

ST MC SDK 5.x 相电流检测与重构 位置、速度信息获取

STM32电动机控制应用系列讲座之三



□ 相电流的检测与重构

- ICS
- 三电阻
- 单电阻

□ 转子位置、速度信息的获取

- 有位置传感器
- 无位置速度传感器

相电流的检测与重构



□ 相电流的检测与重构

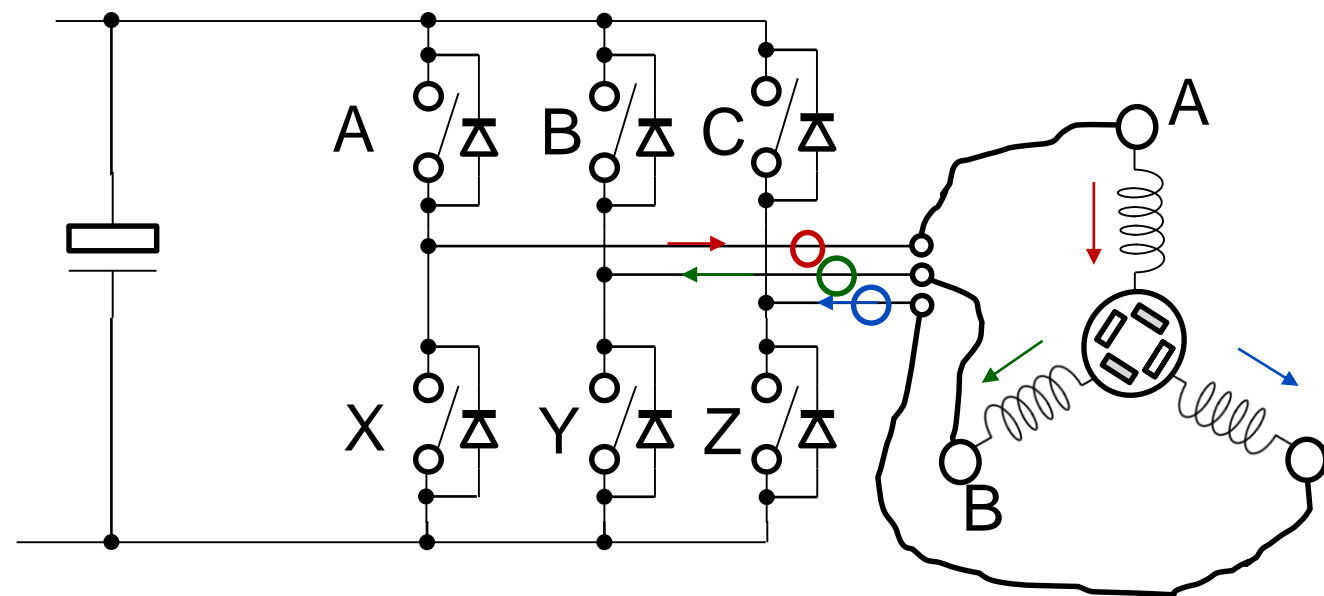
- ICS
- 三电阻
- 单电阻

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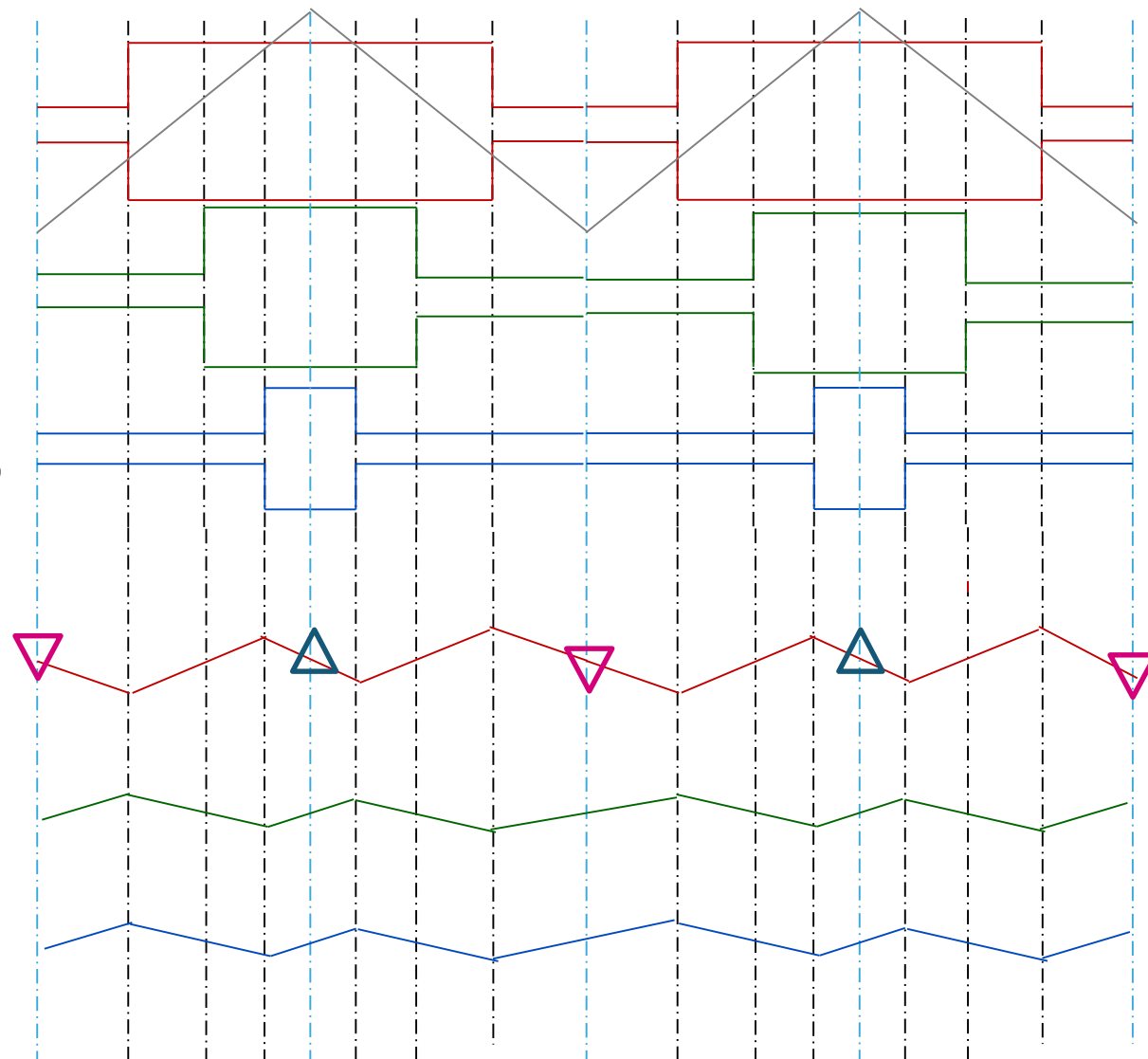
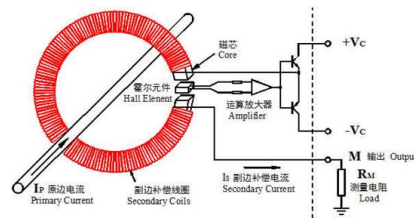
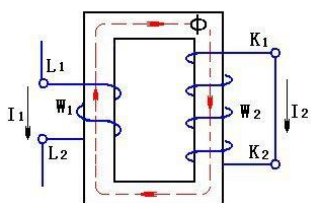
- 有位置传感器
- 无位置速度传感器

电流采样 — ICS

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	ACCT	DCCT
频率范围	>0 Hz ~ tens kHz	DC ~ 100kHz
退磁	需要	不需要
成本	低	高



ST MC SDK5.x ICS采样固件

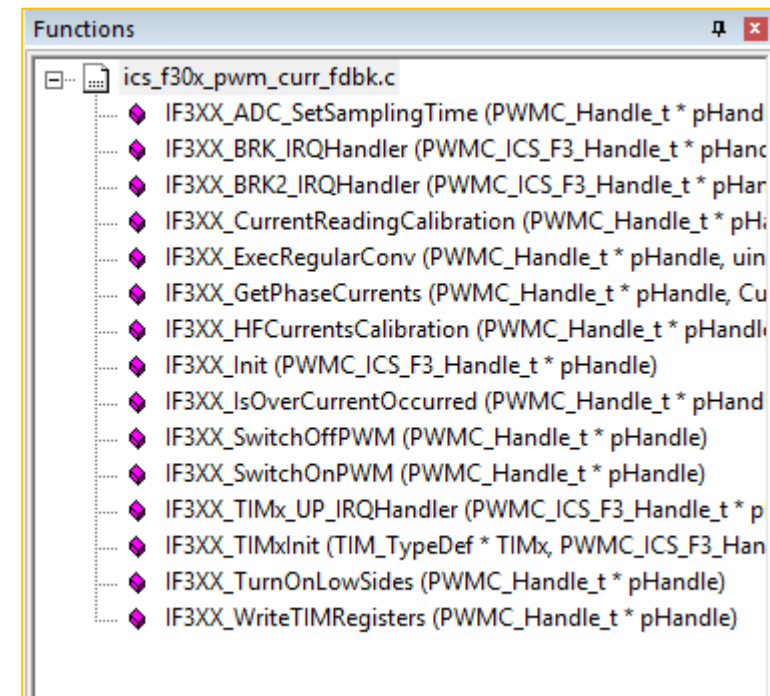
5

➤ 针对STM32系列芯片都有各自的文件:

- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F1xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F3xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F4xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F7xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\L4xx\Src

➤ 文件名称

- ✓ ics_yxx_pwm_curr_fdbk.c
- ✓ y=f1, f3, f4, f7, l4



相电流的检测与重构



□ 相电流的检测与重构

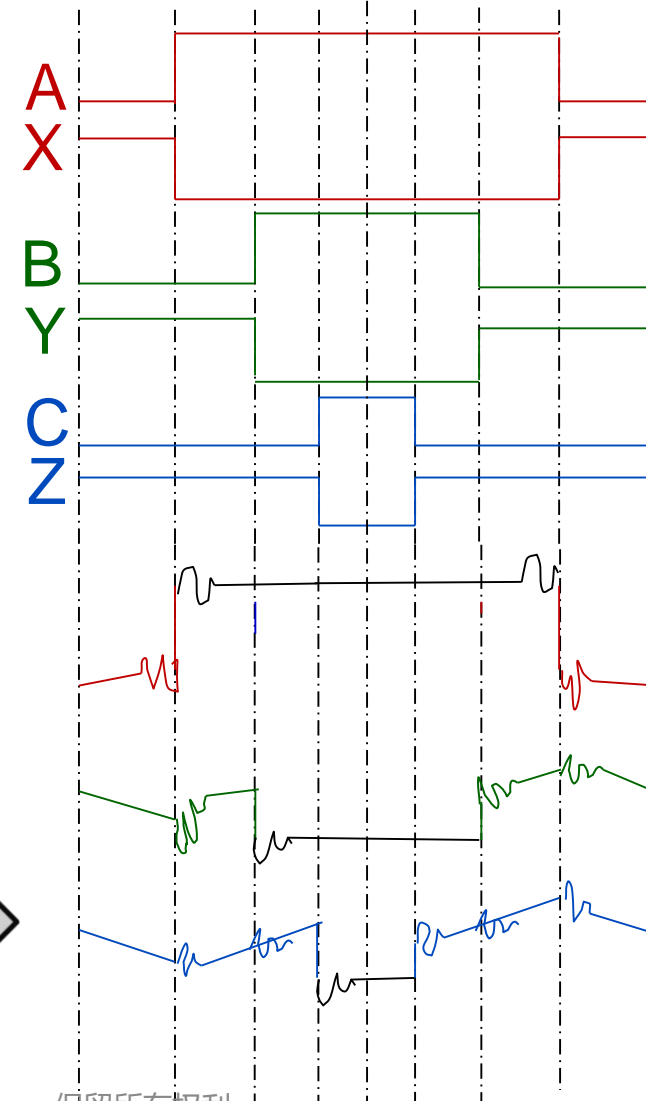
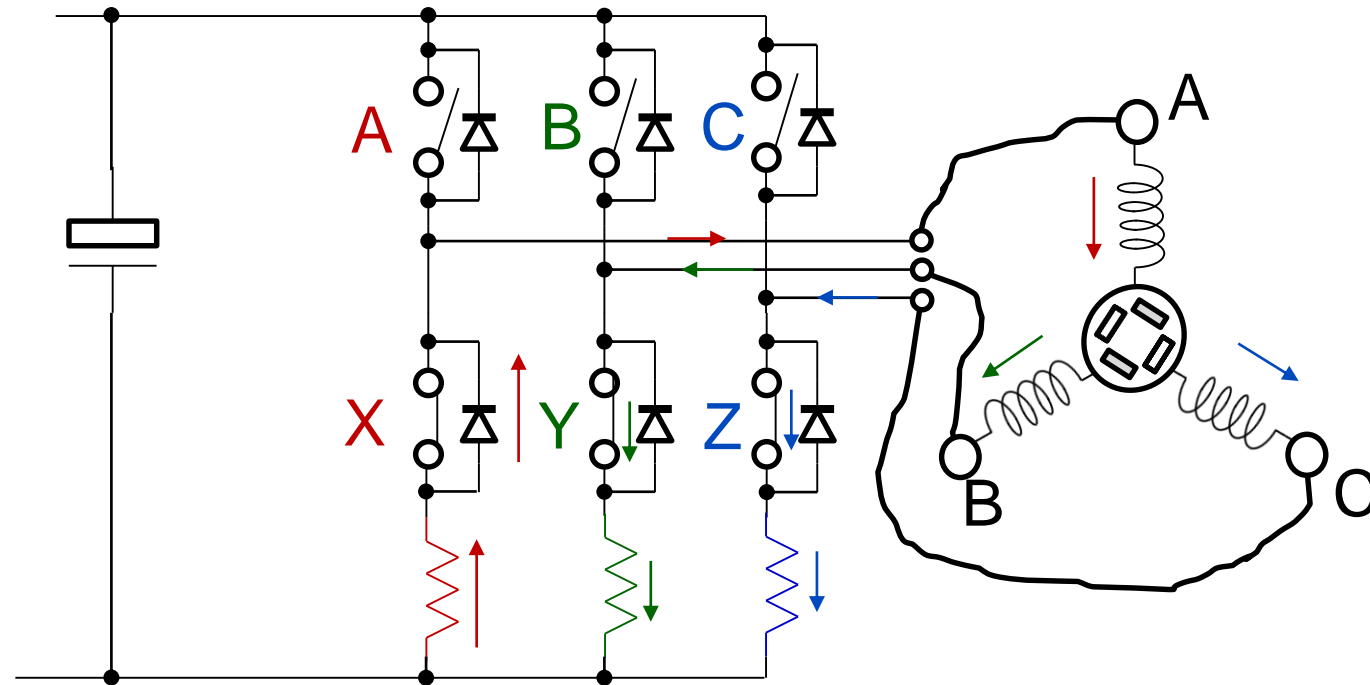
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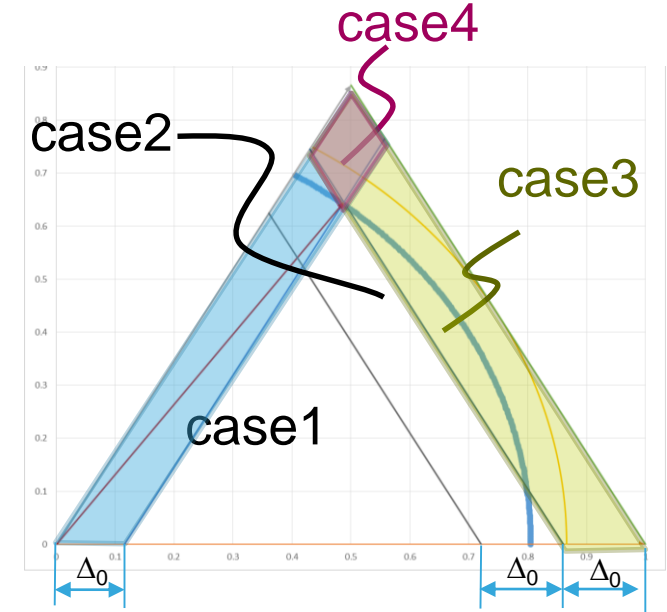
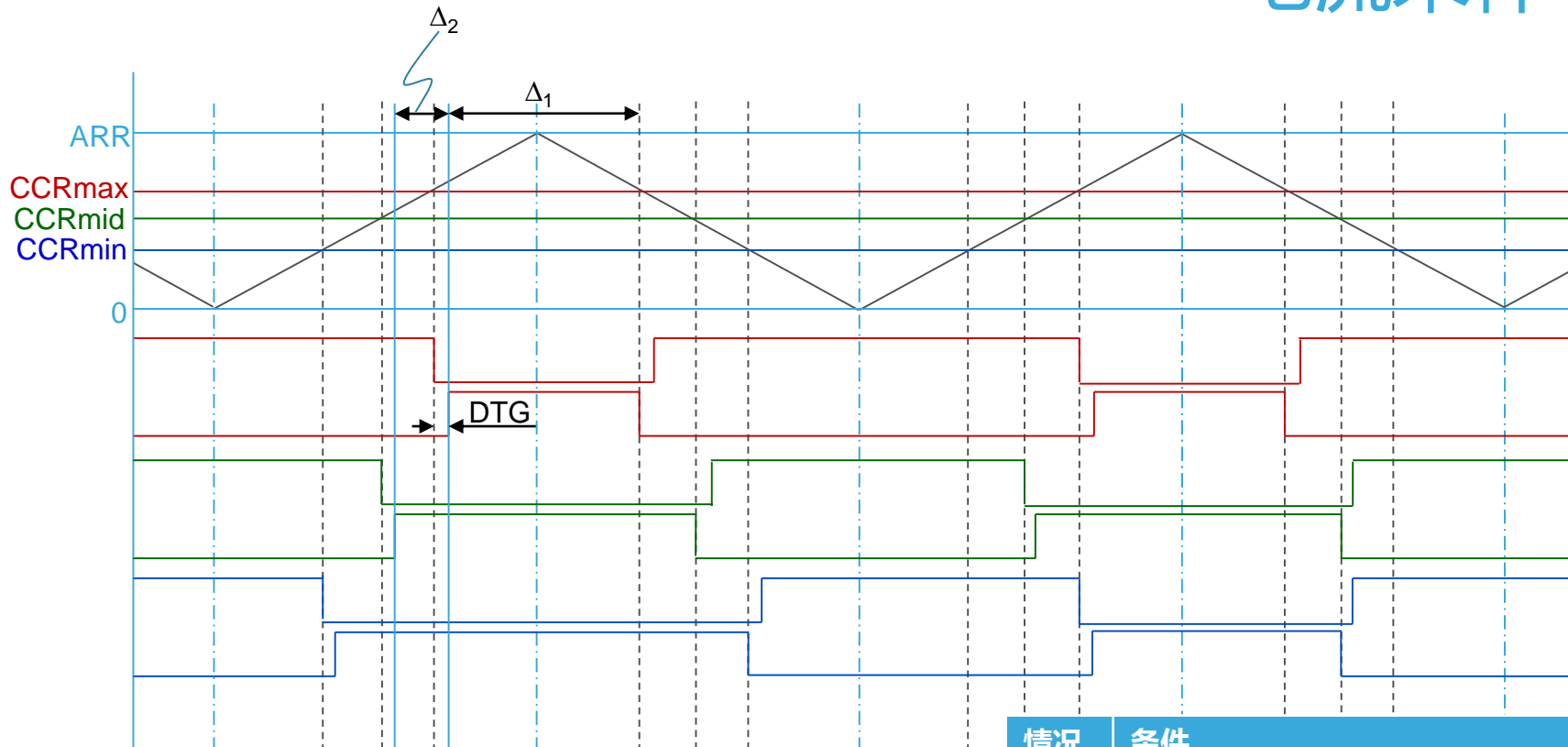
电流采样 — 三电阻(1/2)

7



电流采样 — 三电阻(2/2)

8



$$\Delta_1 = 2 * (ARR - CCRmax - DTG)$$

$$\Delta_2 = CCRmax - CCRmid$$

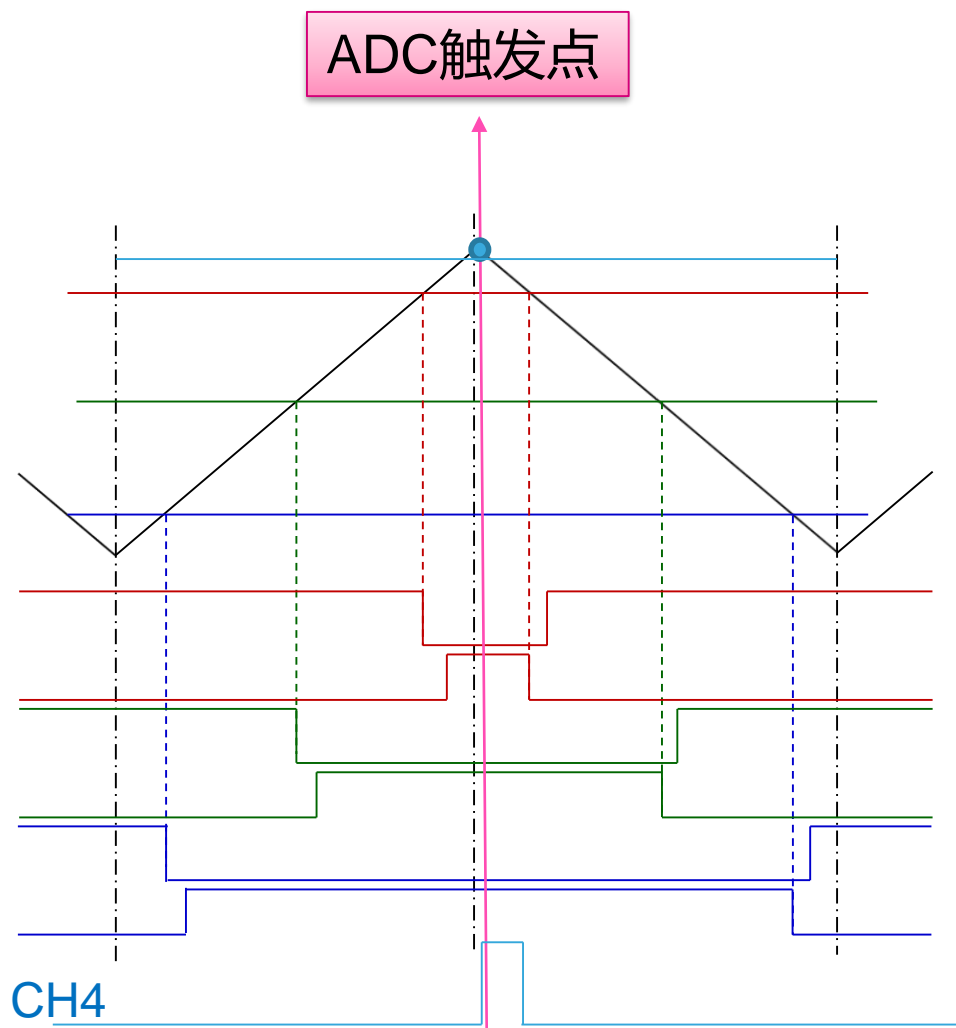
$$\Delta_0 = CNT_Ton + CNT_Tring + CNT_TADCSH(COV), \\ Tring > TADCsta$$

$$\Delta_0 = CNT_Ton + CNT_TADCsta + CNT_TADCSH(COV), TADCsta \geq Tring$$

情况	条件	采样点
1	$\Delta_1 > \max(2 * (CNT_Ton + CNT_Trise + CNT_Ring + tdead/2), CNT_TADCsta + CNT_TADCSH(COV) - tdead/2)$	Middle of PWM
2	$\Delta_1 > \Delta_0$	$CCRmax + tdead + ton + tring + \epsilon$
3	$\Delta_2 > \Delta_0 > \Delta_1$	$CCRmid + tdead + ton + tring + \epsilon$
4	$\Delta_1 < \Delta_0$ and $\Delta_2 < \Delta_0$	Not available

三电阻ADC触发机制说明

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- 配置TIMER CH4为TRGO输出
- TIMER的TRGO输出用于硬件触发ADC采样;
- 如果是拥有两个ADC模块的可以同时触发进行同时采样
- 判断波形的采样位置, 修正CCR4数据

ST MC SDK5.x 三电阻采样固件

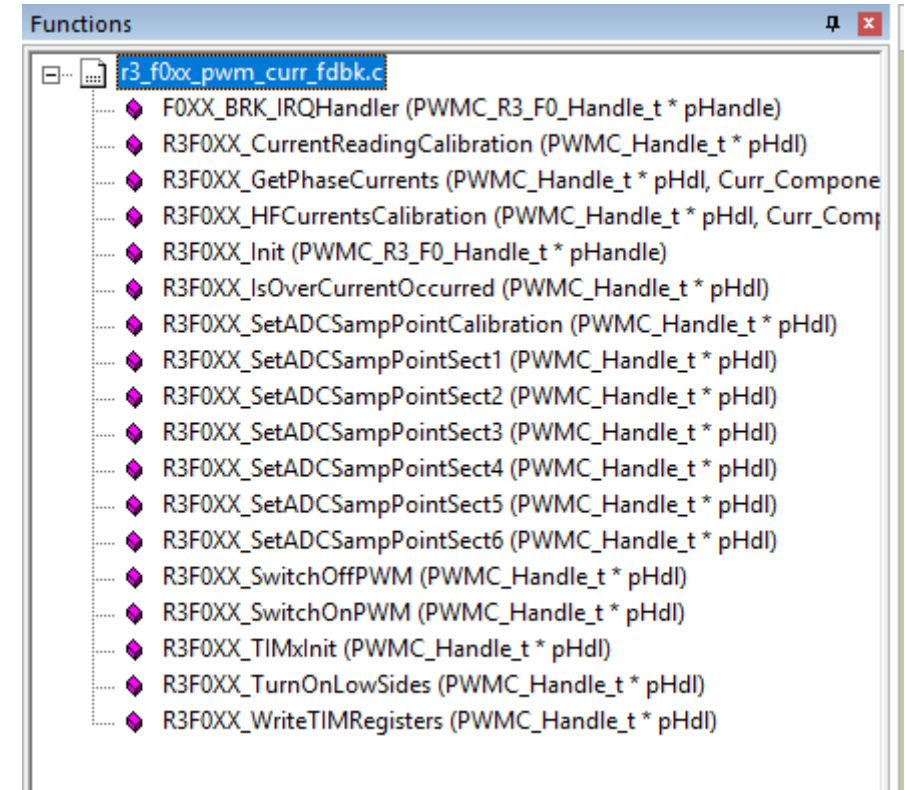
10

❑ 针对STM32系列芯片都有各自的文件：

1. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F0xx\Src
2. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F1xx\Src
3. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F3xx\Src
4. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F4xx\Src
5. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F7xx\Src
6. xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\L4xx\Src

❑ 文件名称

- r3_z_yxx_pwm_curr_fdbk.c
 - ✓ y=f0, f1, f3, f4, f7, l4
 - ✓ z=1,4(for dual motor),[]s



相电流的检测与重构

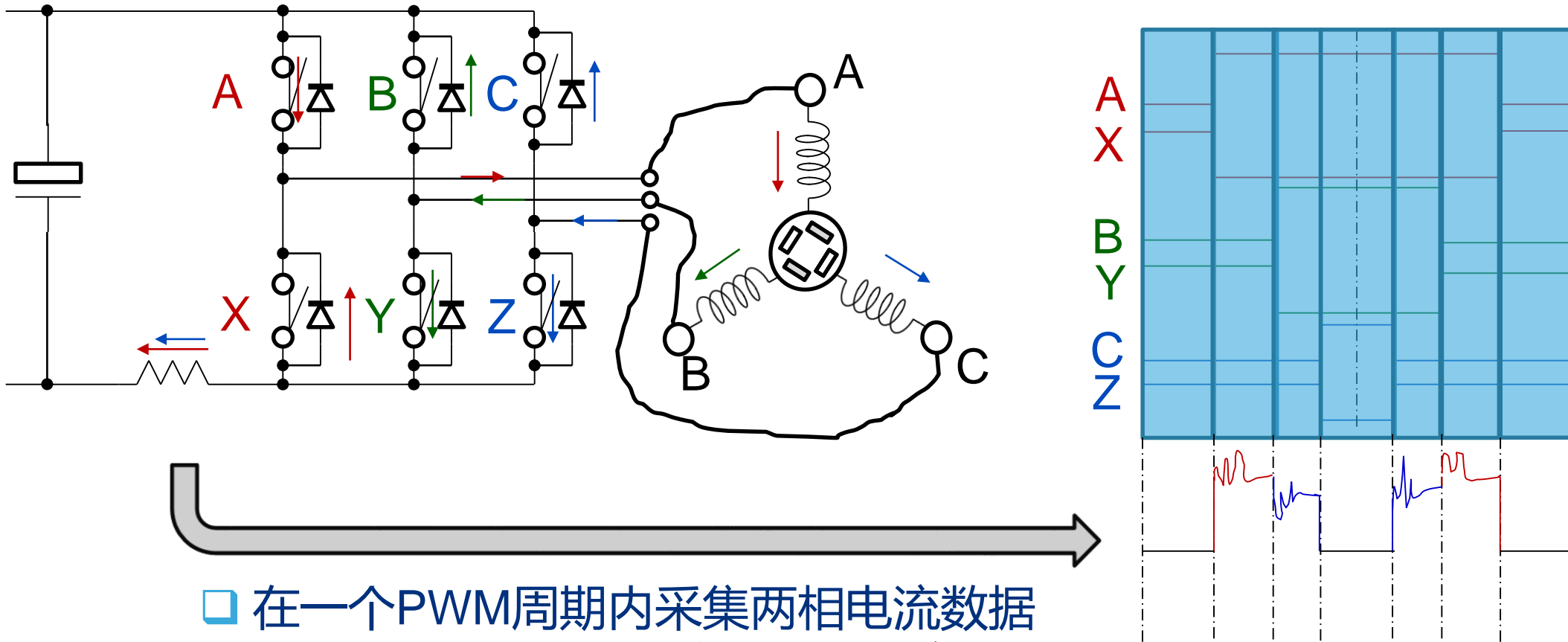


□ 相电流的检测与重构

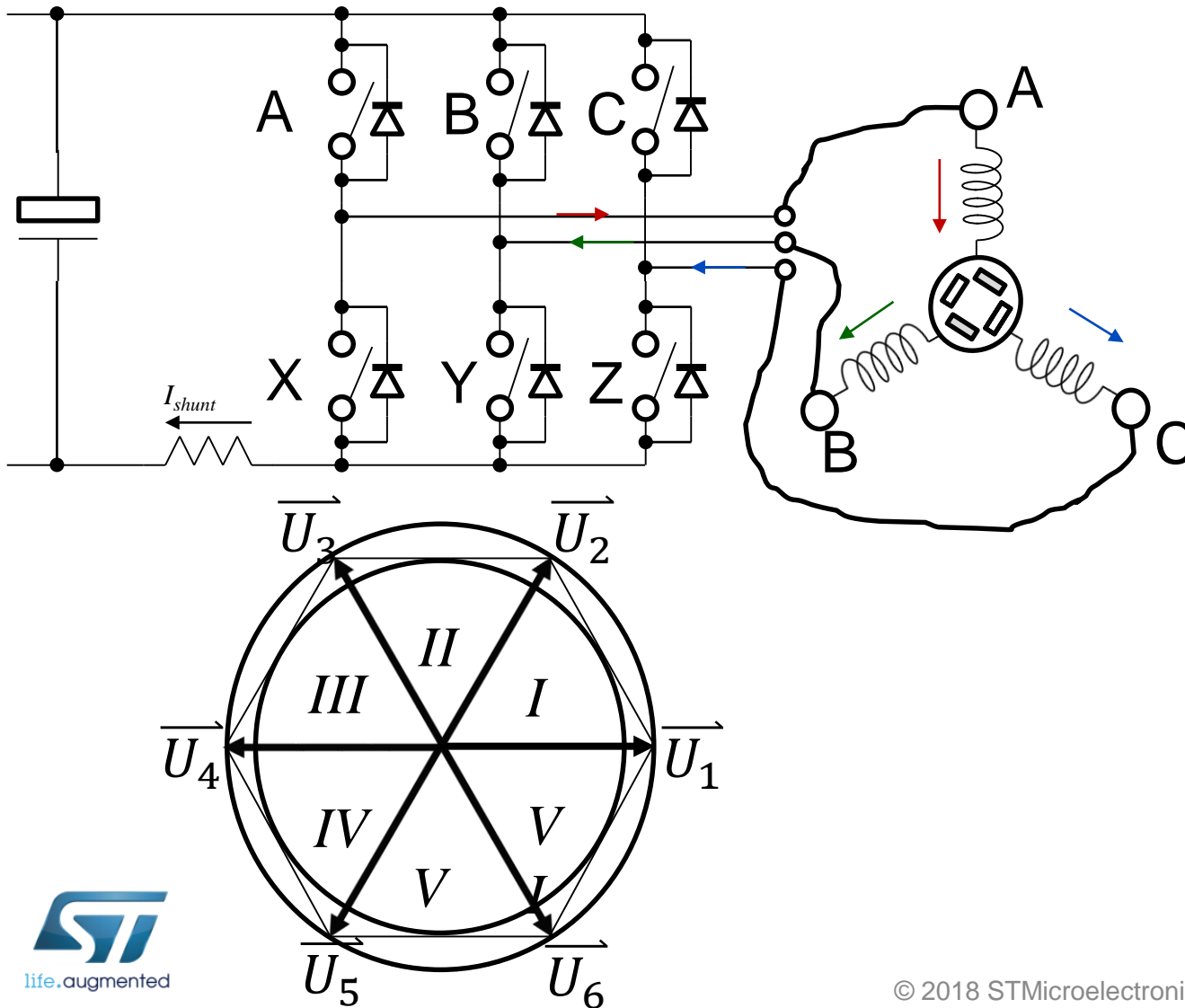
- ICS
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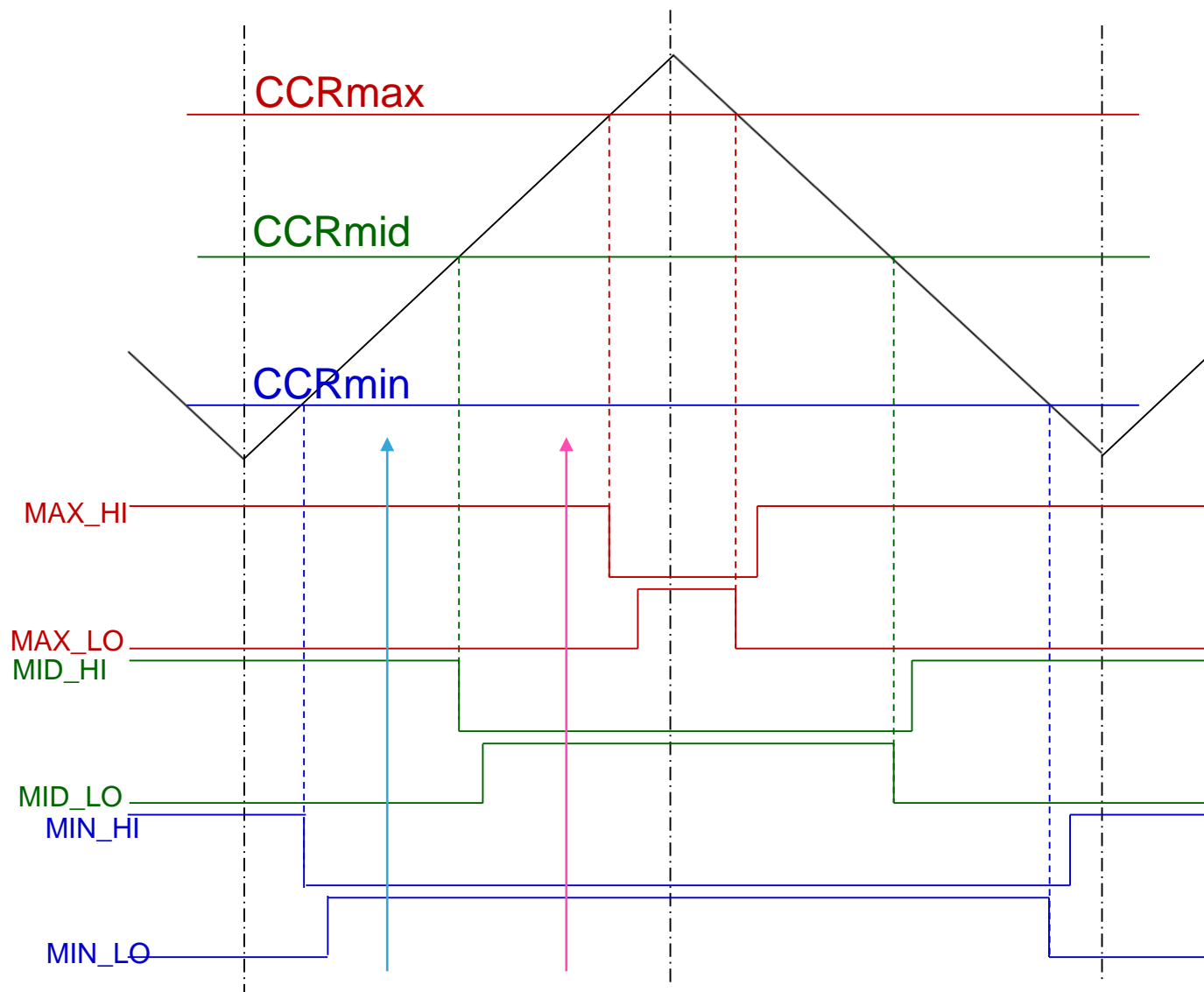


- 在一个PWM周期内采集两相电流数据
- 可根据 $I_a + I_b + I_c = 0$ 构造出三相电流



□ 空间电压矢量与单电阻检测到的信号对应的相电流的关系

Vector	A(X)	B(Y)	C(Z)	I_{shunt}
\vec{U}_0	OFF(ON)	OFF(ON)	OFF(ON)	0
\vec{U}_1	ON(OFF)	OFF(ON)	OFF(ON)	i_A
\vec{U}_2	ON(OFF)	ON(OFF)	OFF(ON)	$-i_C$
\vec{U}_3	OFF(ON)	ON(OFF)	OFF(ON)	i_B
\vec{U}_4	OFF(ON)	ON(OFF)	ON(OFF)	$-i_A$
\vec{U}_5	OFF(ON)	OFF(ON)	ON(OFF)	i_C
\vec{U}_6	ON(OFF)	OFF(ON)	ON(OFF)	$-i_B$
\vec{U}_7	ON(OFF)	ON(OFF)	ON(OFF)	0



$$T_p = T_{dead} + T_{on} + T_{ADC\ s/h} + \text{Max}(T_{ring}, T_{ADCtrigger\ delay})$$

T_p – 电流采样最小脉宽时间
 T_{dead} – 死区时间
 T_{on} – ADC启动时间
 T_{ring} – 振铃时间
 $T_{ADCtrigger\ delay}$ – ADC触发延迟时间
 $T_{ADCs/h}$ – ADC采样时间

ADC采样触发点:

第一点:

当 $T(\text{CCRmid} - \text{CCRmin}) > T_{dead} + T_{ring} + T_{ADC\ s/h}$

采样点为 $\frac{T(\text{CCRmid} + \text{CCRmin}) + T_{dead}}{2}$

否则为 $\text{TCRmid} - T_{ADCtrigger\ delay} - T_{ADC\ s/h}$

第二点:

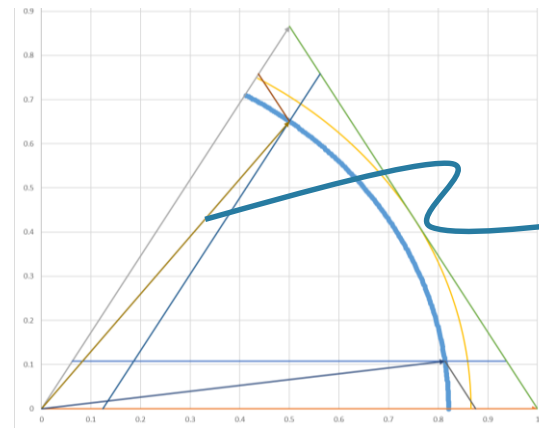
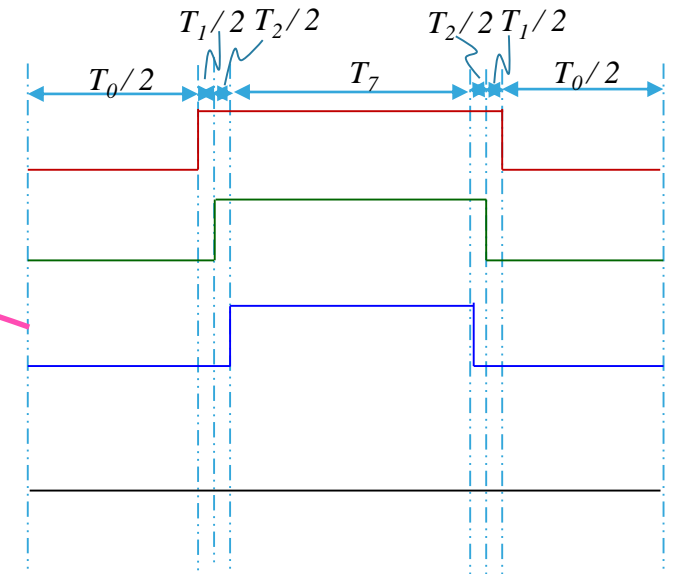
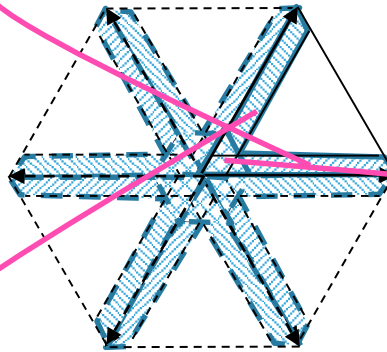
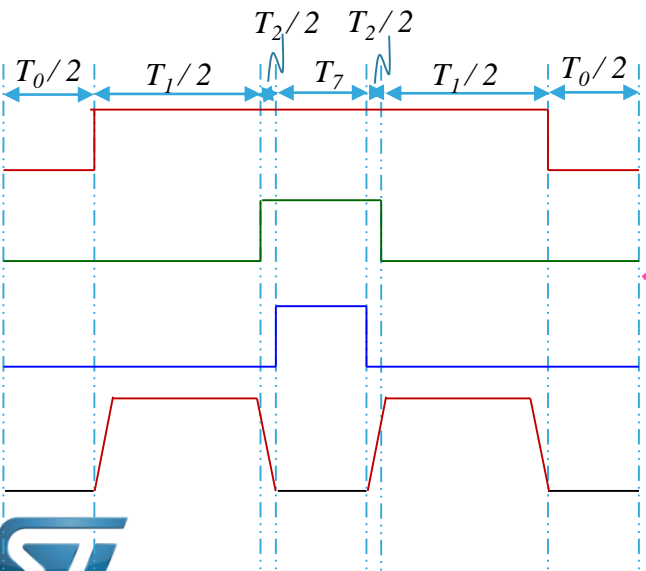
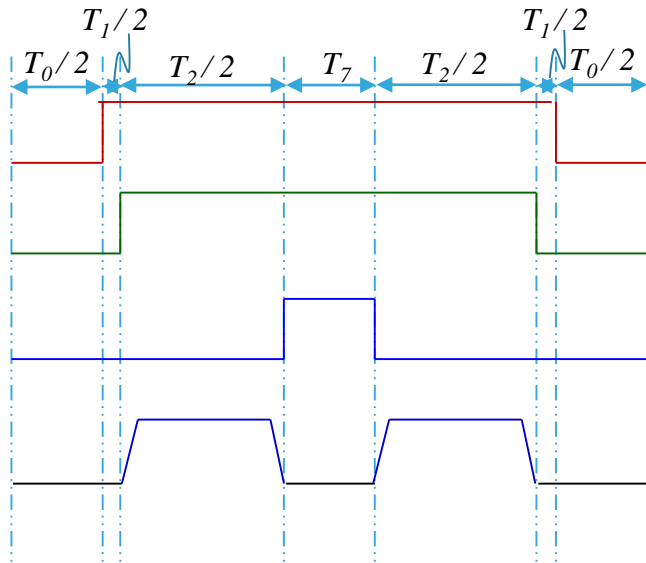
当 $T(\text{CCRmax} - \text{CCRmid}) > T_{dead} + T_{ring} + T_{ADC\ s/h}$

采样点为 $\frac{T(\text{CCRmax} + \text{CCRmid}) + T_{dead}}{2}$

否则为 $\text{TCRmax} - T_{ADCtrigger\ delay} - T_{ADC\ s/h}$

电流采样 — 单电阻(4/8)

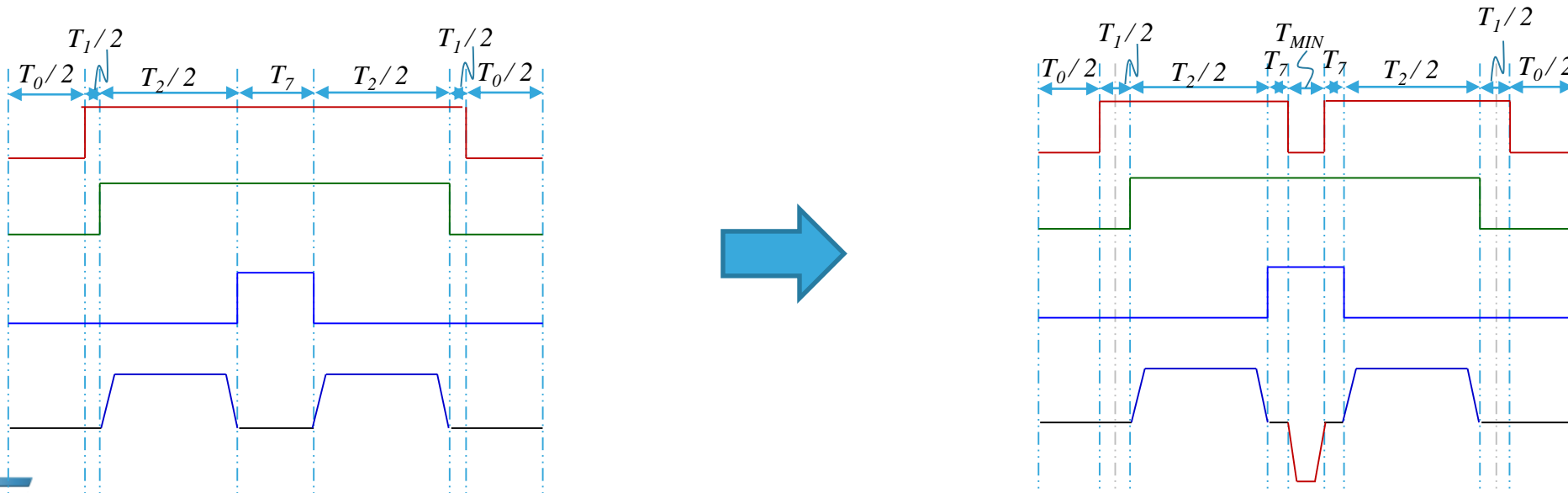
15



MMI=Max Modulation Index

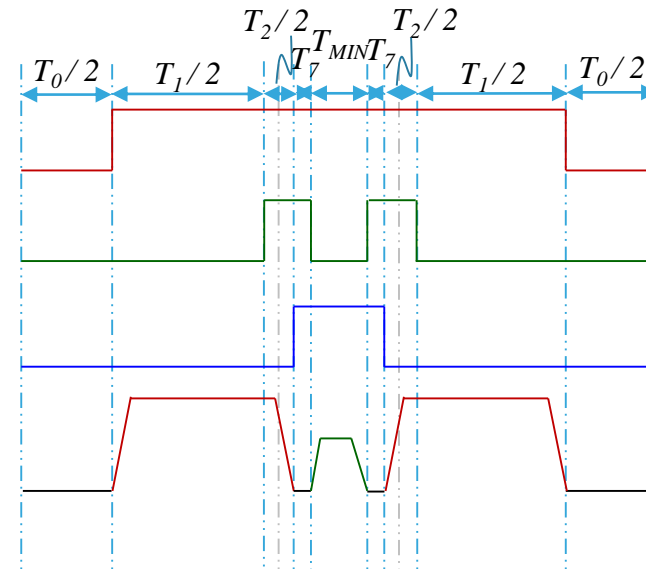
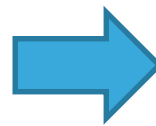
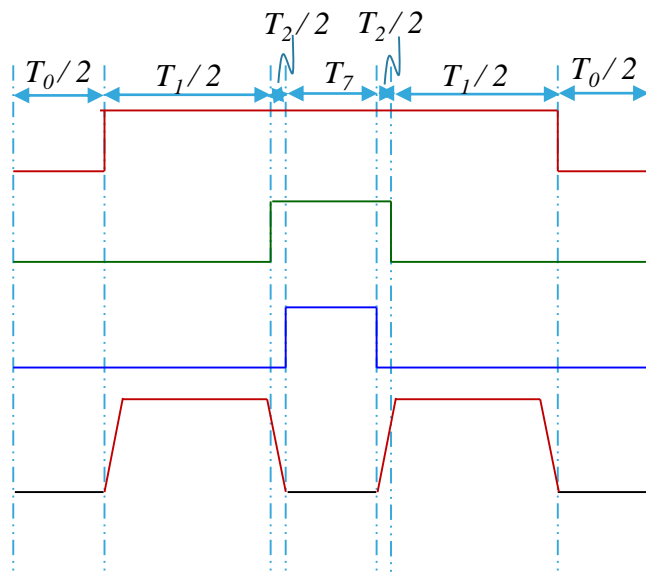
ST 专利
US20090284194 A1

ST 专利 (Pat. Pub. No.: US20090284194 A1) 解决单电阻无法采样问题



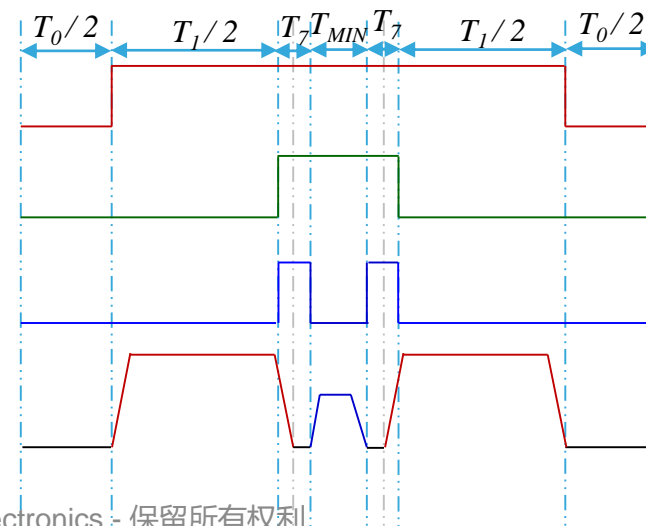
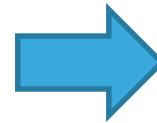
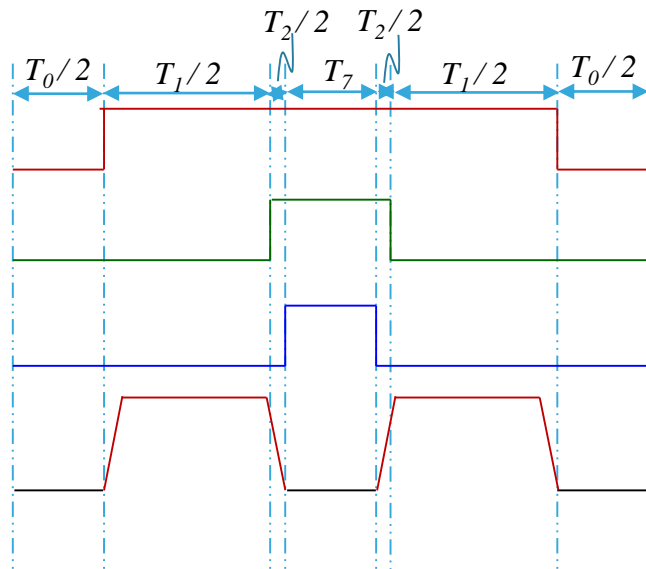
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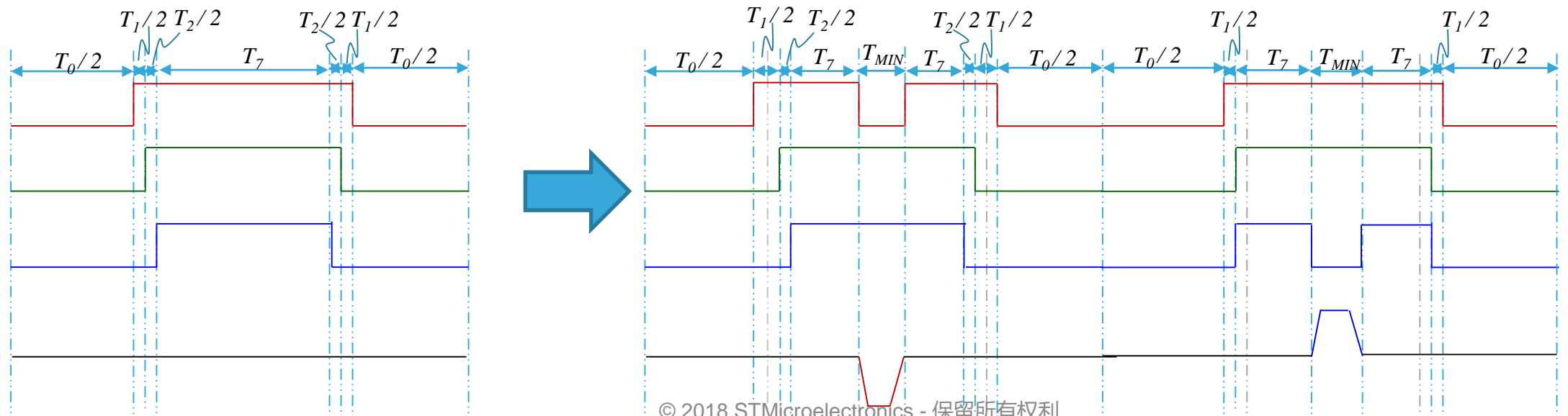
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US20090284194 A1

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ADC采样机制说明

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$t_{latr}^{(1)}$	Trigger conversion latency Regular and injected channels without conversion abort	CKMODE = 00	1.5	2	2.5	$1/f_{ADC}$
		CKMODE = 01	-	-	2	$1/f_{ADC}$
		CKMODE = 10	-	-	2.25	$1/f_{ADC}$
		CKMODE = 11	-	-	2.125	$1/f_{ADC}$
$t_{latrinj}^{(1)}$	Trigger conversion latency Injected channels aborting a regular conversion	CKMODE = 00	2.5	3	3.5	$1/f_{ADC}$
		CKMODE = 01	-	-	3	$1/f_{ADC}$
		CKMODE = 10	-	-	3.25	$1/f_{ADC}$
		CKMODE = 11	-	-	3.125	$1/f_{ADC}$

可在对应芯片数
据手册中查询到
对应参数

触发转换延迟时间

ADC采样保持时间

ADC转换时间

触发沿可选择,
触发源可选

可配置采保时间

ADC转换时间根
据ADC精度而定

上升沿

下降沿

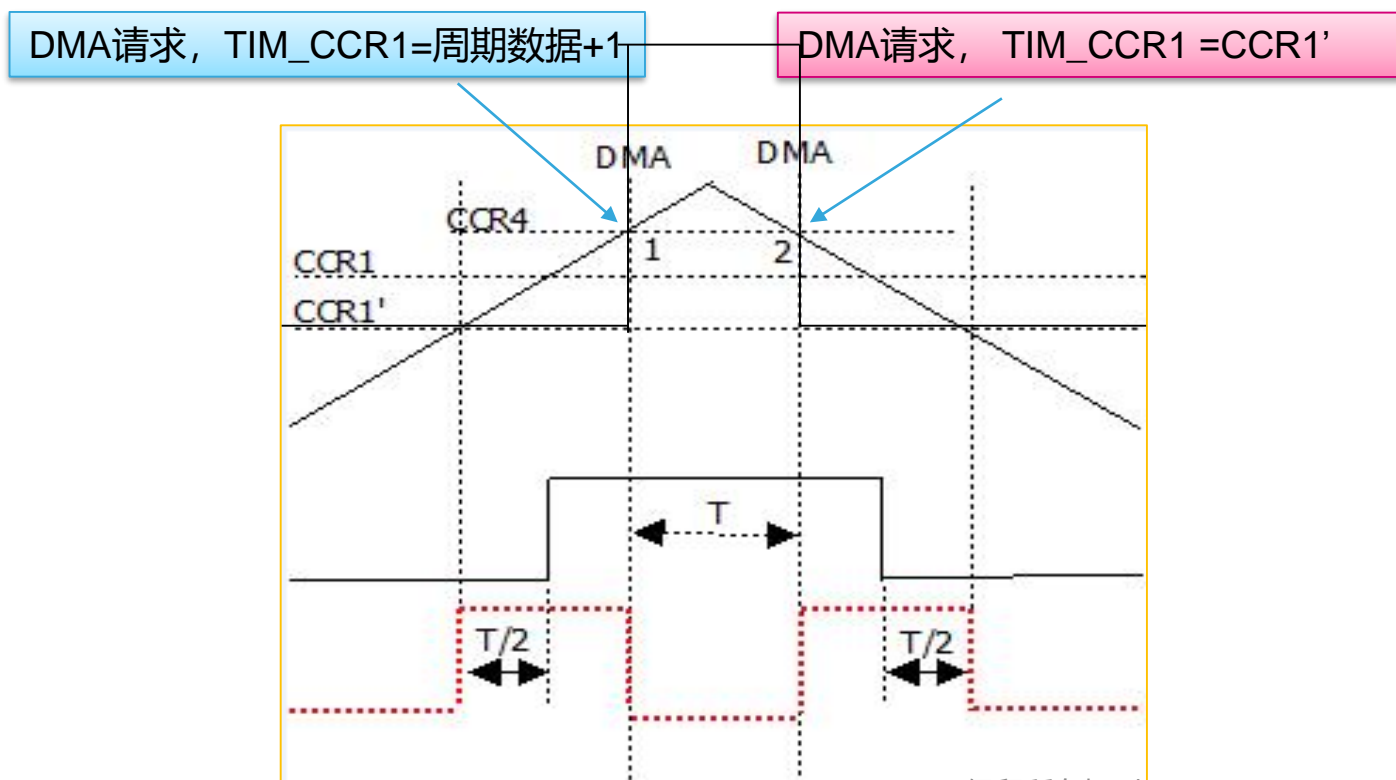
上升/下降沿

Name	Source
JEXT0	TIM1_TRGO event
JEXT1	TIM1_CC4 event
JEXT2	TIM2_TRGO event
JEXT3	TIM2_CC1 event
JEXT4	TIM3_CC4 event
JEXT5	TIM4_TRGO event
JEXT6	EXTI line 15
JEXT7	Reserved
JEXT8	TIM1_TRGO2 event
JEXT9	Reserved
JEXT10	Reserved
JEXT11	TIM3_CC3 event
JEXT12	TIM8_TRGO event

波形变形机制说明

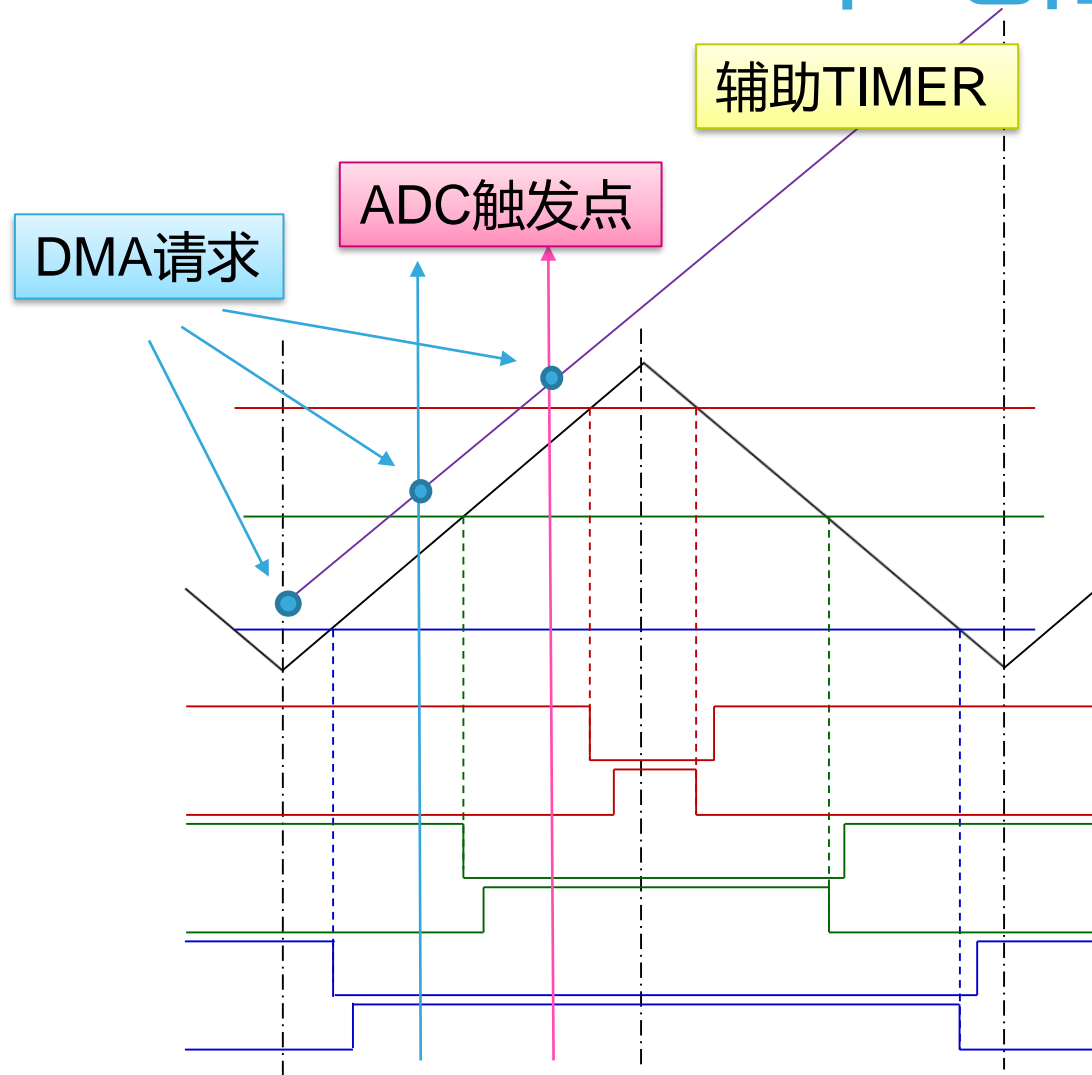
21

- $CCR4 = T_c/2 - \min Pulse/2$ 在CCR4 比较值1部分产生DMA事件; Timer1的preload为禁止状态; $CCR1 = T_c/2 + \delta$
- 在CCR4 比较值2 部分产生DMA事件; $CCR1' = CCR1 - \min Pulse/2$



单电阻ADC触发机制说明

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- 辅助TIMER（比如TIM15）与电机TIMER（如TIM1）做同步动作，同频输出；
- 配置DMA重载辅助TIMER的CCR寄存器；
- 辅助TIMER的TRGO输出用于硬件触发ADC采样；
- ADC配置为非连续模式，序列采样中断，采样两次后进入FOC处理中断中；

在STM32F3xx系列中电机TIMER有自带的机制可以灵活配置

ST MC SDK5.x 单电阻采样固件

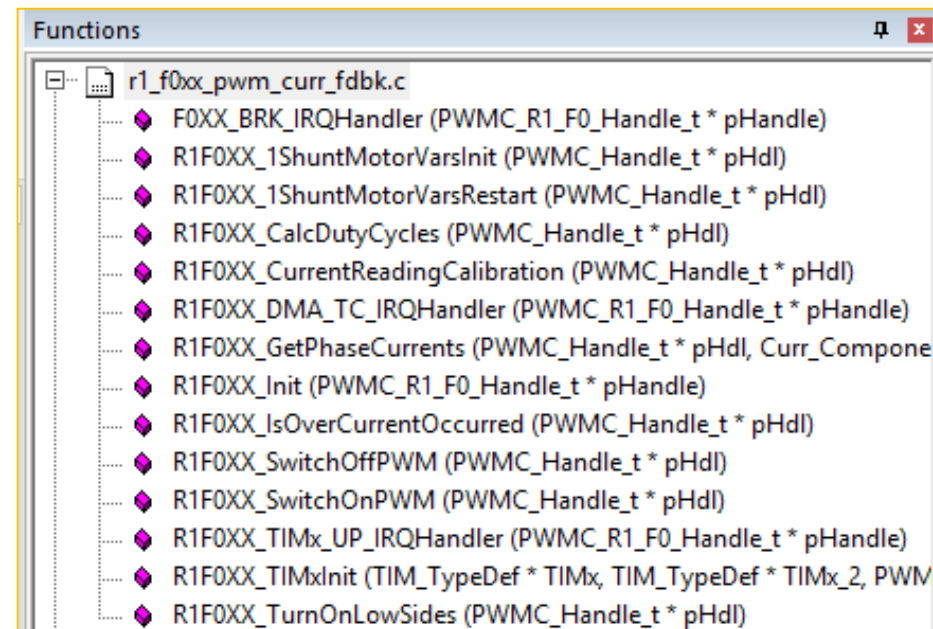
23

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- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F3xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F4xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F7xx\Src
- ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\L4xx\Src

➤ 文件名称

- ✓ r1_**y**xx_pwm_curr_fdbk.c
- ✓ y=f0, f1, f3, f4, f7, l4





转子位置、速度信息的获取

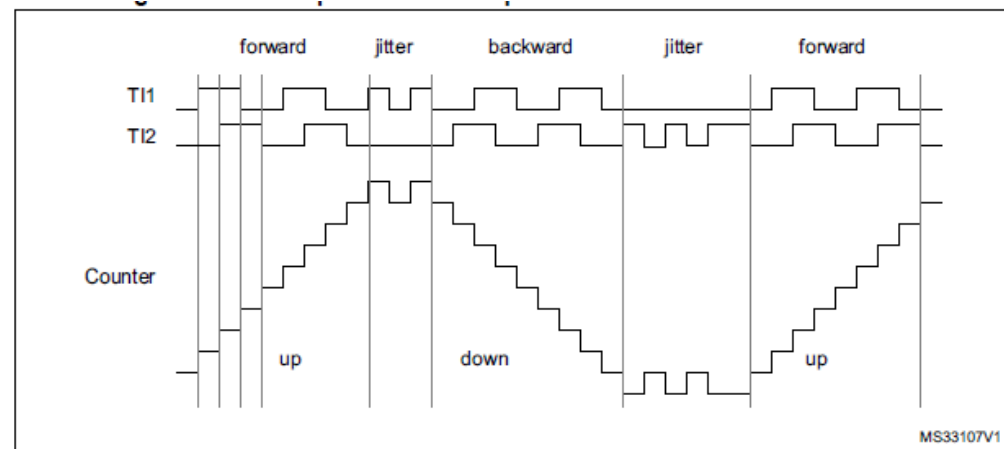
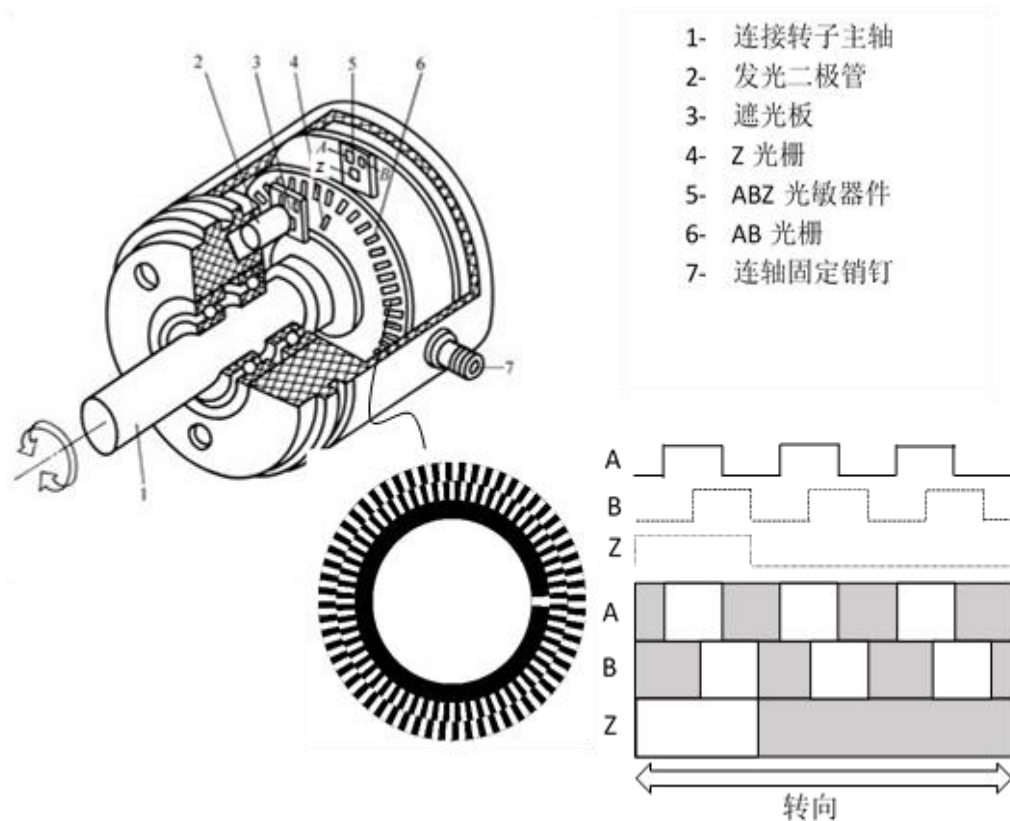
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□ 转子位置、速度信息的获取

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位置速度检测 — Encoder 25

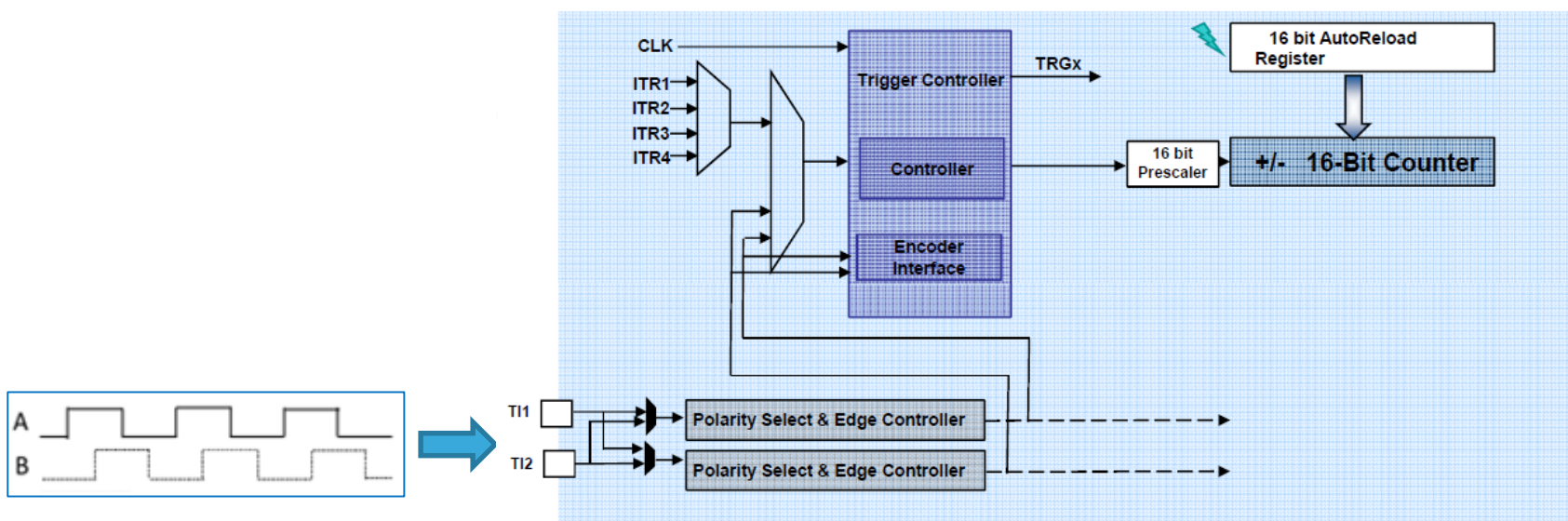


- 使用增量编码器时，在第一次电机启动，任意保护停止或者MCU复位后都要进行预定位操作。
- Z信号（一圈一个）可以使用外部中断或者外部Timer捕捉模式，代表编码器的0度位置，可以用于校准角度位置，可以使用DMA模式对编码器模块赋值；

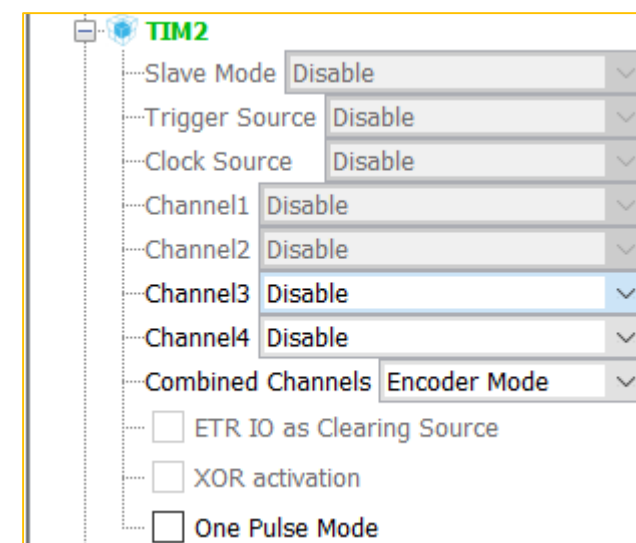
STM32硬件Encoder接口

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- 在全系列STM32中都有硬件增量编码器Encoder接口
- 每个正交沿都可为加/减计数



CubeMx中的配置



ST MC SDK5.x Encoder固件

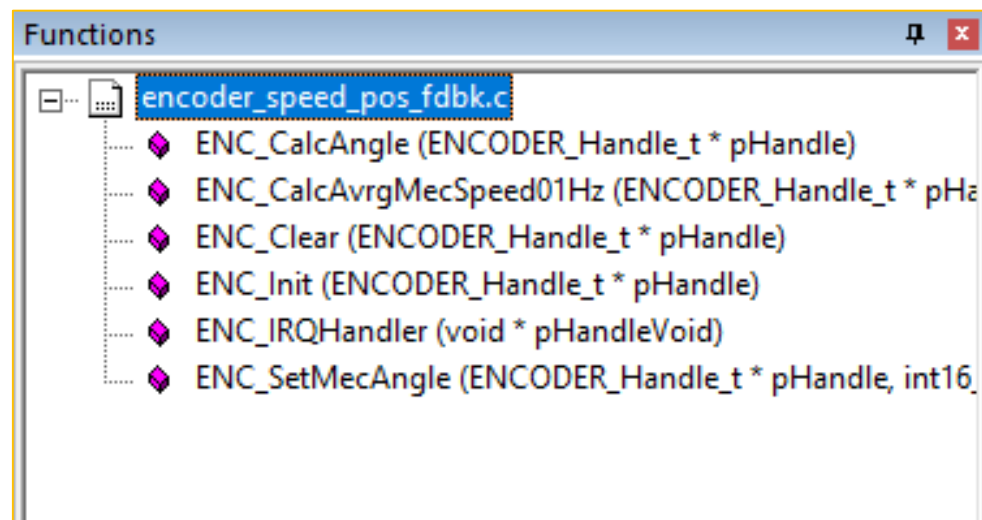
27

➤ 具体文件夹如下:

✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\Any\Src

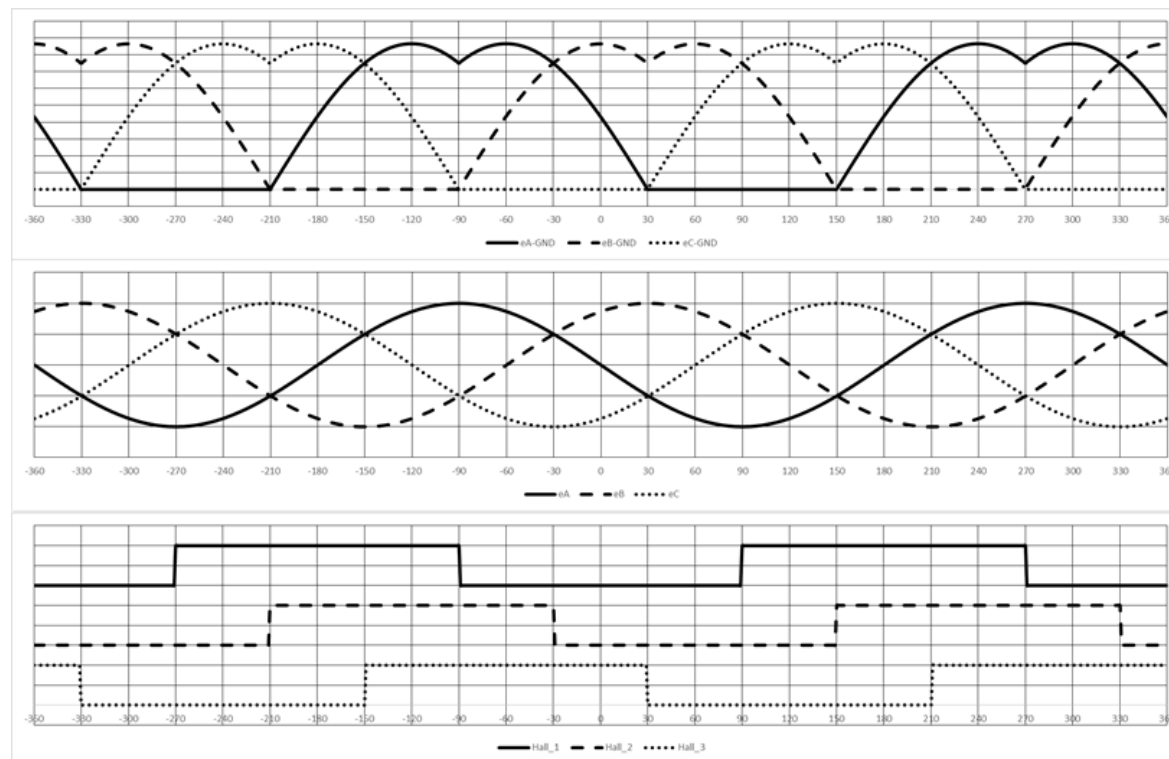
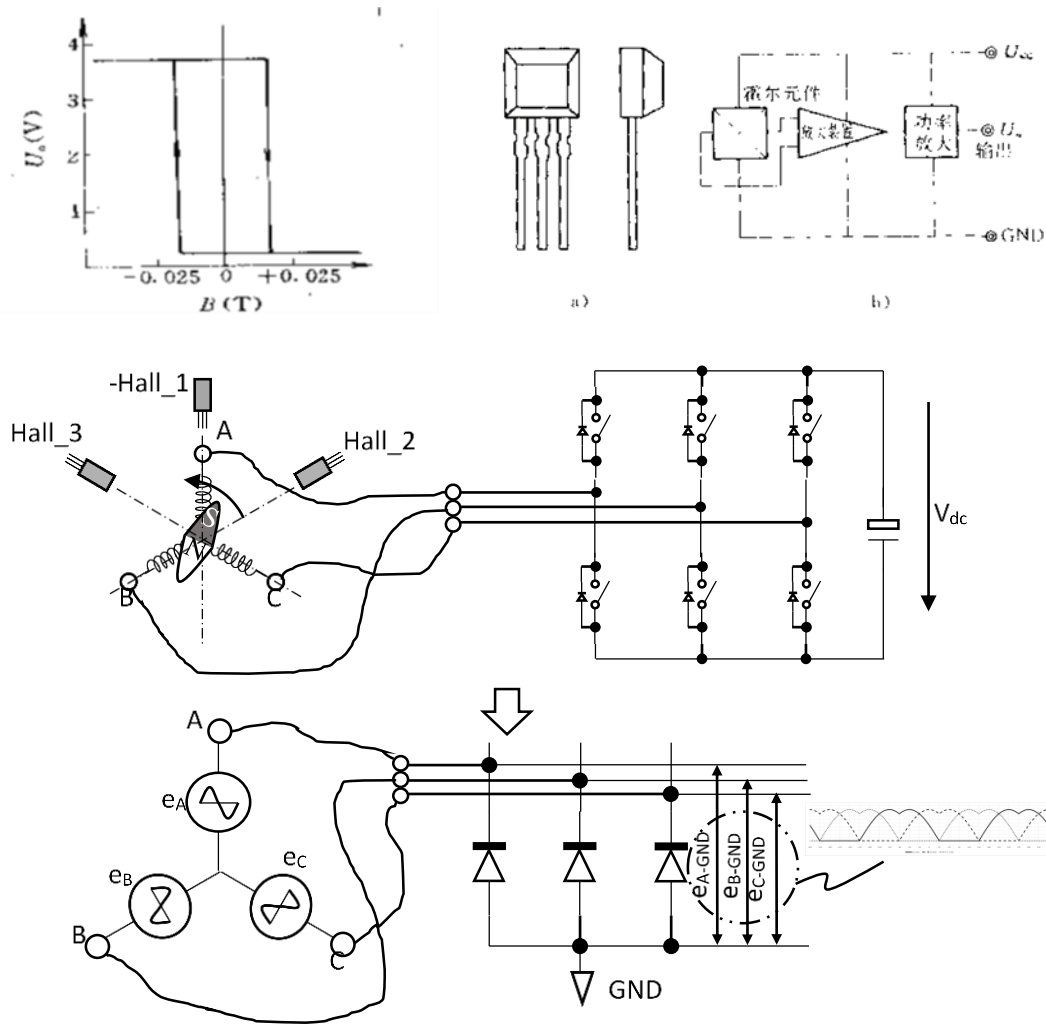
➤ 文件名称

✓ encoder_speed_pos_fdbk.c



位置速度检测 — Hall传感器

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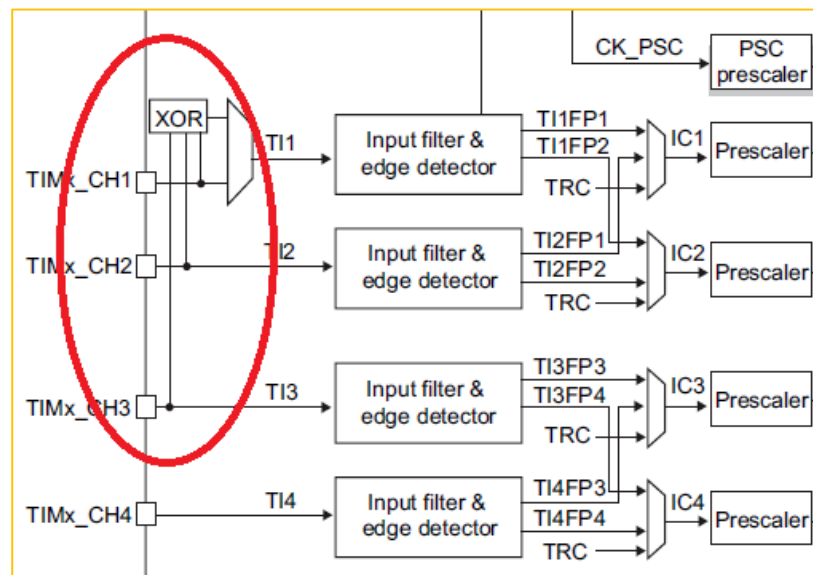
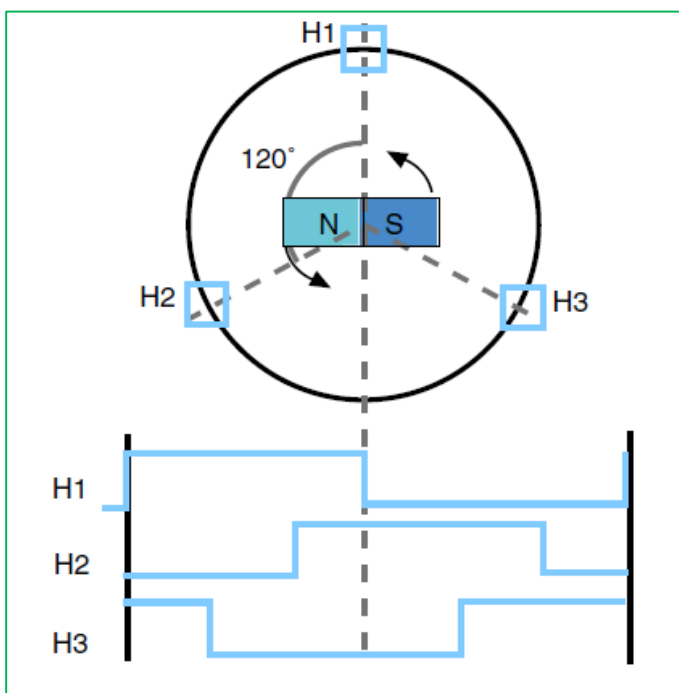


对于60度的Hall信号，可以任意调换三个信号中的任意一个即可得到和120度的处理相似，我们可以很方便使用软件处理。

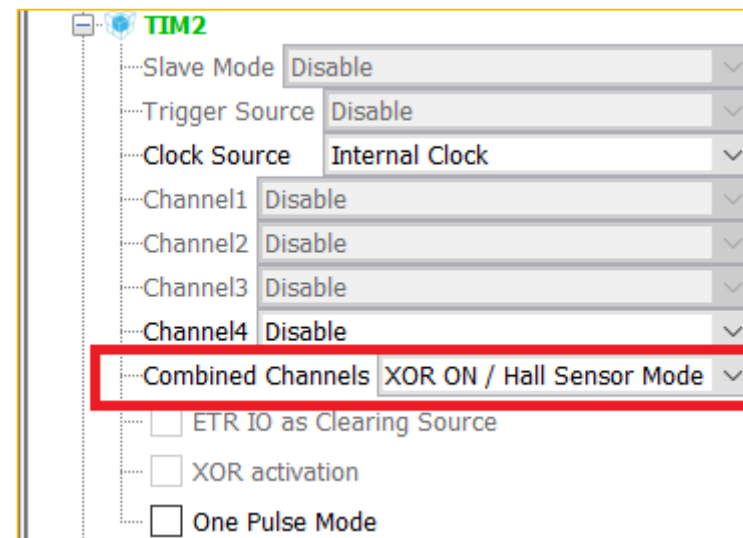
STM32硬件Hall接口

29

- 在全系列STM32中都有硬件Hall接口(XOR输入)
- 可以每个Hall跳变沿都产生中断



CubeMx中的配置



ST MC SDK5.x Hall传感器固件

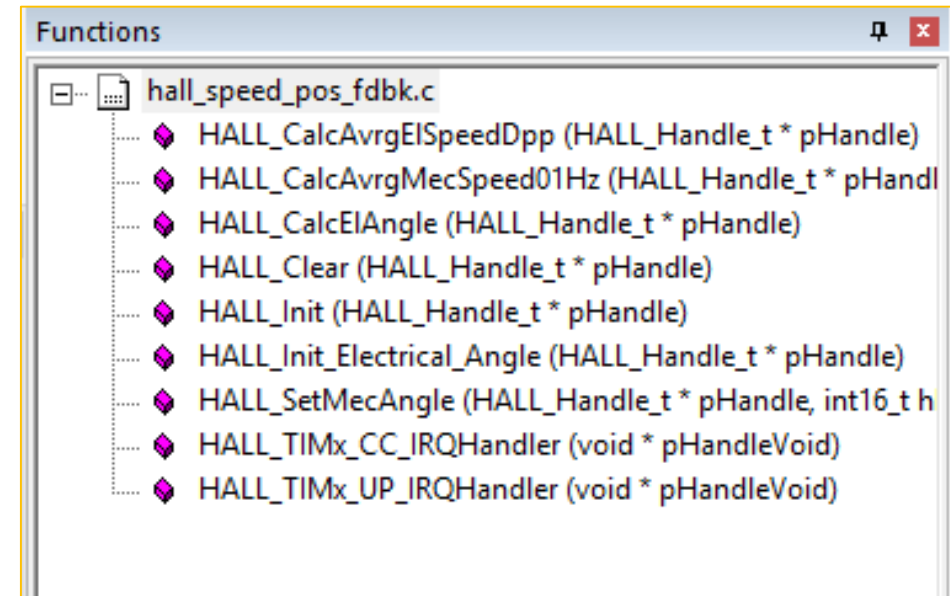
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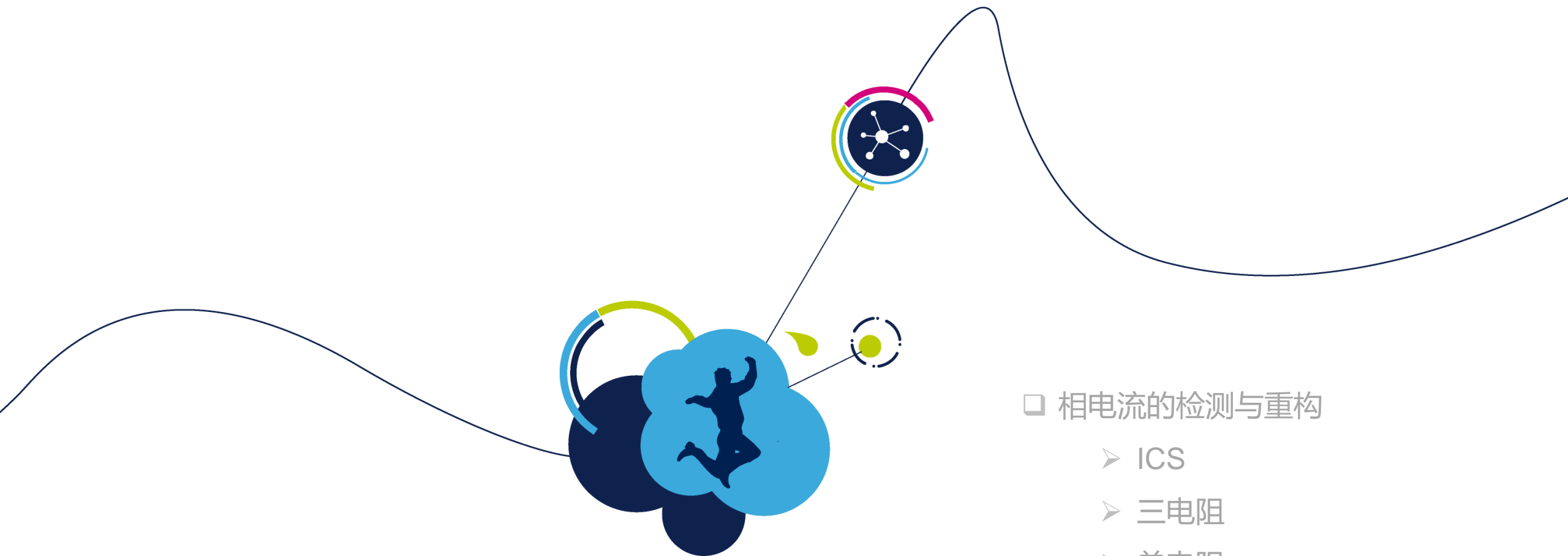
➤ 具体文件夹如下:

✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\Any\Src

➤ 文件名称

✓ hall_speed_pos_fdbk.c





转子位置、速度信息的获取

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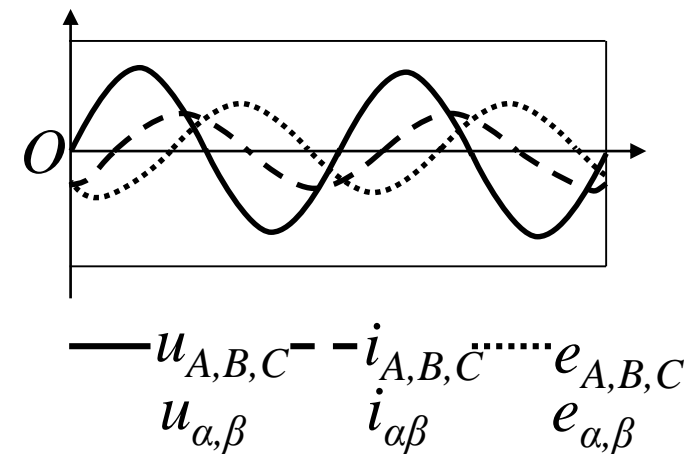
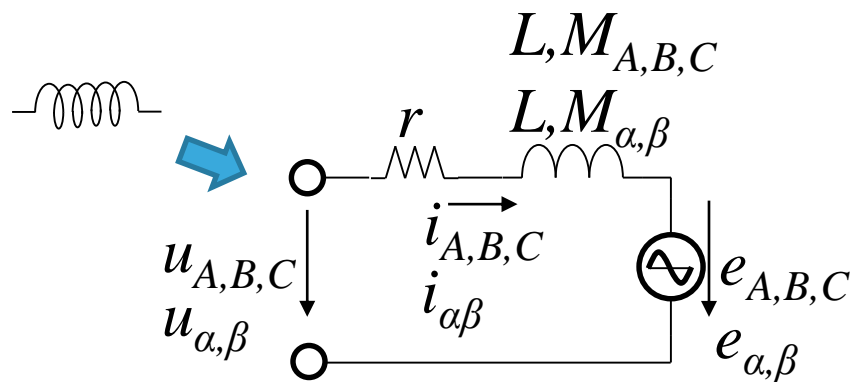
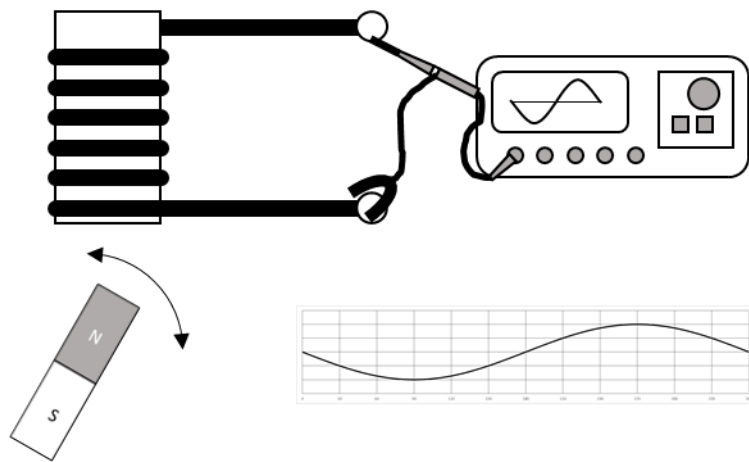
- ICS
- 三电阻
- 单电阻

□ 转子位置、速度信息的获取

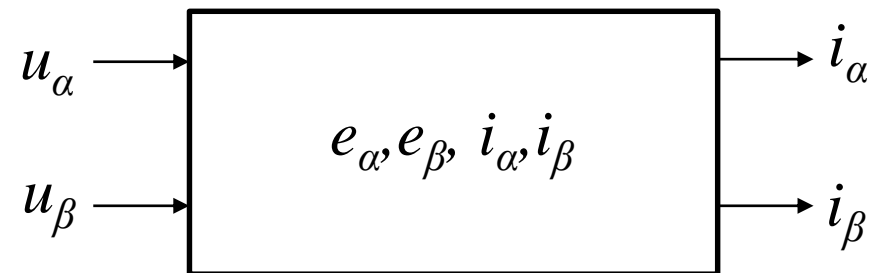
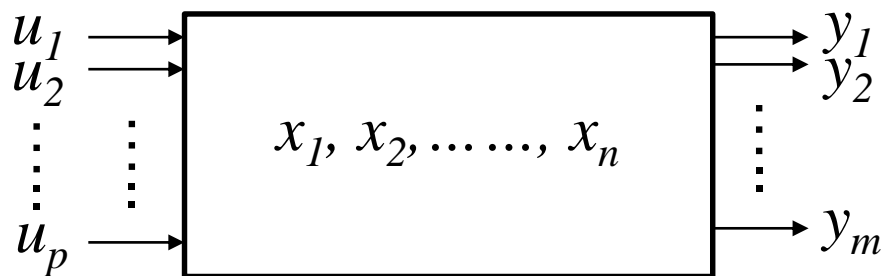
- 有位置传感器
- 无位置速度传感器

位置速度检测 — 观测器(1/13)

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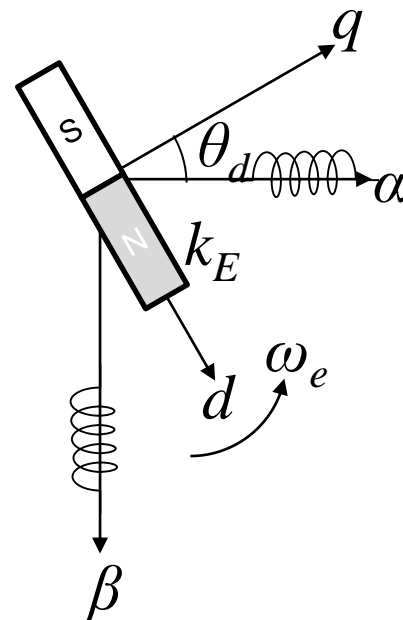
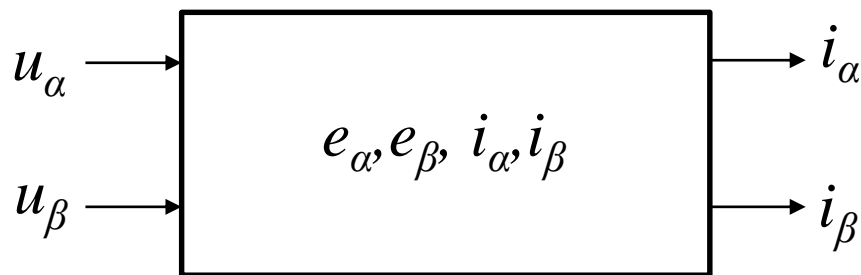
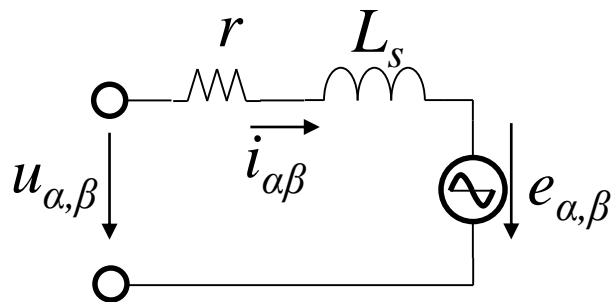


$$u \rightarrow i (\tau_e) \rightarrow \omega_r, \omega_e = p \cdot \omega_r \rightarrow e$$



位置速度检测 — 观测器(2/13)

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$$\begin{cases} e_{\alpha} = k_E \omega_e \cos(\omega_e t) \\ e_{\beta} = -k_E \omega_e \sin(\omega_e t) \end{cases}$$

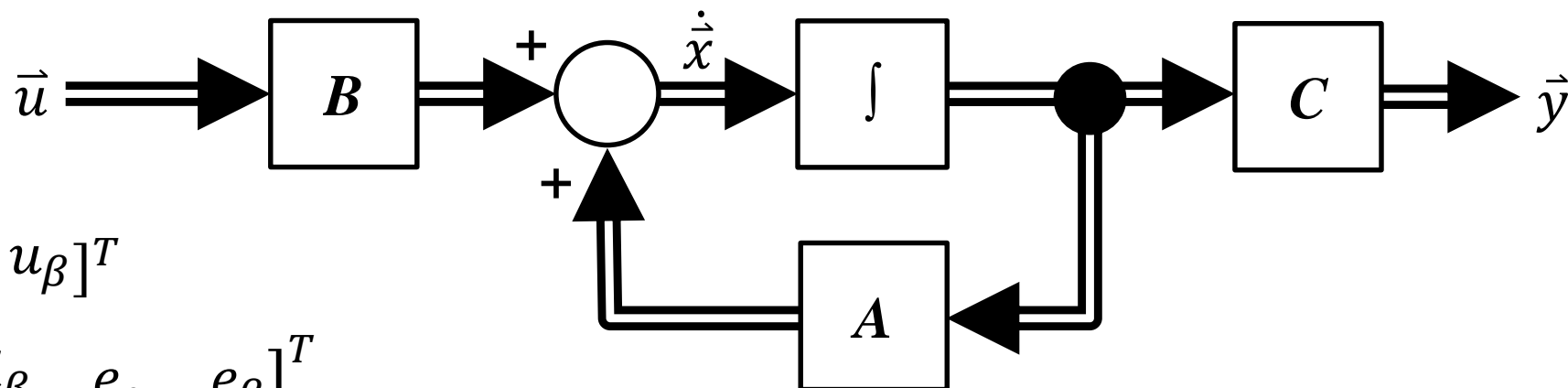
A linear model



$$\begin{cases} \frac{di_{\alpha}}{dt} = -\frac{r}{L_s} i_{\alpha} - \frac{e_{\alpha}}{L_s} + \frac{u_{\alpha}}{L_s} \\ \frac{di_{\beta}}{dt} = -\frac{r}{L_s} i_{\beta} - \frac{e_{\beta}}{L_s} + \frac{u_{\beta}}{L_s} \\ \frac{de_{\alpha}}{dt} = \omega_e e_{\beta} \\ \frac{de_{\beta}}{dt} = -\omega_e e_{\alpha} \end{cases}$$

位置速度检测 — 观测器(3/13)

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$$\vec{u} = [u_\alpha \quad u_\beta]^T$$

$$\vec{x} = [i_\alpha \quad i_\beta \quad e_\alpha \quad e_\beta]^T$$

$$\dot{\vec{x}} = \left[\frac{di_\alpha}{dt} \quad \frac{di_\beta}{dt} \quad \frac{de_\alpha}{dt} \quad \frac{de_\beta}{dt} \right]^T$$

$$\vec{y} = [i_\alpha \quad i_\beta]^T$$

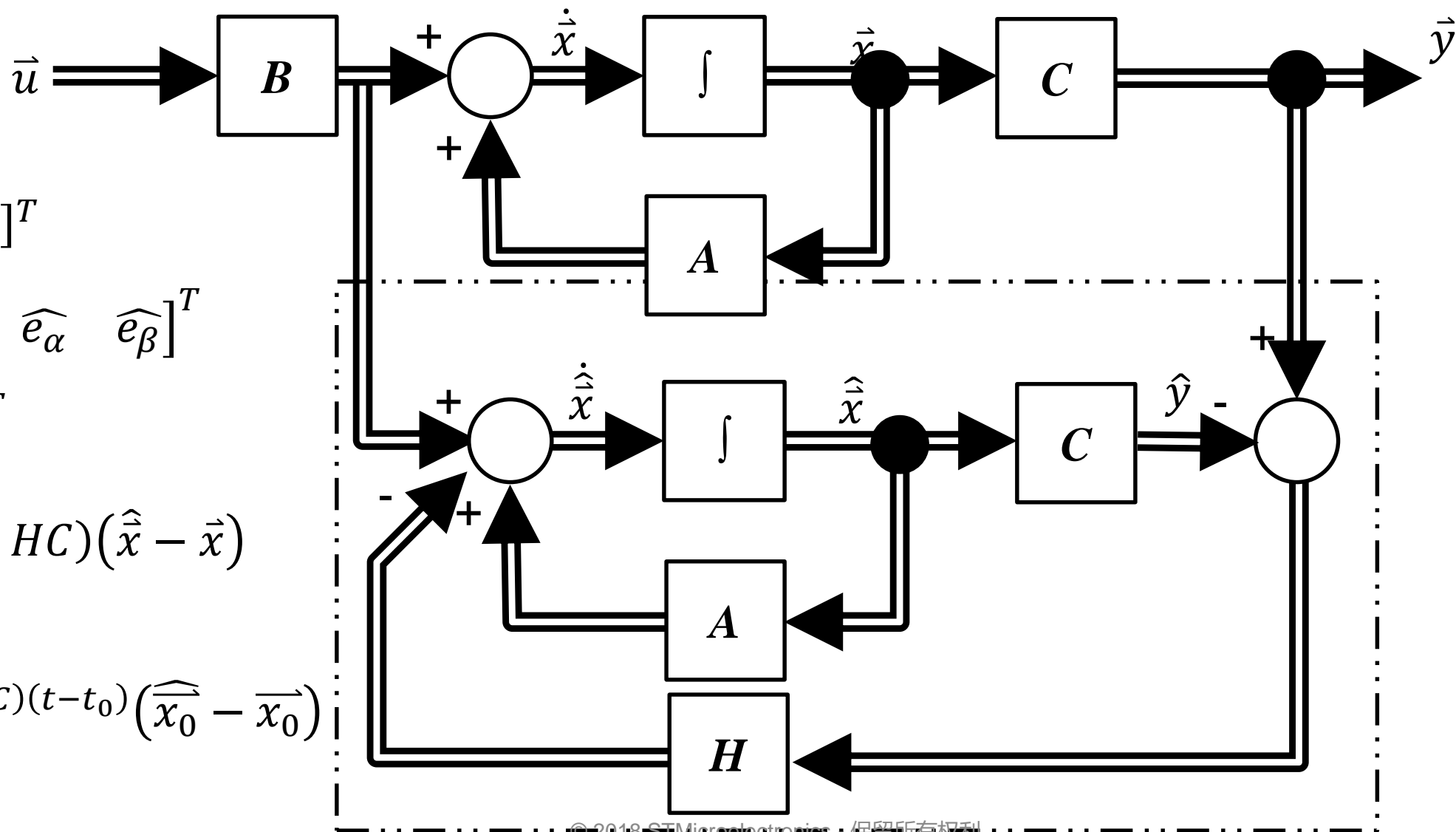
$$\begin{cases} \dot{\vec{x}} = A\vec{x} + B\vec{u} \\ \vec{y} = C\vec{x} \end{cases}$$

$$A = \begin{bmatrix} -\frac{r}{L_s} & 0 & -\frac{1}{L_s} & 0 \\ 0 & -\frac{r}{L_s} & 0 & -\frac{1}{L_s} \\ 0 & 0 & 0 & \omega_e \\ 0 & 0 & -\omega_e & 0 \end{bmatrix} \quad B = \begin{bmatrix} -\frac{1}{L_s} & 0 \\ 0 & -\frac{1}{L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

位置速度检测 — 观测器(4/13)

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$$\vec{u} = [u_\alpha \quad u_\beta]^T$$

$$\hat{\vec{x}} = [\hat{i}_\alpha \quad \hat{i}_\beta \quad \hat{e}_\alpha \quad \hat{e}_\beta]^T$$

$$\hat{y} = [\hat{i}_\alpha \quad \hat{i}_\beta]^T$$

$$\dot{\hat{\vec{x}}} - \dot{\vec{x}} = (A + HC)(\hat{\vec{x}} - \vec{x})$$



$$\hat{\vec{x}} - \vec{x} = e^{(A+HC)(t-t_0)}(\hat{\vec{x}}_0 - \vec{x}_0)$$

位置速度检测 — 观测器(5/13)

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$$\begin{cases} \dot{\vec{x}} = A\vec{x} + B\vec{u} \\ \vec{y} = C\vec{x} \end{cases} \xrightarrow{\text{离散化}} \begin{cases} \frac{\vec{x}[k] - \vec{x}[k-1]}{T_s} = A\vec{x}[k-1] + B\vec{u}[k-1] \\ \vec{y}[k] = C\vec{x}[k] \end{cases}$$

$$\begin{cases} i_\alpha[k] = \left(1 - \frac{rT_s}{L_s}\right) i_\alpha[k-1] - \frac{T_s}{L_s} e_\alpha[k-1] + \frac{T_s}{L_s} u_\alpha \\ i_\beta[k] = \left(1 - \frac{rT_s}{L_s}\right) i_\beta[k-1] - \frac{T_s}{L_s} e_\beta[k-1] + \frac{T_s}{L_s} u_\beta \\ e_\alpha[k] = e_\alpha[k-1] + \omega_e e_\beta[k-1] T_s \\ e_\beta[k] = e_\beta[k-1] - \omega_e e_\alpha[k-1] T_s \end{cases}$$

位置速度检测 — 观测器(6/13)

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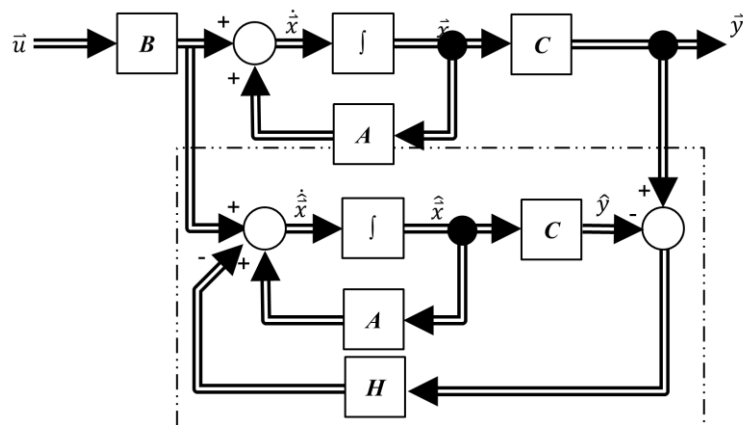
去耦(认为 $\omega_e=0$) 将简化马达模型

$$\begin{cases} i_\alpha[k] = \left(1 - \frac{rT_s}{L_s}\right) i_\alpha[k-1] - \frac{T_s}{L_s} e_\alpha[k-1] + \frac{T_s}{L_s} u_\alpha \\ e_\alpha[k] = e_\alpha[k-1] \end{cases}$$

$$A_{reduced} = \begin{bmatrix} 1 - \frac{rT_s}{L_s} & -\frac{T_s}{L_s} \\ 0 & 1 \end{bmatrix} \xrightarrow[\quad |\lambda I - A| = 0 \quad]{\text{特征值}} \begin{cases} \lambda_1 = 1 - \frac{rT_s}{L_s} \\ \lambda_2 = 1 \end{cases}$$

位置速度检测 — 观测器(7/13)

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$$\dot{\hat{x}} = A\hat{x} + B\bar{u} + H(\hat{y} - \vec{y}) \quad H = \begin{bmatrix} h_1 & 0 \\ 0 & h_1 \\ h_2 & 0 \\ 0 & h_2 \end{bmatrix}$$

$$\begin{cases} \hat{i}_\alpha[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right) \hat{i}_\alpha[k-1] - \frac{T_s}{L_s} \hat{e}_\alpha[k-1] + \frac{T_s}{L_s} u_\alpha[k-1] + h_1T_s(-i_\alpha[k-1]) \\ \hat{i}_\beta[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right) \hat{i}_\beta[k-1] - \frac{T_s}{L_s} \hat{e}_\beta[k-1] + \frac{T_s}{L_s} u_\beta[k-1] + h_1T_s(-i_\beta[k-1]) \\ \hat{e}_\alpha[k] = \hat{e}_\alpha[k-1] + T_s\omega_e \hat{e}_\beta[k-1] + h_2T_s(\hat{i}_\alpha[k-1] - i_\alpha[k-1]) \\ \hat{e}_\beta[k] = \hat{e}_\beta[k-1] - T_s\omega_e \hat{e}_\alpha[k-1] + h_2T_s(\hat{i}_\beta[k-1] - i_\beta[k-1]) \end{cases}$$

位置速度检测 — 观测器(8/13)

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去耦(设定 $\omega_e=0$) 简化观测器模型

$$\begin{cases} \hat{i}_\alpha[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right) \hat{i}_\alpha[k-1] - \frac{T_s}{L_s} \hat{e}_\alpha[k-1] + \frac{T_s}{L_s} u_\alpha[k-1] + h_1T_s(-i_\alpha[k-1]) \\ \hat{e}_\alpha[k] = \hat{e}_\alpha[k-1] + h_2T_s(\hat{i}_\alpha[k-1] - i_\alpha[k-1]) \end{cases}$$

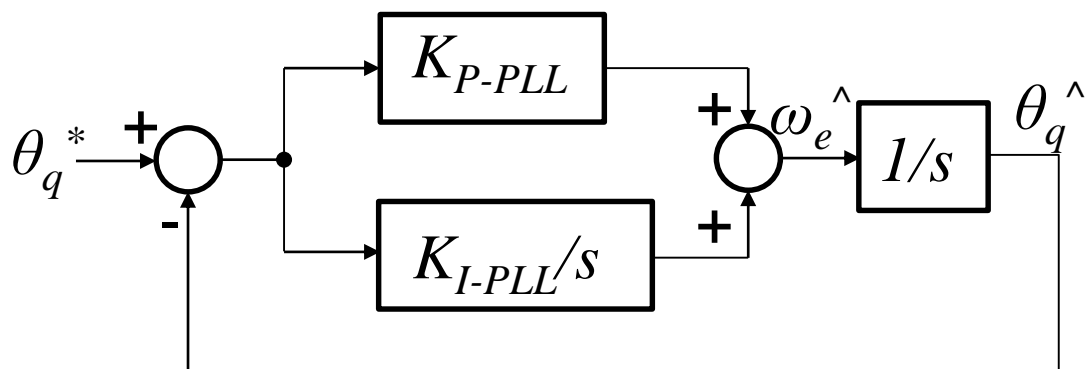
$$A_{reduced-obs} = \begin{bmatrix} 1 - \frac{rT_s}{L_s} + h_1T_s & -\frac{T_s}{L_s} \\ h_2T_s & 1 \end{bmatrix} \quad \begin{cases} \lambda_{1-obs} = \frac{\lambda_1}{k} \\ \lambda_{2-obs} = \frac{\lambda_2}{k} \end{cases} \quad k > 1$$

$$|\lambda I - A_{reduced-obs}| = (\lambda - \lambda_{1-obs})(\lambda - \lambda_{2-obs})$$

$$\begin{cases} h_1 = \frac{\lambda_{1-obs} + \lambda_{2-obs} - 2}{T_s} + \frac{r}{L_s} \\ h_2 = \frac{L_s(1 - \lambda_{1-obs} - \lambda_{2-obs} + \lambda_{1-obs}\lambda_{2-obs})}{T_s^2} \end{cases}$$

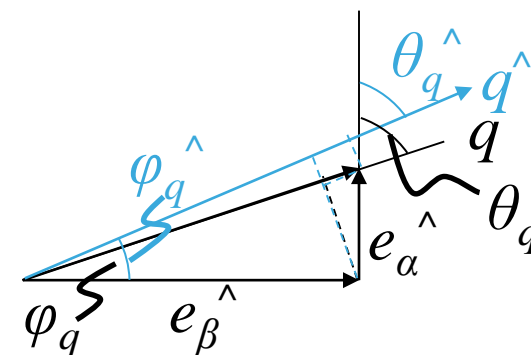
位置速度检测 — 观测器(9/13)

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$$G(s) = \frac{Ts + 1}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$\begin{cases} K_{P-PLL} = \omega_n \\ K_{I-PLL} = \frac{K_{P-PLL}\omega_n}{(2\zeta)^2} \end{cases}$$



$$e = k_E \omega_e = \sqrt{e_{\alpha}^2 + e_{\beta}^2}$$

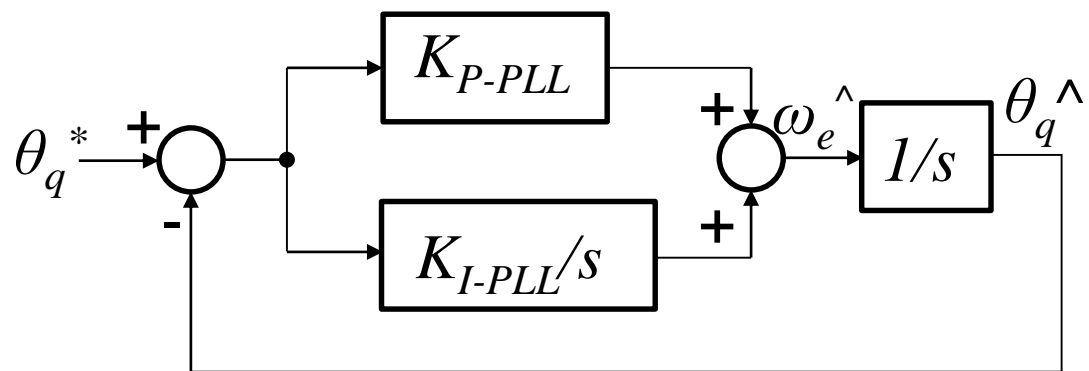
$$e \cdot \sin(\theta_q^{\wedge} - \theta_q) = e_{\beta} \cos(\theta_q^{\wedge}) - e_{\alpha} \sin(\theta_q^{\wedge})$$

↓ 如果 $\theta_q^{\wedge} - \theta_q$ 比较小

$$\theta_q^{\wedge} - \theta_q \approx (e_{\beta} \cos(\theta_q^{\wedge}) - e_{\alpha} \sin(\theta_q^{\wedge})) / (k_E \omega_e)$$

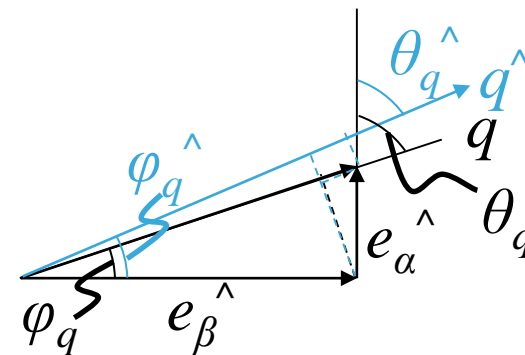
位置速度检测 — 观测器(10/13)

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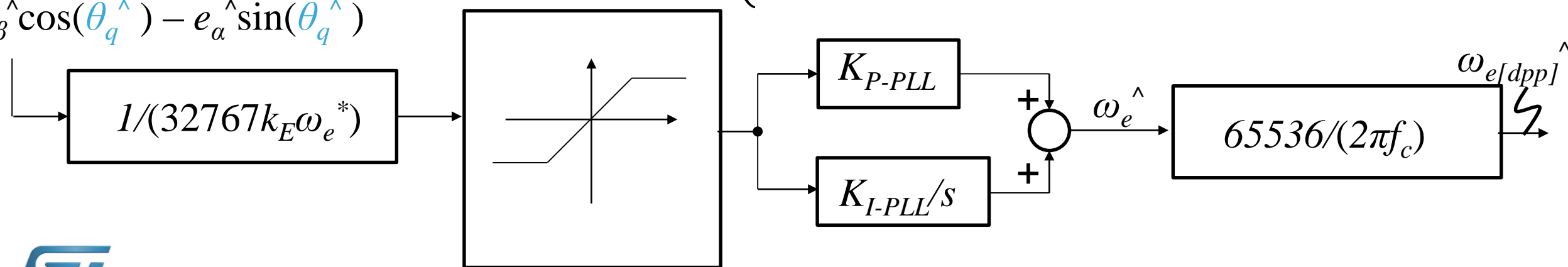


$$e = \sqrt{e_{\alpha}^{\wedge 2} + e_{\beta}^{\wedge 2}} = k_E \omega_e^*$$

$$\begin{cases} K_{P-PLL} = \omega_n \\ K_{I-PLL} = \frac{K_{P-PLL} \omega_n}{(2\zeta)^2} \end{cases}$$

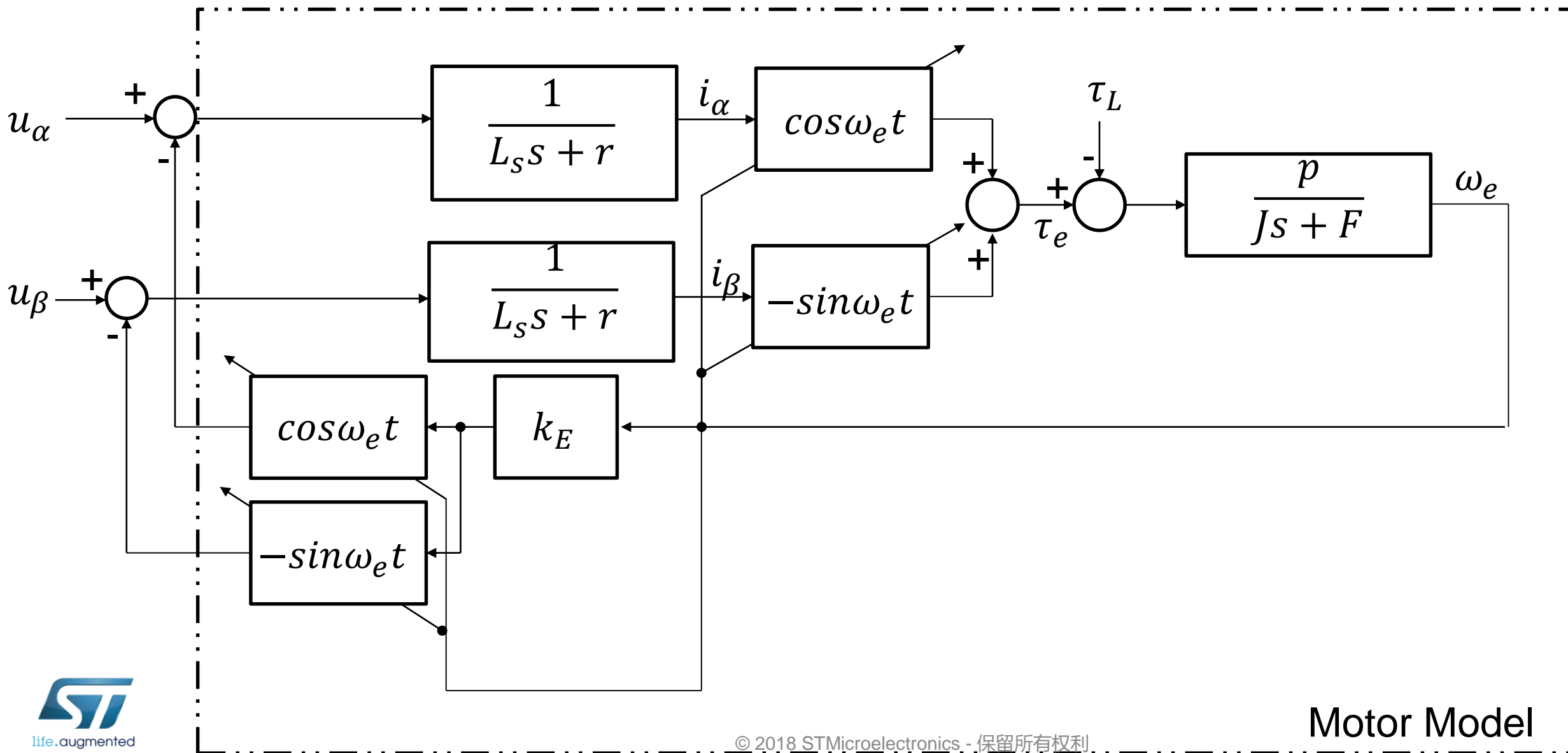


$$e_{\beta}^{\wedge} \cos(\theta_q^{\wedge}) - e_{\alpha}^{\wedge} \sin(\theta_q^{\wedge})$$



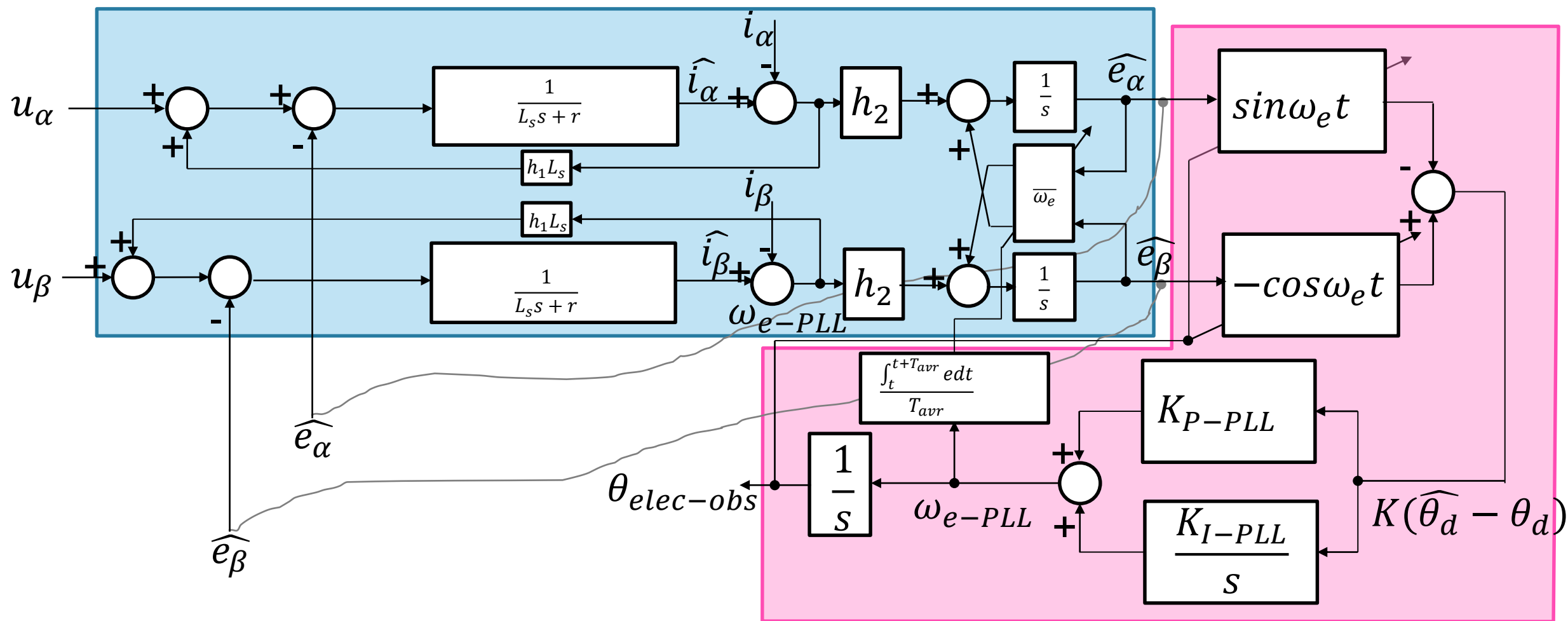
位置速度检测 — 观测器(11/13)

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位置速度检测 — 观测器(12/13)

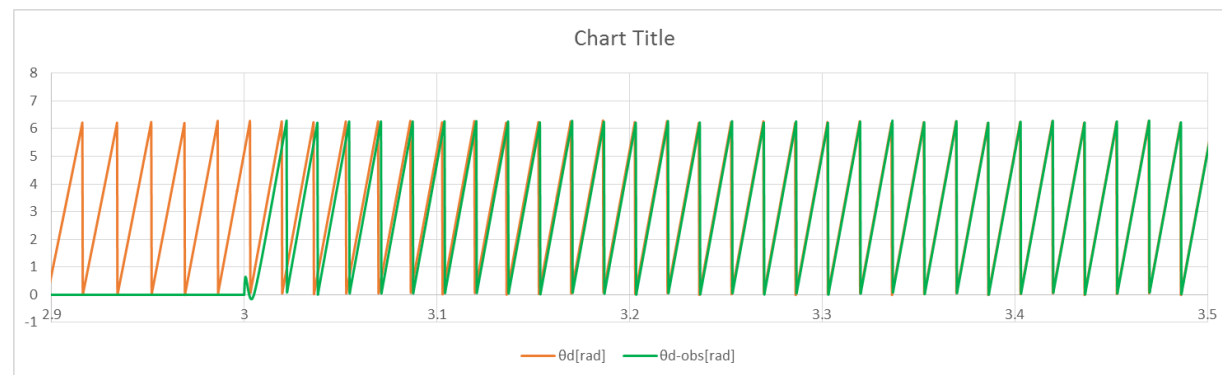
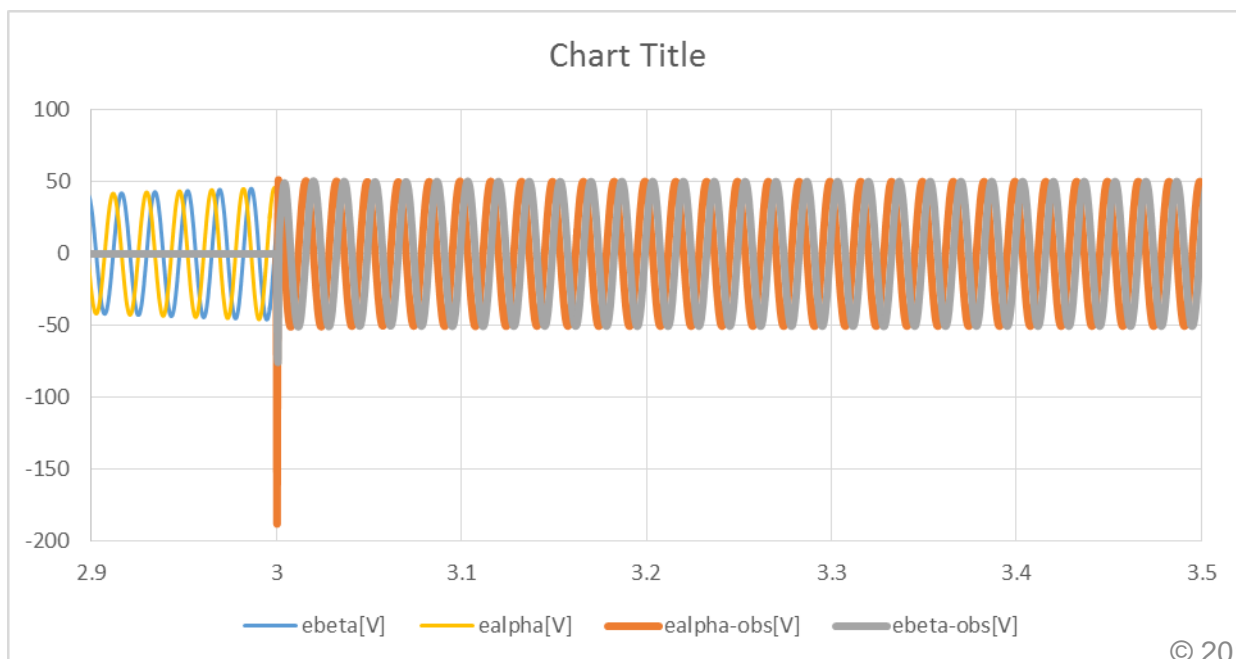
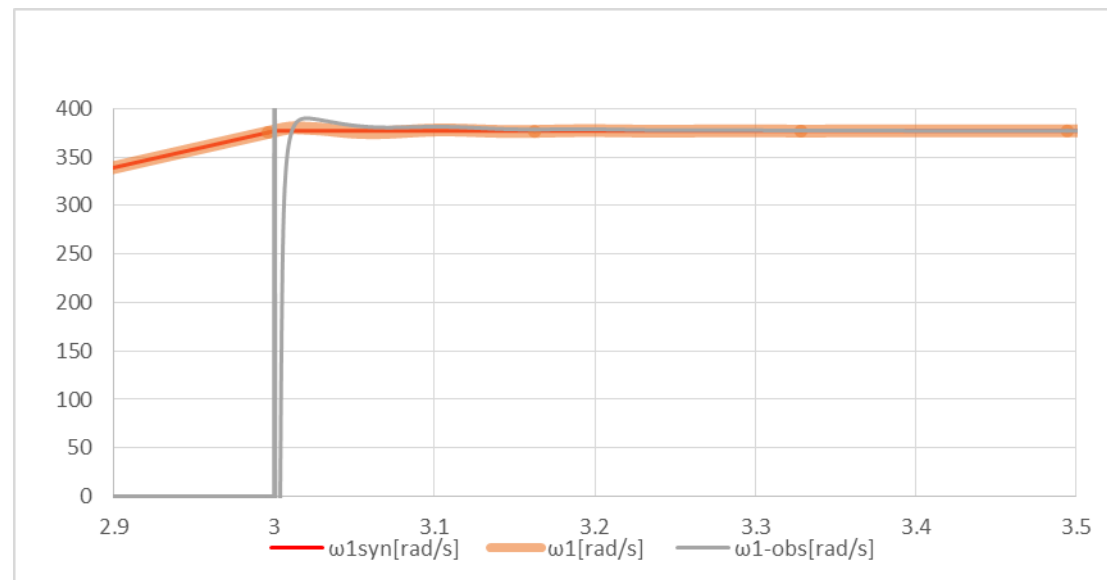
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位置速度检测 — 观测器(13/13)

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$$\begin{cases} \hat{i}_\alpha[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right) \hat{i}_\alpha[k-1] - \frac{T_s}{L_s} \hat{e}_\alpha[k-1] + \frac{T_s}{L_s} u_\alpha[k-1] + h_1T_s i_\alpha[k-1] \\ \hat{i}_\beta[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right) \hat{i}_\beta[k-1] - \frac{T_s}{L_s} \hat{e}_\beta[k-1] + \frac{T_s}{L_s} u_\beta[k-1] + h_1T_s i_\beta[k-1] \\ \hat{e}_\alpha[k] = \hat{e}_\alpha[k-1] + T_s \bar{\omega}_1 \hat{e}_\beta[k-1] + h_2T_s (\hat{i}_\alpha[k-1] - i_\alpha[k-1]) \\ \hat{e}_\beta[k] = \hat{e}_\beta[k-1] - T_s \bar{\omega}_1 \hat{e}_\alpha[k-1] + h_2T_s (\hat{i}_\beta[k-1] - i_\beta[k-1]) \end{cases}$$



ST MC SDK5.x 观测器STO的固件

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➤ 对于X-CUBE-MCSDK：观测器的固件以库的形式提供。




✓ xxx\MCSDK_v5.2.0\MotorControlLib

➤ 头文件名如下：

✓ sto_cordic_speed_pos_fdbk.h

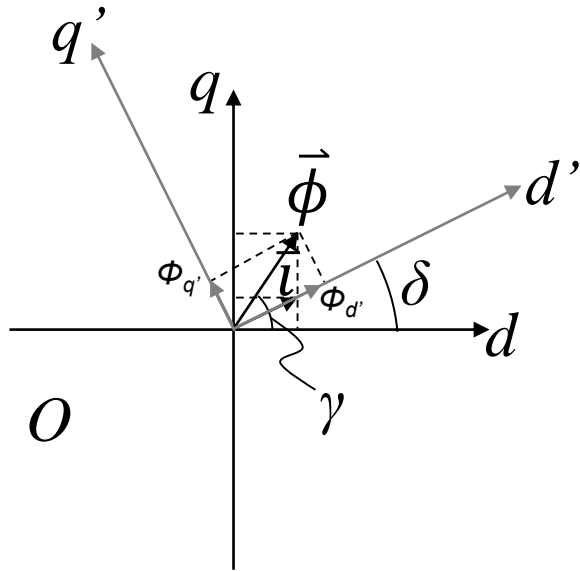
✓ sto_pll_speed_pos_fdbk.h

✓ sto_speed_pos_fdbk.h

 sto_cordic_speed_pos_fdbk.h	STO+Cordic头文件
 sto_pll_speed_pos_fdbk.h	STO+PLL头文件
 sto_speed_pos_fdbk.h	STO Handle定义

位置速度检测 — HFI(1/4)

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$$\tan \delta = \frac{I_q}{I_d}, \tan \gamma = \frac{L_q I_q}{L_d I_d} = \frac{L_q}{L_d} \tan \delta$$

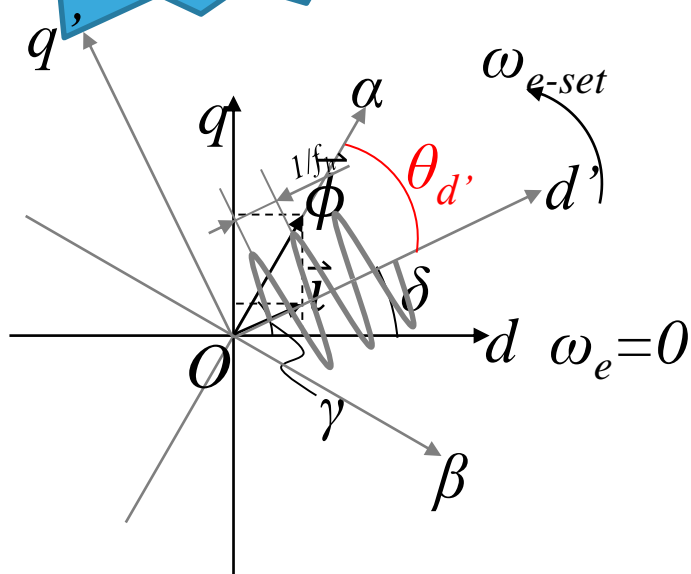
$$\tan(\gamma - \delta) = \frac{\tan \gamma - \tan \delta}{1 + \tan \gamma \tan \delta} = \frac{\left(\frac{L_q}{L_d} - 1\right) \tan \delta}{1 + \frac{L_q}{L_d} \tan^2 \delta} = \frac{(L_q - L_d) \sin 2\delta}{2[L_d + (L_q - L_d) \sin^2 \delta]}$$

$$|\vec{\phi}| = \sqrt{(L_d I_d)^2 + (L_q I_q)^2} = |\vec{l}| \sqrt{L_d^2 + (L_q^2 - L_d^2) \sin^2 \delta}$$

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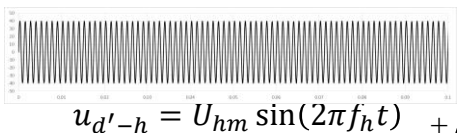
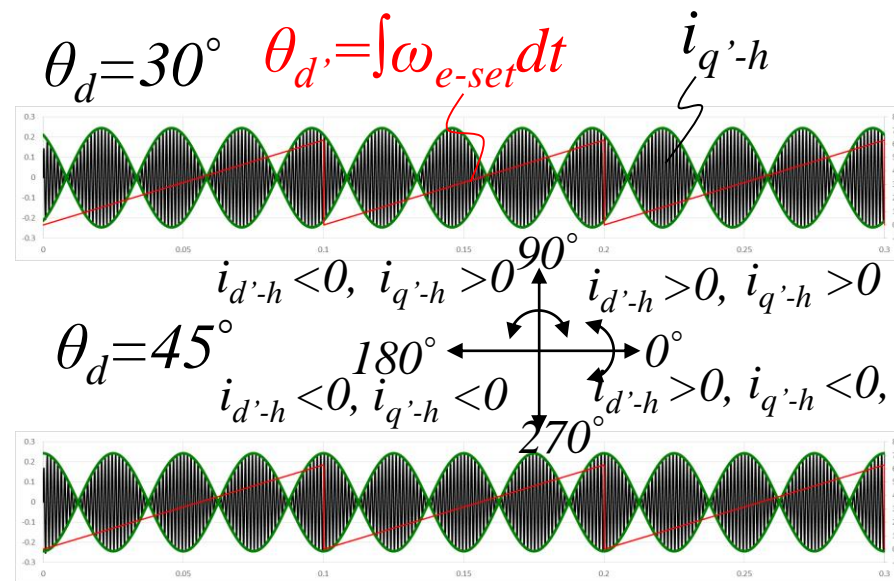
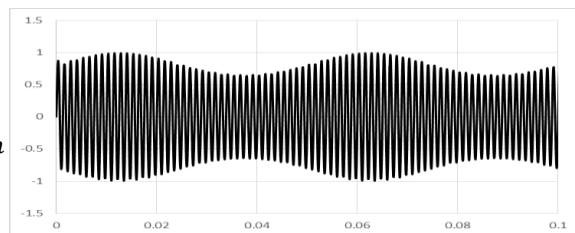
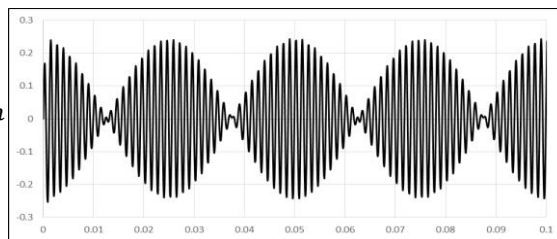
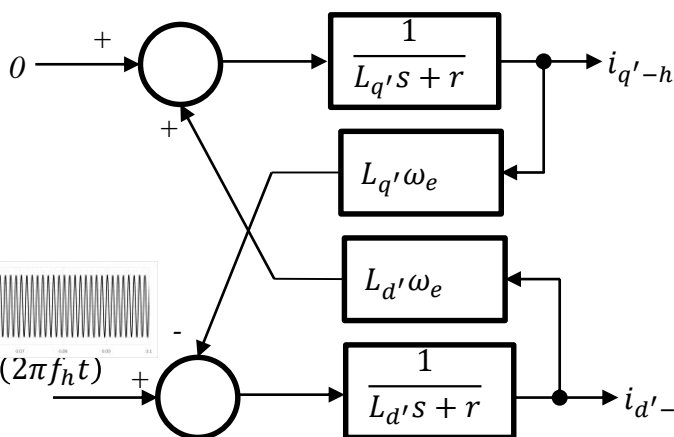
位置速度检测 — HFI(2/4)

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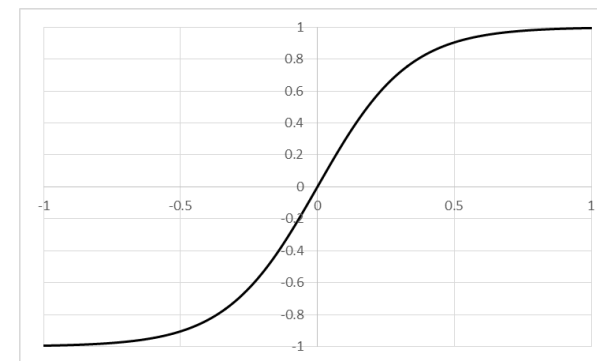
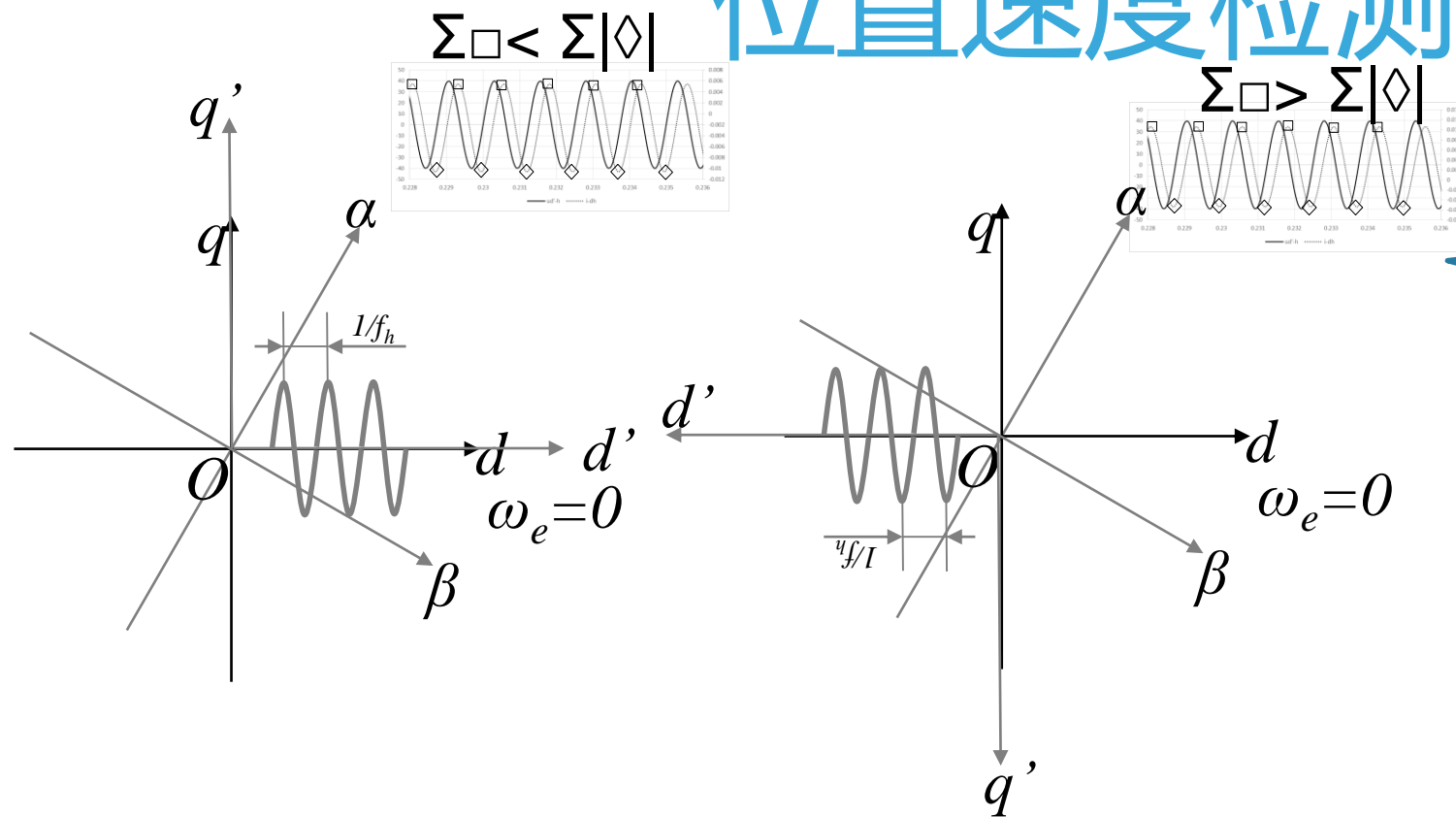
$$|\vec{\phi}| = \sqrt{(L_d I_d)^2 + (L_q I_q)^2} = |\vec{i}| \sqrt{L_d^2 + (L_q^2 - L_d^2) \sin^2 \delta}$$

$$|\vec{\phi}| = I_m \sin(2\pi f_h t) \sqrt{L_d^2 + (L_q^2 - L_d^2) \sin^2(\omega_e t + \delta_0)}$$

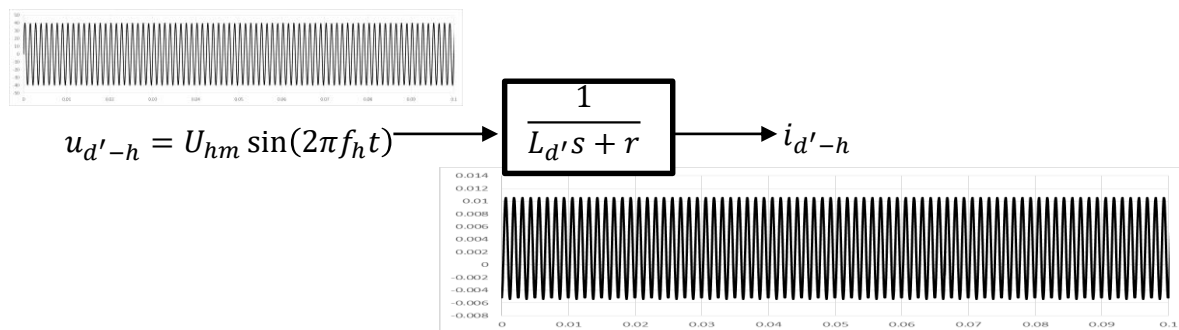


位置速度检测 — HFI(3/4)

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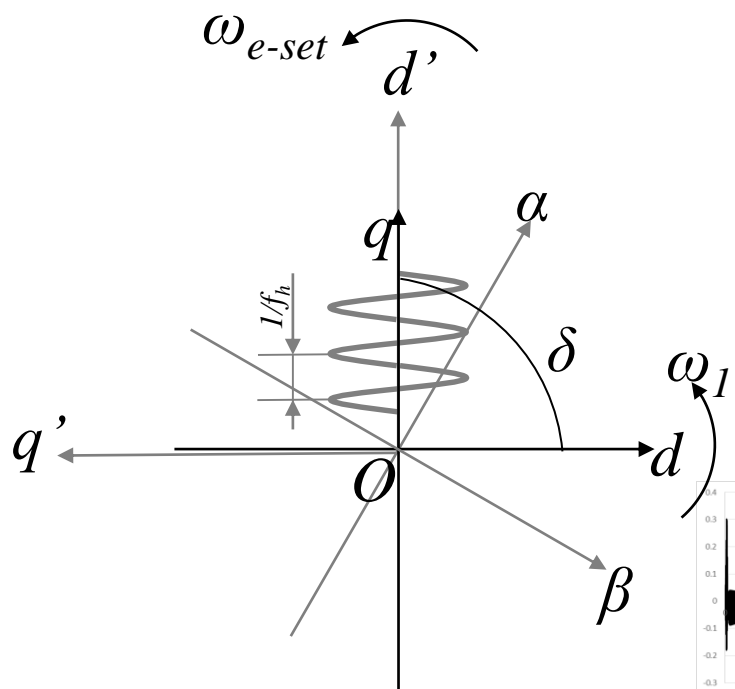


Φ - i 曲线

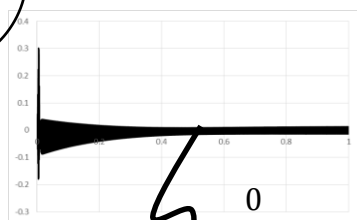


位置速度检测 — HFI(4/4)

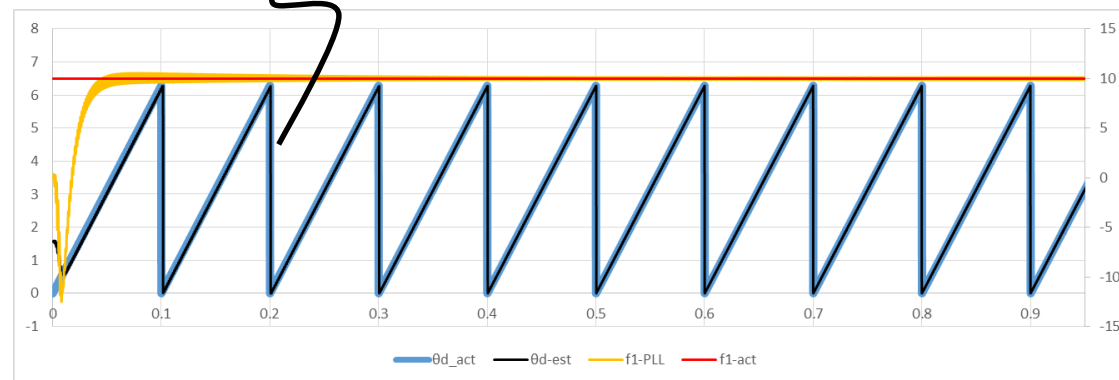
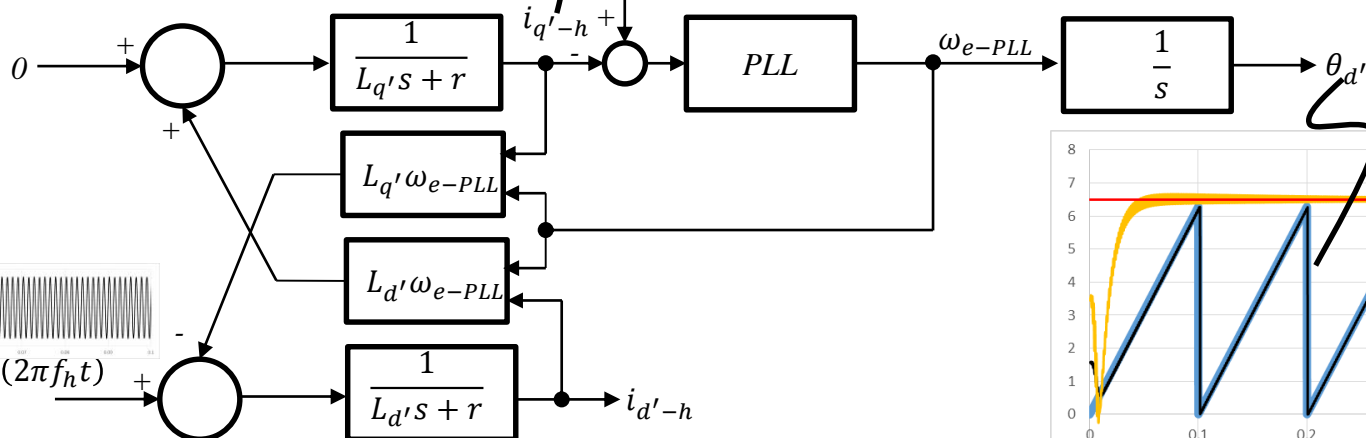
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当电机开始转动后, 保持 $\delta=0$, d' 轴与 q 轴重合, 那么 $i_{q'-h}=0$,
也就是如果保持 $i_{q'-h}=0$, d' - q' 旋转坐标系的速度等于转子速度 $\omega_e = \omega_{e-set}$.



使用PLL,使得 $i_{q'-h}=0$



Releasing your creativity

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- Thank you -

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