

ARFER Y 雅特力

AT32电机库示范讲解 - FOC 增量编码器有感控制

2.20 (四) 13:30-15:30 在线培训

主讲：电机应用软件资深工程师 林明赞 博士

2025.02.20 活动议程

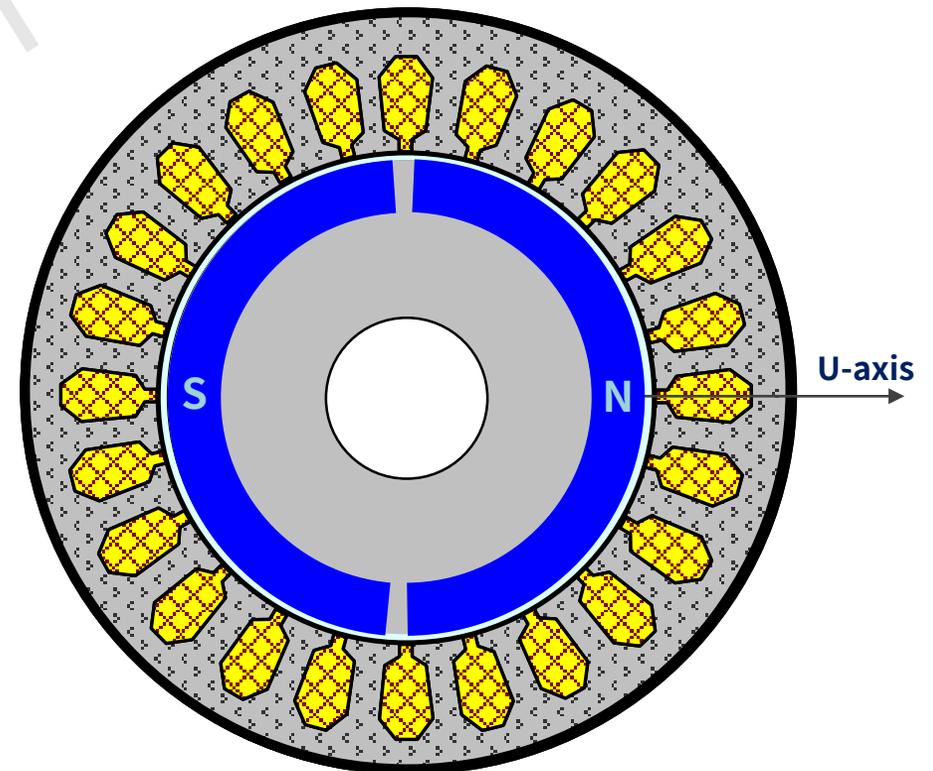
时间	主题	讲师
13:30 -14:30	永磁同步电机FOC增量编码器有感控制解说	电机应用软件 资深工程师 林明赞 博士
中场休息		
14:40 -15:30	AT32 电机库FOC增量编码器控制快速上手操作解说	电机应用软件 资深工程师 林明赞 博士

永磁同步电机 FOC控制原理



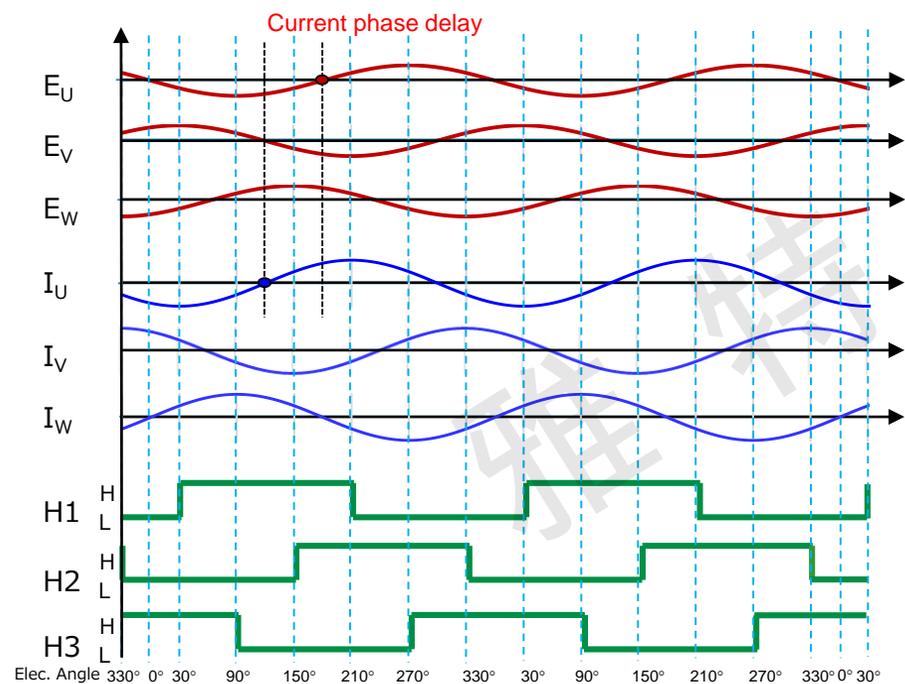
交流永磁同步电机介绍

- 定子为分布式绕组线圈，转子为表贴圆弧磁钢或内嵌式磁钢
- 反电势为正弦波，以三相弦波电流驱动
- 优点
 - 弦波电流构成空间均匀旋转磁场
 - 可输出稳定连续扭力
 - 搭配FOC控制，精确控制扭矩
 - 运转噪音小，效率高，响应快
- 缺点
 - 控制法则较复杂

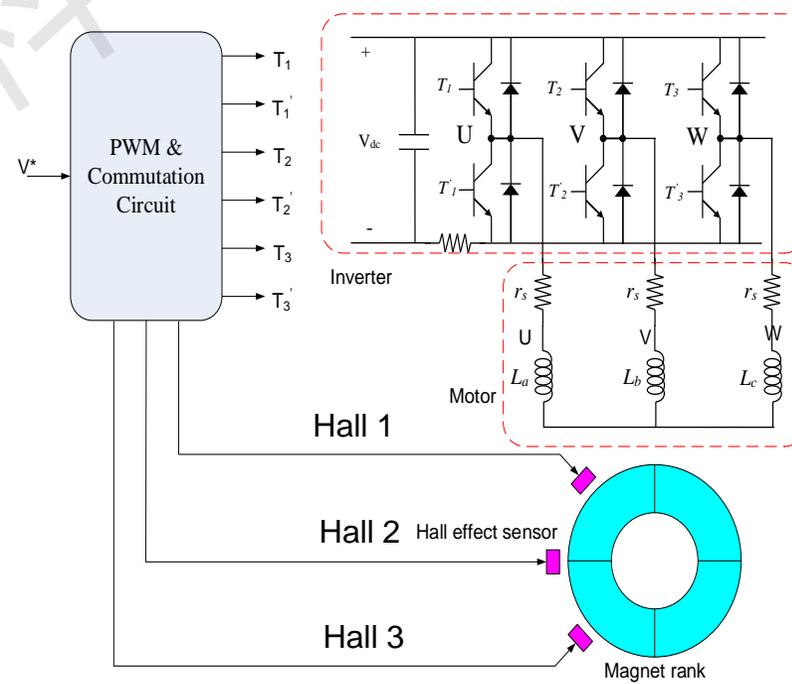


弦波电压控制技术 (电压矢量)

- 根据编码器/霍尔传感器，估算磁极角度，再依据角度产生三相弦波电压
- 因马达电感效应，电流落后反电势，造成马达扭力变小



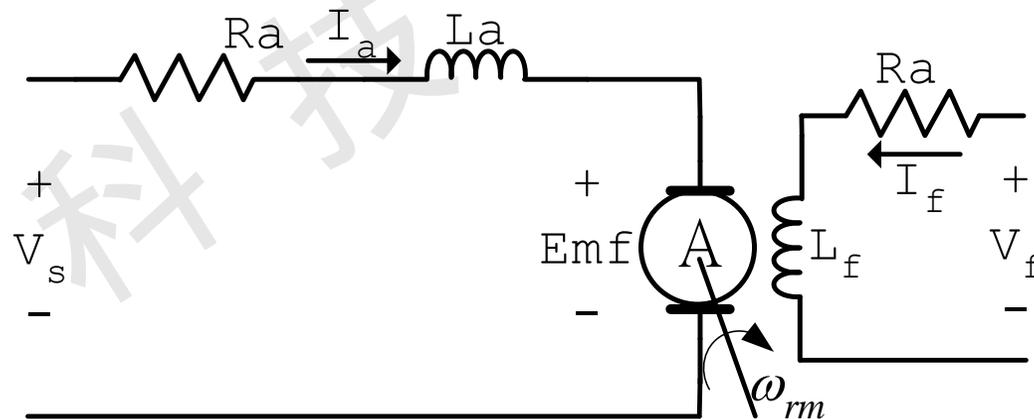
PMSM驱动电压/电流



PMSM 驱动电路

直流有刷电机控制

- 直流有刷电机转矩输出线性，控制方法简单
- 经FOC控制可将三相弦波矢量转换为两轴直流矢量
- 使交流电机可类比于直流电机控制



电磁转矩方程式

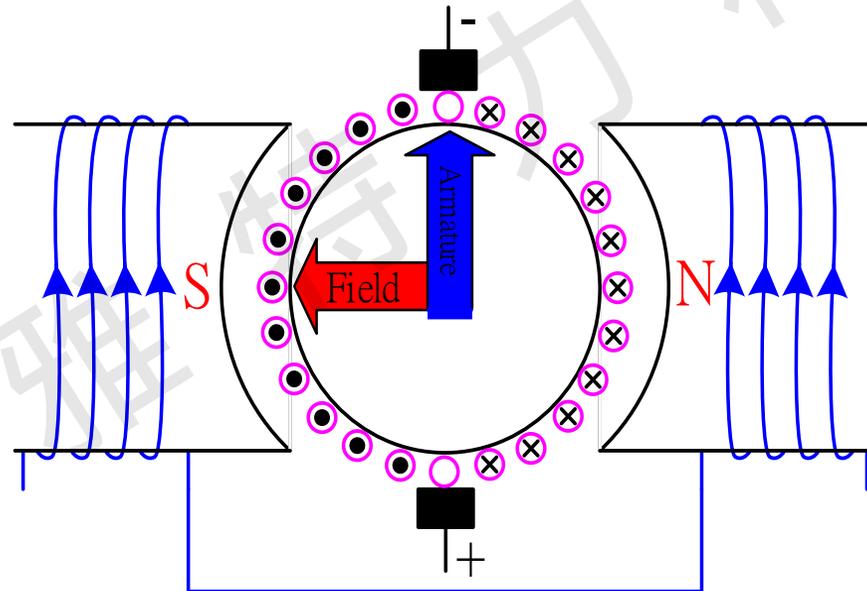
$$T_e = K_a I_a (K_f I_f) = K_t I_a I_f$$

转矩动态方程式

$$\frac{d\omega_{rm}}{dt} = \frac{1}{J_s} (T_e - T_l - B_m \omega)$$

矢量控制 (电流矢量)

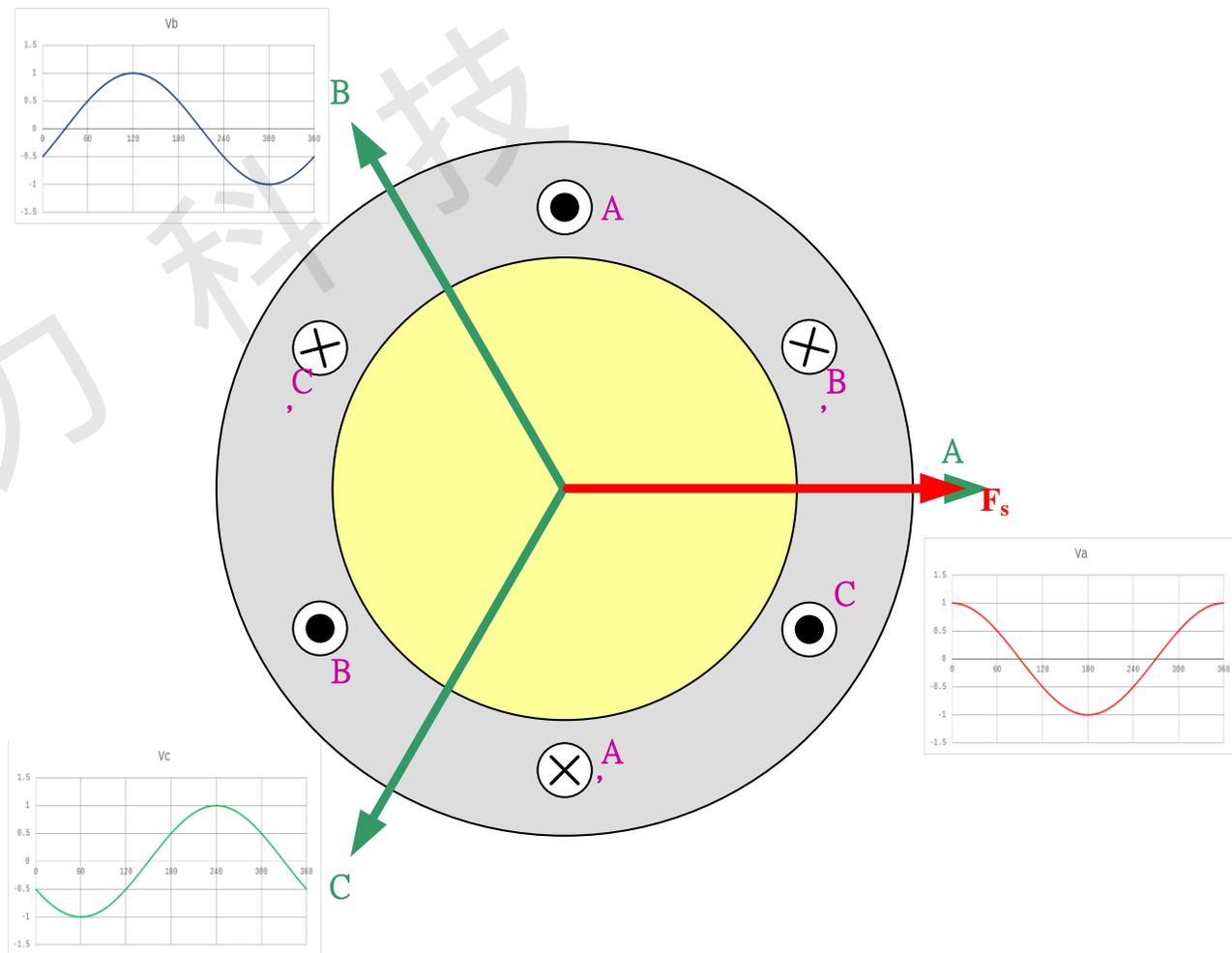
- 电机矢量：磁场磁通、电枢磁通
- 直流有刷马达藉由碳刷与换相片之间的机械作用，变换线圈电流极性
- 使得定子磁场磁通与转子电枢磁通垂直正交，产生扭力



直流有刷电机示意图

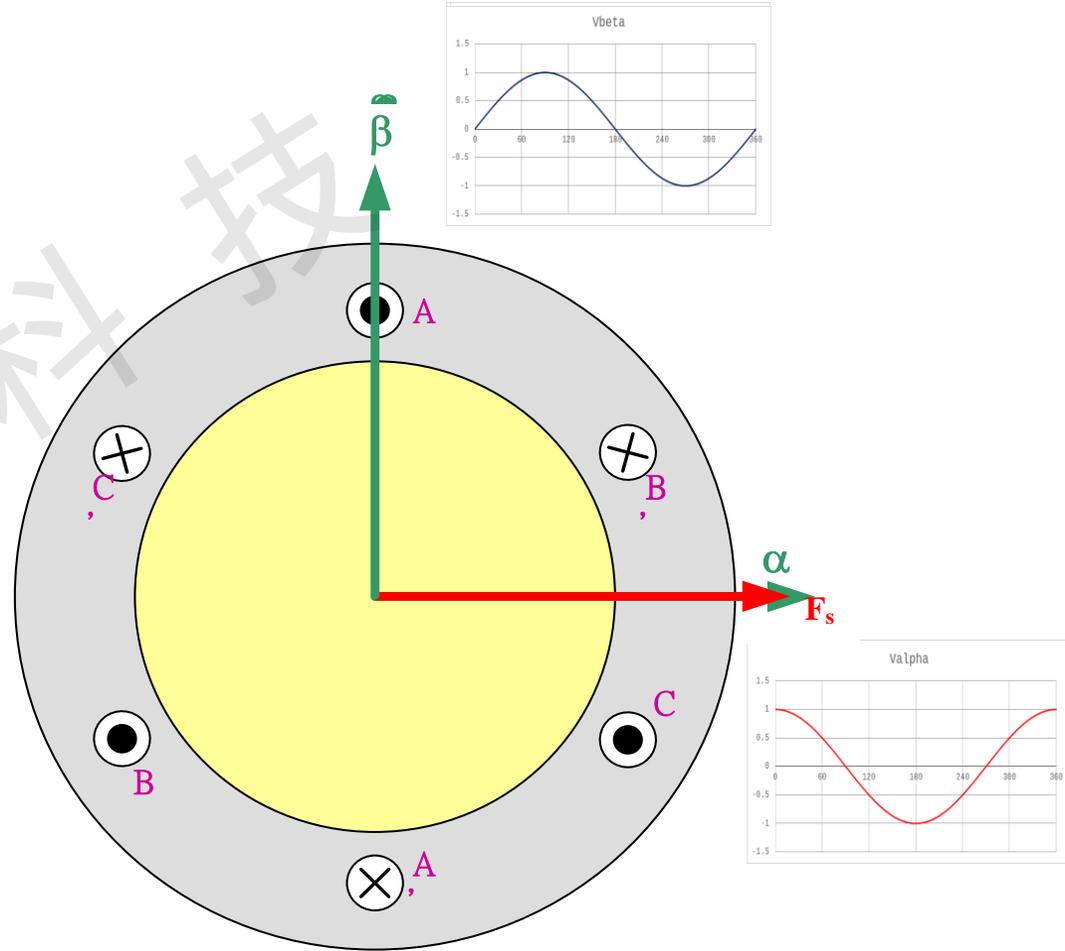
三相静止坐标

- 三相a-b-c座标于空间中相位差 120°
- 三相座标的弦波分量为电机中旋转矢量(电压/电流)的投影
- 三相弦波信号彼此相差 120°
- 因位于同平面，可用两相座标表示该旋转矢量



两相垂直静止坐标

- 两相 α - β 座标于空间中相位差 90°
- 两相座标的弦波分量为电机中旋转矢量(电压/电流)的投影
- 两相弦波信号为正交相差 90°
- 三相静止座标可用Clarke转换至两相静止座标
- 两相静止座标可用Inv-Clarke转换至三相静止座标



Clarke转换与Inv-Clarke转换

- Clarke转换 (同幅值转换)

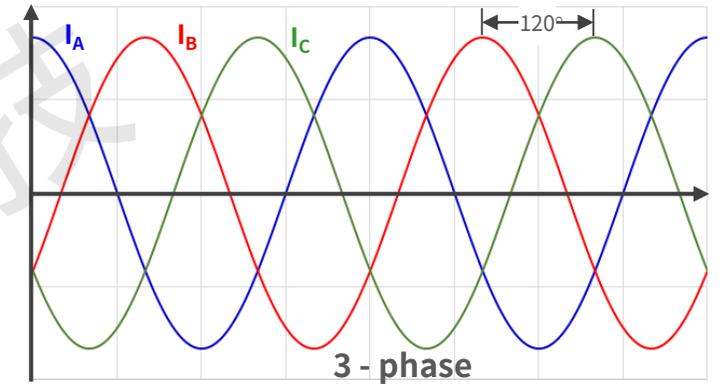
$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

- Inv-Clarke转换 (同幅值转换)

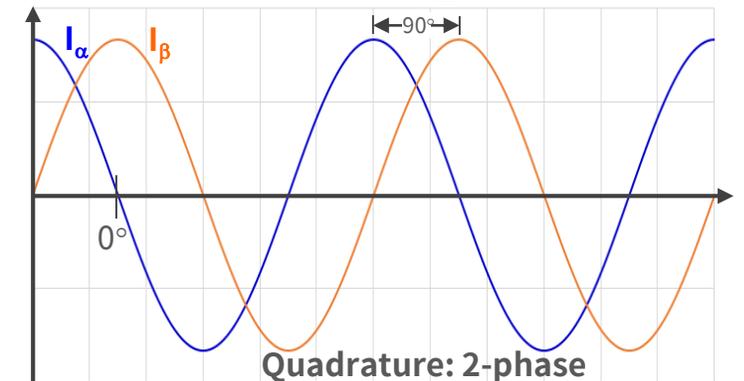
$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & \frac{3}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} & \frac{3}{2} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & 1 \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix}$$



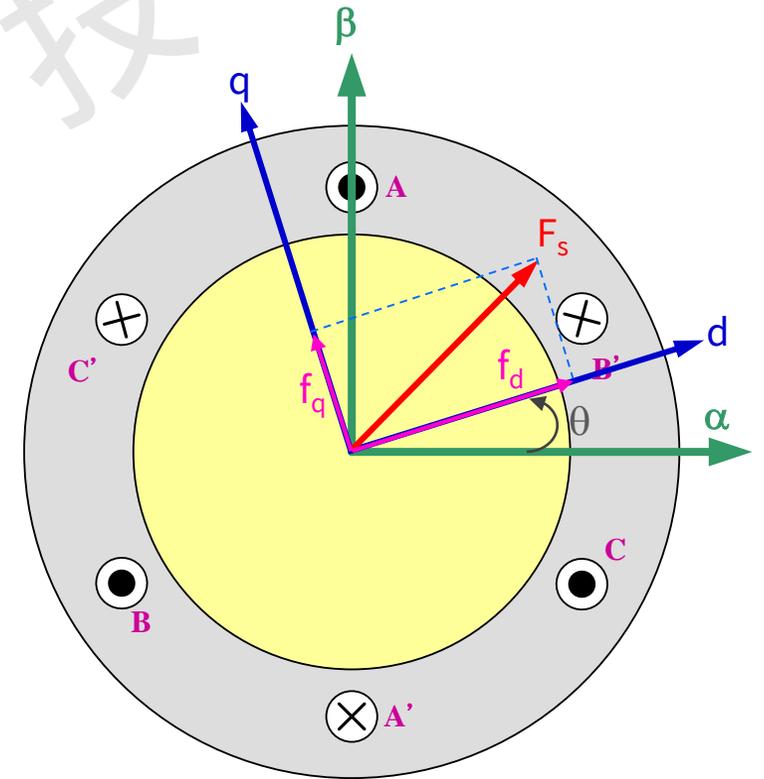
Clarke

Inv_Clarke



两相旋转坐标

- 两相d-q旋转坐标随着电机中旋转矢量(电压/电流)同步旋转
- 旋转矢量投影到两相旋转坐标的分量为定值
- 两相 α - β 静止坐标可用Park转换变换至两相d-q旋转坐标
- 两相d-q旋转坐标可用Inv-Park转换变换至两相 α - β 静止坐标
- 将静止坐标的弦波矢量变换为旋转坐标的直流矢量



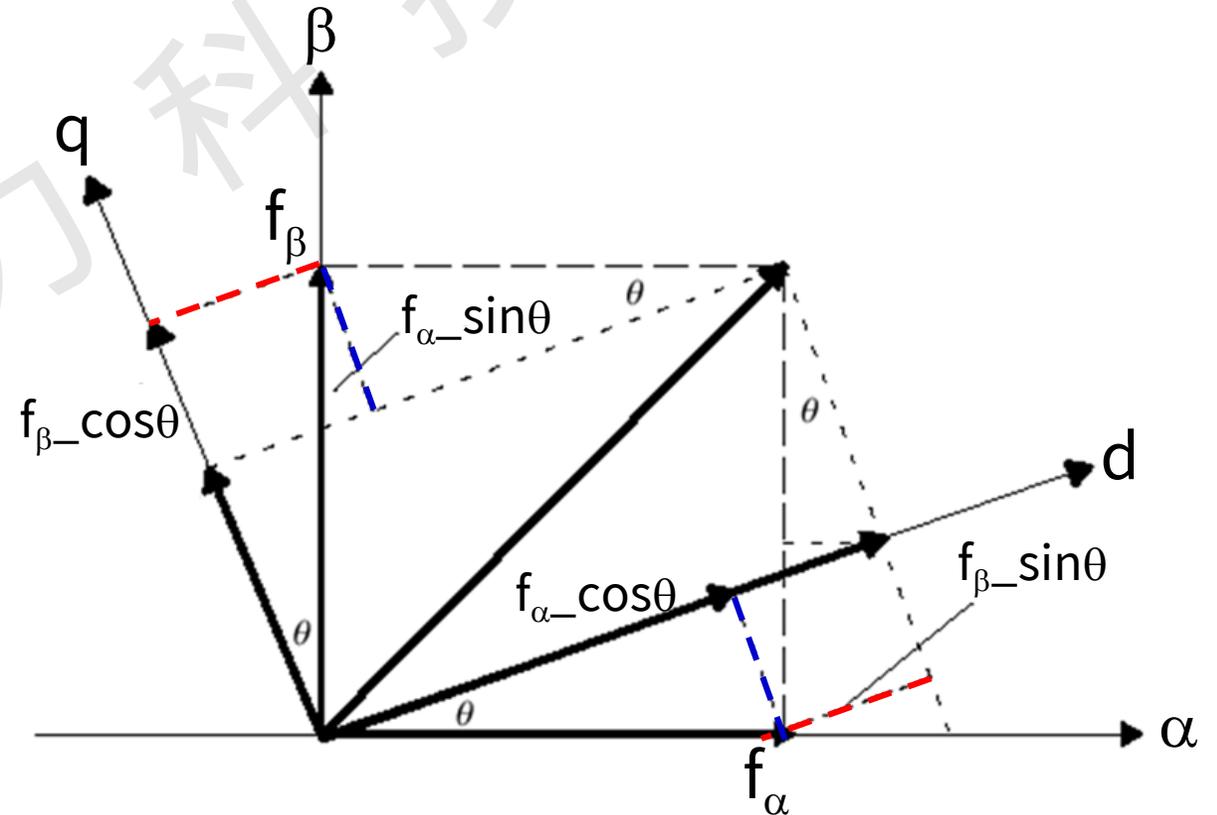
Park转换与Inv-Park转换

- Park 转换

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

- Inv-Park 转换

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$



交流永磁同步电机数学模型

- 三相静止坐标表示的数学模型

- 三相电气方程式

$$v_a = r_s i_a + d\lambda_a / dt$$

$$v_b = r_s i_b + d\lambda_b / dt$$

$$v_c = r_s i_c + d\lambda_c / dt$$

- 线圈自感方程式

$$L_{aa} = L_{ls} + L_A + L_B \cos 2\theta_r$$

$$L_{bb} = L_{ls} + L_A + L_B \cos(2\theta_r + 2\pi/3)$$

$$L_{cc} = L_{ls} + L_A + L_B \cos(2\theta_r - 2\pi/3)$$

- 磁通链方程式

$$\lambda_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \lambda_m \sin \theta$$

$$\lambda_b = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + \lambda_m \sin(\theta - \frac{2\pi}{3})$$

$$\lambda_c = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + \lambda_m \sin(\theta + \frac{2\pi}{3})$$

- 线圈互感方程式

$$L_{ab} = L_{ba} = -\frac{1}{2} L_A + L_B \cos(2\theta_r - 2\pi/3)$$

$$L_{bc} = L_{cb} = -\frac{1}{2} L_A + L_B \cos 2\theta_r$$

$$L_{ca} = L_{ac} = -\frac{1}{2} L_A + L_B \cos(2\theta_r + 2\pi/3)$$

交流永磁同步电机数学模型

- 两相旋转坐标表示的数学模型

- 三相电气方程式

$$v_d = r_s i_d + (L_{ls} + L_{md}) di_d / dt - \omega_e L_{mq} i_q$$

$$v_q = r_s i_q + (L_{ls} + L_{mq}) di_q / dt + \omega_e L_{md} i_d + \omega_e \lambda_m$$

- d-q轴耦合电感方程式

$$L_{md} = \frac{3}{2} (L_A - L_B)$$

$$L_{mq} = \frac{3}{2} (L_A + L_B)$$

- 电磁转矩方程式

$$T_e = \frac{3}{2} \frac{Pole}{2} (\lambda_m i_q + (L_d - L_q) i_d i_q)$$

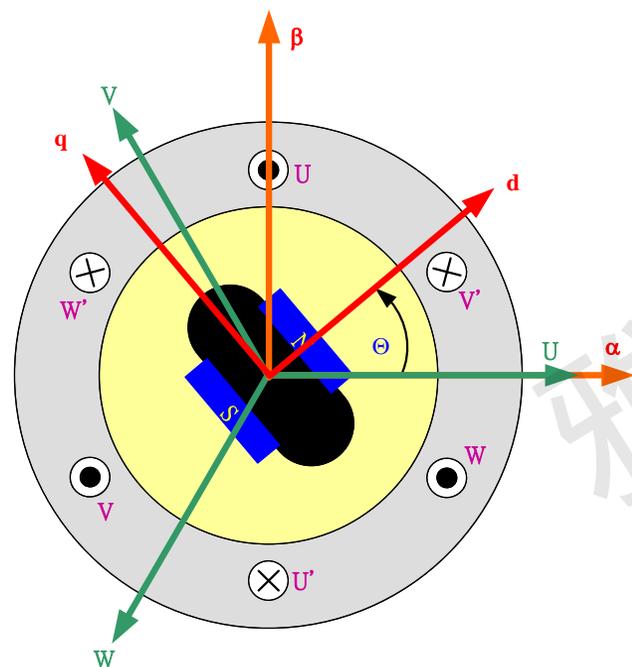
- 转轴动态方程式

$$d\omega_r / dt = (T_e - T_l - B\omega_r) / J$$

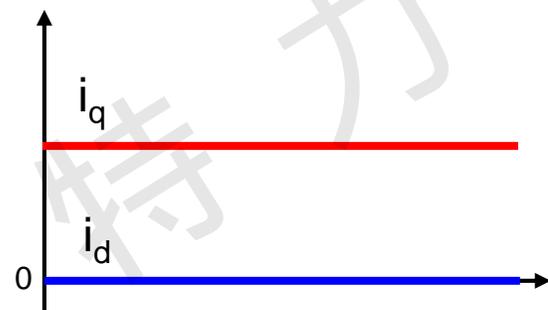
$$\omega_e = \frac{Pole}{2} \omega_r$$

矢量控制技术

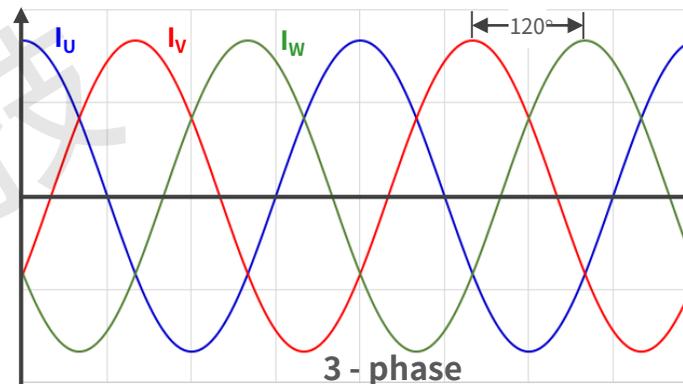
- 藉由坐标转换将交流讯号转换成直流讯号
- I_d : 磁场电流, I_q : 电枢电流
- 须感知两相电流与磁极位置信息



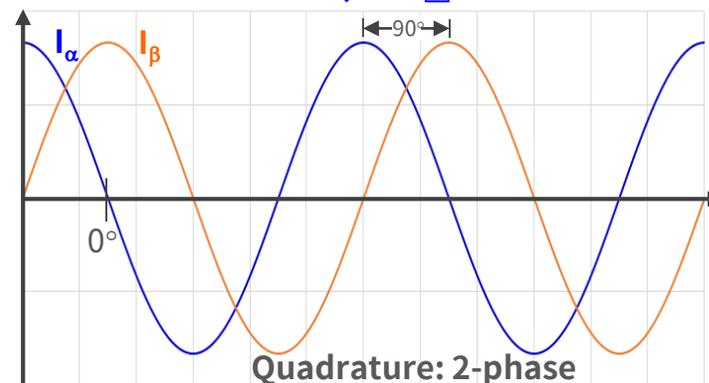
电机矢量坐标示意图



Inv_Park
Park



Clarke
Inv_Clarke



磁场导向控制(Field Oriented Control)技术

- 藉由两个PI控制器调整马达d-q轴电压，使马达电流追随电流命令
- 控制马达电流即可控制马达扭力

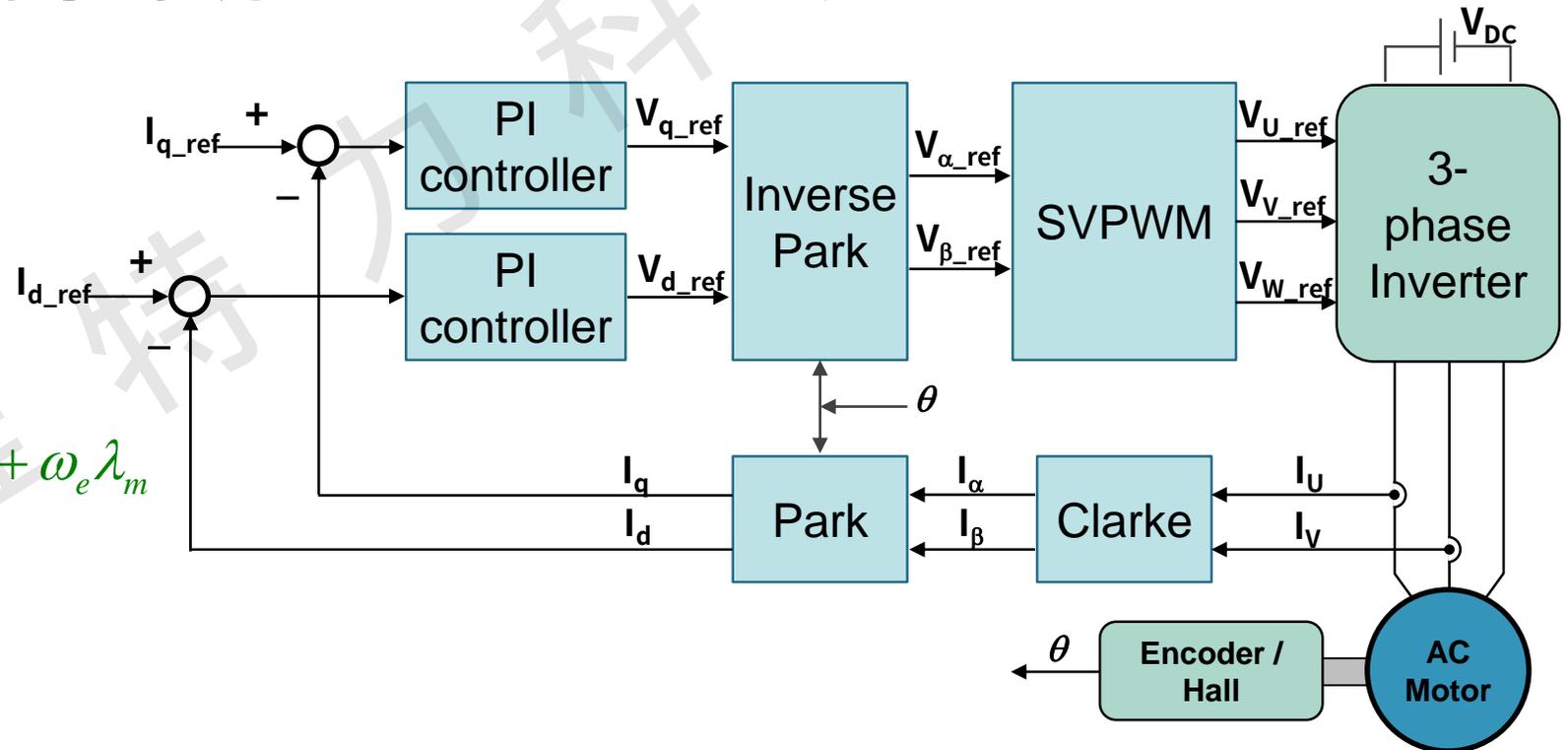
永磁电机电气方程式

$$v_d = r_s i_d + (L_{ls} + L_{md}) di_d / dt - \omega_e L_{mq} i_q$$

$$v_q = r_s i_q + (L_{ls} + L_{mq}) di_q / dt + \omega_e L_{md} i_d + \omega_e \lambda_m$$

转子转矩方程式

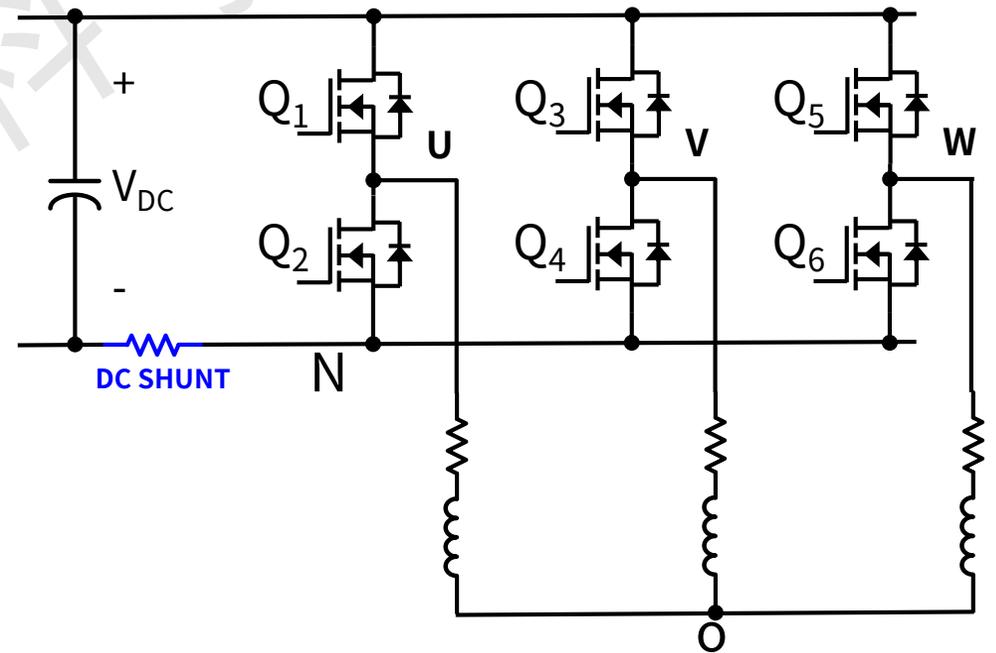
$$T_e = \frac{3}{2} \frac{Pole}{2} (\lambda_m i_q + (L_d - L_q) i_d i_q)$$



三相电压源全桥驱动电路

- 切换状态与电压矢量表

State Mode	Q ₁ (Q ₂)	Q ₃ (Q ₄)	Q ₅ (Q ₆)	Voltage Vector
Mode 0	0 (1)	0 (1)	0 (1)	V ₀
Mode U ⁺	1 (0)	0 (1)	0 (1)	V ₁
Mode W ⁻	1 (0)	1 (0)	0 (1)	V ₂
Mode V ⁺	0 (1)	1 (0)	0 (1)	V ₃
Mode U ⁻	0 (1)	1 (0)	1 (0)	V ₄
Mode W ⁺	0 (1)	0 (1)	1 (0)	V ₅
Mode V ⁻	1 (0)	0 (1)	1 (0)	V ₆
Mode 0	1 (0)	1 (0)	1 (0)	V ₀



三相电压源全桥瞬时电压

- 三相线电压

$$V_{AB} = V_{AN} - V_{BN} = V_{AO} - V_{BO}$$

$$V_{BC} = V_{BN} - V_{CN} = V_{BO} - V_{CO}$$

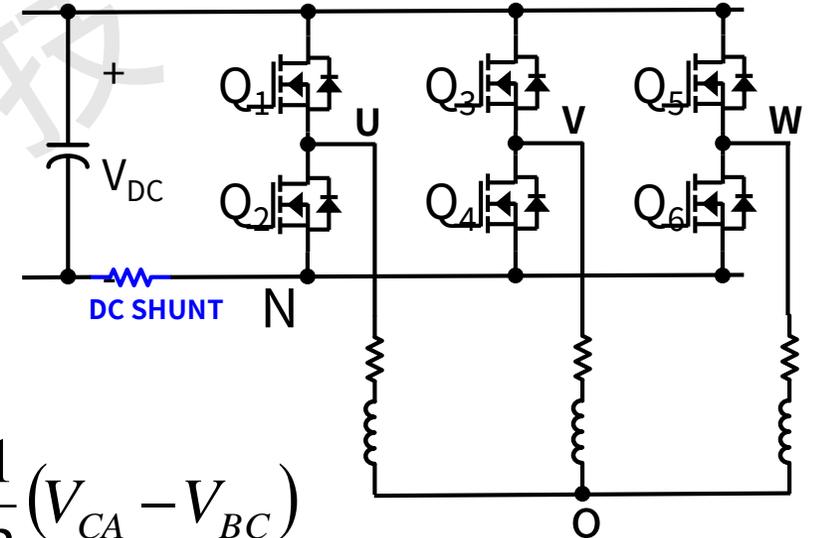
$$V_{CA} = V_{CN} - V_{AN} = V_{CO} - V_{AO}$$

- 因 $V_{AO} + V_{BO} + V_{CO} = 0$

- 可得 $V_{AO} = \frac{1}{3}(V_{AB} - V_{CA})$ $V_{BO} = \frac{1}{3}(V_{BC} - V_{AB})$ $V_{CO} = \frac{1}{3}(V_{CA} - V_{BC})$

- 故 $V_{AO} = \frac{1}{3}(2V_{AN} - V_{BN} - V_{CN})$ $V_{BO} = \frac{1}{3}(2V_{BN} - V_{AN} - V_{CN})$

$$V_{CO} = \frac{1}{3}(2V_{CN} - V_{AN} - V_{BN})$$

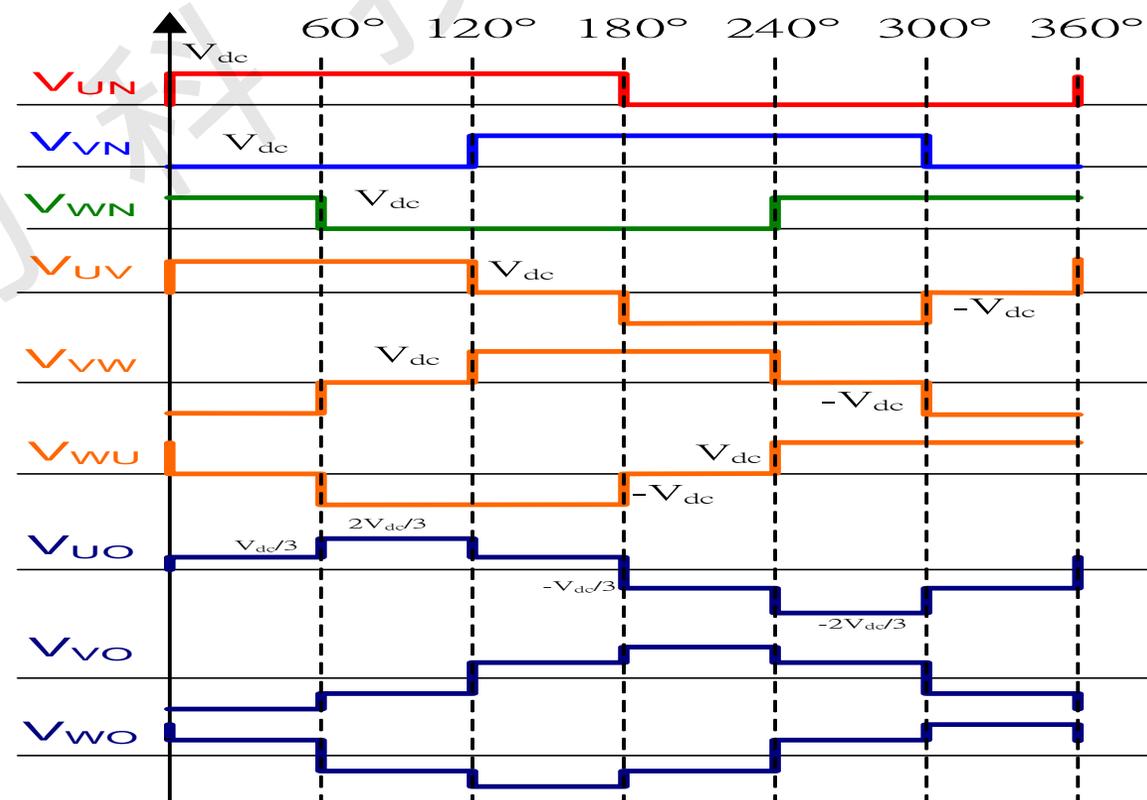


六步方波电压向量

相电压与线电压矢量表

W	V	U	V_{UO}	V_{VO}	V_{WO}	V_{UV}	V_{VW}	V_{WU}
0	0	0	0	0	0	0	0	0
0	0	1	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	V_{dc}	0	$-V_{dc}$
0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}$	V_{dc}	0
0	1	1	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	0	V_{dc}	$-V_{dc}$
1	0	0	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	0	$-V_{dc}$	V_{dc}
1	0	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	V_{dc}	$-V_{dc}$	0
1	1	0	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-V_{dc}$	0	V_{dc}
1	1	1	0	0	0	0	0	0

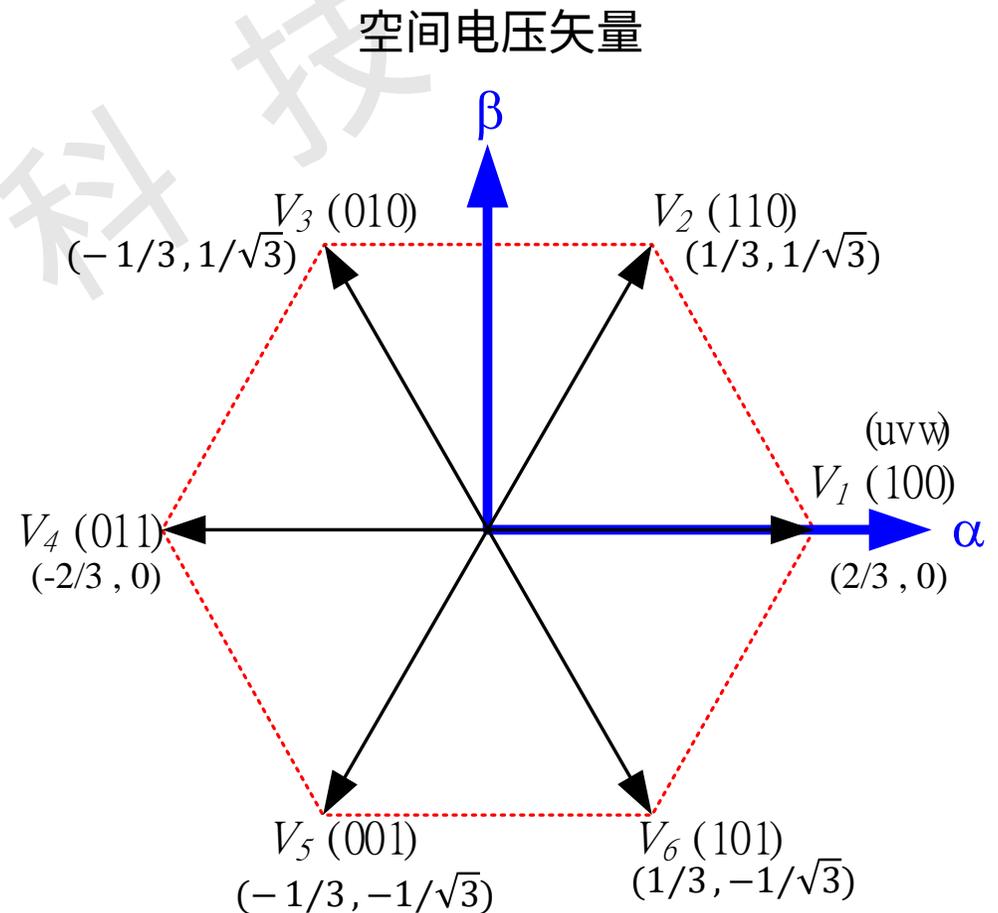
六步方波电压



两相坐标下电压矢量

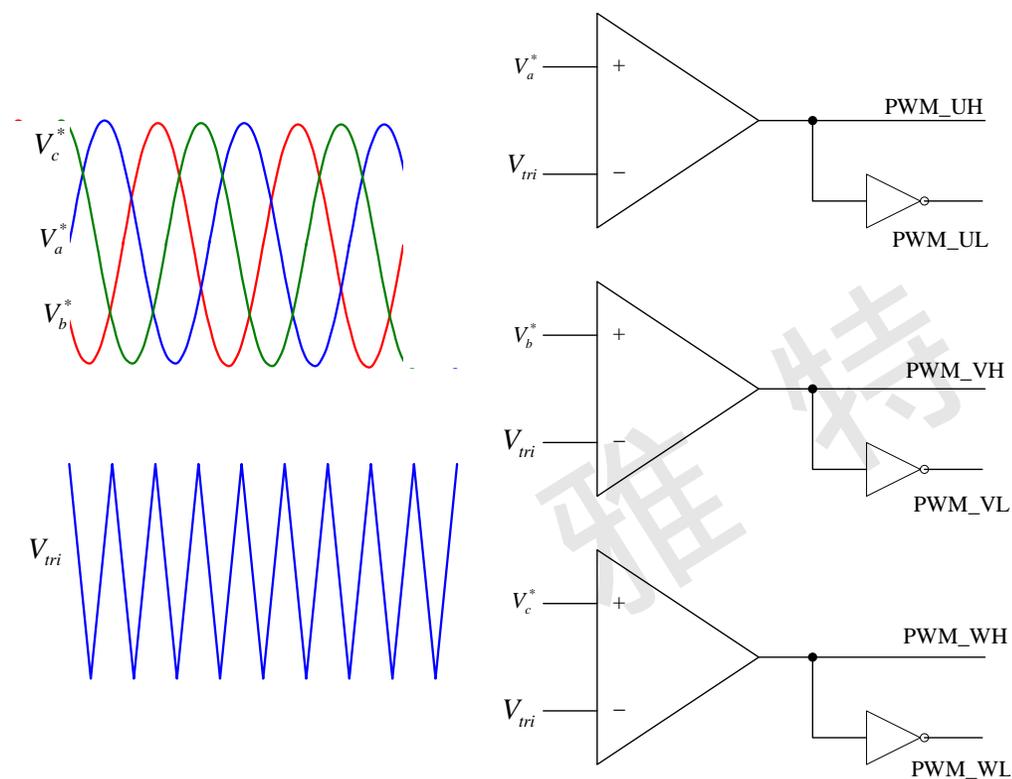
- 电压矢量表

U	V	W	V_α	V_β
0	0	0	0	0
1	0	0	$2V_{dc}/3$	0
0	1	0	$-V_{dc}/3$	$V_{dc}/\sqrt{3}$
1	1	0	$V_{dc}/3$	$V_{dc}/\sqrt{3}$
0	0	1	$-V_{dc}/3$	$-V_{dc}/\sqrt{3}$
1	0	1	$V_{dc}/3$	$-V_{dc}/\sqrt{3}$
0	1	1	$-2V_{dc}/3$	0
1	1	1	0	0

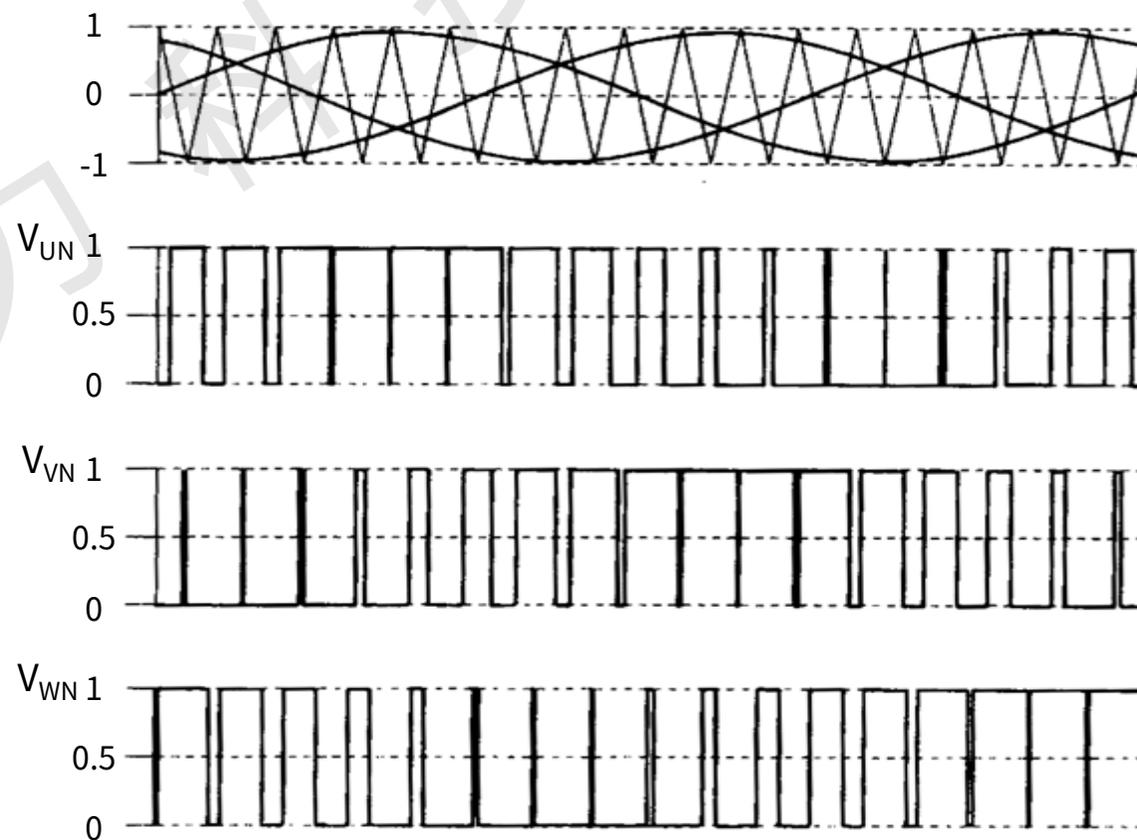


正弦脉波宽度调变(SPWM)

- 将三相弦波与调变三角波比较



三相SPWM输出电压



SPWM输出电压限制

- 调变指数 截波比例

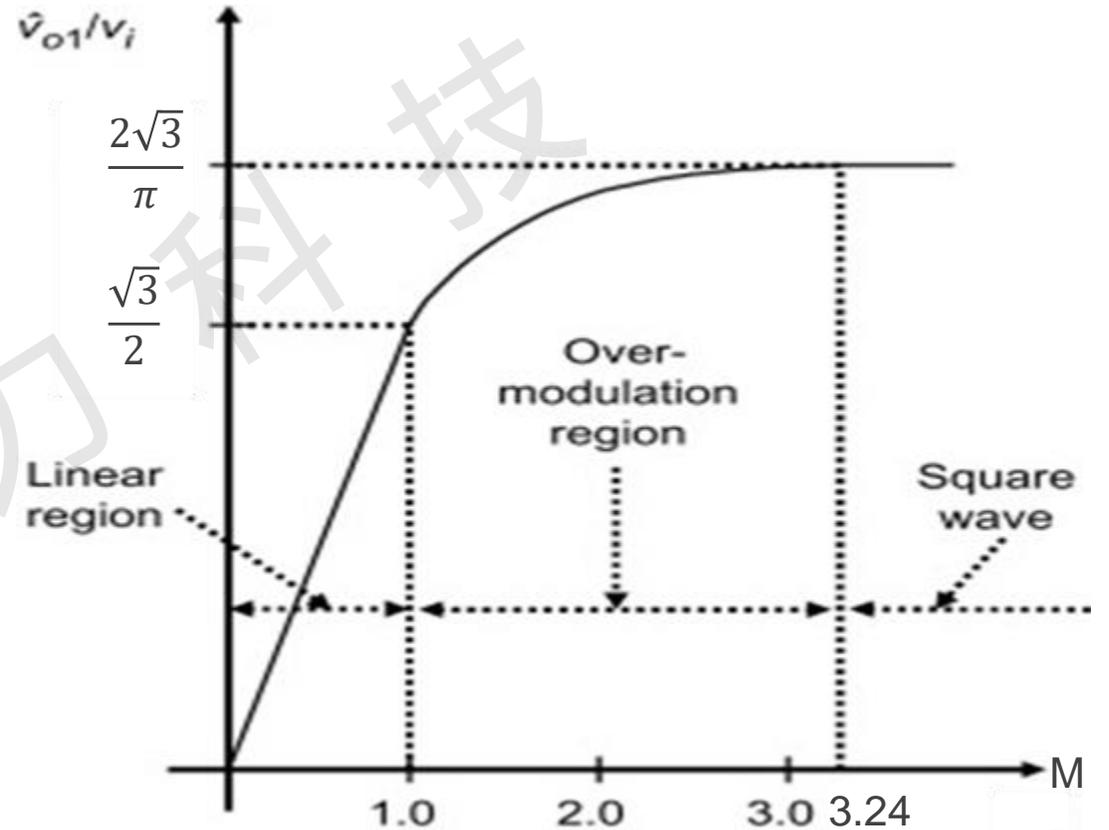
$$M = \frac{V_{\sin}}{V_{tri}} \quad R = \frac{f_{tri}}{f_{\sin}}$$

- 相电压基本波

$$V_{AN1} = M V_{DC} / 2$$

- 线电压基本波

$$\begin{aligned} V_{LL1} &= \sqrt{3} V_{AN1} \\ &= \sqrt{3} M \frac{V_{dc}}{2} \cong 0.866 M V_{dc} \end{aligned}$$



最大输出电压仅有母线电压的0.866倍

空间矢量脉波宽度调变(SVPWM)

- 通过选择相邻的两个有效矢量和零矢量，经一定时间比例组合，合成目标电压矢量
- 合成的目标电压矢量可以平滑地旋转，从而生成接近正弦波的输出电压
- 电压正规化

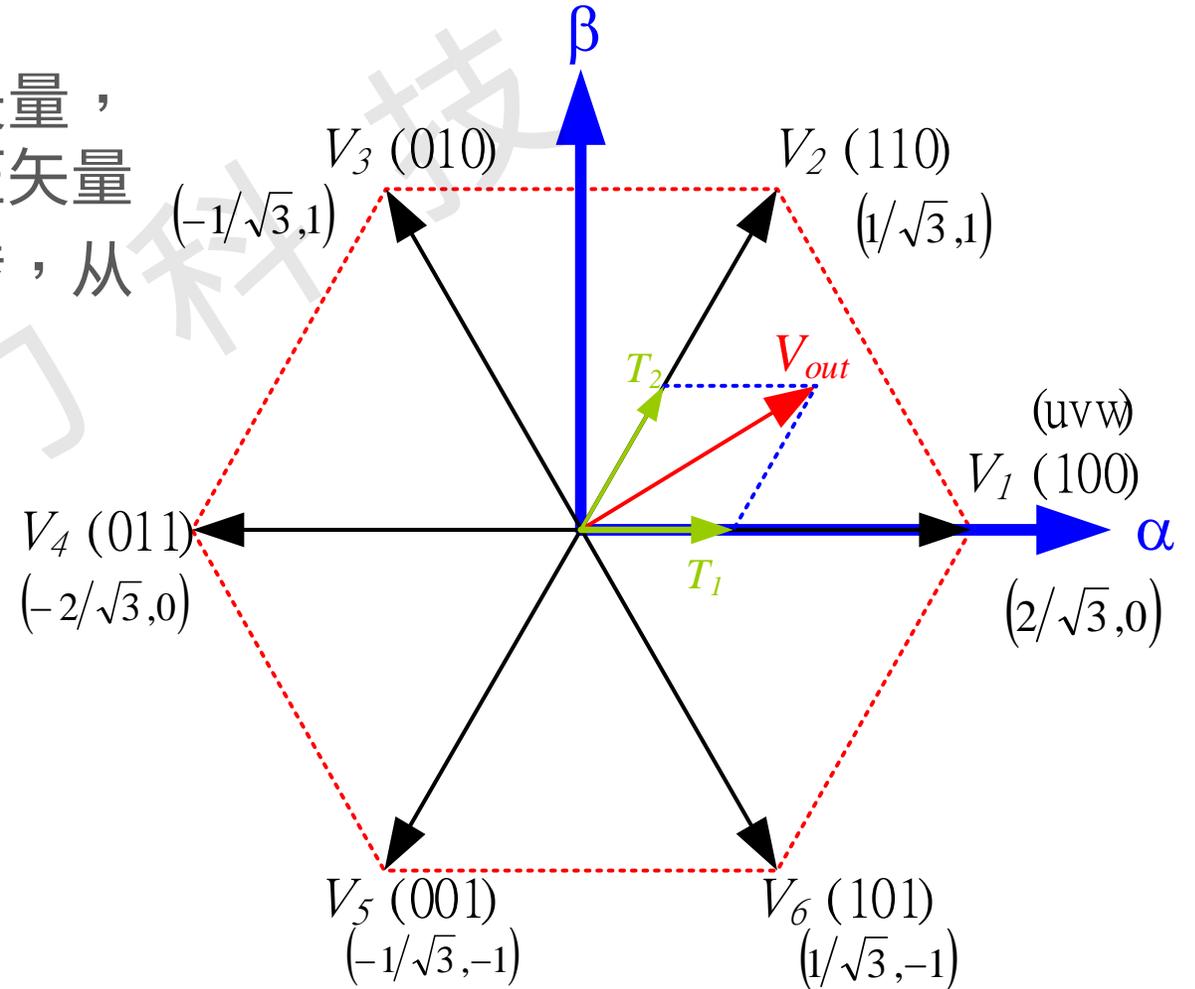
$$V_{LL(max)} = V_{DC}$$

$$V_{ph(max)} = V_{DC} / \sqrt{3}$$

$$V_{ph(norm)} = V_{ph} / V_{ph(max)}$$

$$= \left(\frac{2}{3} V_{DC} \right) / \left(\frac{1}{\sqrt{3}} V_{DC} \right)$$

$$= \frac{2}{\sqrt{3}}$$



SVPWM空间矢量合成

- 空间合成向量

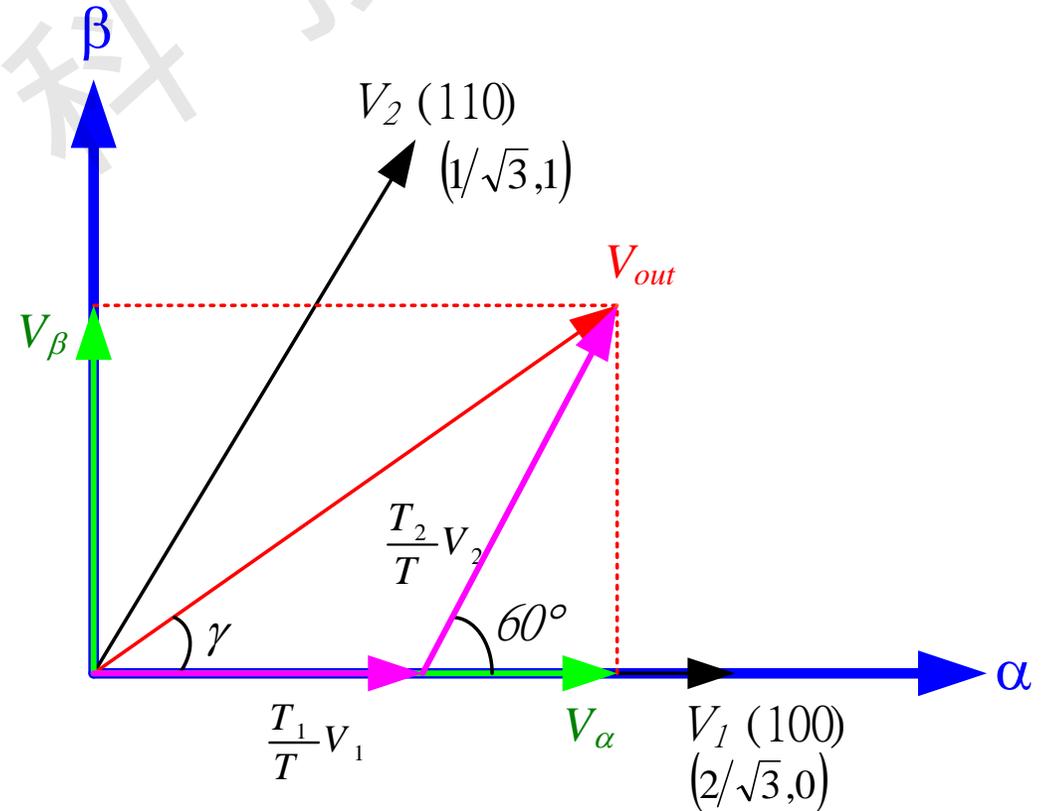
$$\begin{cases} T = T_1 + T_2 + T_0 \\ V_{out} = \frac{T_1}{T} V_1 + \frac{T_2}{T} V_2 + \frac{T_0}{T} V_{0(7)} \end{cases}$$

- 两轴垂直分量

$$\begin{cases} V_\beta = V_{out} \sin \gamma = \frac{T_2}{T} |V_2| \sin 60^\circ \\ V_\alpha = V_{out} \cos \gamma = \frac{T_1}{T} |V_1| + \frac{T_2}{T} |V_2| \cos 60^\circ \end{cases}$$

- 向量输出时间

$$\begin{cases} T_1 = \frac{T}{2} (\sqrt{3} V_\alpha - V_\beta) \\ T_2 = T V_\beta \\ T_0 = T - T_1 - T_2 \end{cases}$$



简易SVPWM计算

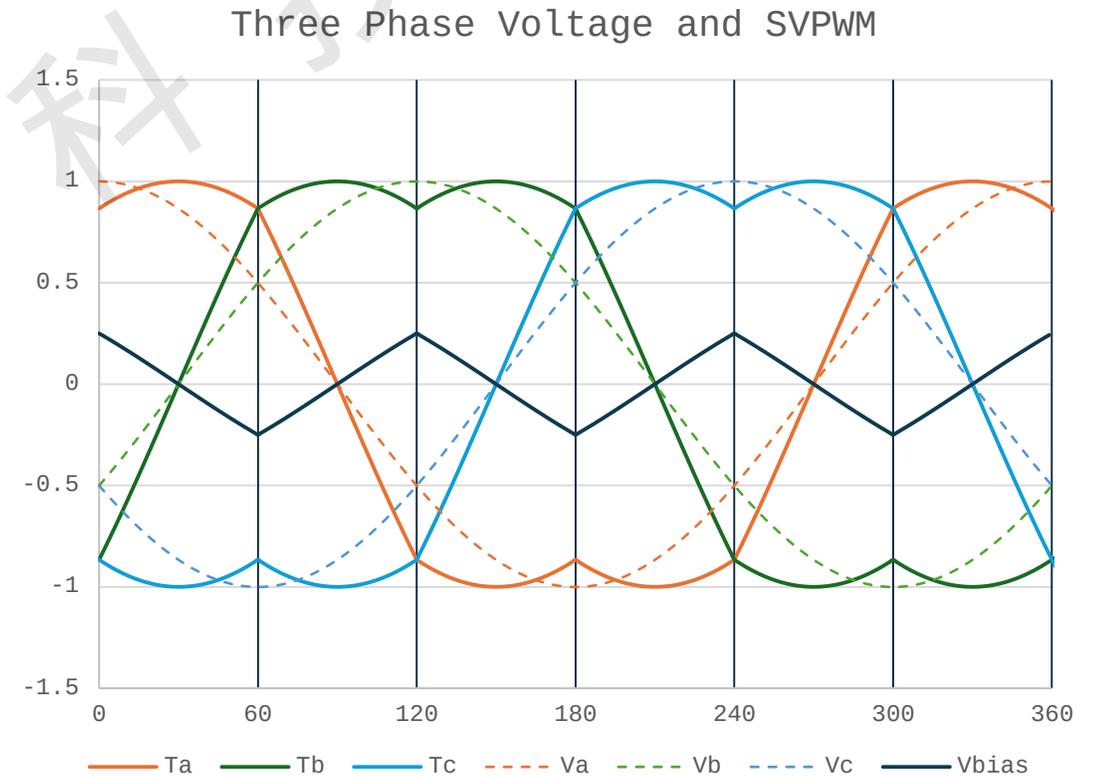
- 取每60°区间中最大电压与最小电压之平均，求得电压偏移点 V_{bias}
- 将各相电压扣除电压偏移点 V_{bias} 后除以 $\sqrt{3}$ 得出以0为基准点的半幅占空比
- 再加上1/2占空比即得各相输出占空比
- 以0°~60°区间为例

$$V_{bias} = (V_a + V_c) / 2$$

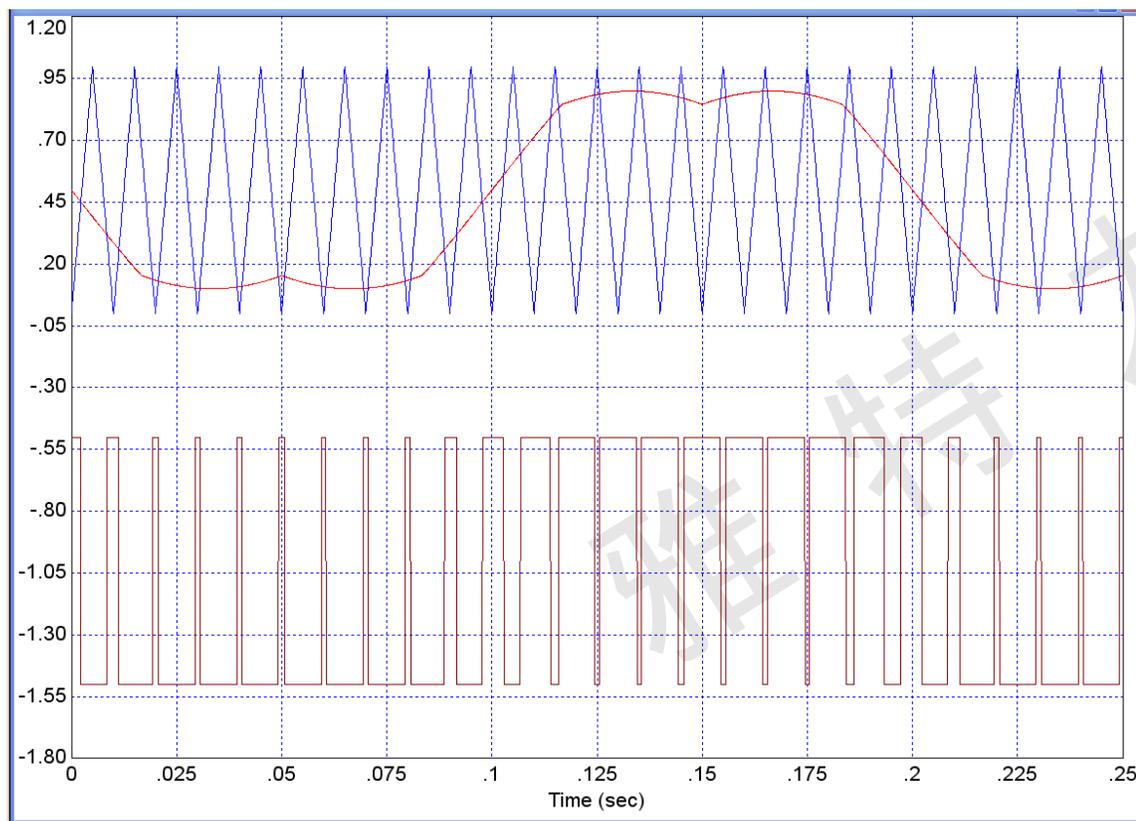
$$V_{a_duty} = (V_a - V_{bias}) / \sqrt{3} + full_duty / 2$$

$$V_{b_duty} = (V_b - V_{bias}) / \sqrt{3} + full_duty / 2$$

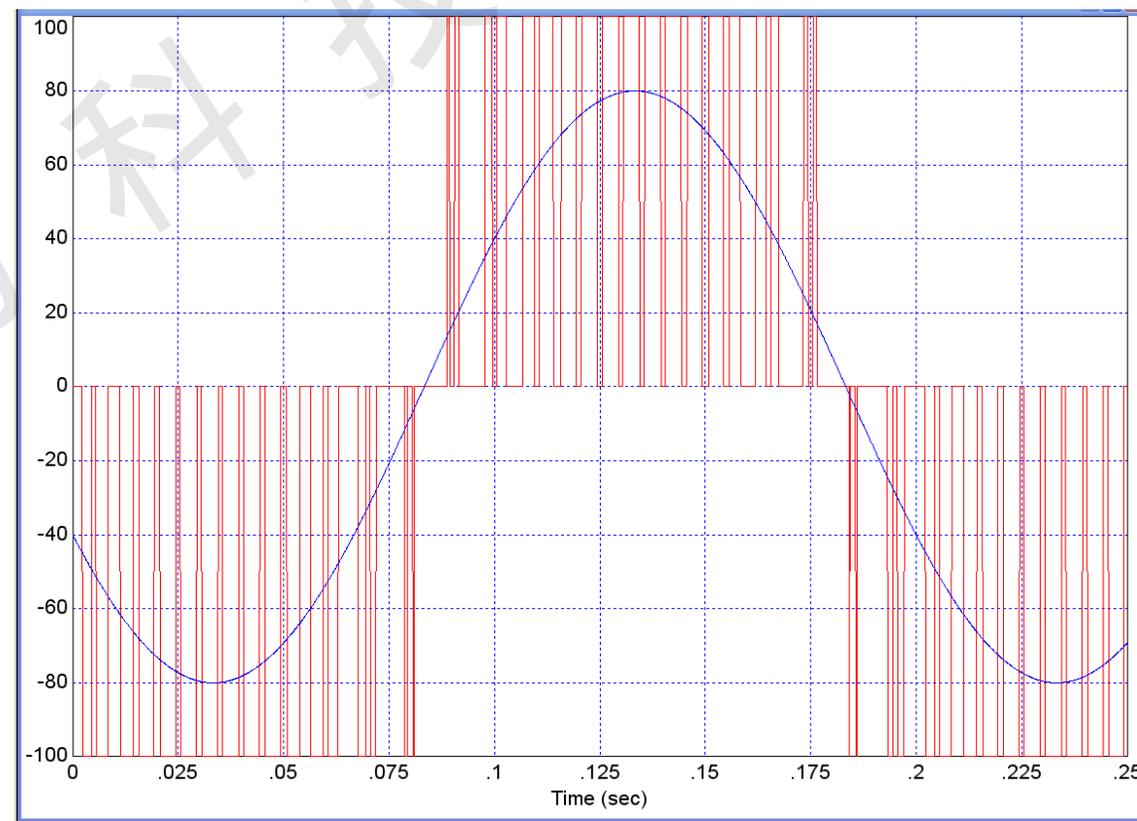
$$V_{c_duty} = (V_c - V_{bias}) / \sqrt{3} + full_duty / 2$$



SVPWM输出波形



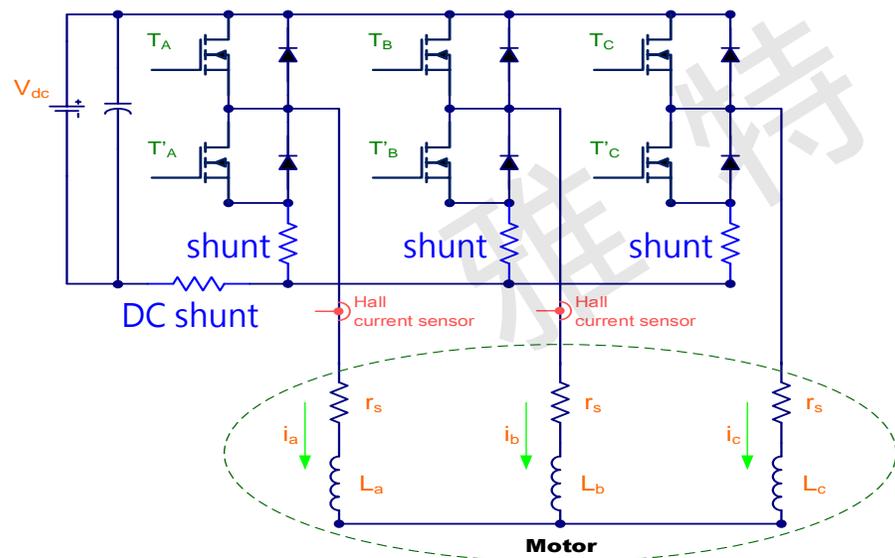
相电压PWM



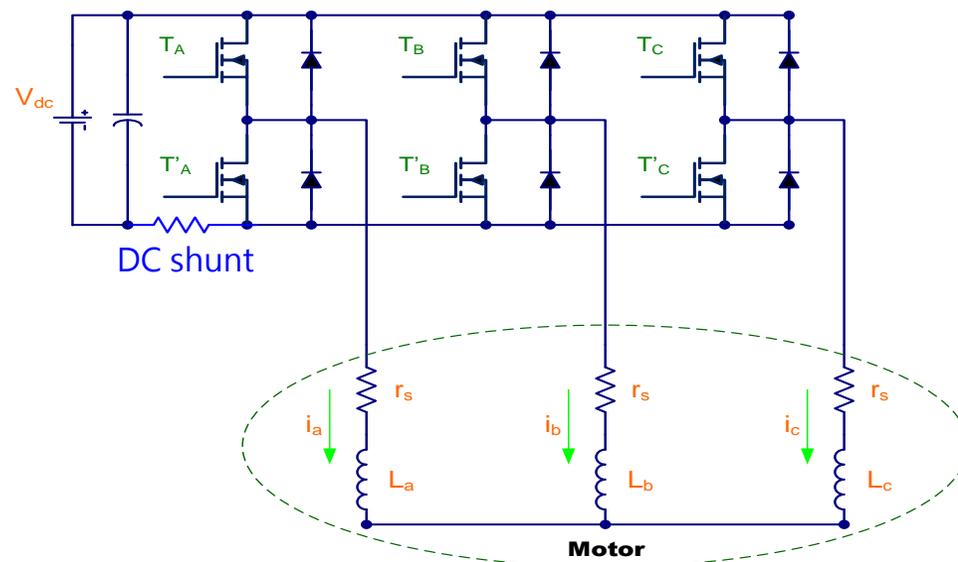
线电压PWM

驱动电路架构

- 一般FOC三相全桥电路
 - 使用3-shunt or 2-shunt 电流感测，或Hall 电流传感器，感测两相电流
 - DC shunt 侦测过电流
 - 大电流驱动器，shunt电阻功率消耗大

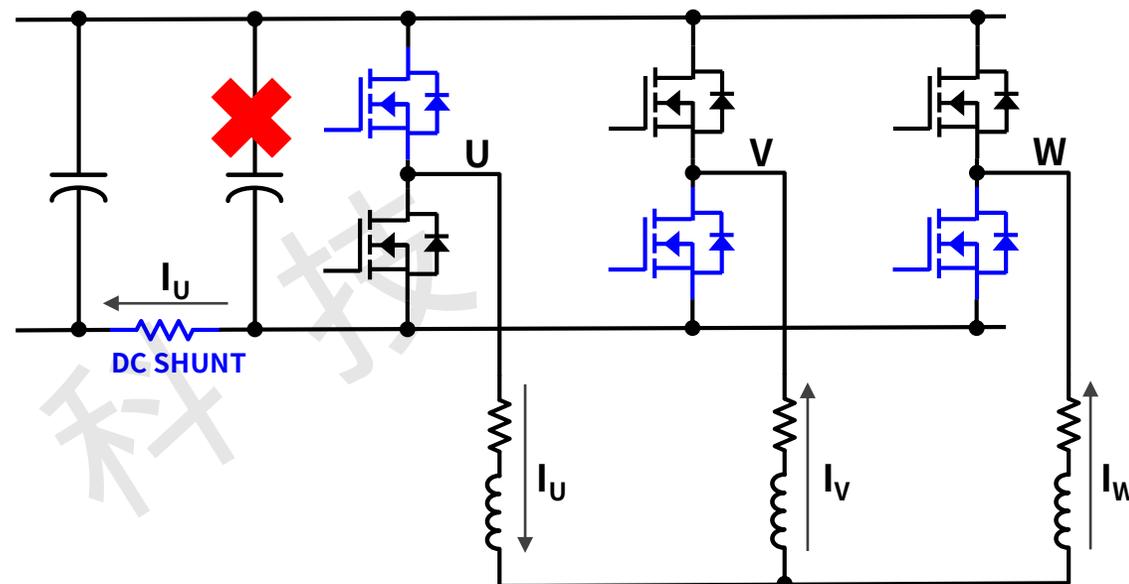
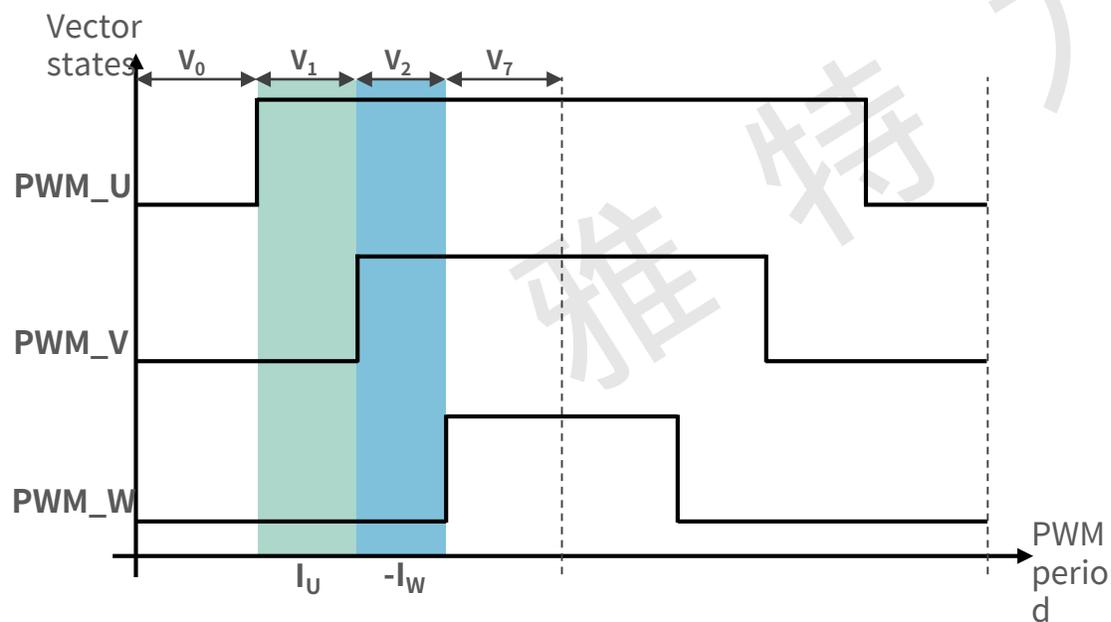


- 简化FOC三相全桥电路
 - 与BLDC驱动电路相同
 - 使用DC shunt 侦测两相电流与过流
 - 感测电流方式比较复杂



单电阻电流感测技术

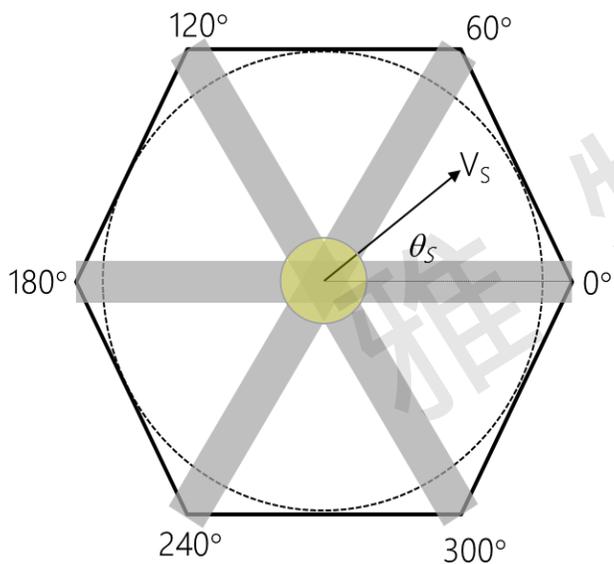
- 利用每个PWM周期中的两种不同开关切换状态，可分别侦测两相电流
- 但每个开关切换状态时间不可过小，否则来不及取样，必须将PWM适当位移



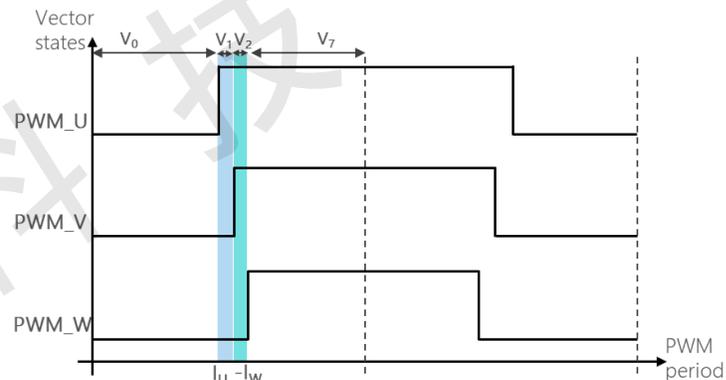
Voltage Vector	DC-Link Current
V ₀ (0 0 0)	0
V ₁ (1 0 0)	+I _u
V ₂ (1 1 0)	-I _w
V ₃ (0 1 0)	+I _v
V ₄ (0 1 1)	-I _u
V ₅ (0 0 1)	+I _w
V ₆ (1 0 1)	-I _v
V ₇ (1 1 1)	0

单电阻电流感测难以取样区域

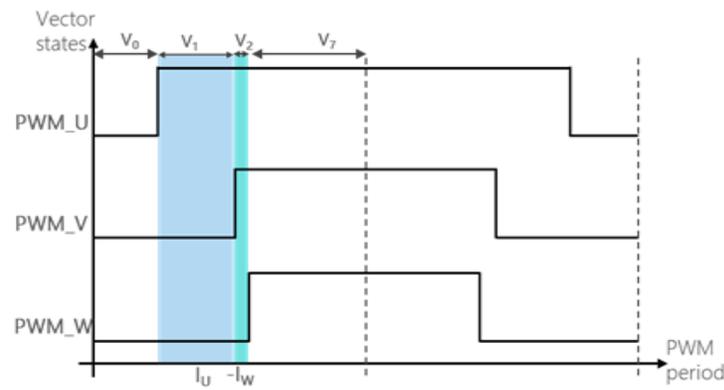
- 空间向量集中于单一电压向量区间时
- 低电压时有效电压向量的输出时间均太短
- 须进行脉波宽度调变位移



单电阻电流感测难以取样区域



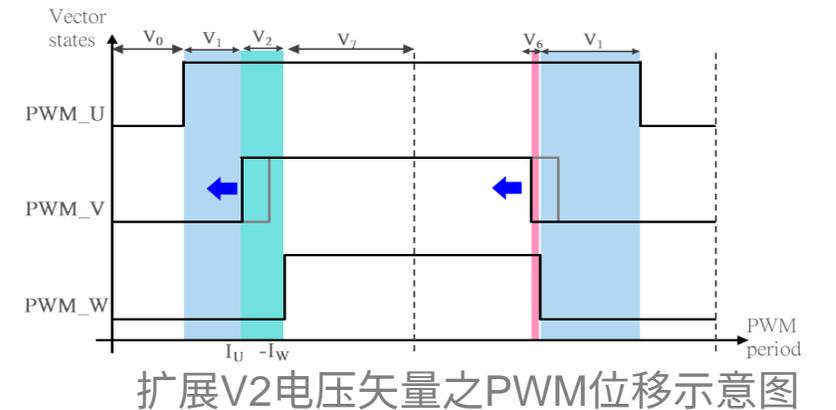
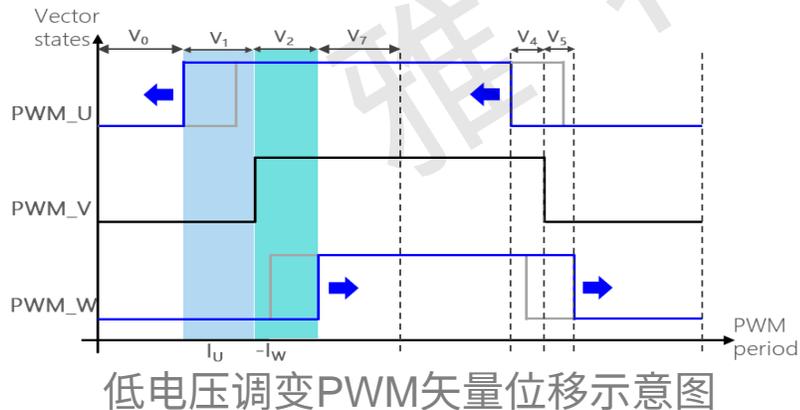
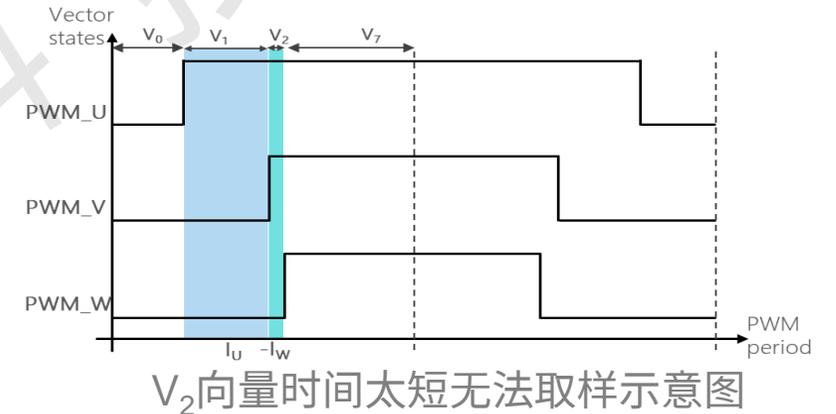
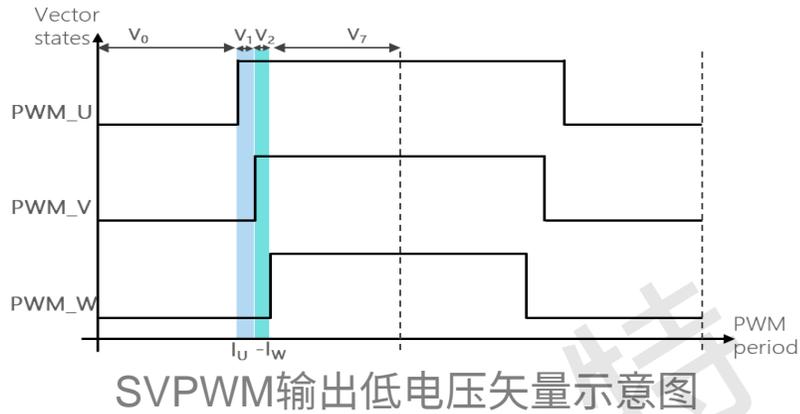
SVPWM输出低电压矢量示意图



V_2 向量时间太短无法取样示意图

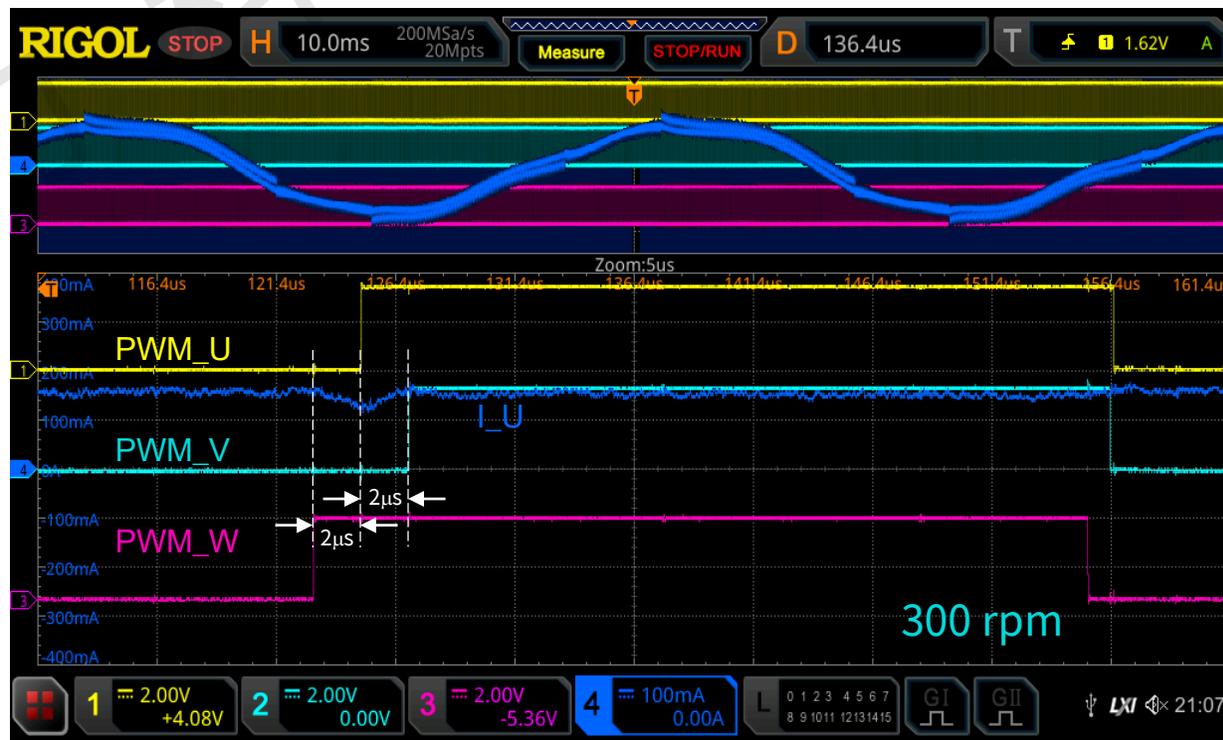
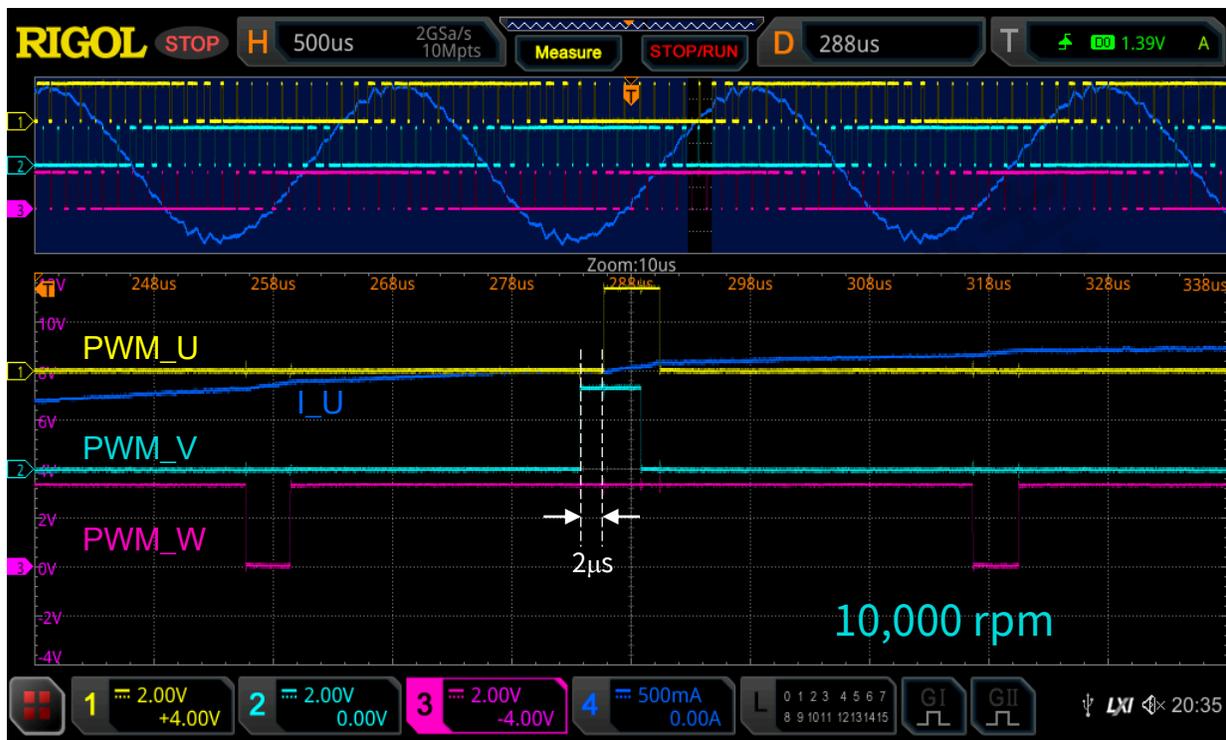
PWM电压位移电流取样

- 当某个电压矢量波宽太窄，小于电流取样时间时，须进行PWM脉宽位移



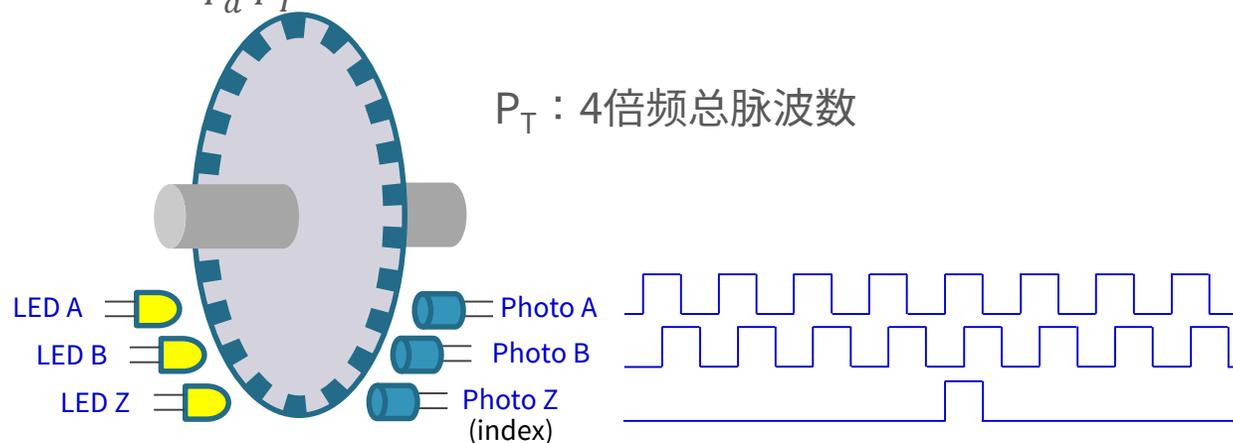
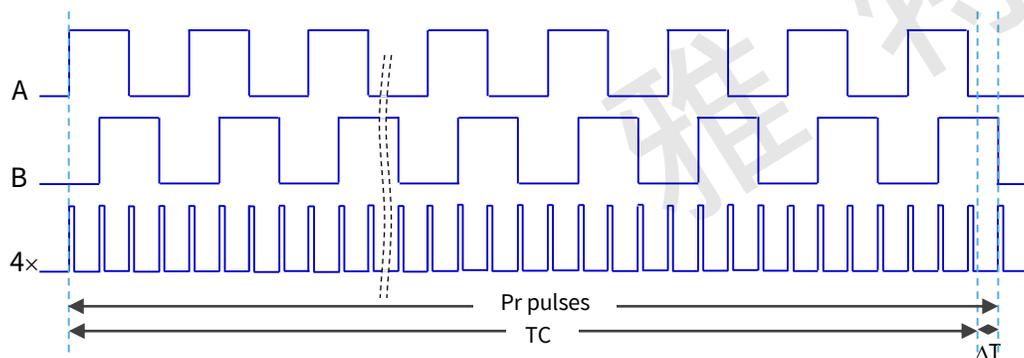
单电阻电流感测之电流响应

- 得利于快速ADC取样，小幅度偏移PWM相位即可采样电流
- 在高/低电压输出时，输出电流均平顺无转折，谐波成分小



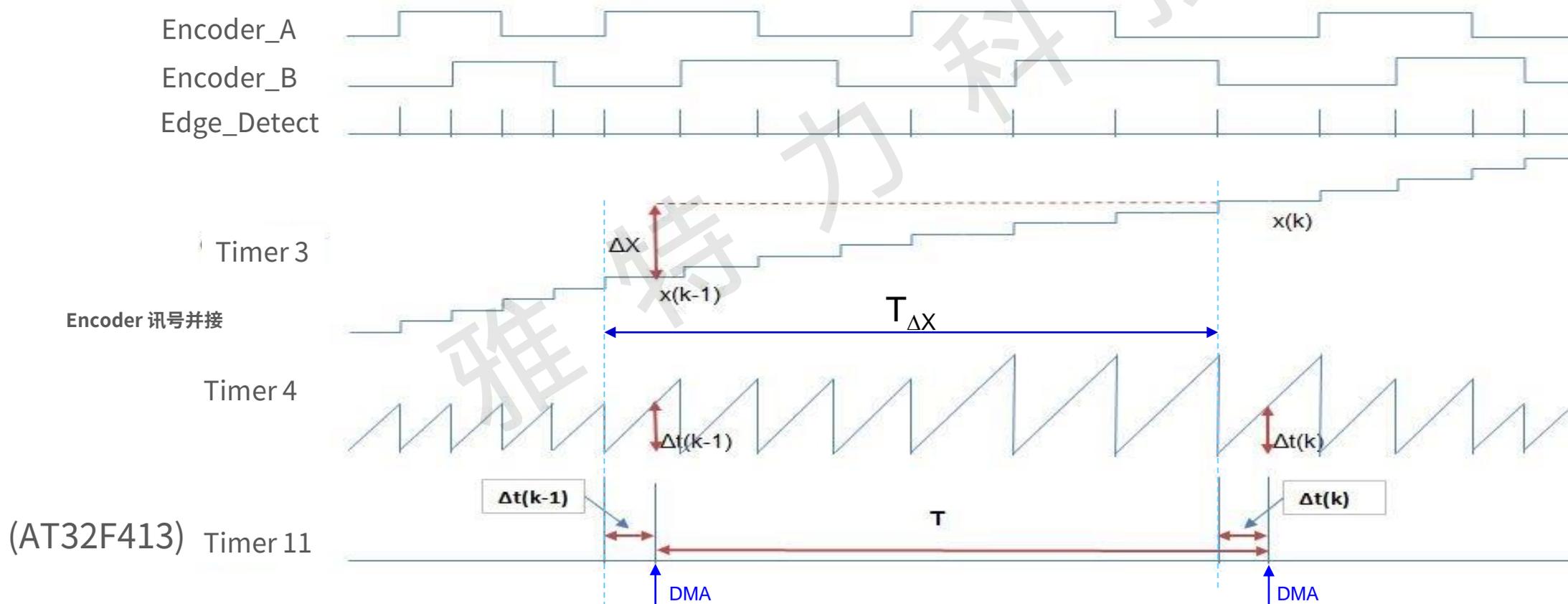
增量编码器感测转子角度与估测转速

- 增量编码器角度计算 $\theta_r = P_r / P_T \times 360^\circ$, P_T 为编码器一圈脉波数
- 增量编码器转速估测方法
 - M模式估测：在一个固定的取样时间 T_s 内计数编码器脉波数, $\text{speed} = \frac{60 \cdot P_r}{T_s \cdot P_T} \text{ rpm}$, 不适合低速
 - T模式估测：计算两个数编码器脉波之间的时间 T_r , $\text{speed} = \frac{60}{T_r \cdot P_T} \text{ rpm}$, 不适合高速
 - M/T模式估测：在一个固定计时间 T_c 内取得脉波计数值 (P_r), 再计算 T_c 期间与完整的脉波数时间差 ΔT , 根据 $T_d = T_c + \Delta T$ 与脉波数 P_r 计算速度, $\text{speed} = \frac{60 \cdot P_r}{T_d \cdot P_T} \text{ rpm}$, 需专用硬体或使用三个以上计时器



增量编码器M/T 模式转速估测

- 计算完整的 ΔX 脉波数时间 $T_{\Delta X} = T + \Delta t(k-1) - \Delta t(k)$



PMSM有感电机库 架构解说



电机库 - 有感 FOC

■ 转子位置检测方式

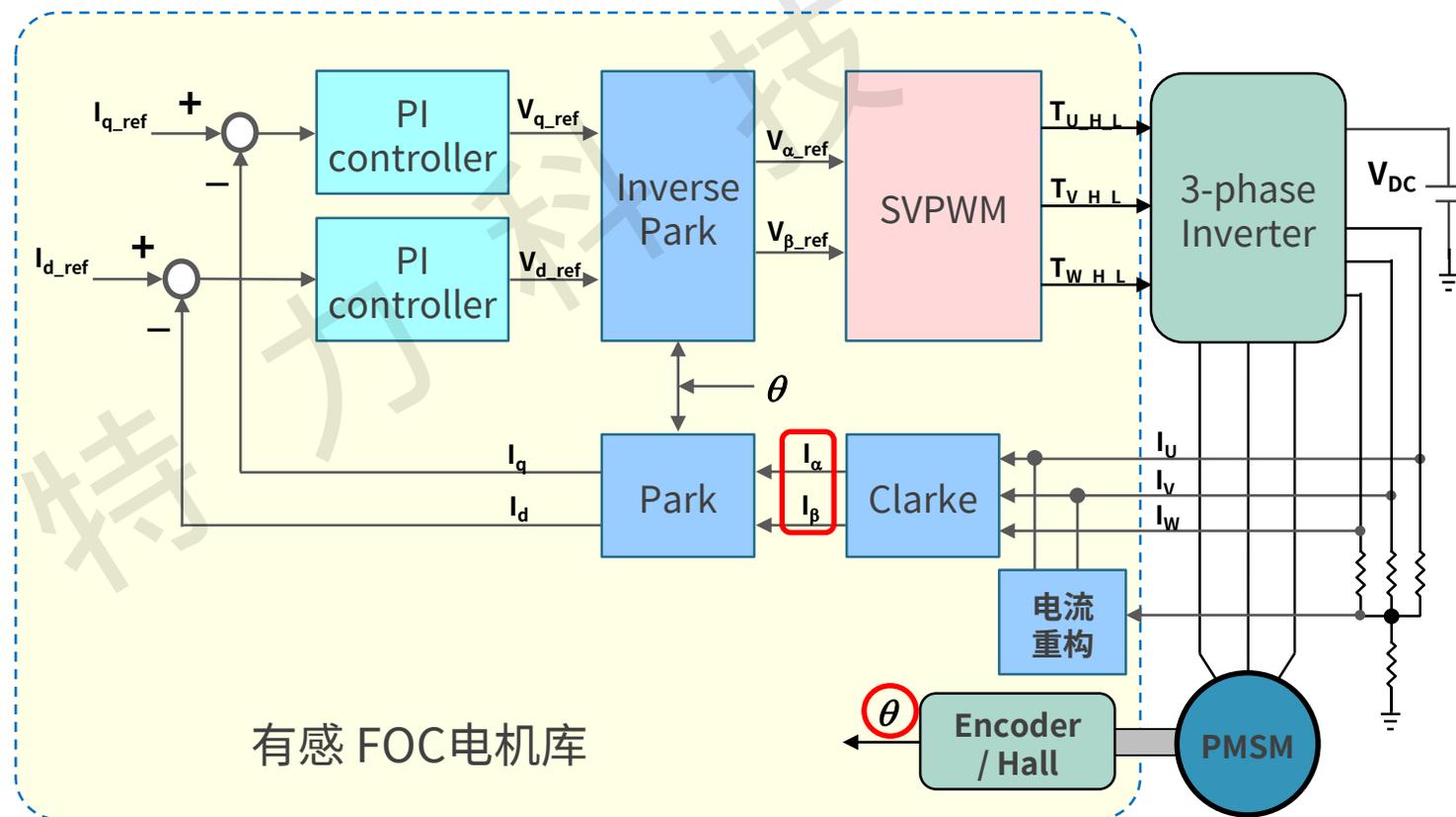
- 霍尔效应位置传感器
- 增量型编码器
- 绝对位置磁编码器

■ 相电流检测方法

- 三电阻电流检测
- 双电阻电流检测
- 单电阻电流检测与电流重构

■ 可实现有传感器弦波控制方法

- 电压矢量控制
- 转矩控制 (电流矢量控制)
- 转速控制
- 弱磁控制
- 定位控制
- 回生刹车



PMSM电机库控制技术与应用方案

应用产品		高速风机	低速风机	压缩机	电动工具	滑板车 电动自行车	电摩	定位云台	轮式机器人
矢量技术	磁场导向控制 FOC	●	●	●	●	●	●	●	●
	弱磁控制			●	●	●	●	●	●
控制回路	转矩/速度控制	●	●	●	●	●	●	●	●
	定位控制							●	●
电流感测	3 or 2电阻电流感测	●	●	●	●	●	●	●	●
	单电阻电流感测	●	●	●	●	●		●	●
有传感器	霍尔传感器	●	●		●	●	●		●
	增量编码器				●		●		●
	磁编码器							●	●
无传感器	转子初始角度侦测	●	●	●	●				
	反电势角度估测	●	●	●	●	●	●		

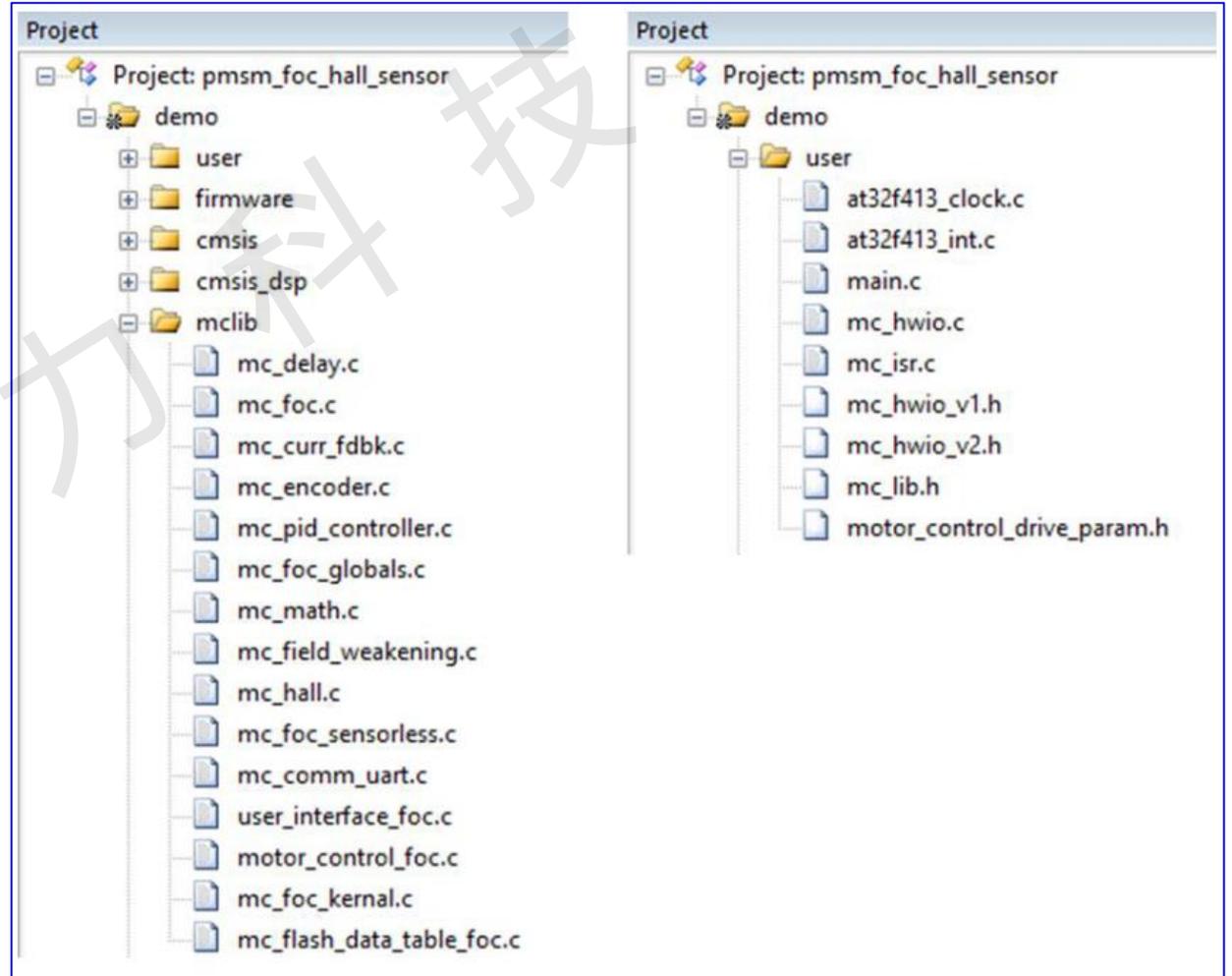
PMSM有感工程专案文件说明

PMSM FOC/BLDC 共通文档	
mc_lib.h	头文件统一管理
motor_control_drive_param.h	用户定义电机驱动架构模式、电机参数、控制参数、驱动器参数
mc_hwio.c	硬件外设配置
mc_hwio_v1.h	硬件IO接口宏定义配置(电机开发版AT-MOTOR-EVB V1.x)
mc_hwio_v2.h	硬件IO接口宏定义配置(电机开发版AT-MOTOR-EVB V2.x)
mc_isr.c	相关电机控制中断函数
mc_type.h	全局变量类型定义、枚举定义
mc_delay.c	时间延迟相关函数
mc_delay.h	时间延迟相关函数宣告
mc_comm_uart.c	通讯界面相关外设配置
mc_comm_uart.h	通讯uart相关函数宣告、配置
mc_pid_control.c	PID控制器相关函数
mc_pid_control.h	PID控制器相关函数宣告
mc_curr_fdbk.c	电流检测相关函数
mc_curr_fdbk.h	电流检测相关函数宣告
mc_math.c	滤波器相关函数
mc_math.h	滤波器相关函数宣告
mc_hall.c	霍尔传感器相关函数
mc_hall.h	霍尔传感器相关函数宣告

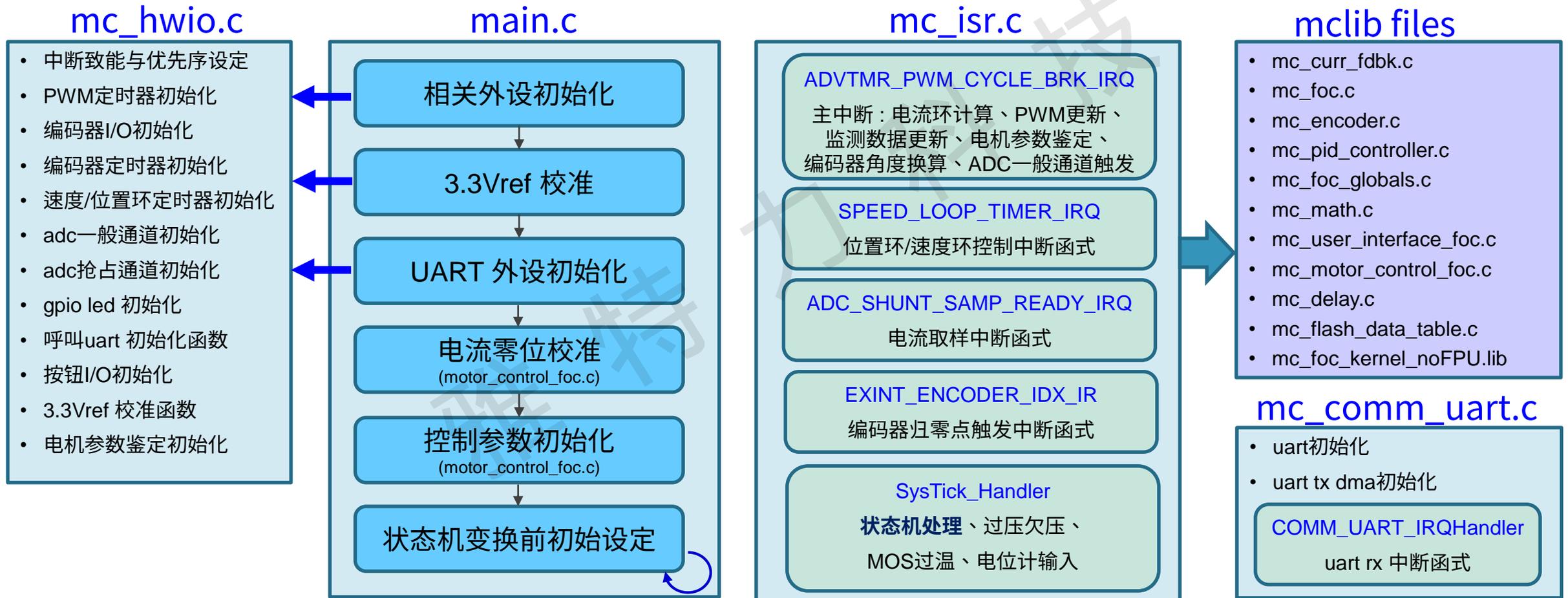
PMSM FOC专用文档	
mc_foc_kernal.lib	电机库核心函数(Keil专用)(适用于芯片有FPU)
mc_foc_kernal_noFPU.lib	电机库核心函数(Keil专用)(适用于芯片无FPU)
libmc_foc_kernal.a	电机库核心函数(AT32IDE专用)(适用于芯片有FPU)
libmc_foc_kernal_noFPU.a	电机库核心函数(AT32IDE专用)(适用于芯片无FPU)
mc_foc_kernal.h	电机库核心函数宣告
motor_control_foc.c	电机控制相关函数
motor_control_foc.h	电机控制相关函数宣告
mc_foc.c	FOC相关函数
mc_foc.h	FOC控制相关函数宣告
mc_encoder.c	编码器相关函数
mc_encoder.h	编码器相关函数宣告
mc_foc_sensorless.c	无传感器相关函数
mc_foc_sensorless.h	无传感器相关函数宣告
mc_foc_globals.c	全局变量定义与默认值设定、全局函数定义
mc_foc_globals.h	全局变量、全局函数宣告、宏定义
user_interface_foc.c	通讯界面相关函数
user_interface_foc.h	通讯界面相关函数宣告
mc_flash_data_table_foc.c	写入flash参数表
mc_flash_data_table_foc.h	写入flash参数表的相关配置

PMSM感控制专案工程结构

- user 文件夹
 - 主程序、外设规划程序以及参数定义头文件
- firmware 文件夹
 - MCU 外设驱动程序
- cmsis 文件夹
 - CMSIS DSP 函数程序
- mclib 文件夹
 - 为电机库程序包含PI控制函数、有感电机库函数、全局变量设定与通讯函数等等

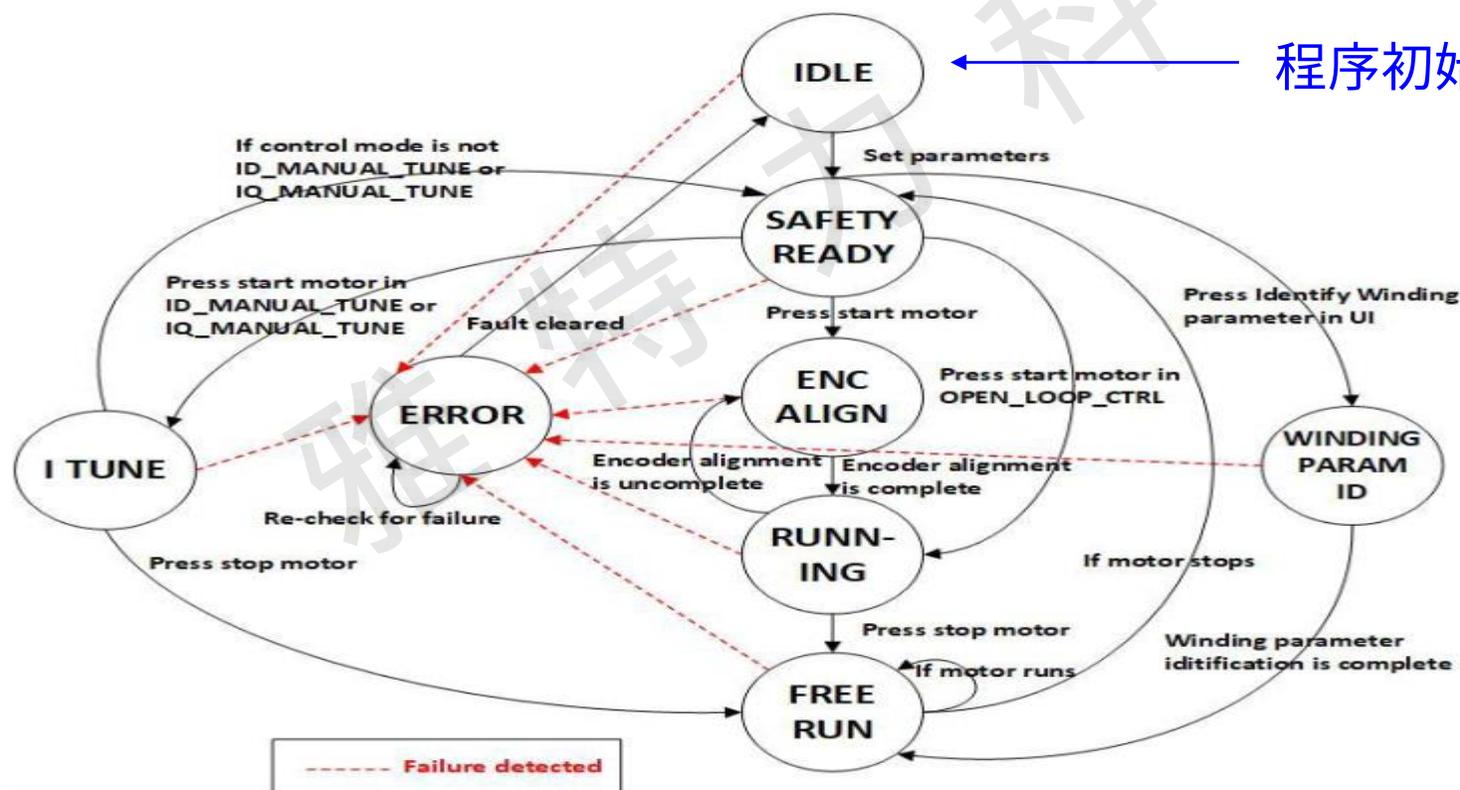


FOC有感控制程序流程图



程序状态机流程图

- 程序初始时须做编码器零位校准
- 主要工作于Running运转模式，用户可于UI界面实时调整参数或用外部电位计改变命令



电机库下载

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电机控制

USB应用

以太网应用

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USB应用

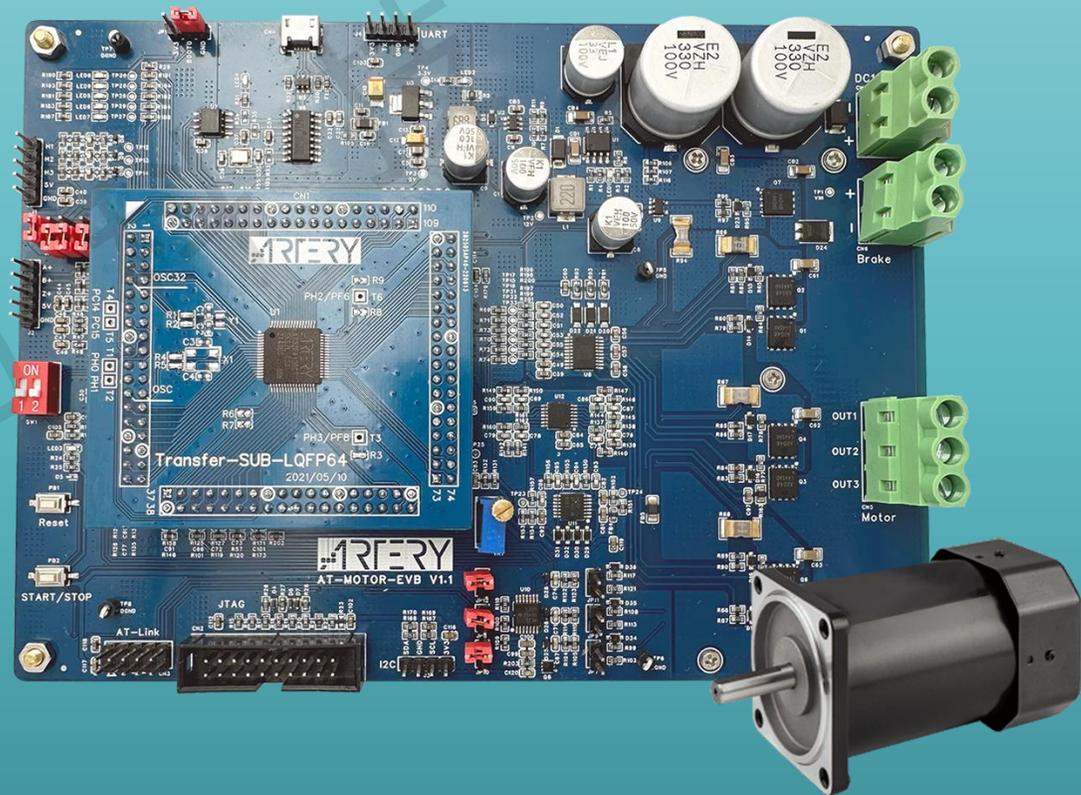
以太网应用

Quick Start Guide(快速入门指南)

简介	中文文档	英文(EN)文档	支持型号	版本	日期
AT32 BLDC Hall 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 BLDC电机库调适不同型号带霍尔传感器的电机运转。	AN0213	AN0213	AT32F413 AT32F421	V2.1.0	2024/05/17
AT32 BLDC Sensorless 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 BLDC电机库调适不同型号无传感器的电机运转。	AN0214	AN0214	AT32F421 AT32F413	V2.1.0	2024/05/17
AT32 PMSM FOC Incremental Encoder 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 PMSM FOC电机库调适不同型号带光电增量编码器的电机运转。	AN0217	/	AT32F403A AT32F413 AT32F415 AT32F421 AT32F423	V2.1.0	2024/05/24
AT32 PMSM FOC Hall 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 PMSM FOC电机库调适不同型号带霍尔传感器的电机运转。	AN0218	/	AT32F413 AT32F415 AT32F403A AT32F421 AT32F423	V2.1.0	2024/05/24
AT32 PMSM FOC Hall(E-Bike-Scooter) 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 PMSM FOC电机库调适不同型号带霍尔传感器的电机运转并应用在电动自行车、电瓶车、电动滑板车等应用。	AN0219	/	AT32F403A AT32F413 AT32F415 AT32F421 AT32F423	V2.1.0	2024/05/24
AT32 PMSM FOC Sensorless 快速入门指南 描述了如何快速使用AT-MOTOR-EVB电机开发板搭配AT32 PMSM FOC电机库调适不同型号无传感器的电机运转。	AN0220	/	AT32F403A AT32F413 AT32F415 AT32F421 AT32F423	V2.1.0	2024/05/24

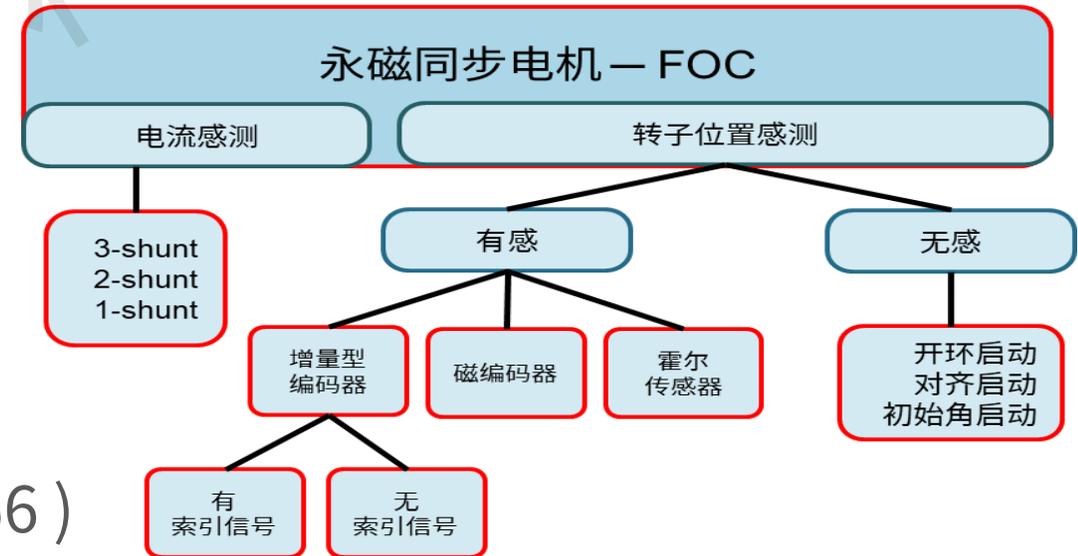
网址：https://www.arterytek.com/cn/support/motor_control.jsp?index=0

AT32 电机库 FOC 快速上手 操作讲解



PMSM FOC电机控制库支持

- 支援FOC控制
- 提供AT32F421、AT32F413、AT32F415、AT32F407、AT32F403A、AT32F423、AT32F435/437、AT32L021应用范例
- 支持免费AT32IDE编译环境
- 只须设定mc_hwio_v2(v1).h和motor_control_drive_param.h头文件
- 宏定变量的说明可参阅AT32电机库使用指南(AN0064)
- FOC增量编码器专案的说明可参阅(AN0166)
- PMSM FOC增量编码器快速入门指南(AN02174)



参数头文件 – 电机控制形式 (FOC)

motor_control_drive_param.h
控制型式

```
#define AT_MOTOR_EVB_V2
// #define AT_MOTOR_EVB_V1

/* gate driver low side inverting logic input or non-inverting
#define GATE_DRIVER_LOW_SIDE_INVERT

#define FOC_CONTROL

#define THREE_SHUNT
// #define TWO_SHUNT
// #define ONE_SHUNT

#ifdef TWO_SHUNT
#define U_V_SHUNT
// #define V_W_SHUNT
// #define U_W_SHUNT
#endif

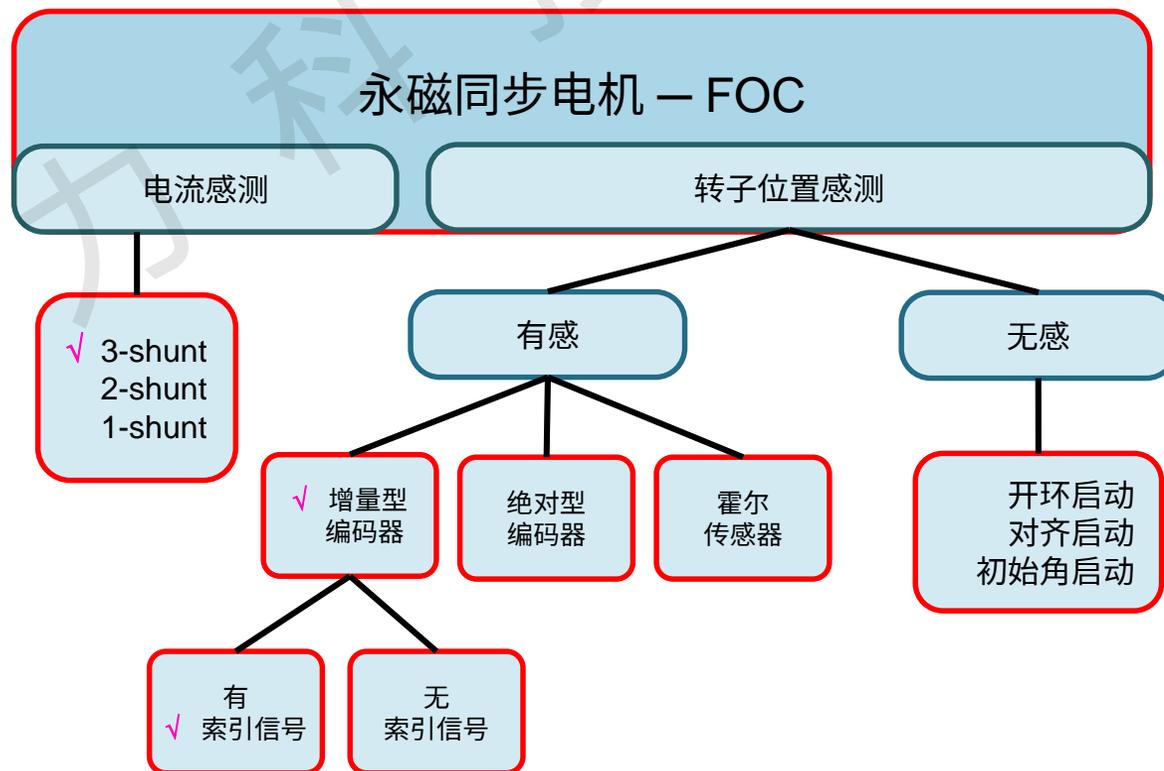
#define INCREM_ENCODER

#ifdef INCREM_ENCODER || defined MAGNET_ENCODER_W_ABZ
// #define REVERSE_ENCODER_COUNT
#endif

#ifdef INCREM_ENCODER
#define ABZ
// #define AB
#endif

#ifdef INCREM_ENCODER || defined MAGNET_ENCODER_W_ABZ
#define M_METHOD
#endif
```

- 选择宏定义宣告项目，完成电机控制形式设定



参数头文件 – 电机参数

motor_control_drive_param.h

电机参数 (Motor-related parameter)

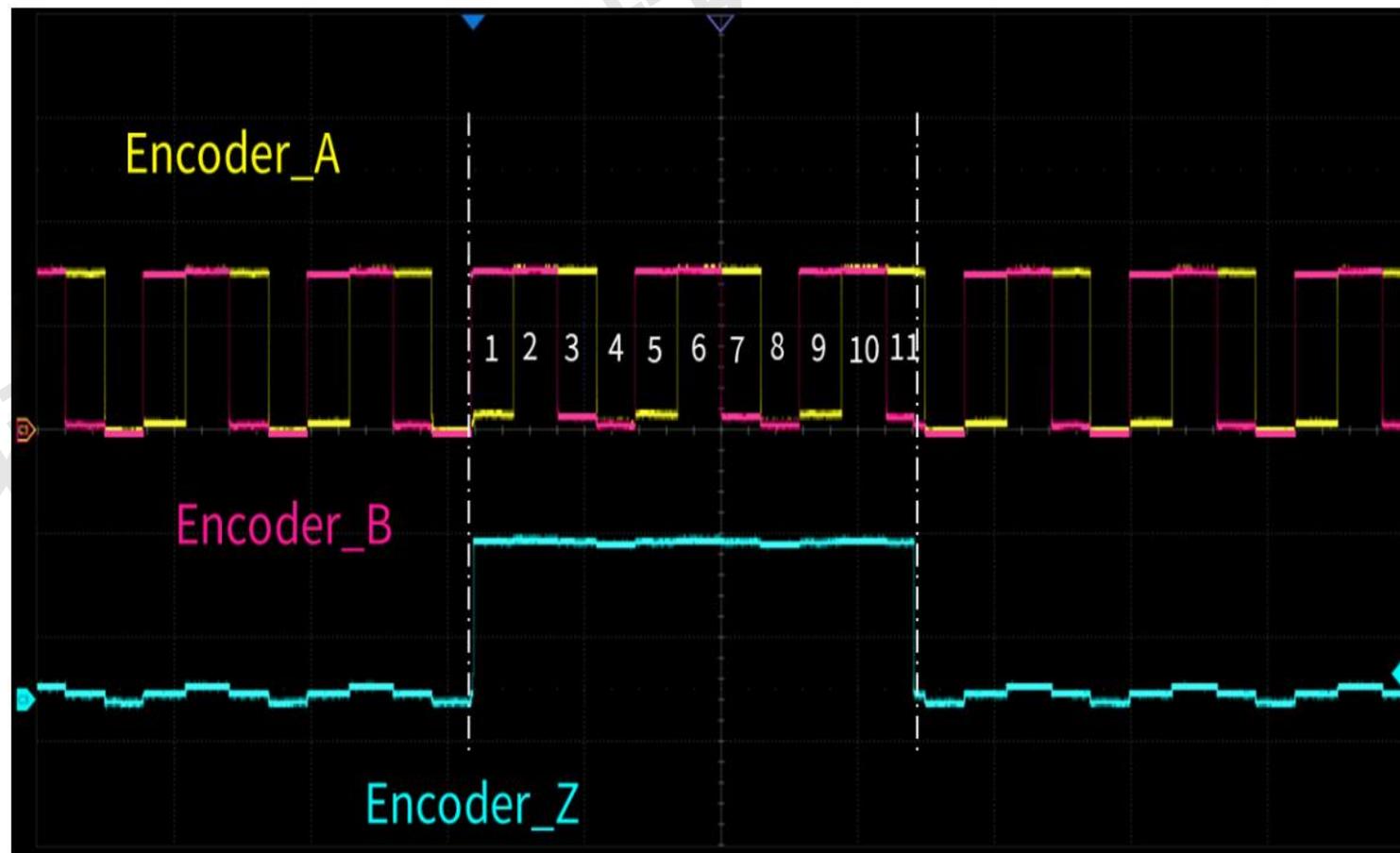
```
/****** Motor-related para
#define POLE_PAIRS          (8/2)
#define RS_LL               (1.89f)
#define LS_LL               (0.002387f)
#define LD_LQ_RATIO        (1.0f)
#define KE                  (0.003437f)
#define NOMINAL_CURRENT    (1.7f)

/**/ Quadrature encoder ***/
#define ENCODER_PPR         (1000)
#define ENC_IDX_COUNT      (11)
#define ENC_STALL_TIME     (1000)
```

- POLE_PAIRS : 电机极对数
- RS_LL : 绕组线对线电阻值
- LS_LL : 绕组线对线电感值
- NOMINAL_CURRENT : 额定电流
- ENC_IDX_COUNT : 编码器归零点脉宽
- ENC_STALL_TIME : 编码器无脉波判定故障延时时间

编码器零位信号宽度

- ENC_IDX_COUNT
编码器零位信号宽度
- Z 信号的上升沿到下降沿的宽度对齐于 AB 信号为 11 个 count 数
- 则定义 ENC_IDX_COUNT 为 11



参数头文件 - 控制环相关参数

motor_control_drive_param.h

控制参数 (Control-related parameter)

```
#define PWM_FREQ (16000) /* Hz */
#define MOTOR_CONTROL_MODE (OPEN_LOOP_CTRL)
#define CTRL_SOURCE (CTRL_SOURCE_SOFTWARE)
#define UI_UART_BAUDRATE (1500000UL)

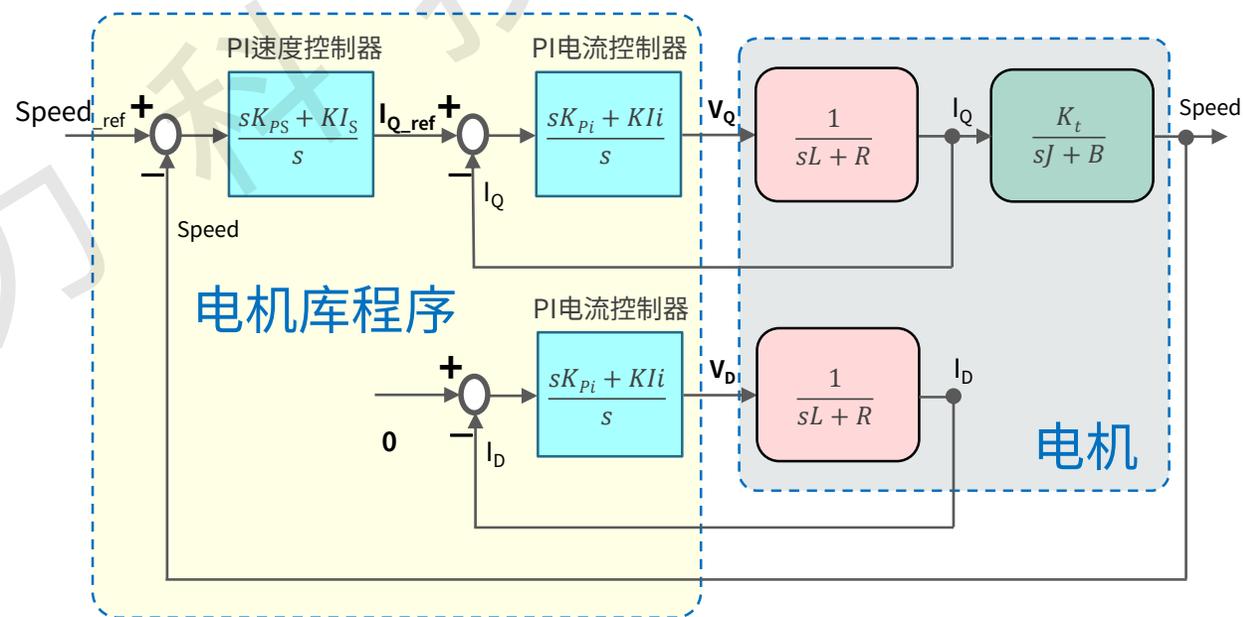
/* SPEED */
#define SPEED_LOOP_FREQ (1000) /* Hz */
#define MIN_SPEED_RPM (10)
#define MAX_SPEED_RPM (6000)
#define MIN_POSCTL_SPD (100)
#define MIN_CONTROL_SPEED (200)
#define ACC_SPD_SLOPE (5) /* (rpm/ms) */
#define DEC_SPD_SLOPE (5)

/* POSITION */
#define POSITION_LOOP_FREQ (200) /* Hz */
#define MAX_POSITION_ANGLE (360000) /* Degree */
#define MIN_POSITION_ANGLE (-MAX_POSITION_ANGLE)
#ifdef HALL_SENSORS
#define CMD_TO_VAL_GAP (20000) /* hall electric ar
#else
#define CMD_TO_VAL_GAP (1000) /* counts (ex: enc
#endif
#define SMALL_POS_CMD_GAP (100)
#define ROTOR_LOCK_ANGLE_GAP (120.0f)

/* encoder parameter */
#define ALIGN_VOLT (0.8f) /* (V) */
#define ENC_OFFSET (0)

/* current pid auto-tune */
#define CURRENT_BANDWIDTH (3500) /* 2*pi*freq */

/* Id/Iq pid parameter */
#define PID_ID_KP_DEFAULT (7500)
#define PID_ID_KI_DEFAULT (6000)
#define PID_ID_KP_GAIN_DIV (512)
#define PID_ID_KP_GAIN_DIV_LOG (LOG2(PID_ID_KP_GAIN_DIV))
#define PID_ID_KI_GAIN_DIV (8192)
#define PID_ID_KI_GAIN_DIV_LOG (LOG2(PID_ID_KI_GAIN_DIV))
```



ID_Kp = PID_ID_KP_DEFAULT / PID_ID_KP_DIV
ID_Ki = PID_ID_KI_DEFAULT / PID_ID_KI_DIV

外设定义头文件 - 外设参数定义

外设定义参数 (mc_hwio.h)

```

/* adc reading pin definition */
#define ADC_CONVERTER          ADC1
#define ADC_CONVERTER_CRM_CLK  CRM_ADC1_PERIPH_CLOCK
#define ADC_CONVERTER_CRM_CLK_DIV  CRM_ADC_DIV_8
#define ADC_SHUNT_SAMP_READY_IRQ  ADC1_2_IRQHandler
#define ADC_SHUNT_SAMP_READY_IRQn  ADC1_2_IRQn
#define ADC_ORDINARY_CH_LEN      6

/* dma1 ch1 for adc ordinary conversion */
#define ADC_ORDINARY_DMA_CRM_CLK  CRM_DMA1_PERIPH_CLOCK
#define ADC_ORDINARY_DMA_CHANNEL  DMA1_CHANNEL1
#define ADC_ORDINARY_DMA         DMA1
#define ADC_ORDINARY_DMA_FLEX     DMA_FLEXIBLE_ADC1
#define ADC_ORDINARY_DMA_FLEX_CH  FLEX_CHANNEL1

#define CURR_PHASE_A_ADC_CH      ADC_CHANNEL_0
#define CURR_PHASE_A_ADC_GPIO_CRM_CLK  CRM_GPIOA_PERIPH_CLOCK
#define CURR_PHASE_A_ADC_PORT    GPIOA
#define CURR_PHASE_A_ADC_GPIO_PIN  GPIO_PINS_0

#define CURR_PHASE_B_ADC_CH      ADC_CHANNEL_1
#define CURR_PHASE_B_ADC_GPIO_CRM_CLK  CRM_GPIOA_PERIPH_CLOCK
#define CURR_PHASE_B_ADC_PORT    GPIOA
#define CURR_PHASE_B_ADC_GPIO_PIN  GPIO_PINS_1

#define CURR_PHASE_C_ADC_CH      ADC_CHANNEL_2
#define CURR_PHASE_C_ADC_GPIO_CRM_CLK  CRM_GPIOA_PERIPH_CLOCK
#define CURR_PHASE_C_ADC_PORT    GPIOA
#define CURR_PHASE_C_ADC_GPIO_PIN  GPIO_PINS_2
    
```

控制器MCU pin map

Peripheral function	AT32F421C8T6		AT32F413RCT7	
VBAT	1	VBAT	1	VBAT
STATUS_LED1	2	PC13	2	PC13
STATUS_LED2	3	PC14	3	PC14
STATUS_LED3	4	PC15	4	PC15
ENCODER_A+			18	TMR5_CH1(PF4)
ENCODER_B+			19	TMR5_CH2(PF5)
MODE_SW1	35	PF6	47	PF6
MODE_SW2	36	PF7	48	PF7
OSC_IN	5	OSC_IN	5	OSC_IN
OSC_OUT	6	OSC_OUT	6	OSC_OUT
RESET	7	NRST	7	NRST
SPEED_VR(F413)			8	ADC12_IN10(PC0)
			9	ADC12_IN11(PC1)
			10	ADC12_IN12(PC2)
			11	ADC12_IN13(PC3)
VSSA	8	VSSA	12	VSSA
VDDA	9	VDDA	13	VDDA
CURR_FDBK1	10	ADC_IN0(PA0)	14	ADC_IN0(PA0)
CURR_FDBK2	11	ADC_IN1(PA1)	15	ADC_IN1(PA1)
CURR_FDBK3	12	ADC_IN2(PA2)	16	ADC_IN2(PA2)
IBUS_FDBK	13	ADC_IN3(PA3)	17	ADC_IN3(PA3)
BEMF1_LF	14	ADC_IN4(PA4)	20	ADC_IN4(PA4)
BEMF2_LF	15	ADC_IN5(PA5)	21	ADC_IN5(PA5)
BEMF3_LF	16	ADC_IN6(PA6)	22	ADC_IN6(PA6)
VBUS	17	ADC_IN7(PA7)	23	ADC_IN7(PA7)
ENCODER_Z+			24	PC4
			25	ADC_IN15(PC5)

UI程序与电机控制调校

定义头档相关参数

I/O mapping

Board param.

Motor param.

Control param.

Drive mode

- FOC_CONTROL
- ONE_SHUNT
- SENSORLESS

电机控制程序

Motor control project

UI程序调校PID控制参数

a. 在线调整控制参数

Parameter	Value	Unit
Flux KP	25000	
Flux KI	3000	
Flux KP DIV	2048	
Flux KI DIV	4096	

b. 实时观察输出响应

c. 控制参数写入Flash

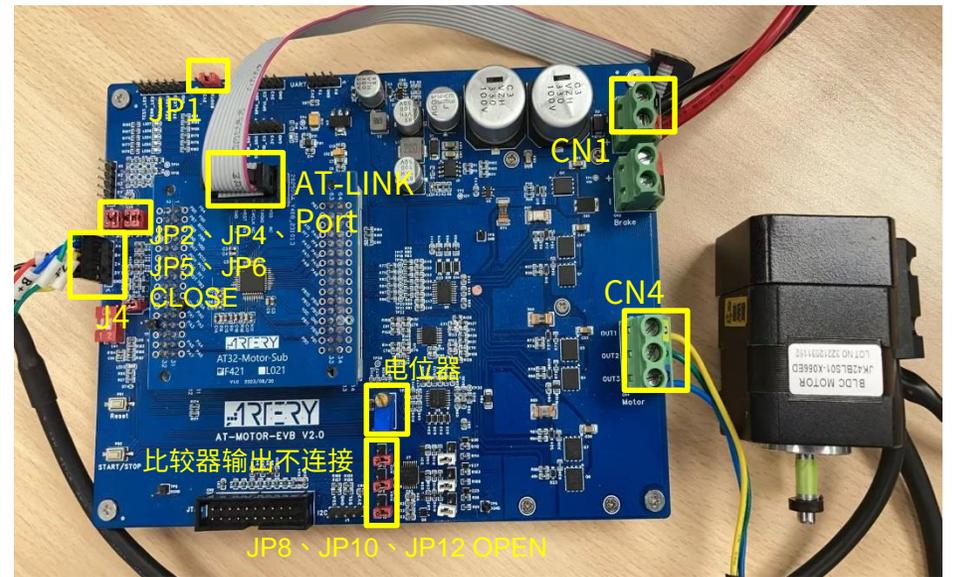
实时监控看响应特性与数据

实时监控看响应特性与数据

实时观察输出响应

AT32 MOTOR开发板接线

- 检查JP1 Boot0是否接地(GND)
- 将编码器排线连接到J4
- 将JP2、JP4、JP5、JP6短接，将编码器信号连接至MCU 接脚
- 将JP8、JP10、JP12段开
- 将AT-LINK连接到小板
- 连接电机线到CN4 (依线色)
- 连接电源供应器电源接线到CN1 (依标示)
- 设定电源供应器电压24V / 3A
- 开启电源供应器输出
- PC端执行上位机程序后建立联机
(ArteryMotorMonitor.exe)



电机与开发板接线图

监控界面软件运行操作 - 自整定功能

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and the menu bar includes "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM Port:** "COM37: ATLink-USART" with a "关闭" button and a "绘图" icon.
- Motor ID:** "AT32F421_ML_V2.1.3".
- 程序状态 (ESC_STATE_SAFETY_READY):** A list of error states with checkboxes: "no error" (checked), "over voltage error", "under voltage error", "over temperature error", "over current error", "encoder error", "hall error", "parameter identify error", "hall learn error", and "startup error".
- 线圈参数识别 (Winding parameter Identification):** A table showing identified process state and parameters.
- 电流环 PI参数自整定 (Auto-tune PI parameter of Current controller):** A table showing PI parameters for torque control.
- 命令 (启动/停止电机):** Buttons for "启动电机" and "停止电机".
- 编码器对齐 (编码器对齐):** A button for encoder alignment.
- 错误解除 (错误状态解除):** A button for clearing error states.
- 写入闪存 (写入闪存):** A button for writing to flash memory.
- 控制型式 (read):** A dropdown menu currently set to "SPMSM - encoder".
- 控制模式:** A dropdown menu currently set to "Speed Control".
- 控制来源:** A dropdown menu currently set to "software control".
- 运行日志 (传输状态记录):** A log table showing system events.

Identified process state	尚未运行	
RS_LL	1.89	Ω
LS_LL	0.002387	H

Torque KP	7500	
Torque KI	6000	
Torque KP DIV	512	
Torque KI DIV	8192	

1	11:24:58	Load ok
2	11:24:58	Set REG 8 = 5 ok
3	11:24:55	Exec Stop Motor...ok
4	11:23:12	Exec Start Motor...ok

监控界面软件运行操作 - 开环控制

- 设定初始开环电压
- 设定初始开环角度递增值
- 增加一点开环电压
- 增加一点角度递增值
- 依次递增电压与角度递增值，逐步拉高转速

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and the menu bar includes "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM37: ATLink-USART**: Shows the connection port and a "关闭" (Close) button.
- 程序状态 (Program Status)**: Displays "ESC_STATE_SAFETY_READY".
- 错误状态 (Error Status)**: A list of error conditions with checkboxes: "no error" (checked), "over voltage error", "under voltage error", "over temperature error", "over current error", "encoder error", "hall error", "parameter identify error", "hall learn error", and "startup error".
- 开环参数设定 (Open Loop Control Parameters)**: A table with the following data:

Open loop control		
Open Loop Voltage	0.000	V
Open Loop Angle Increments	0	
- 命令 (Commands)**: Includes buttons for "启动电机" (Start Motor), "停止电机" (Stop Motor), "编码器对齐" (Encoder Alignment), "错误解除" (Error Clear), and "写闪存" (Write Flash).
- 控制模式 (Control Mode)**: A dropdown menu currently set to "SPMSM - encoder".
- 运行日志 (Run Log)**: A table with the following data:

Index	Time	Message
1	11:28:17	Exec Auto-tune Current PI parameter...
2	11:28:13	Exec Identify Winding parameter...ok
3	11:28:10	Load ok
4	11:28:10	Set REG 8 = 0 ok

监控界面软件运行操作 – 编码器零位校准

- 将控制模式设为**非开环模式**的其中一种
- 设定编码器零位校准参数
- 启动编码器零位校准
- Align process state **显示成功**即可

The screenshot displays the Artery Motor Monitor V2.1.18 interface with several key sections highlighted by red boxes and Chinese annotations:

- 程序状态 (Program Status):** Shows the status as ESC_STATE_SAFETY_READY.
- 错误状态 (Error Status):** A list of error checkboxes, with 'no error' checked. Other errors include over voltage, under voltage, over temperature, over current, encoder error, hall error, parameter identify error, hall learn error, and startup error.
- 启动/停止电机 (Start/Stop Motor):** Buttons for '启动电机' (Start Motor) and '停止电机' (Stop Motor).
- 编码器校准 (Encoder Calibration):** A section for '编码器对齐' (Encoder Alignment) with buttons for '错误解除' (Error Release) and '写入闪存' (Write to Flash).
- 控制型式 (Control Mode):** A dropdown menu currently set to 'SPMSM - encoder'.
- 编码器零位校准参数 (Encoder Zeroing Calibration Parameters):** A table showing:

Encoder Align Voltage	0.776	V
Encoder Offset	-468	
Align process state	成功	
- 传输状态记录 (Transmission Status Record):** A log table showing the following entries:

1	11:35:16	Load ok
2	11:35:16	Set REG 8 = 1 ok
3	11:28:17	Exec Auto-tune Current PI parameter...ok
4	11:28:13	Exec Identify Winding parameter...ok

监控界面软件运行操作 - 电压控制

- 设定q轴电压Vq
- 启动电机即可运转
- 逐步增加Vq电压
- 可观测Id与Iq电流
- 适当调整d轴电压Vd使Id电流接近于0
- 在电流环未适当调整时，可在电压模式观察电流回授状态

The screenshot shows the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and the menu bar includes "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM37: ATLink-USART**: Includes a "关闭" button and a "绘图" button.
- 程序状态**: Shows "ESC_STATE_SAFETY_READY".
- 基本**: Includes "Power board status" with a table:

Bus Voltage measured	23.302	volt
Mos temperature measured	23	°C
- Speed**: Includes a table:

Maximum application speed	6000	rpm
Minimum application speed	200	rpm
Speed measured	0	rpm
- Current**: Includes a table:

Maximum Current	4.999	A
Minimum Current	-4.999	A
- Diagram parameter setting**: Includes "Flux(current) measured (Id)" and "Torque(current) measured (Iq)" dropdowns, and a "保存" button.
- 命令**: Includes "启动/停止电机" section with "启动电机" and "停止电机" buttons.
- 编码器校准**: Includes "编码器对齐" and "错误解除" buttons.
- 写入闪存**: Includes "写入闪存" button.
- 控制型式 (read)**: Includes "SPMSM - encoder" and "Voltage Control" dropdowns.
- 控制模式**: Includes "控制型式" label.
- d-q轴电压命令**: Includes "Voltage control" section with "Vq reference" (0.000 V) and "Vd reference" (0.000 V) fields.
- 传输状态记录**: Includes "运行日志" table:

1	11:35:16	Load ok
2	11:35:16	Set REG 8 = 1 ok
3	11:28:17	Exec Auto-tune Current PI parameter...ok
4	11:28:13	Exec Identify Winding parameter...ok

监控界面软件运行操作 - 电流环参数实时调整

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The main window is divided into several sections:

- Program Status (程序状态):** Shows the current state as `ESC_STATE_SAFETY_READY`.
- Error Status (错误状态):** A list of error flags, all of which are currently unchecked, including `no error`, `over voltage error`, `under voltage error`, `over temperature error`, `over current error`, `encoder error`, `hall error`, `parameter identify error`, `hall learn error`, and `startup error`.
- Command (命令):** Includes buttons for `启动电机` (Start Motor) and `停止电机` (Stop Motor).
- Control Mode (控制模式):** A dropdown menu currently set to `ID Tune`.
- Unit step config (步阶电流命令参数):**

Current Tune target current	0.999	A
Current Tune total period	100	ms
Current Tune step period	2	ms
- ID Current control (d轴电流控制器PI 参数):**

Flux KP	7950
Flux KI	6055
Flux KP DIV	512
Flux KI DIV	8192
- Run Log (传输状态记录):**

1	11:55:56	Load ok
2	11:55:56	Set REG 8 = 2 ok
3	11:35:16	Load ok
4	11:35:16	Set REG 8 = 1 ok
- Monitor Graph (电流环调适响应波形实时监看):** A real-time plot showing the response of the current loop. The x-axis represents time in milliseconds (942000 to 942125), and the y-axis represents current in Amperes (A) (-0.5 to 1.5). The graph shows a step change in the reference current, with the measured current following the step and stabilizing around 1.0 A.

监控界面软件运行操作 – 转矩控制

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and the menu bar includes "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM Port:** "COM37: ATLink-USART" with a "关闭" button and a "绘图" (Plot) button.
- Device Info:** "AT32F421_ML_V2.1.3".
- 程序状态 (Program Status):** "ESC_STATE_SAFETY_READY".
- 错误状态 (Error Status):** A list of error conditions with checkboxes: "no error" (checked), "over voltage error", "under voltage error", "over temperature error", "over current error", "encoder error", "hall error", "parameter identify error", "hall learn error", and "startup error".
- 命令 (Commands):** "启动电机" (Start Motor) and "停止电机" (Stop Motor) buttons.
- 编码器对齐 (Encoder Alignment):** "编码器对齐" button.
- 错误解除 (Error Clear):** "错误解除" button.
- 写入闪存 (Write Flash):** "写入闪存" button.
- 控制型式 (Control Mode):** "SPMSM - encoder" (read).
- 控制模式 (Control Mode):** "Torque Control".
- 控制来源 (Control Source):** "software control".
- 参数调整 (Parameter Adjustment):**
 - Iq Current control:** Torque KP (7950), Torque KI (6055), Torque KP DIV (512), Torque KI DIV (8192). Labeled "电流环Iq PI参数".
 - Id Current control:** Flux KP (7950), Flux KI (6055), Flux KP DIV (512), Flux KI DIV (8192). Labeled "电流环Id PI参数".
- d-q轴电流命令 (d-q Axis Current Command):** Torque(current) reference (Iq) 0.000 A, Flux(current) reference (Id) 0.000 A.
- 运行日志 (Run Log):** A table with columns for log ID, time, and message. Labeled "传输状态记录".

Log ID	Time	Message
1	12:00:16	Load ok
2	12:00:16	Set REG 8 = 4 ok
3	12:00:04	Exec Stop Motor...ok
4	11:58:31	Load ok

监控界面软件运行操作 - 速度控制

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and it includes a menu bar with "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM Port:** "COM37: ATLink-USART" with a "关闭" button and a "绘图" icon.
- Device Info:** "AT32F421_ML_V2.1.3".
- 程序状态 (ESC_STATE_SAFETY_READY):** A list of error status options, with "no error" checked. Other options include "over voltage error", "under voltage error", "over temperature error", "over current error", "encoder error", "hall error", "parameter identify error", "hall learn error", and "startup error".
- 速度环 PI参数 (Speed control):** A table of parameters for speed control with current control loop.

Parameter	Value	Unit
Speed KP	2000	
Speed KI	50	
Speed KP DIV	1024	
Speed KI DIV	4096	
Speed acceleration	5	rpm/ms
Speed deceleration	5	rpm/ms
- 弱磁控制 PI参数 (Flux weakening tuning):** A table of parameters for flux weakening tuning.

Parameter	Value	Unit
Max. Flux weakening Current	0.499	A
Flux weakening KP	10	
Flux weakening KI	2000	
Flux weakening KP DIV	2048	
Flux weakening KI DIV	32768	
- 命令 (启动/停止电机):** Buttons for "启动电机" and "停止电机".
- 编码器对齐 (编码器对齐):** A button for encoder alignment.
- 错误解除 (错误状态解除):** A button for clearing error status.
- 写入闪存 (写入闪存):** A button for writing to flash memory.
- 控制型式 (read):** A dropdown menu currently set to "SPMSM - encoder".
- 控制模式:** A dropdown menu currently set to "Speed Control".
- 控制来源:** A dropdown menu currently set to "software control".
- Target speed (d-q轴电流命令):** A field for "Speed reference" set to "0 rpm".
- 运行日志 (传输状态记录):** A log table showing system events.

Index	Time	Event
1	12:03:51	Load ok
2	12:03:51	Set REG 8 = 5 ok
3	12:00:16	Load ok
4	12:00:16	Set REG 8 = 4 ok

监控界面软件运行操作 - 定位控制

The screenshot displays the Artery Motor Monitor V2.1.18 software interface. The window title is "Artery Motor Monitor V2.1.18" and the menu bar includes "文件", "设置", and "帮助". The main interface is divided into several sections:

- COM Port:** "COM37: ATLink-USART" with a "关闭" button and a "绘图" icon.
- Device:** "AT32F421_ML_V2.1.3".
- State (状态):** "ESC_STATE_SAFETY_READY". A list of error states is shown, with "no error" checked. A red box highlights this section with the label "程序状态" and "错误状态".
- Position Controller (位置环 PI参数):** A table of parameters:

Position KP	800
Position KI	0
Position KI stable	200
Position KD	0
Position KP DIV	4096
Position KI DIV	65536
Position KD DIV	65536

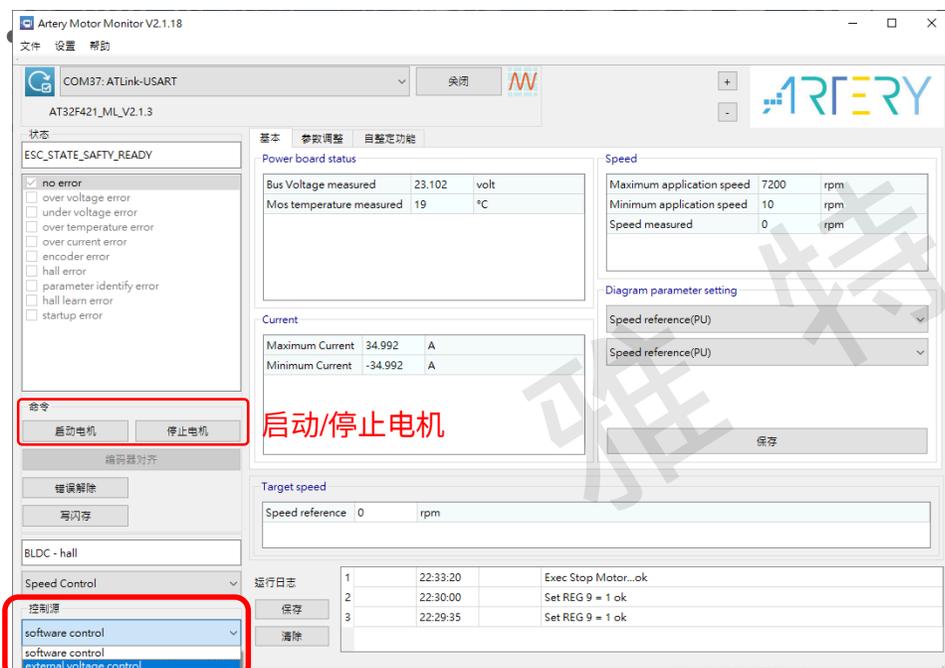
A red box highlights this section with the label "位置环 PI参数".
- Commands (命令):** "启动/停止电机" with buttons for "启动电机" and "停止电机".
- Encoder Alignment (编码器对齐):** A button labeled "编码器对齐".
- Error Reset (错误解除):** A button labeled "错误解除".
- Flash Write (写闪存):** A button labeled "写闪存".
- Control Mode (控制型式):** A dropdown menu showing "SPMSM - encoder" and "Position control".
- Target Angle (位置命令):** A table showing "Position reference" as 35.46 degree.
- Actual Angle (转子实际位置):** A table showing "Position measured" as 35.46 degree.
- Run Log (传输状态记录):** A table of log entries:

1	12:06:24	Load ok
2	12:06:24	Set REG 8 = 6 ok
3	12:03:51	Load ok
4	12:03:51	Set REG 8 = 5 ok

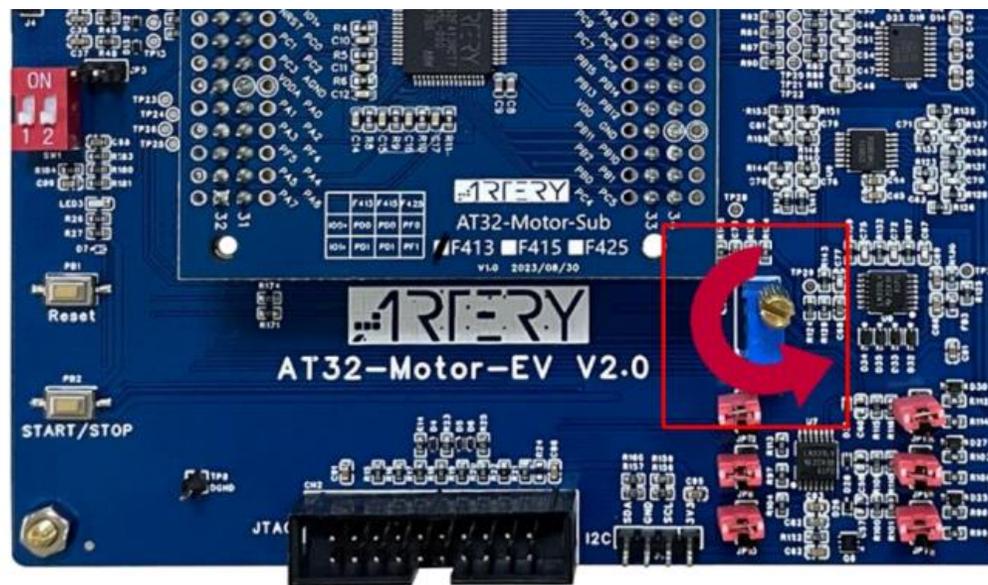
A red box highlights this section with the label "传输状态记录".

外部命令控制

- 在控制源选择外部电压控制，只能正转
- 或在motor_control_drive_param.h头文件中定义'CTRL_SOURCE'为'CTRL_SOURCE_EXTERNAL'



外部控制源



提问时间

10分钟

Q & A

ARTERY 联系我们



中文官网



English Website



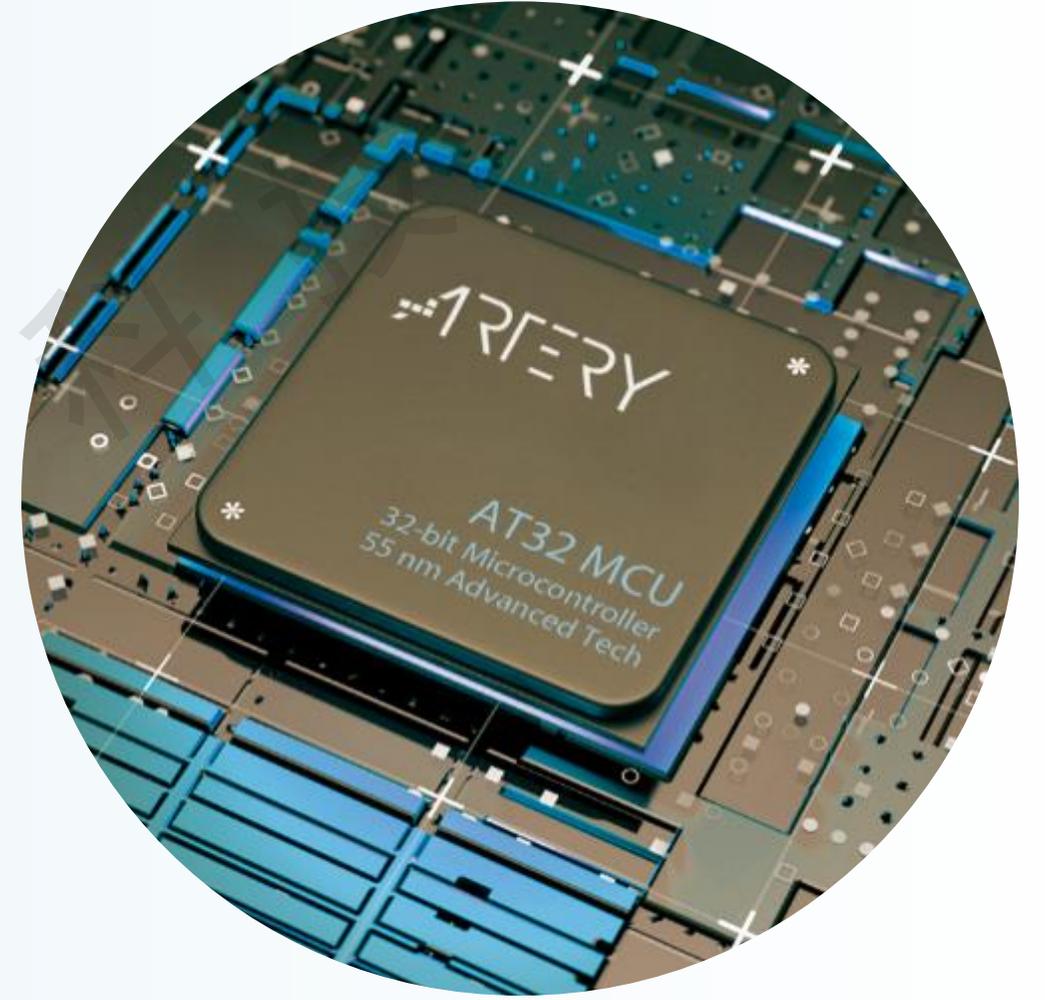
微信公众号



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Thank you!



雅特力