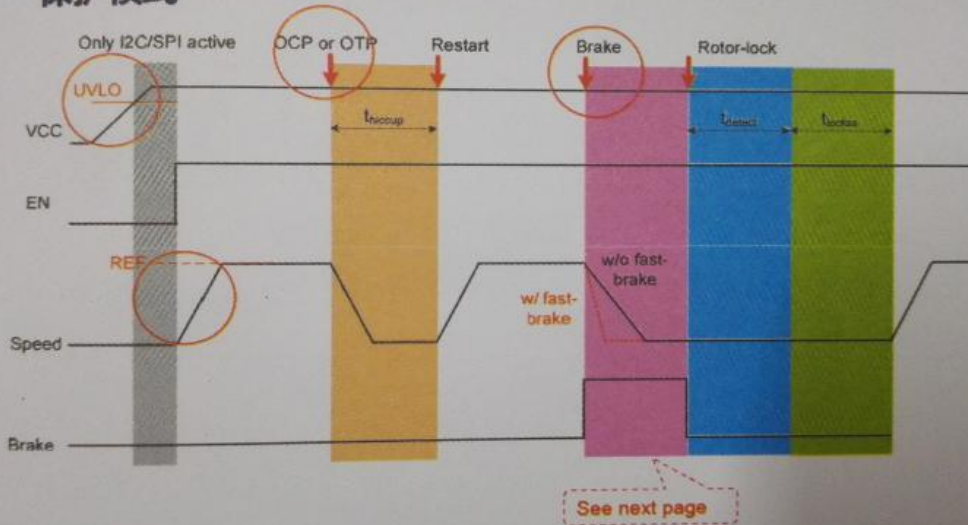
基于FOC方案的MPS高度集成控制方案及应用

- 控制系统框图

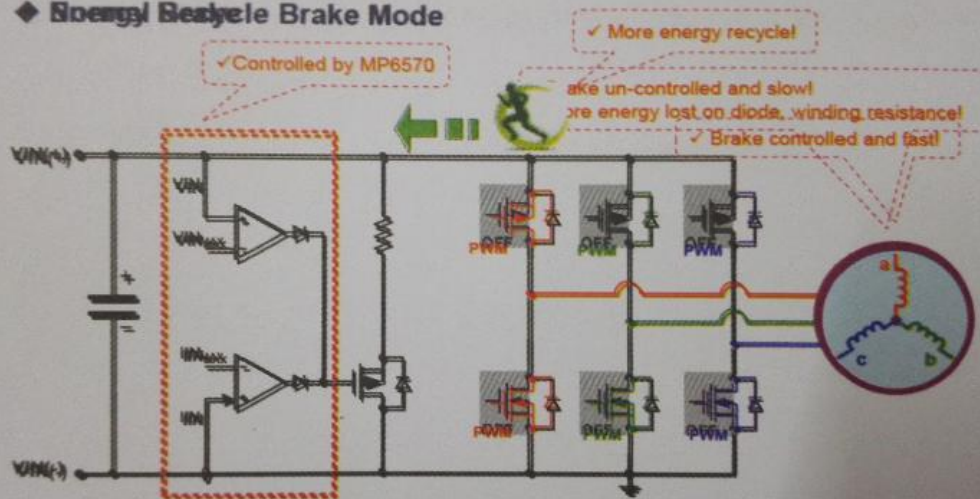


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• 保护模式



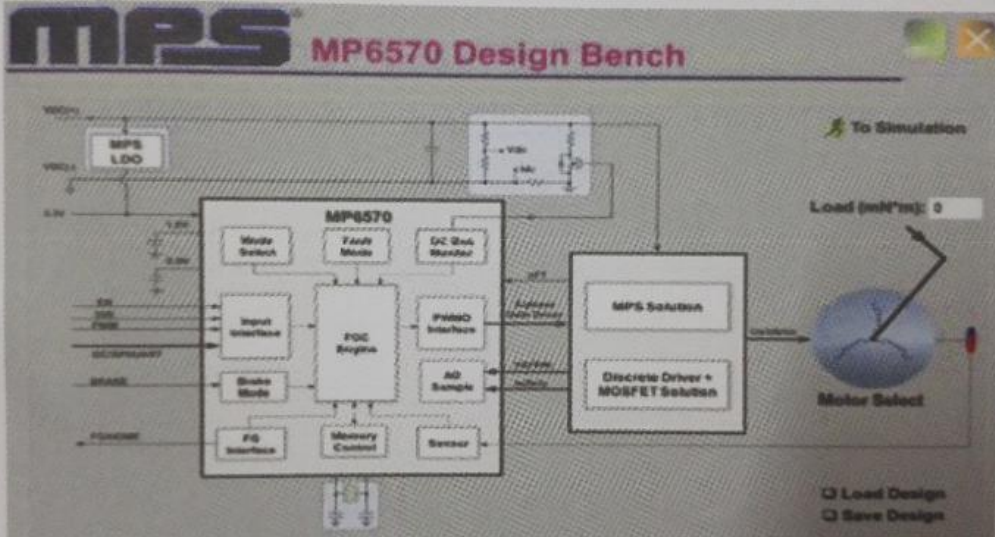
◆ Energy Recycle Brake Mode



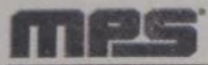


基于FOC方案的MPS高度集成控制方案及应用

• Smart & Easy Use GUI应用软体

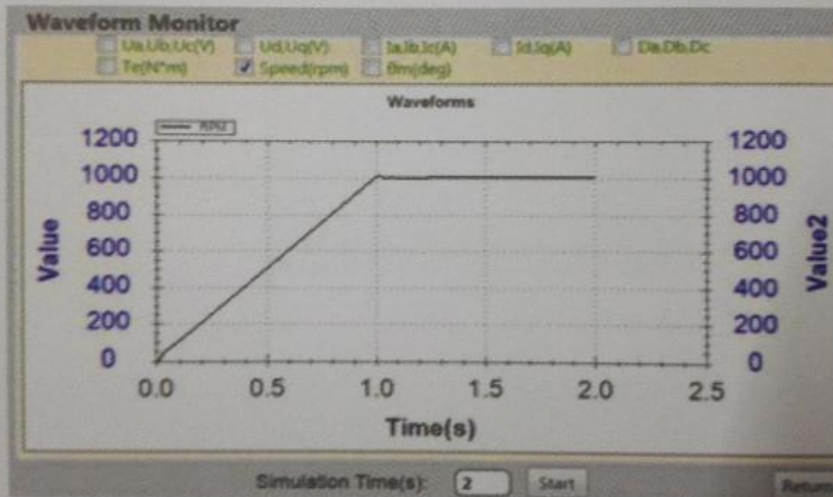


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基于FOC方案的MPS高度集成控制方案及应用

• Smart & Easy Use GUI应用软体

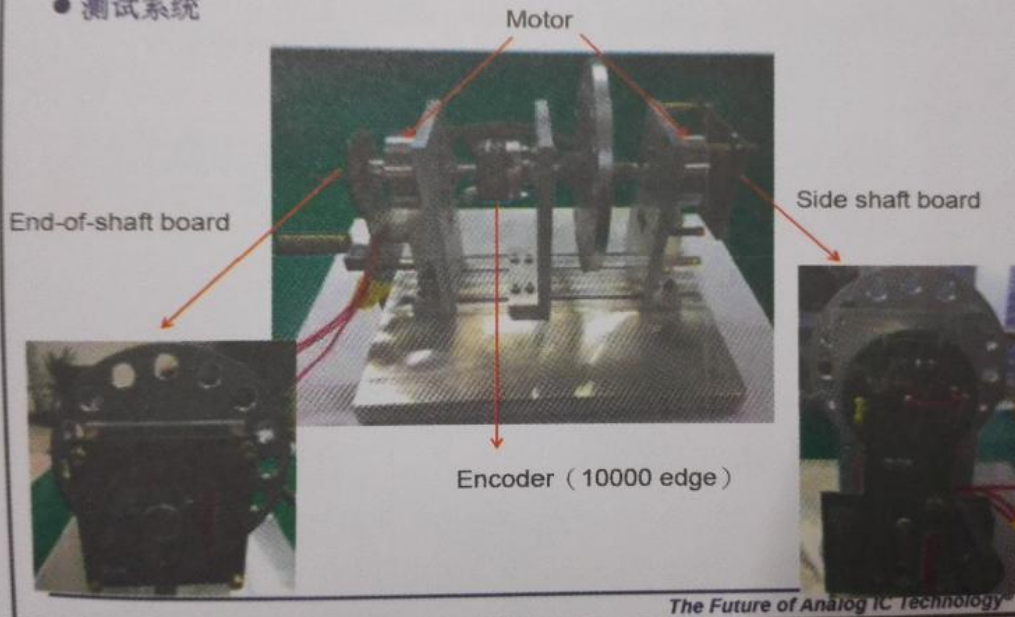


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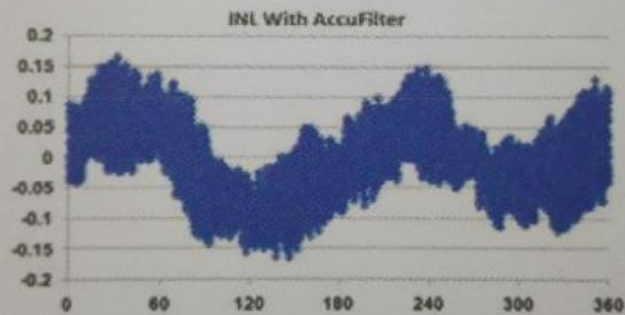
• 测试系统



基于FOC方案的MPS高度集成控制方案及应用

• Internal Sensor INL

- End Shaft Setup, 2500-pulse encoder, 5000 points sample@20RPM

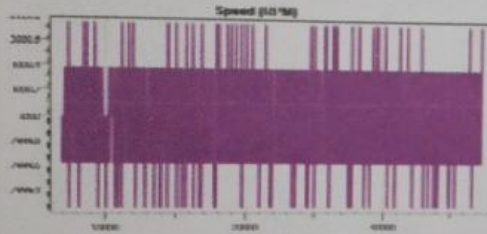




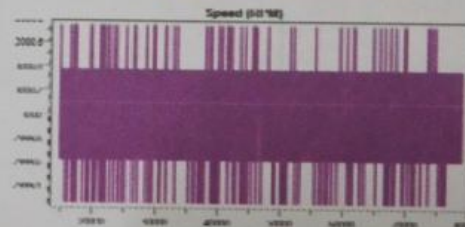
Speed Mode Bench Test

- Speed Ripple Test @ 3000 RPM, $J=3100\text{g}\cdot\text{cm}^2$

No Load



Full Load (90mN*m)

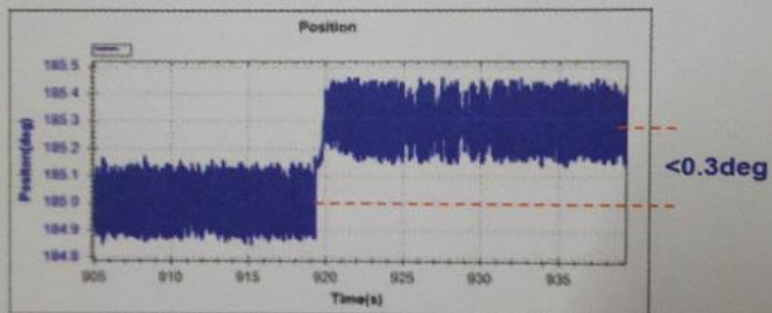


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Position Mode Bench Test

- Position Mode Test @NO Load, $J=3100\text{g}\cdot\text{cm}^2$



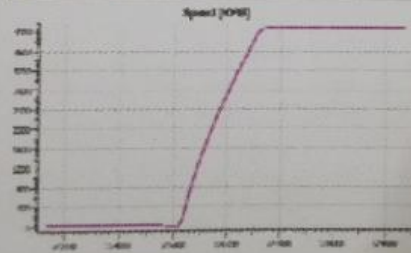
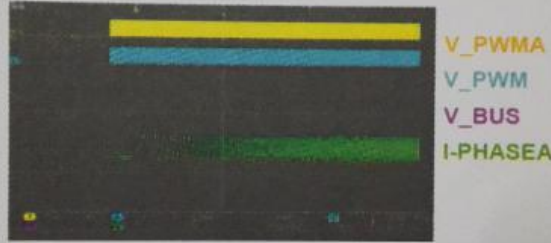
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基于FOC方案的MPS高度集成控制方案及应用

• Torque Loop Test

- VIN=12V, Iq=1A



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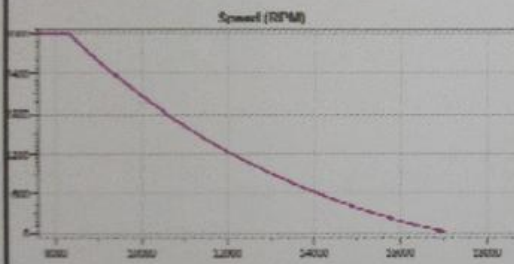


Brake Mode Bench Test

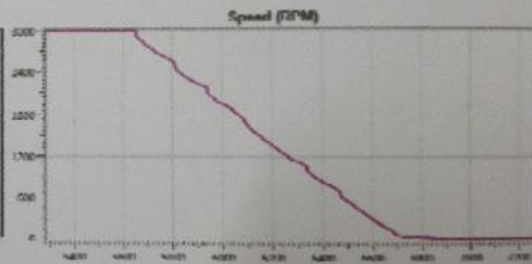
- 3000RPM to 0RPM, $T_{BRAKE} = -70mN*m$, $J = 3100g*cm^2$

Coasting Mode

Energy Recycle Mode



~8.8s brake time

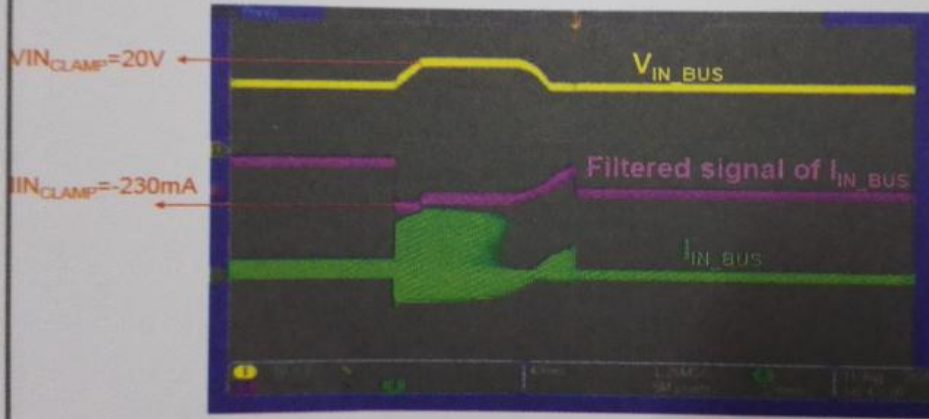


~1s brake time

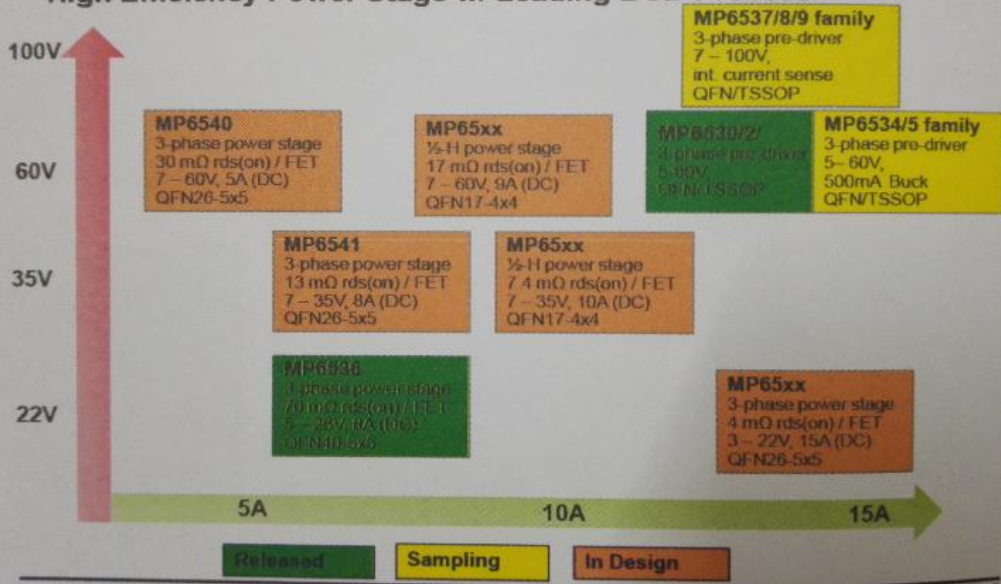
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• VIN & IIN Protection @ $T_{BRAKE} = -70mN \cdot m$, $J = 3100g \cdot cm^2$

3000RPM to 0RPM, $J = 3100g \cdot cm^2$



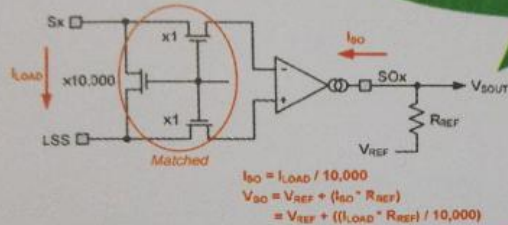
• High Efficiency Power Stage w/ Leading BCD Process



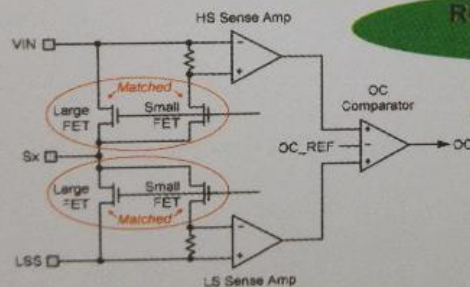


基于FOC方案的MPS高度集成控制方案及应用

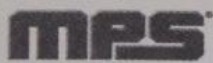
Accurate Current Sense
w/ phase LSMOS



Robust OCP w/ Each MOS

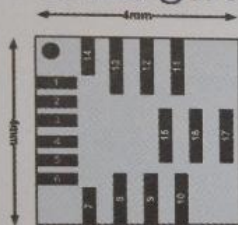


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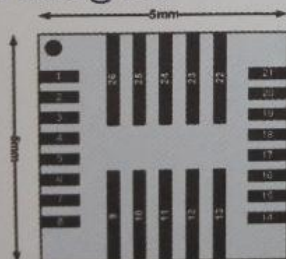


基于FOC方案的MPS高度集成控制方案及应用

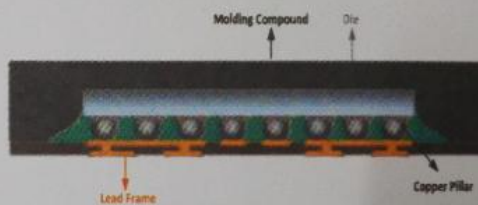
1/2-H: 17 pads, 4mm x 4mm,
2.8 Watts @ 25°C



3-phase: 26 pads, 5mm x 5mm,
3.5 Watts @ 25°C



Mesh Connect™
(No Wire Bond)



Advantages over standard packages:

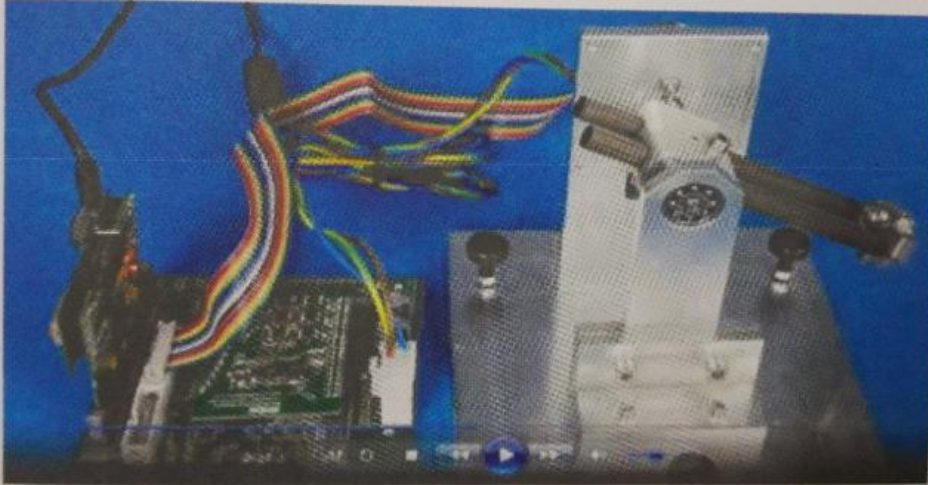
- Very low parasitic resistance
- Very low inductance
- Reduced thermal resistance
- Small size
- Low cost

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MPS 永磁同步电机方案及机器人抛球装置介绍

- 机器人抛球装置介绍



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Q & A

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