# 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

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## ❑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

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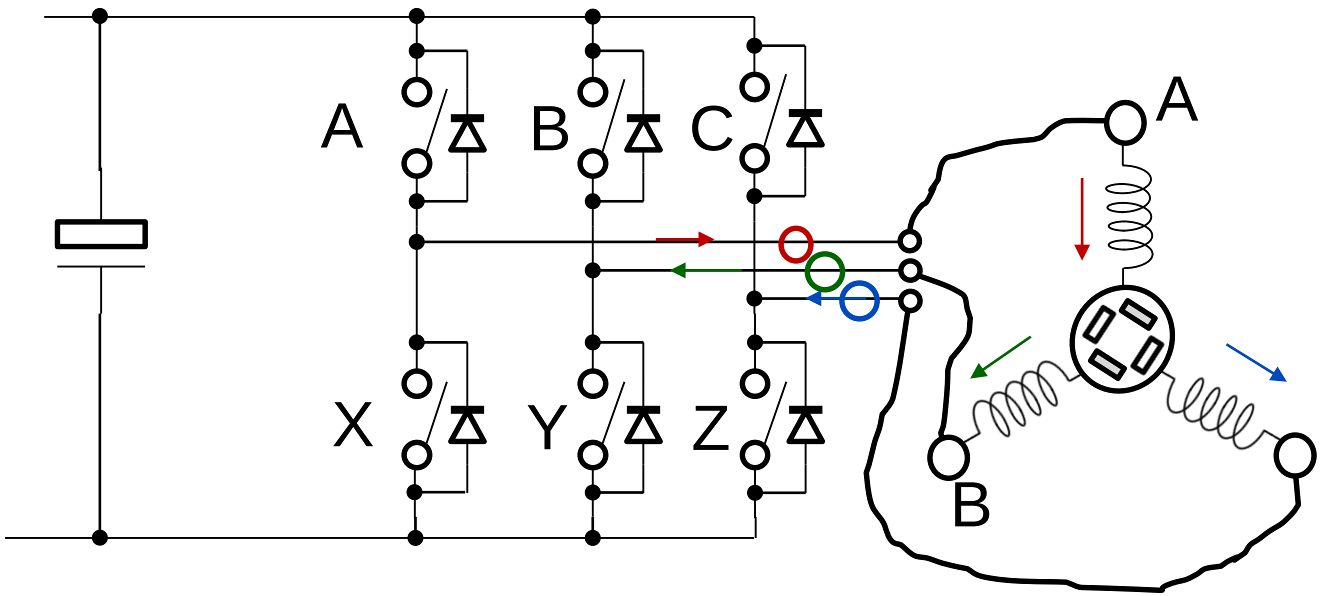
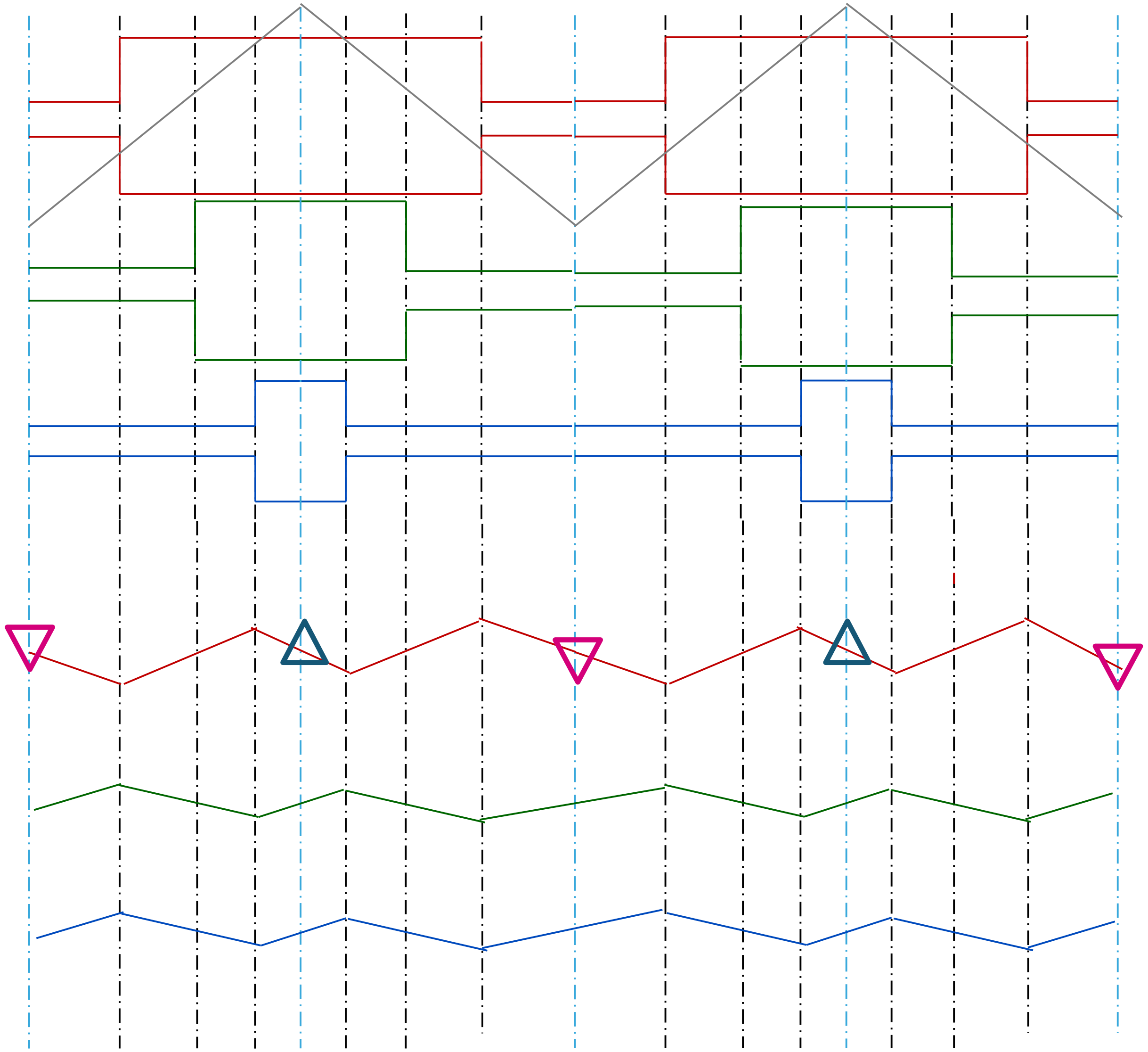
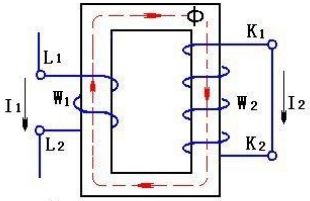
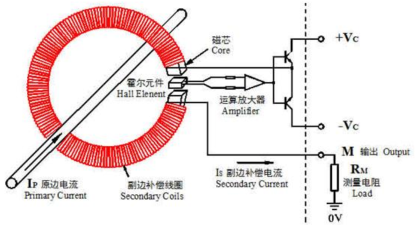
# 电流采样 — ICS



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

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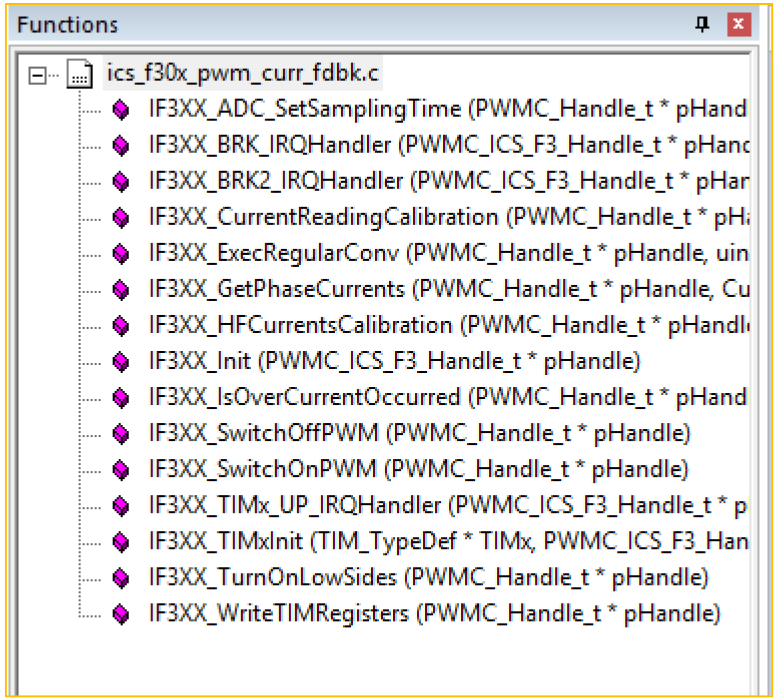
# ST MC SDK5.x ICS采样固件



- 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

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# 相电流的检测与重构

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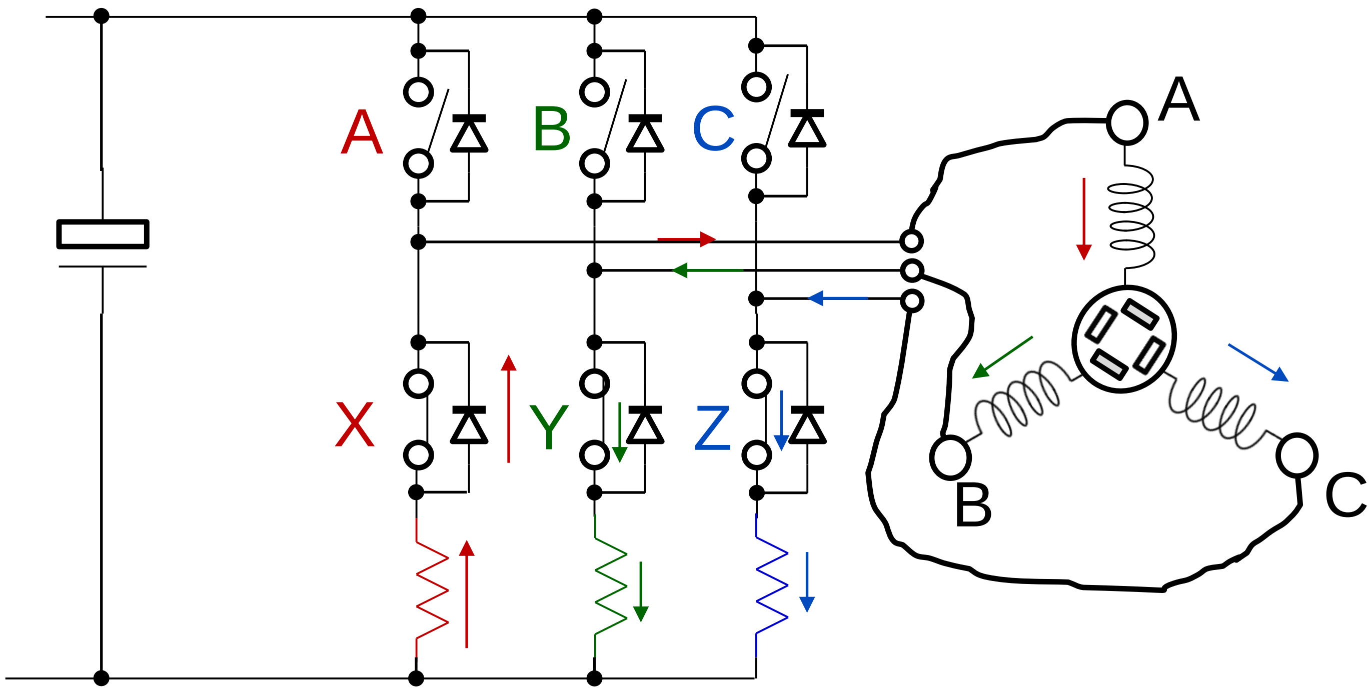
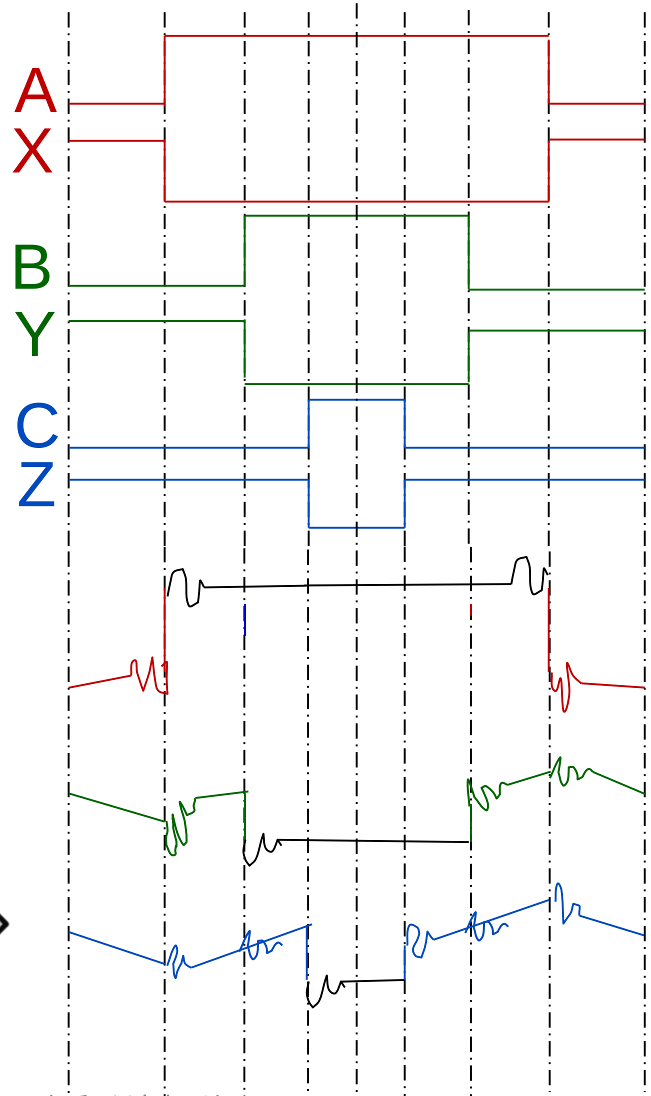
# 电流采样 — 三电阻(1/2)

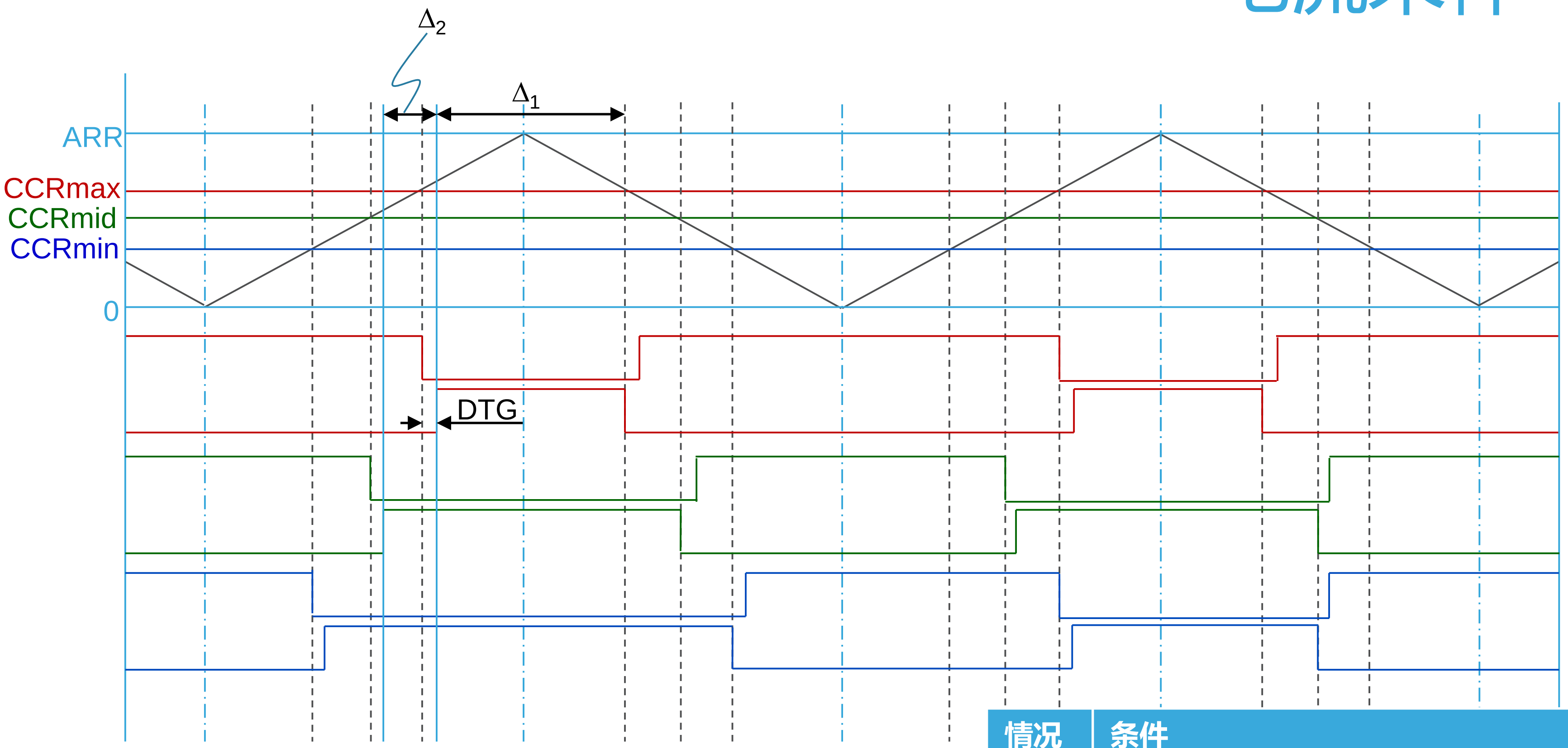


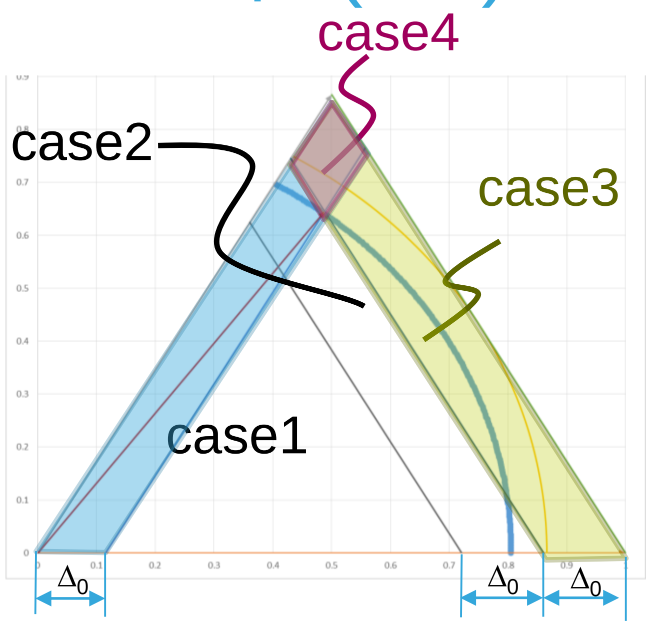


# 电流采样 — 三电阻(2/2)






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

$\Delta_2 = CCRmax - CCRmid$

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

$\Delta_0$ = CNT_Ton + CNT_TADCsta+CNT_TADCSH(COV), TADCsta>=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+ε |
| 3 | $\Delta_2 > \Delta_0 > \Delta_1$ | CCRmid + tdead+ton+tring+ε |
| 4 | $\Delta_1 < \Delta_0$ and $\Delta_2 < \Delta_0$ | Not available |

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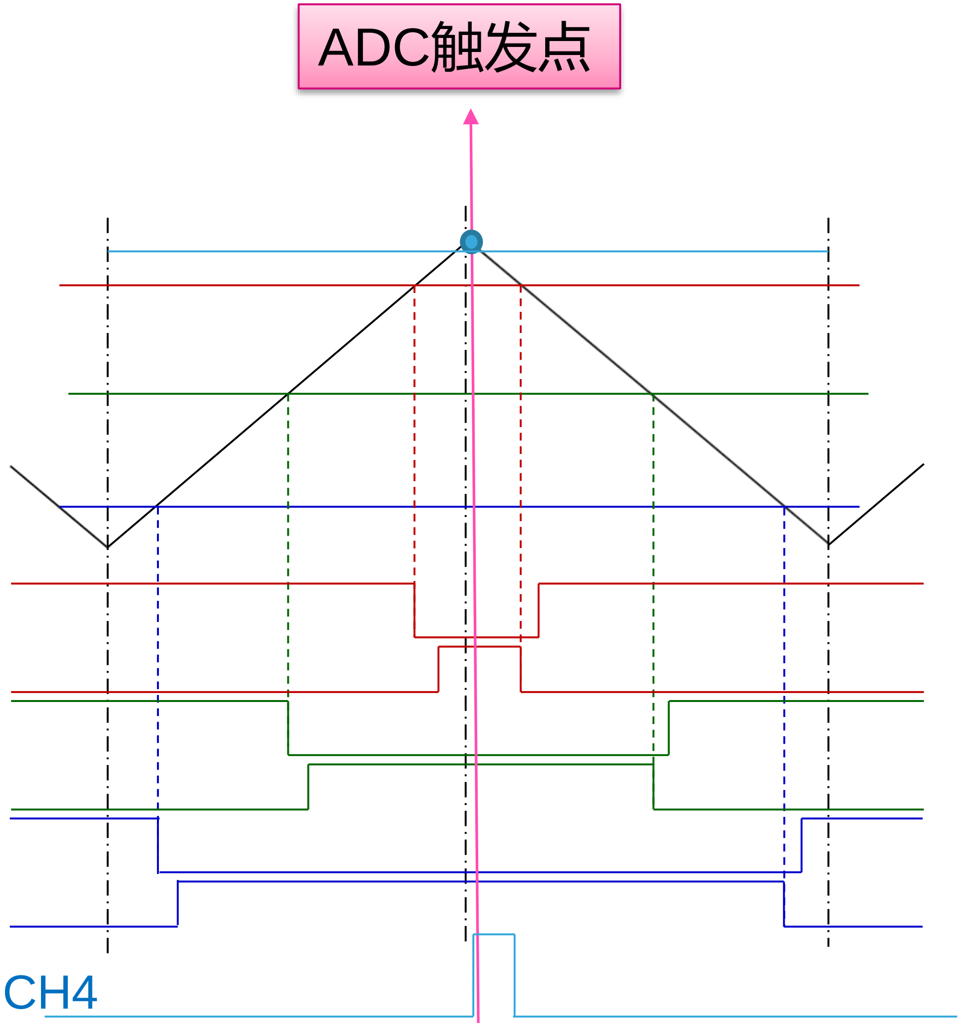
# 三电阻ADC触发机制说明






- 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

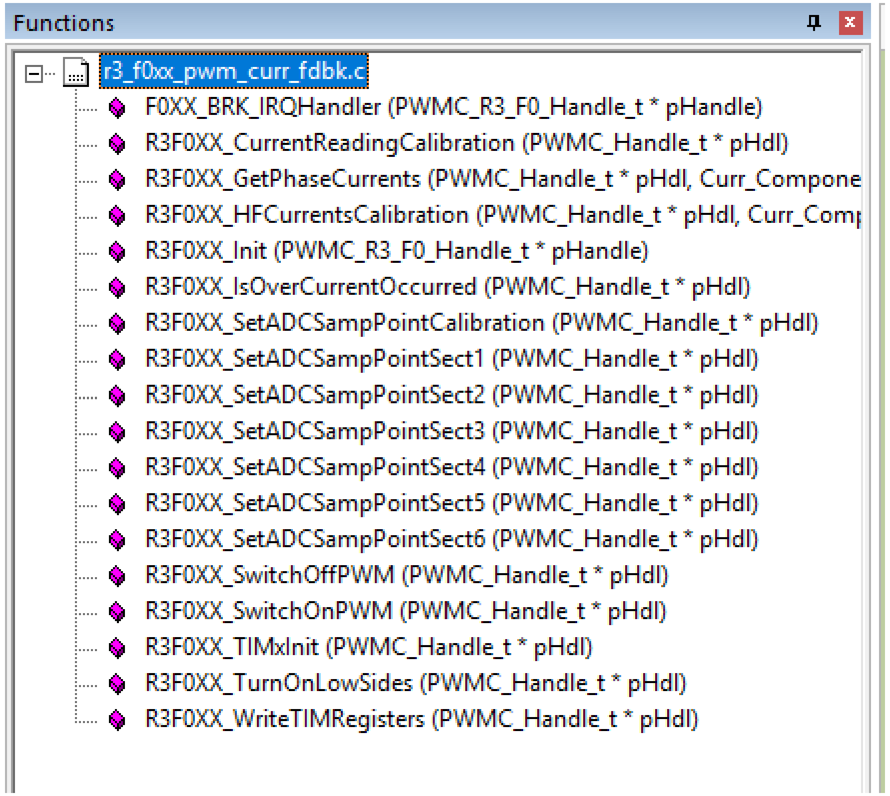


## ❑ 针对STM32系列芯片都有各自的文件：

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



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# 相电流的检测与重构

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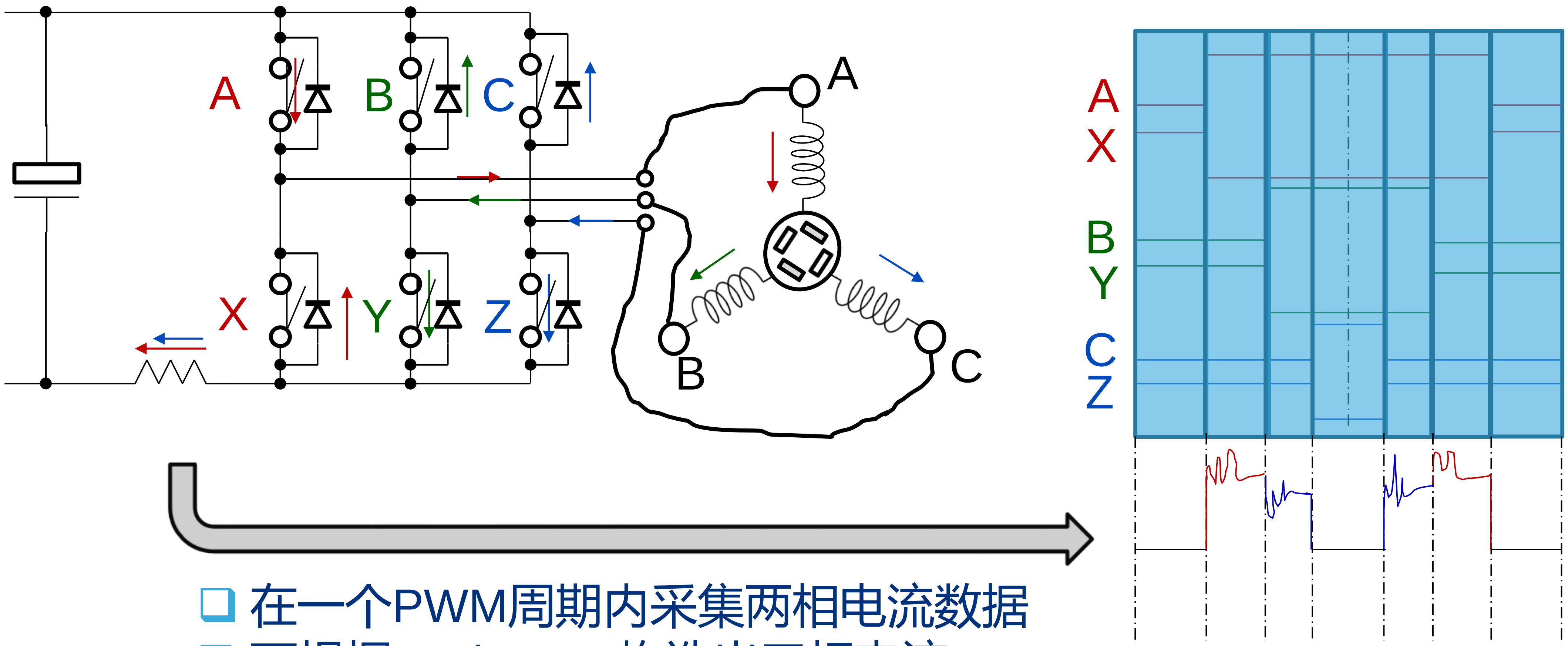
# 电流采样 — 单电阻(1/8)






- 在一个PWM周期内采集两相电流数据
- 可根据Ia+Ib+Ic=0构造出三相电流

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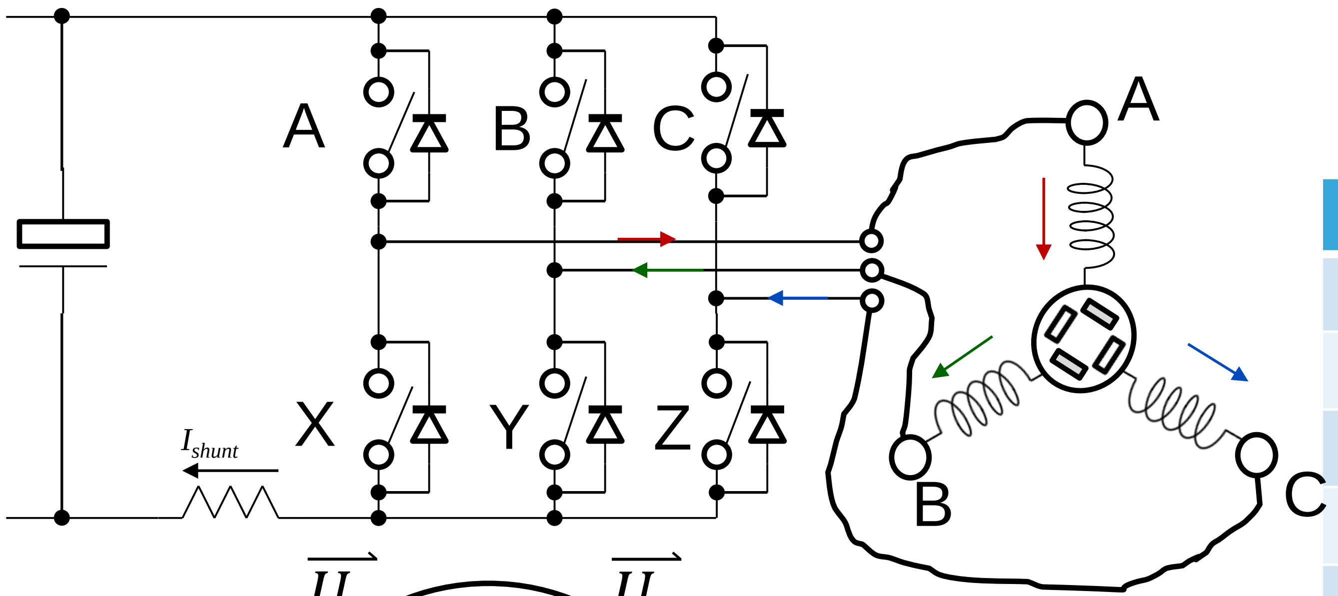
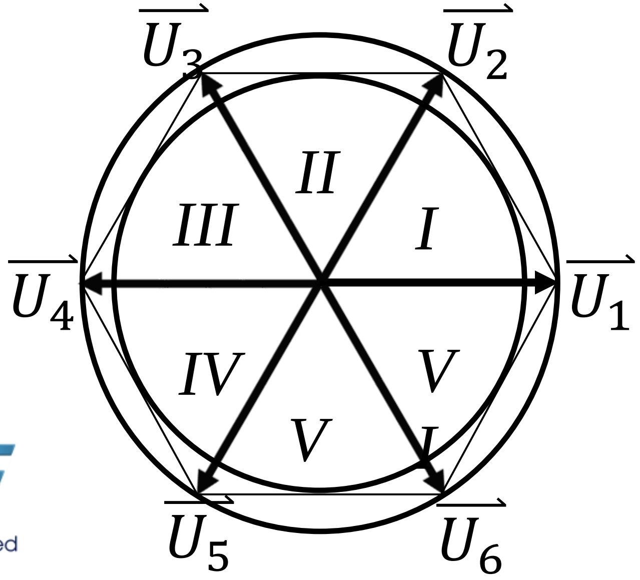
# 电流采样 — 单电阻(2/8)




## ❑ 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)* | *Ishunt* |
|---|---|---|---|---|
| $\vec{U}_0$ | 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) | $0$ |

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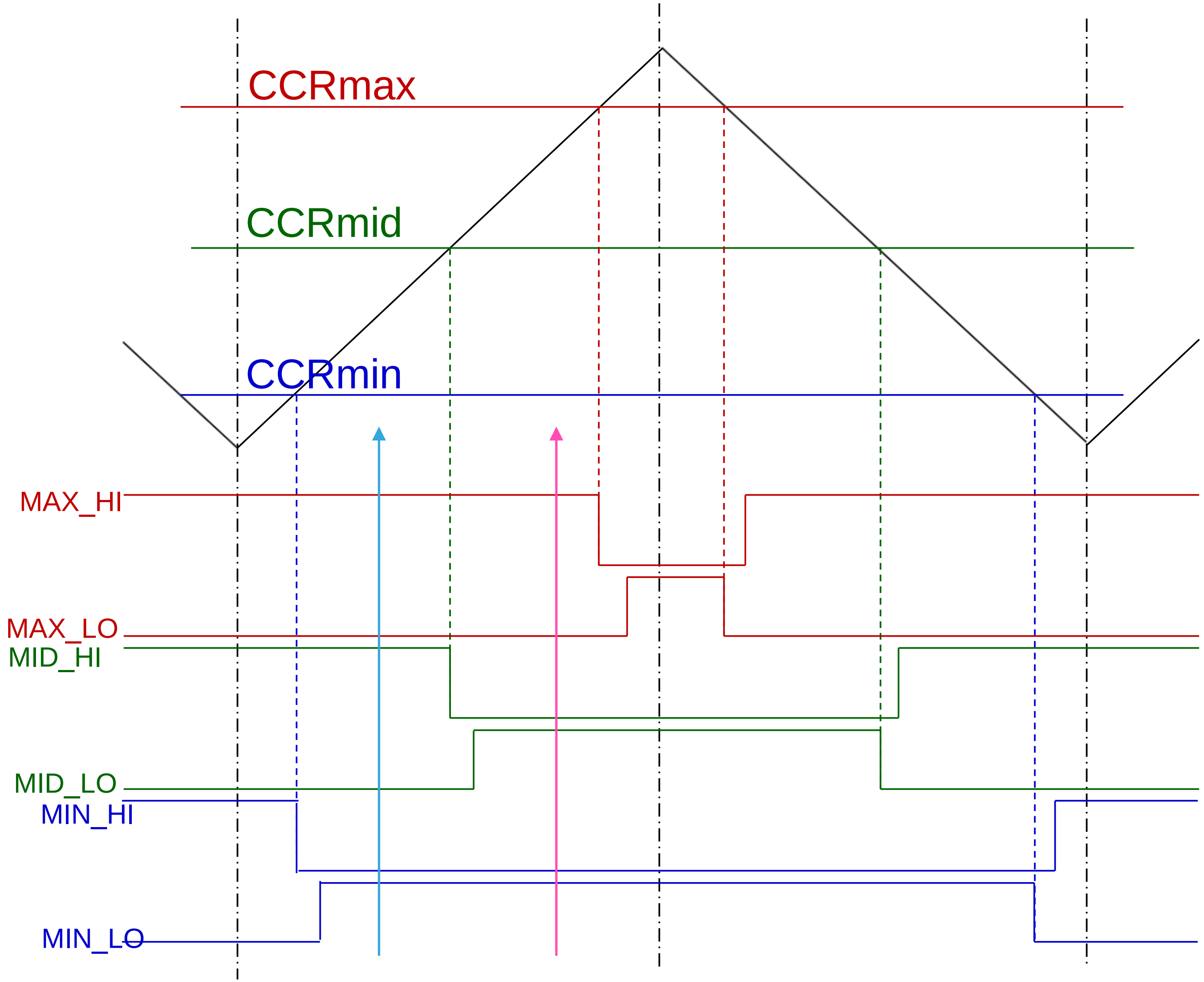
# 电流采样 — 单电阻(3/8)






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

$T_p$ – 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(CCRmid – CCRmin) > $T_{dead} + T_{ring} + T_{ADC\ s/h}$

采样点为$\frac{T(CCRmid + CCRmin) + Tdead}{2}$

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

第二点:

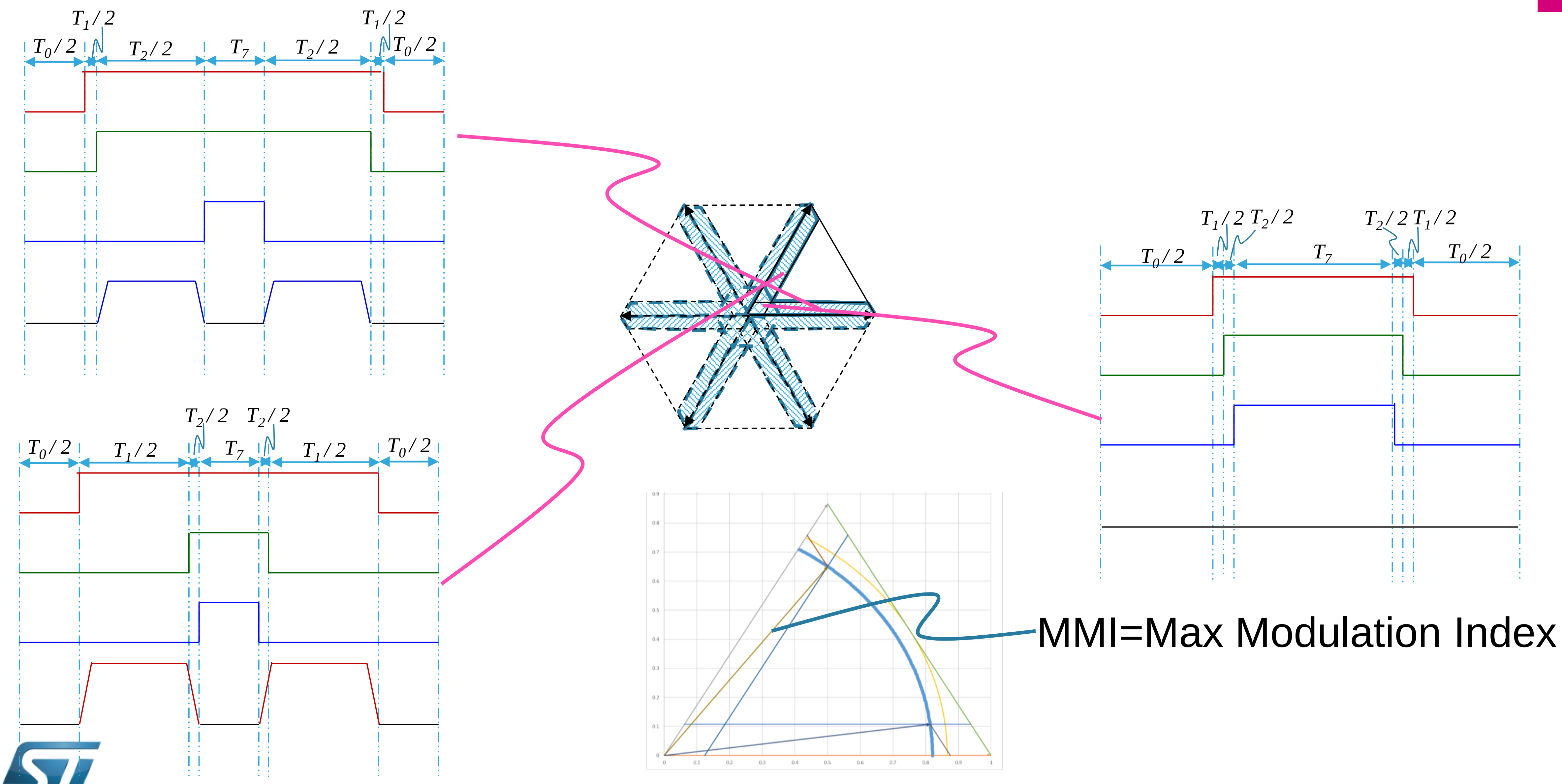
当T(CCRmax – CCRmid) > $T_{dead} + T_{ring} + T_{ADC\ s/h}$

采样点为$\frac{T(CCRmax + CCRmid) + Tdead}{2}$

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

# 电流采样 — 单电阻(4/8)

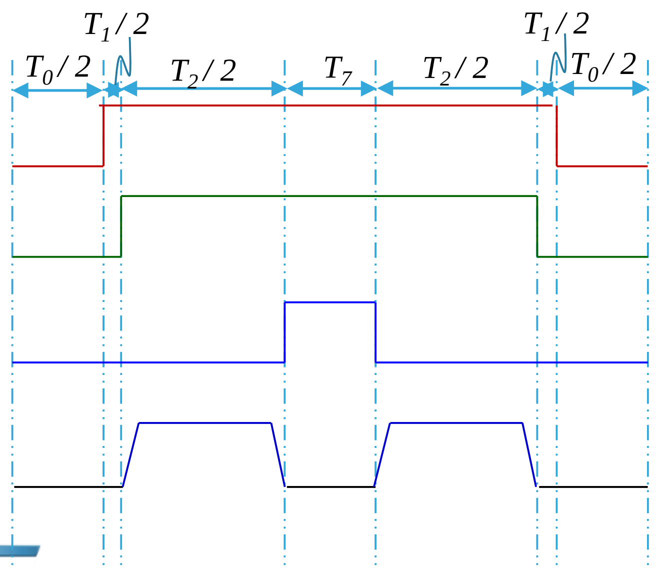


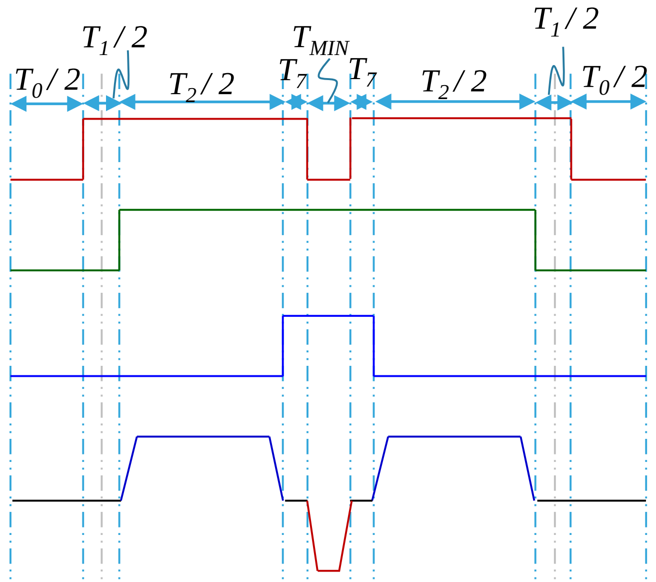


# 电流采样 — 单电阻(5/8)

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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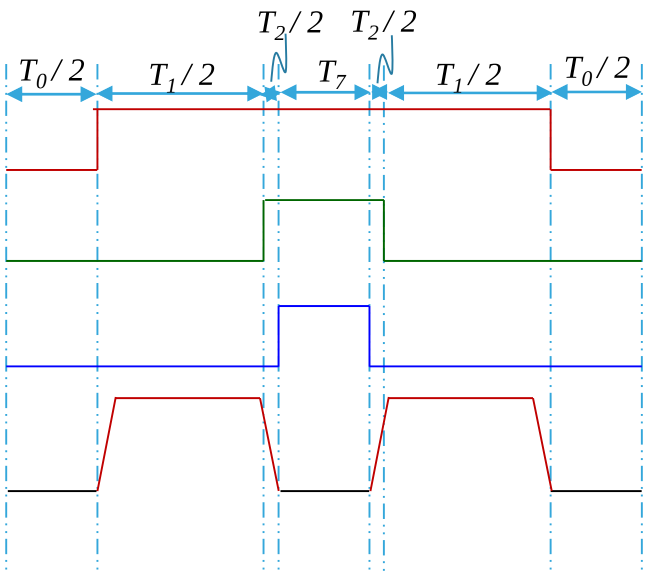
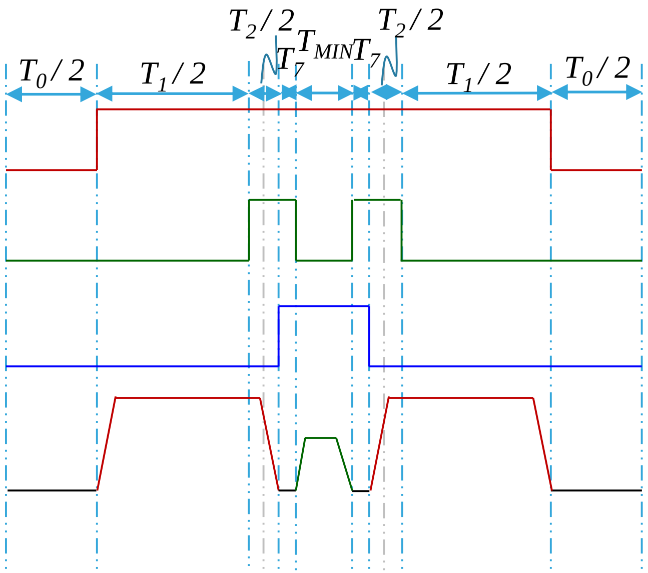
# 电流采样 — 单电阻(6/8)



ST 专利
US20090284194 A1

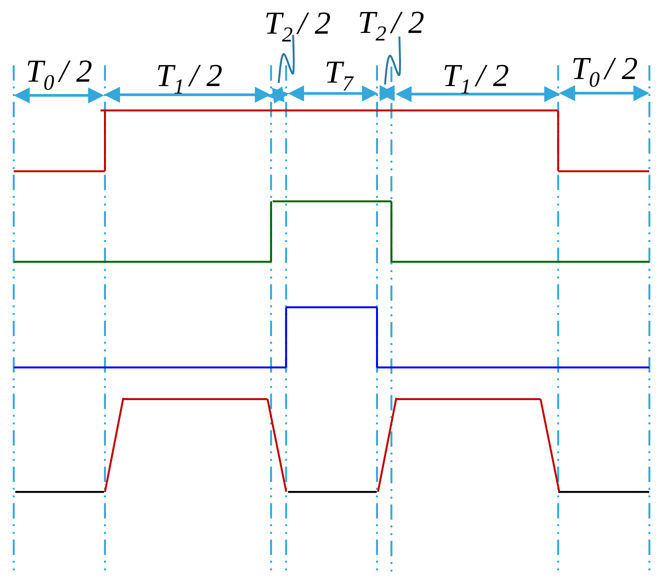
ST 专利 (Pat. Pub. No.: US20090284194 A1) 解决单电阻无法采样问题

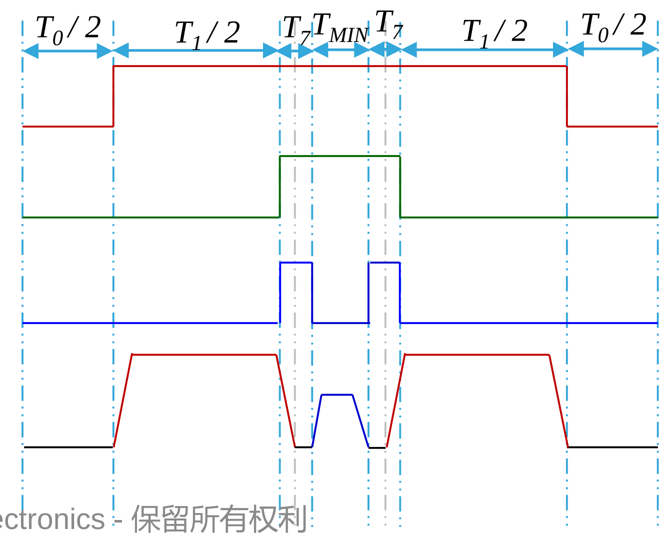


ST 专利
US20090284194 A1

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

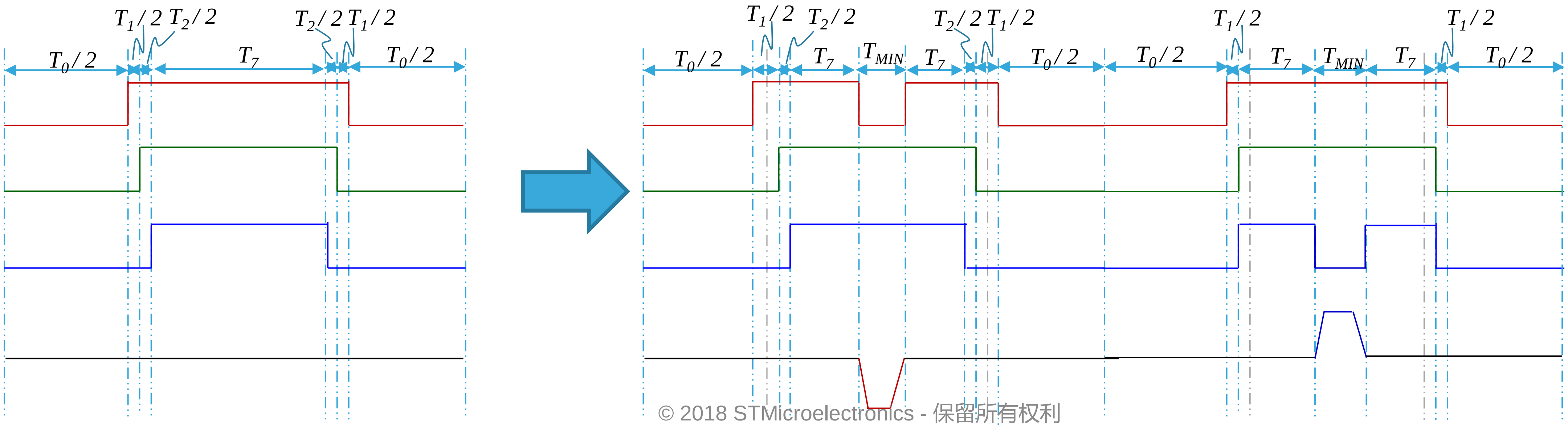


# 电流采样 — 单电阻(8/8)

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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# ADC采样机制说明



| | | | | | | |
|---|---|---|---|---|---|---|
| $t_{latr}$ (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

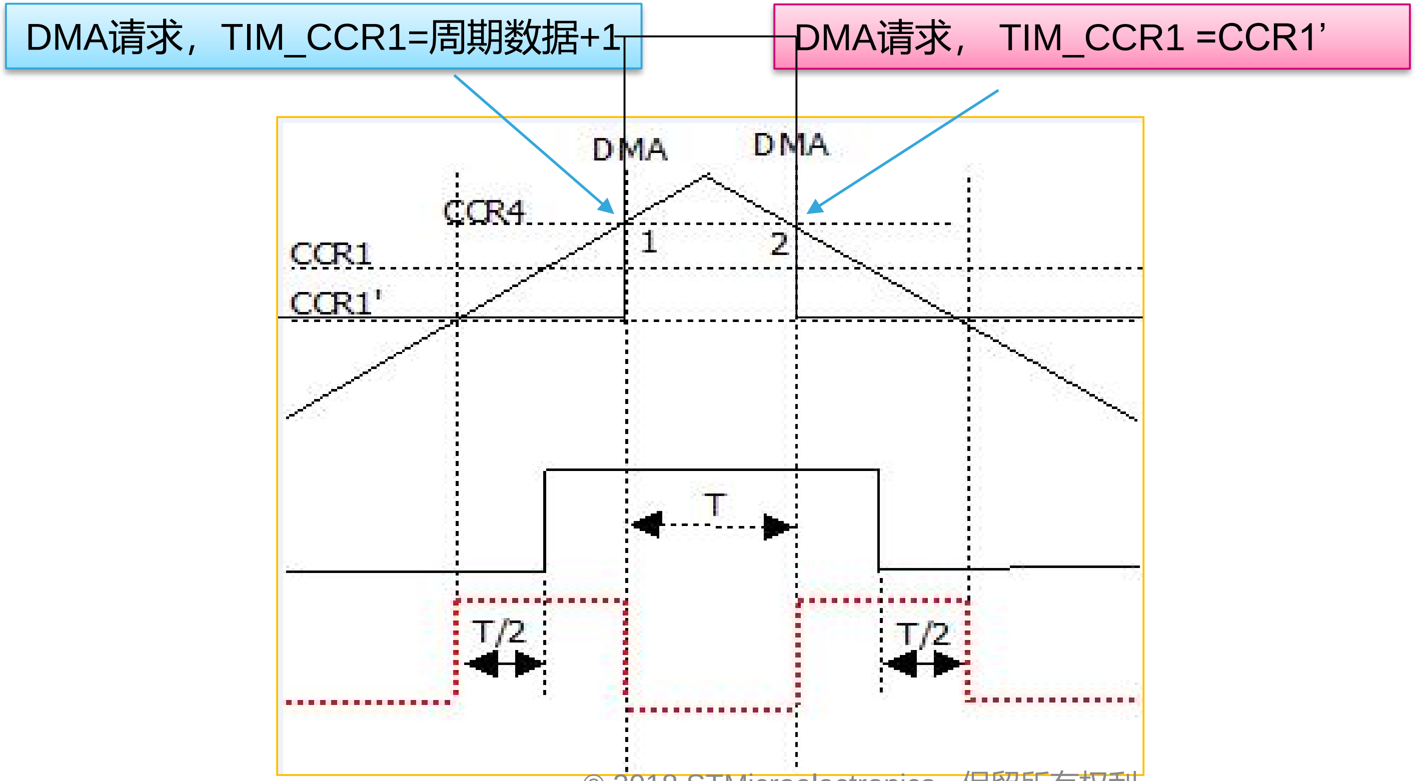
| |
|---|
| 上升沿 |
| 下降沿 |
| 上升/下降沿 |

| 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 | TIM3_TRGO event |

# 波形变形机制说明



- ❑ CCR4 = Tc/2 – minPulse/2 在CCR4 比较值1部分产生DMA事件:,Timer1的preload为禁止状态； CCR1 = Tc/2 + delt
- ❑ 在CCR4 比较值2 部分产生DMA事件； CCR1‘ = CCR1 - minPulse/2



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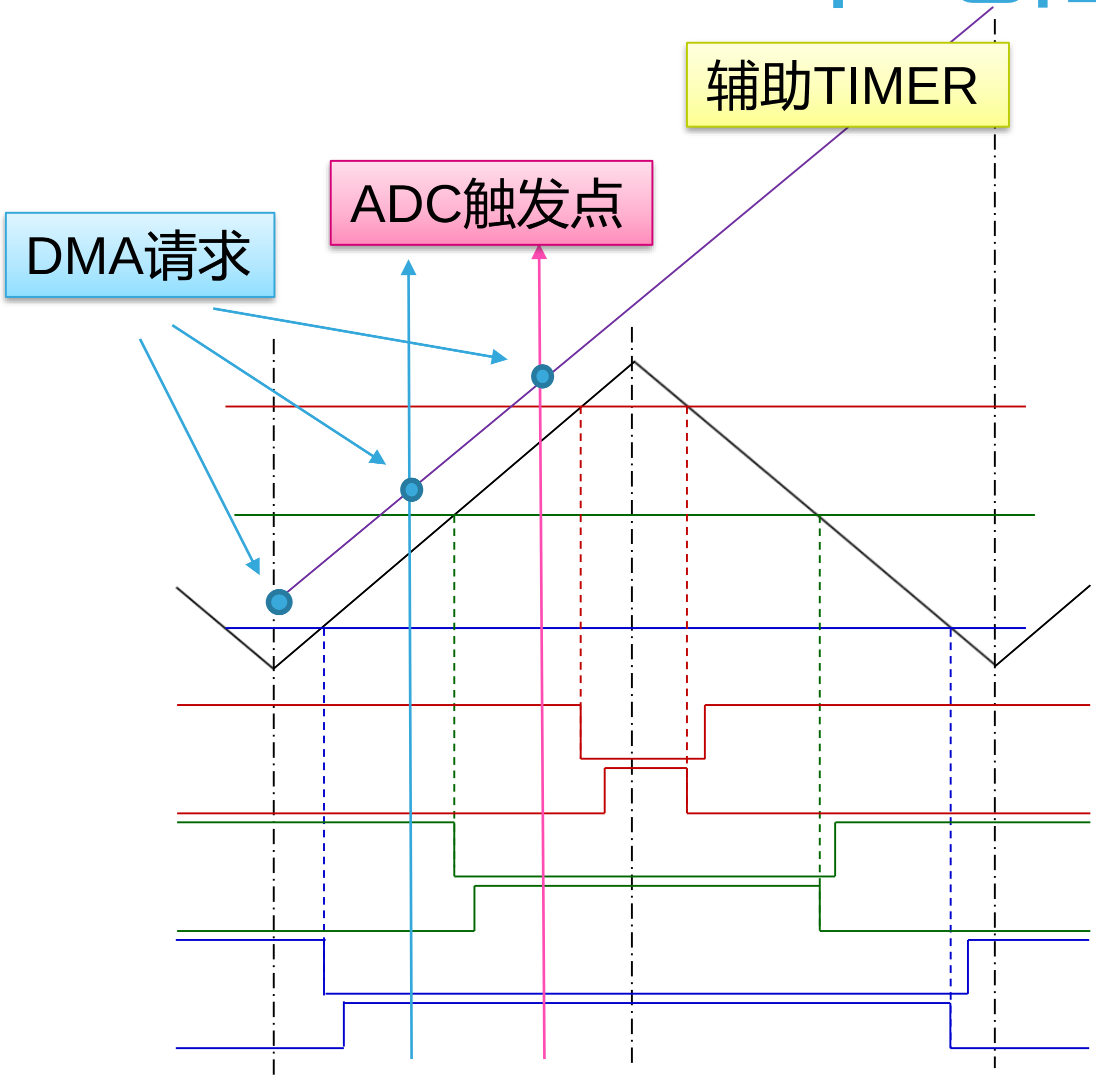
# 单电阻ADC触发机制说明




- 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

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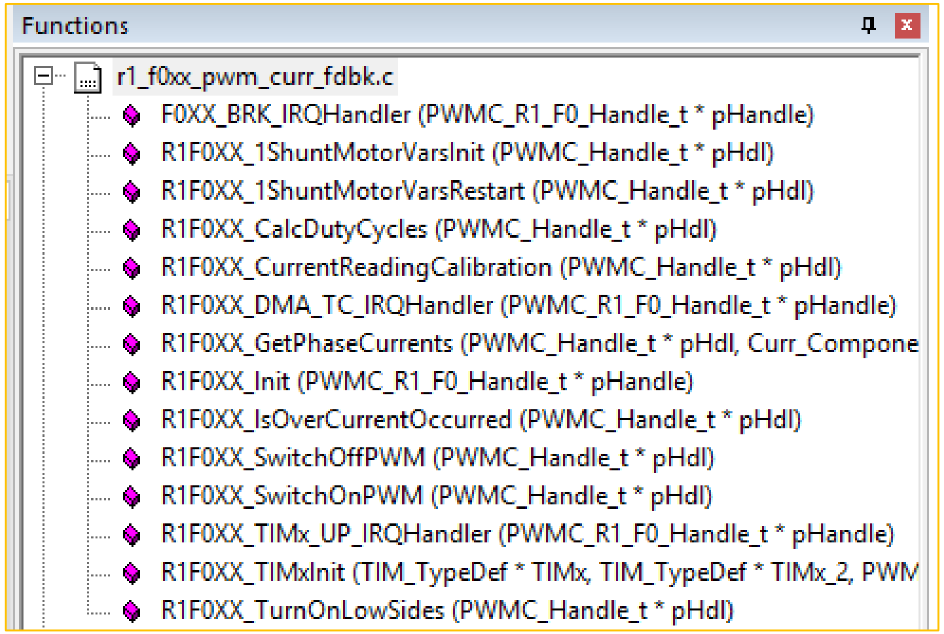
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F0xx\Src
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F1xx\Src
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F3xx\Src
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F4xx\Src
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\F7xx\Src
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\L4xx\Src

- 文件名称
  - ✓ r1_yxx_pwm_curr_fdbk.c
  - ✓ y=f0, f1, f3, f4, f7, l4

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# 转子位置、速度信息的获取

- ❑ 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

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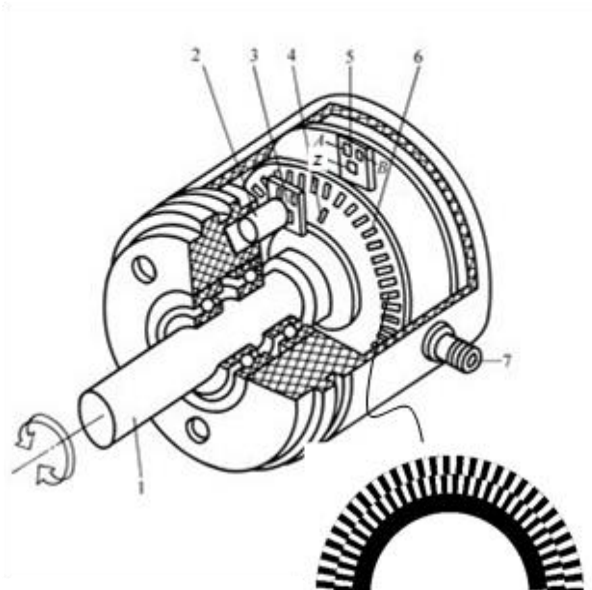
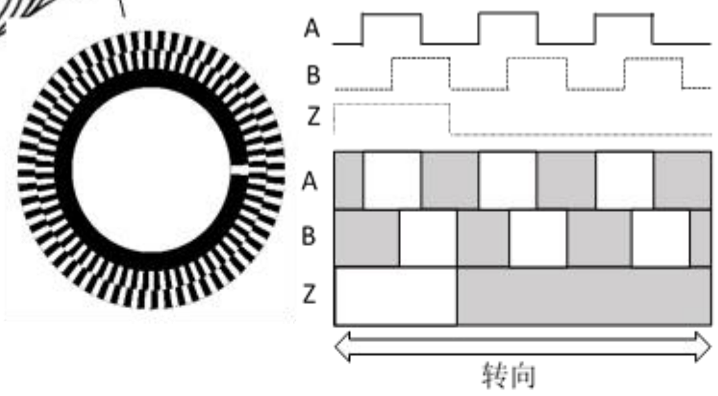
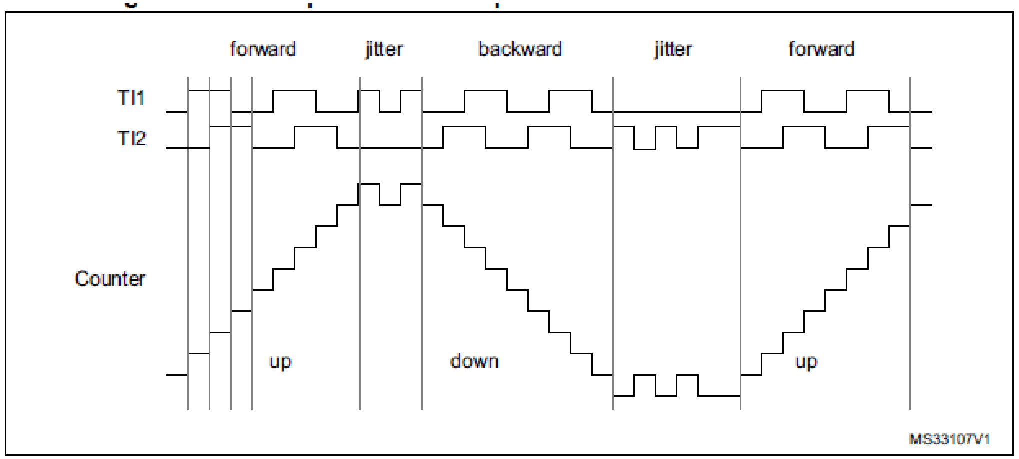
# 位置速度检测 — Encoder




1- 连接转子主轴
2- 发光二极管
3- 遮光板
4- Z 光栅
5- ABZ 光敏器件
6- AB 光栅
7- 连轴固定销钉

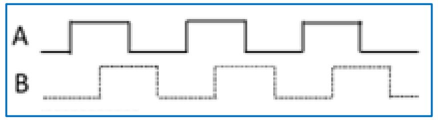


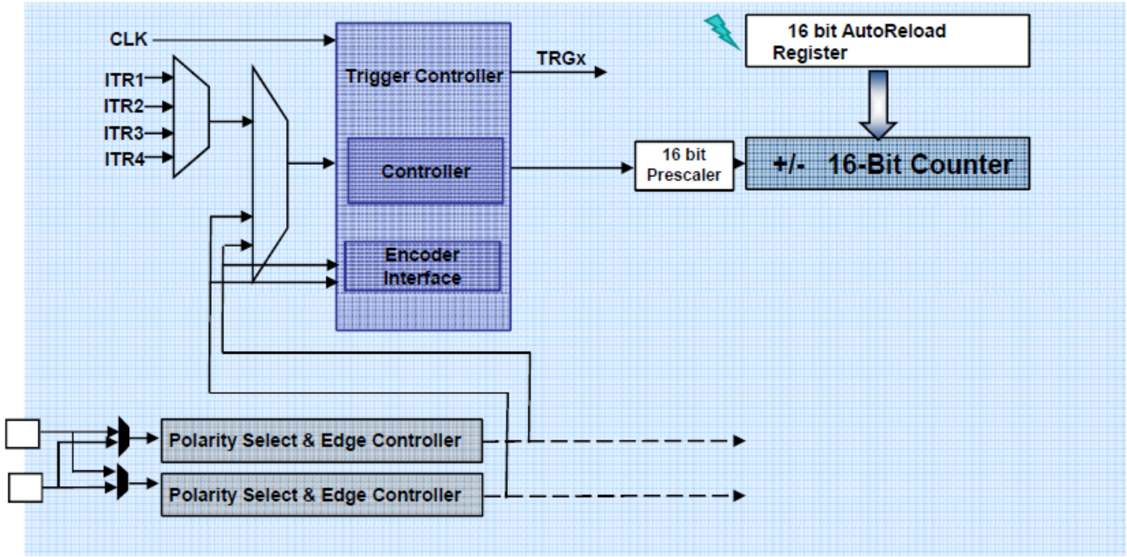




- 使用增量编码器时，在第一次电机启动，任意保护停止或者MCU复位后都要进行预定位操作。
- Z信号（一圈一个）可以使用外部中断或者外部Timer捕捉模式，代表编码器的0度位置，可以用于校准角度位置，可以使用DMA模式对编码器模块赋值；

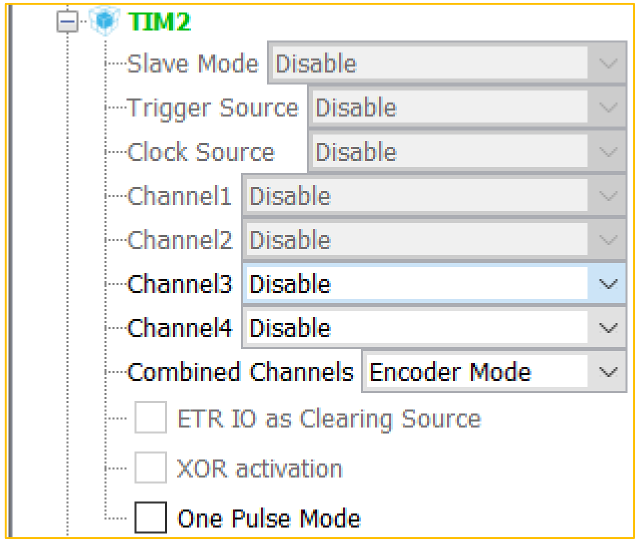
# STM32硬件Encoder接口

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




CubeMx中的配置

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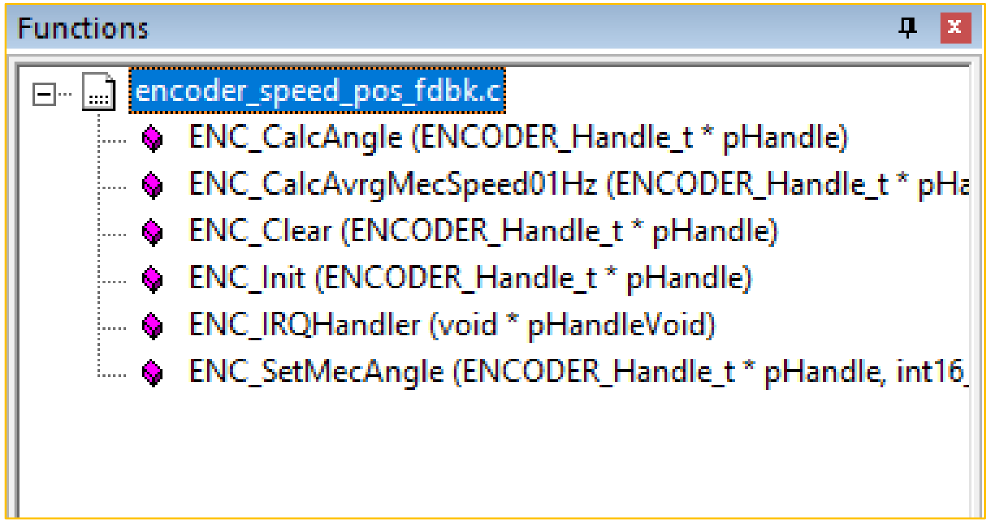
# ST MC SDK5.x Encoder固件

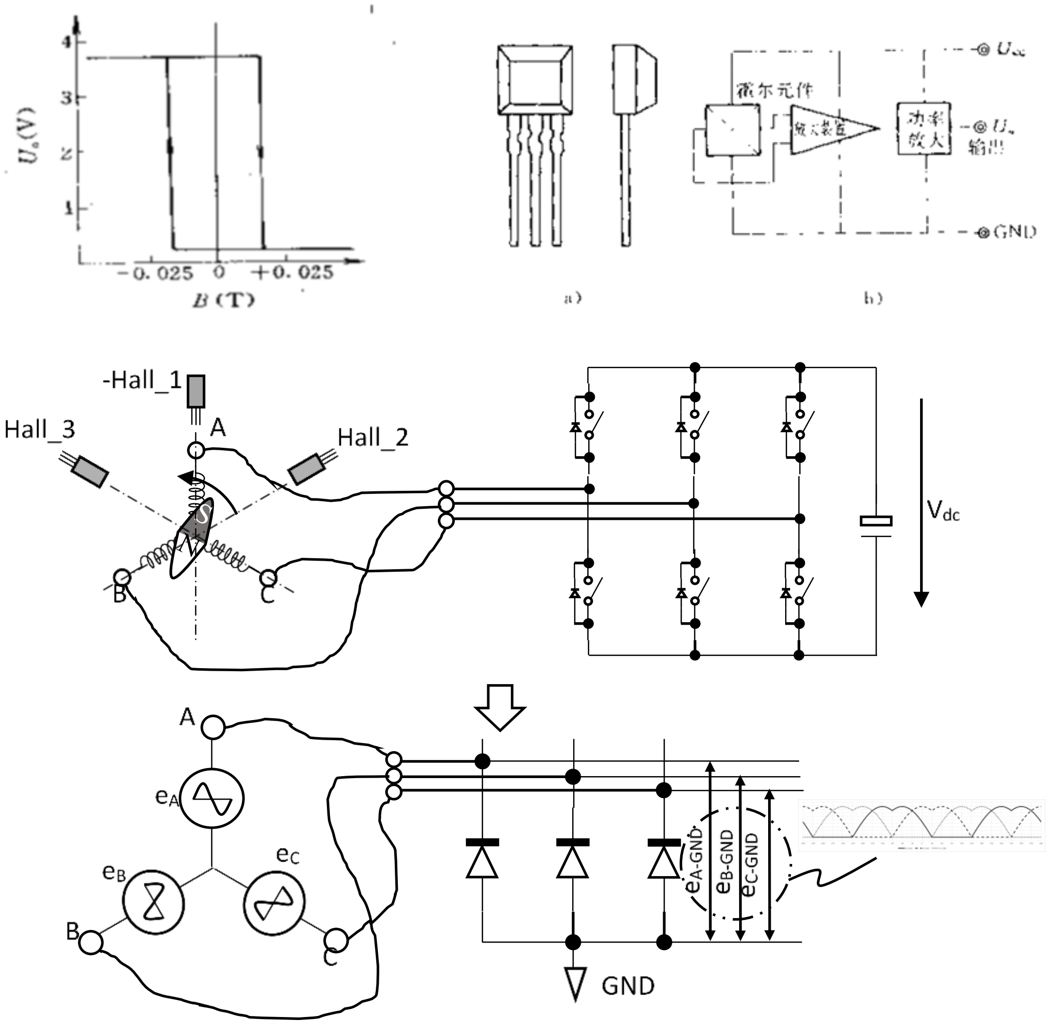


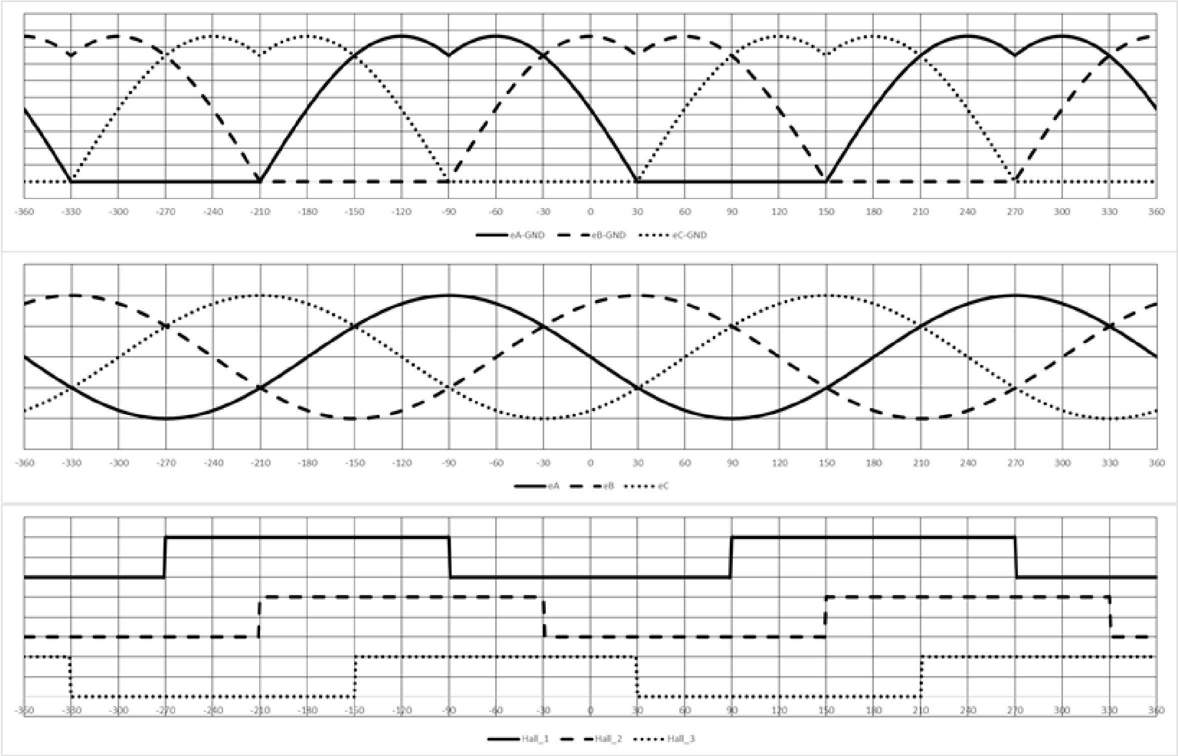
- 具体文件夹如下：
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\MCSDK\MCLib\Any\Src
- 文件名称
  - ✓ encoder_speed_pos_fdbk.c



# 位置速度检测 — Hall传感器





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。

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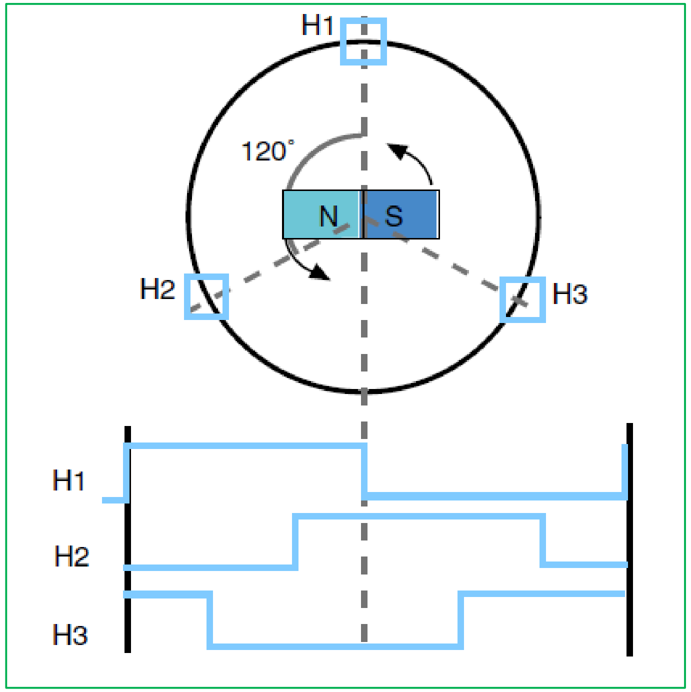
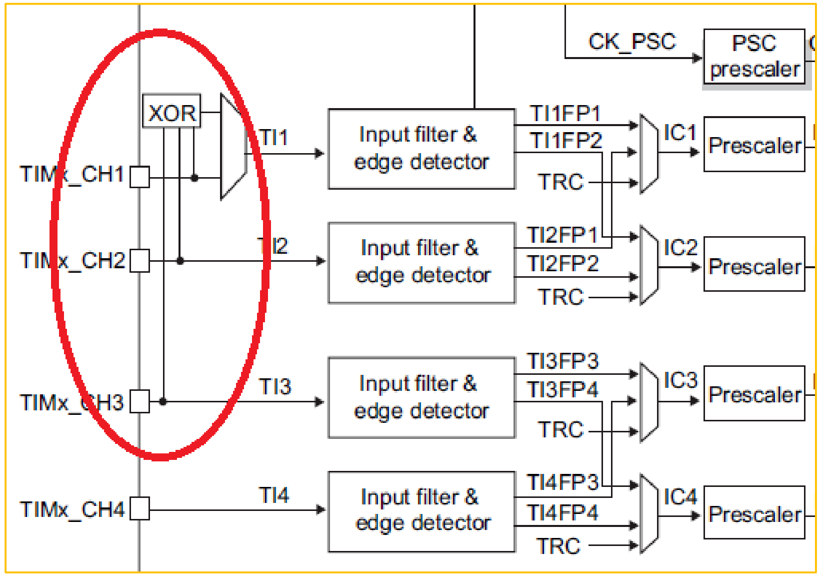
# STM32硬件Hall接口

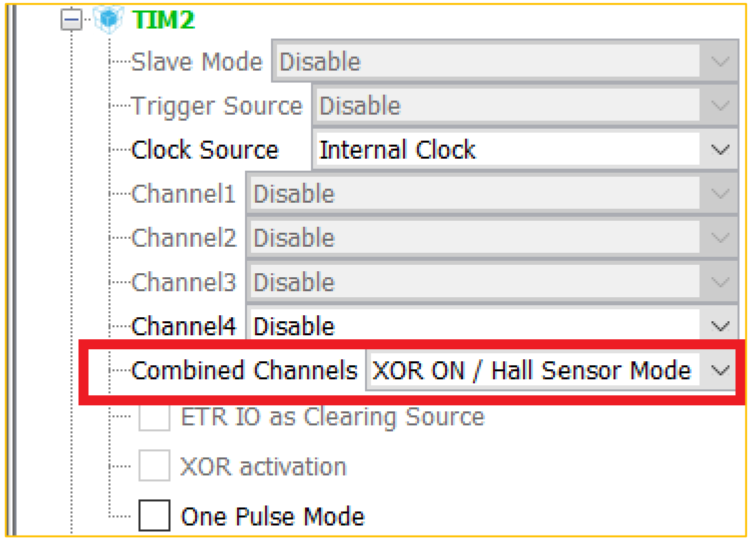


- 在全系列STM32中都有硬件Hall接口(XOR输入)
- 可以每个Hall跳变沿都产生中断




CubeMx中的配置

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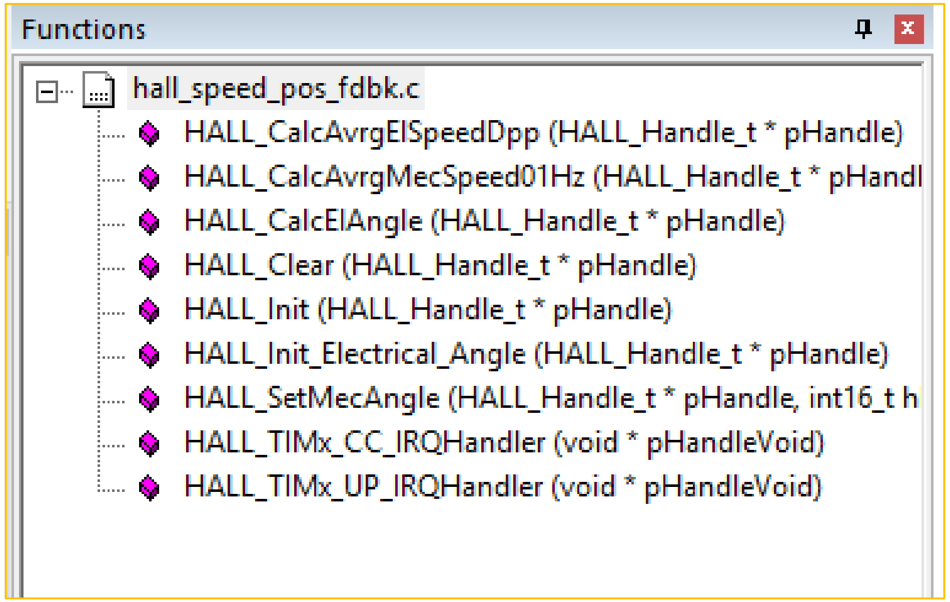
# ST MC SDK5.x Hall传感器固件



- 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

- ❑ 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

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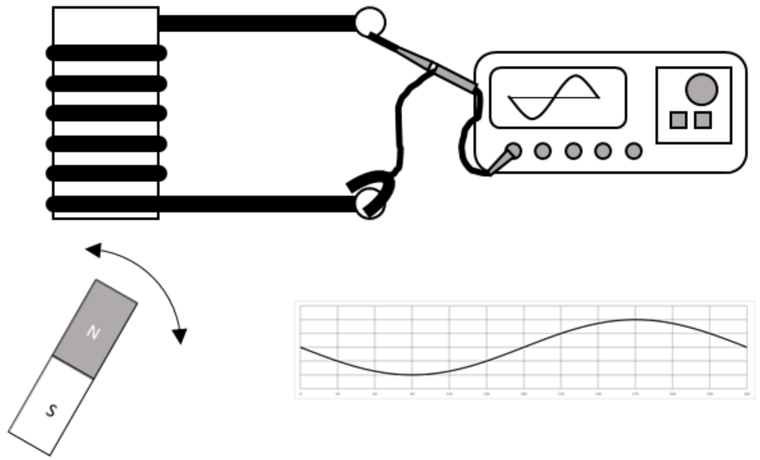
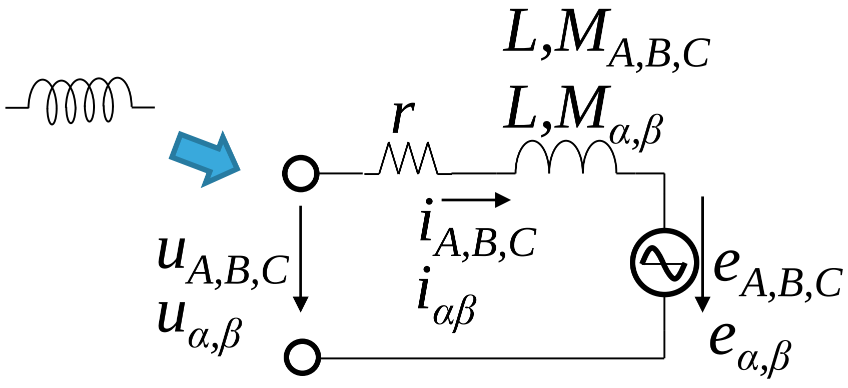
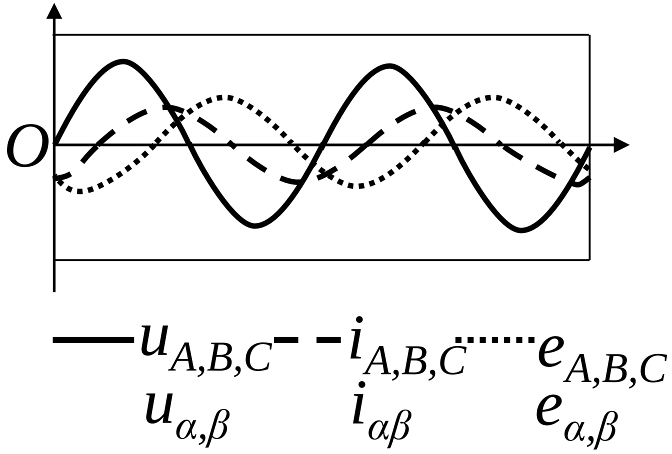
# 位置速度检测 — 观测器(1/13)

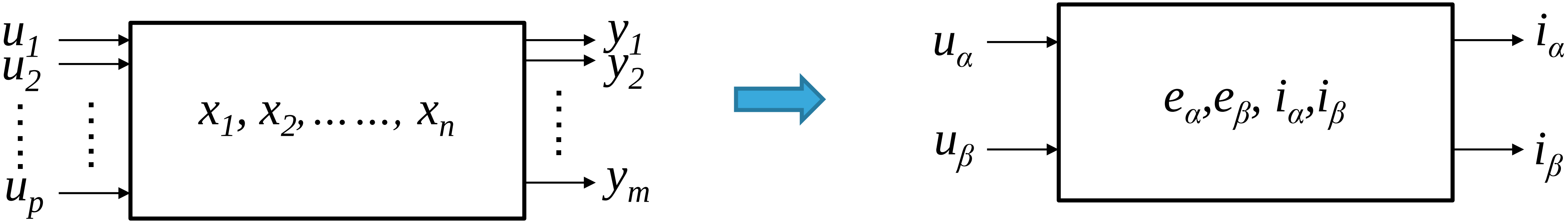




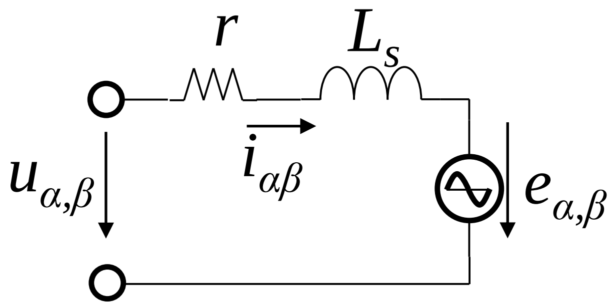


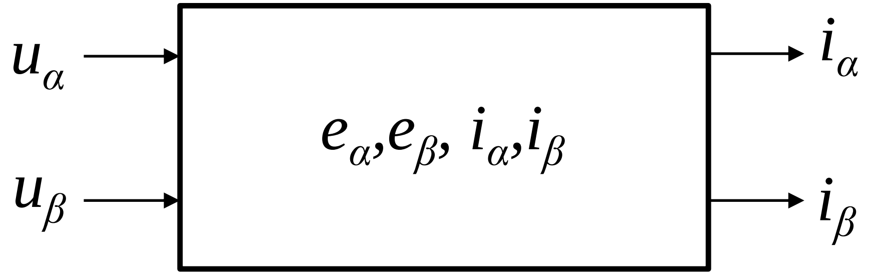



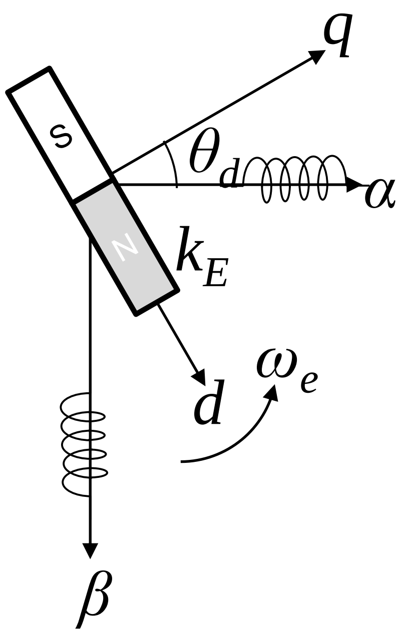

$u \text{ -> } i\ (\tau_e) \text{ -> } \omega_r, \omega_e = p\cdot \omega_r \text{ - > } e$



# 位置速度检测 — 观测器(2/13)



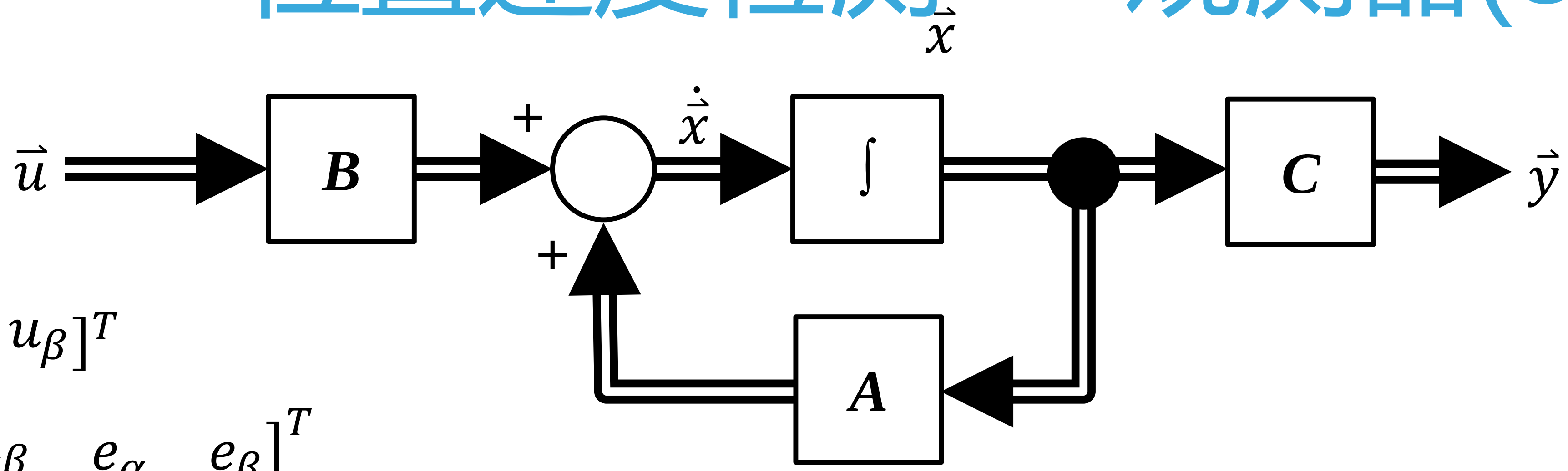

$$
\begin{cases}
e_\alpha = k_E \omega_e \cos(\omega_e t) \\
e_\beta = -k_E \omega_e \sin(\omega_e t)
\end{cases}
$$

A linear model

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

# 位置速度检测 — 观测器(3/13)






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

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

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

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

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

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

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

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# 位置速度检测 — 观测器(4/13)



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

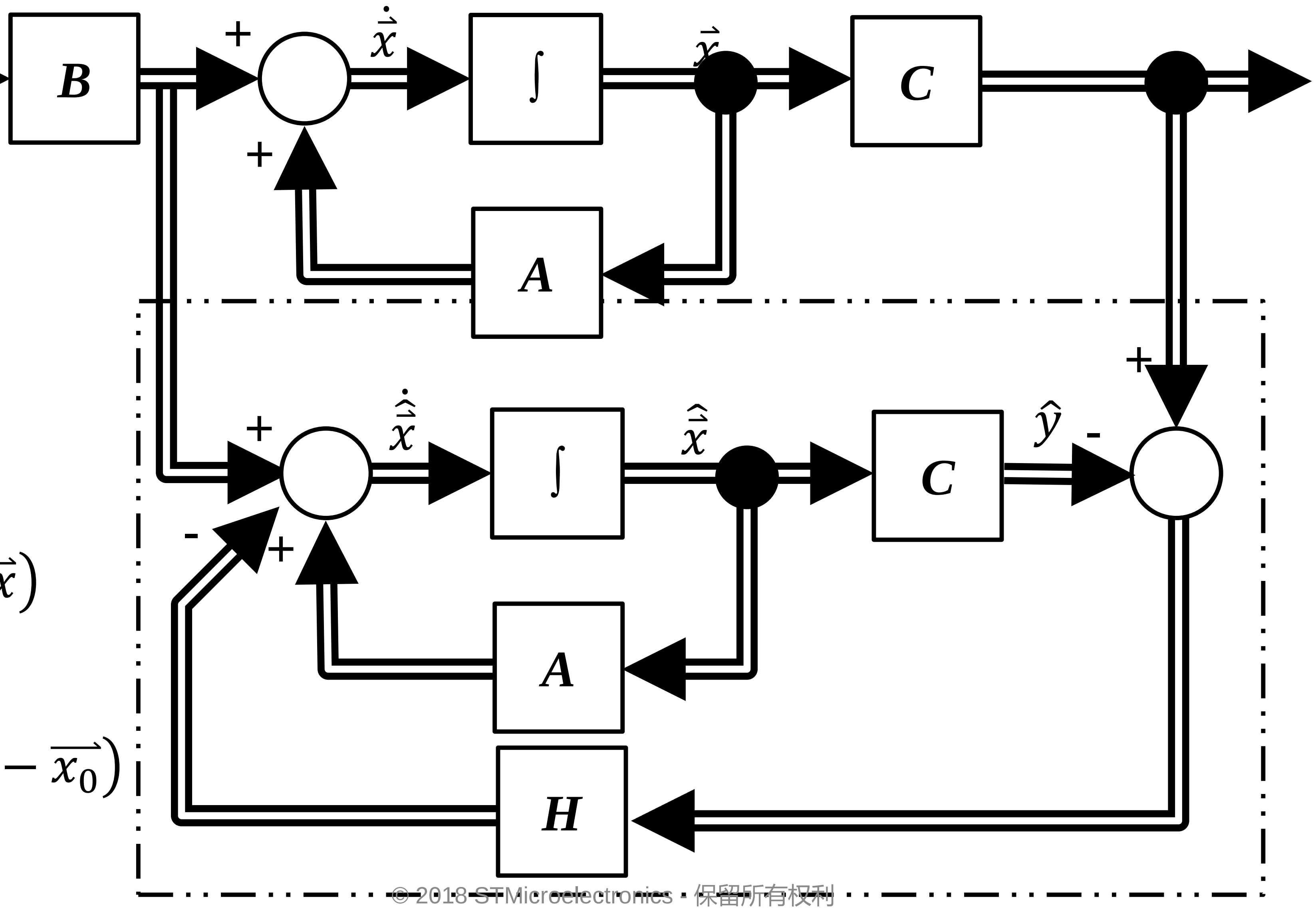
$$\hat{\vec{x}} = [\widehat{i_\alpha} \quad \widehat{i_\beta} \quad \widehat{e_\alpha} \quad \widehat{e_\beta}]^T$$

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

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

⇩

$$\hat{\vec{x}} - \vec{x} = e^{(A+HC)(t-t_0)}(\widehat{\vec{x_0}} - \vec{x_0})$$



# 位置速度检测 — 观测器(5/13)



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

离散化

$$\dot{\vec{x}} = \frac{d\vec{x}}{dt} \approx \frac{\vec{x}[k] - \vec{x}[k-1]}{T_s}$$

$$\begin{cases} \dfrac{\vec{x}[k] - \vec{x}[k-1]}{T_s} = A\vec{x}[k-1] + B\vec{u}[k-1] \\ \vec{y}[k] = C\vec{x}[k] \end{cases}$$

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

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# 位置速度检测 — 观测器(6/13)



去耦(认为$\omega_e$=0) 将简化马达模型

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

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

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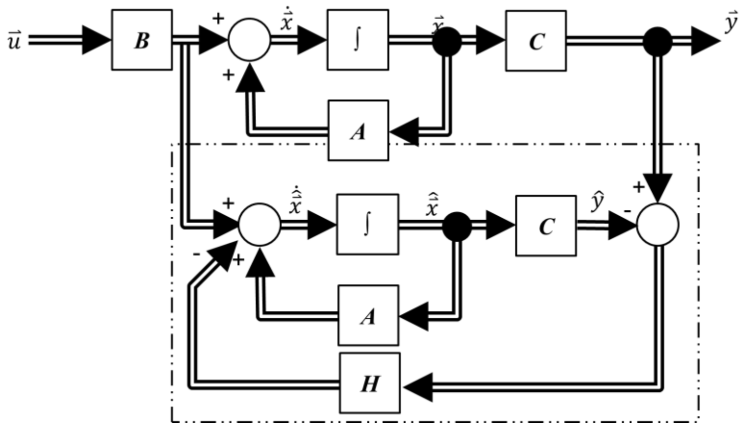
# 位置速度检测 — 观测器(7/13)






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

$$\begin{cases} \widehat{i_\alpha}[k] = \left(1 - \frac{rT_s}{L_s} + h_1 T_s\right)\widehat{i_\alpha}[k-1] - \frac{T_s}{L_s}\widehat{e_\alpha}[k-1] + \frac{T_s}{L_s}u_\alpha[k-1] + h_1 T_s(-i_\alpha[k-1]) \\ \widehat{i_\beta}[k] = \left(1 - \frac{rT_s}{L_s} + h_1 T_s\right)\widehat{i_\beta}[k-1] - \frac{T_s}{L_s}\widehat{e_\beta}[k-1] + \frac{T_s}{L_s}u_\beta[k-1] + h_1 T_s\left(-i_\beta[k-1]\right) \\ \widehat{e_\alpha}[k] = \widehat{e_\alpha}[k-1] + T_s\omega_e\widehat{e_\beta}[k-1] + h_2 T_s\left(\widehat{i_\alpha}[k-1] - i_\alpha[k-1]\right) \\ \widehat{e_\beta}[k] = \widehat{e_\beta}[k-1] - T_s\omega_e\widehat{e_\alpha}[k-1] + h_2 T_s\left(\widehat{i_\beta}[k-1] - i_\beta[k-1]\right) \end{cases}$$

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# 位置速度检测 — 观测器(8/13)

去耦(设定$\omega_e$=0) 简化观测器模型

$$\begin{cases} \widehat{i_\alpha}[k] = \left(1 - \frac{rT_s}{L_s} + h_1 T_s\right)\widehat{i_\alpha}[k-1] - \frac{T_s}{L_s}\widehat{e_\alpha}[k-1] + \frac{T_s}{L_s}u_\alpha[k-1] + h_1 T_s(-i_\alpha[k-1]) \\ \widehat{e_\alpha}[k] = \widehat{e_\alpha}[k-1] + h_2 T_s(\widehat{i_\alpha}[k-1] - i_\alpha[k-1]) \end{cases}$$

$$A_{reduced-obs} = \begin{bmatrix} 1 - \frac{rT_s}{L_s} + h_1 T_s & -\frac{T_s}{L_s} \\ h_2 T_s & 1 \end{bmatrix}$$

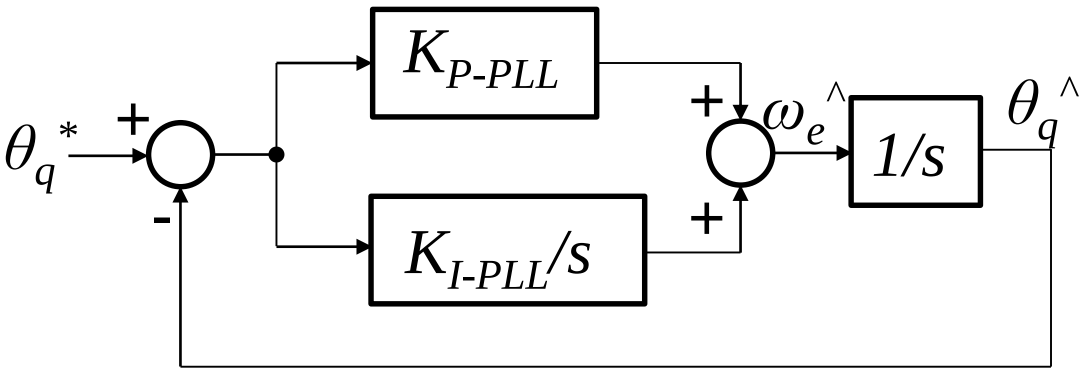
$$\begin{cases} \lambda_{1-obs} = \frac{\lambda_1}{k} \\ \lambda_{2-obs} = \frac{\lambda_2}{k} \end{cases} \quad k > 1$$

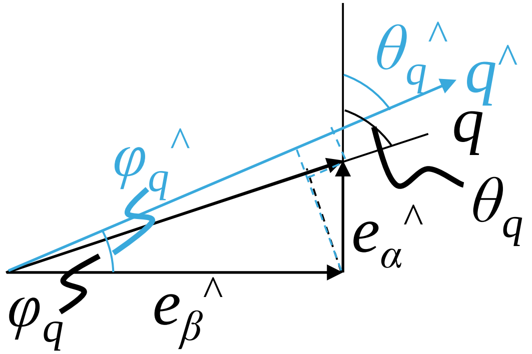
$$|\lambda I - A_{reduced-obs}| = (\lambda - \lambda_{1-obs})(\lambda - \lambda_{2-obs})$$

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

# 位置速度检测 — 观测器(9/13)






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

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

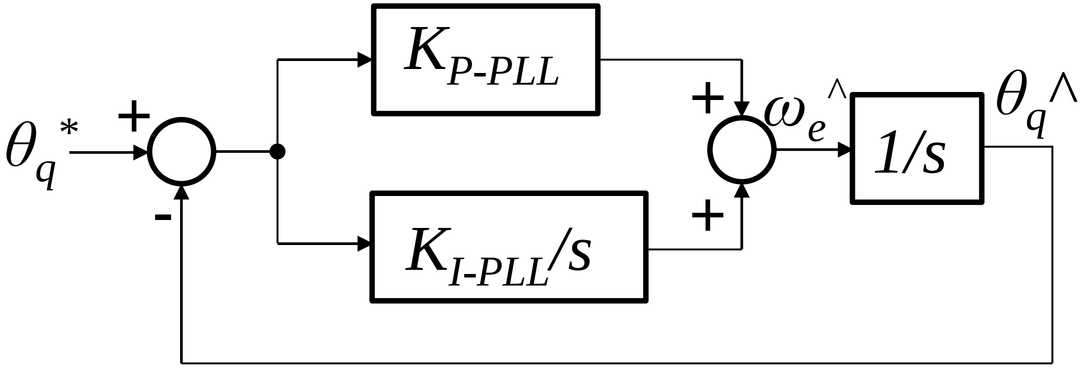
$$e = k_E\omega_e = \sqrt{e_\alpha^{\wedge 2} + e_\beta^{\wedge 2}}$$

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

如果$\theta_q^\wedge - \theta_q$比较小

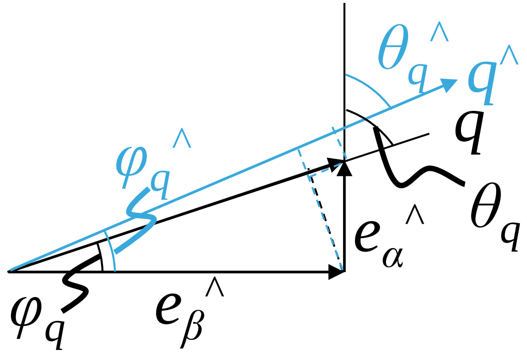
$$\theta_q^\wedge - \theta_q \approx (e_\beta\cos(\theta_q^\wedge) - e_\alpha\sin(\theta_q^\wedge))/(k_E\omega_e)$$

# 位置速度检测 — 观测器(10/13)

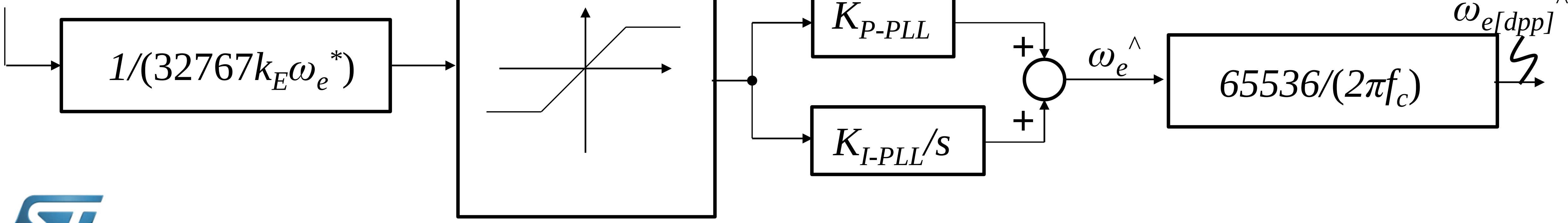



$$e=\sqrt{e_\alpha^{\wedge 2}+e_\beta^{\wedge 2}}=k_E\omega_e^*$$

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

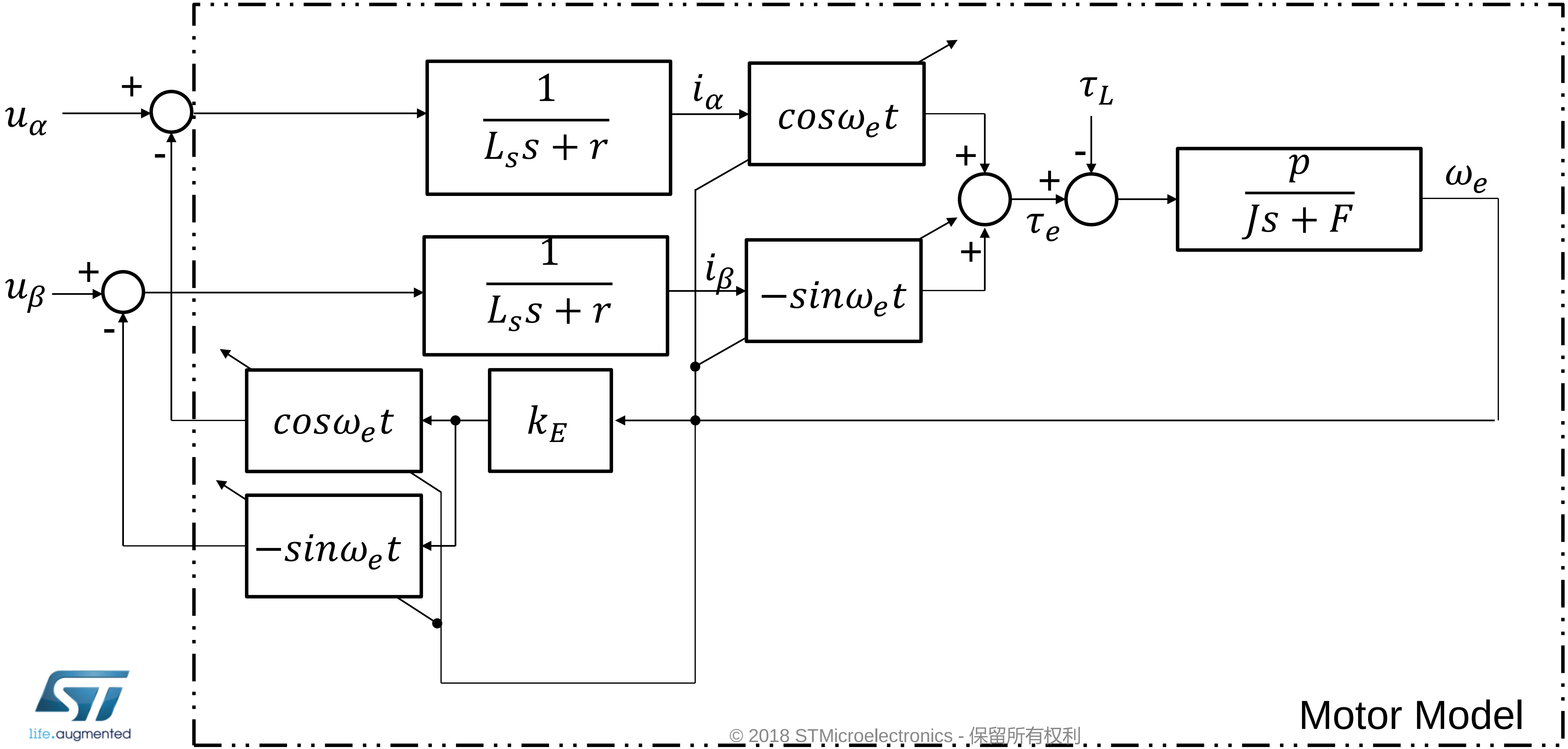



$e_\beta^\wedge\cos(\theta_q^\wedge)-e_\alpha^\wedge\sin(\theta_q^\wedge)$



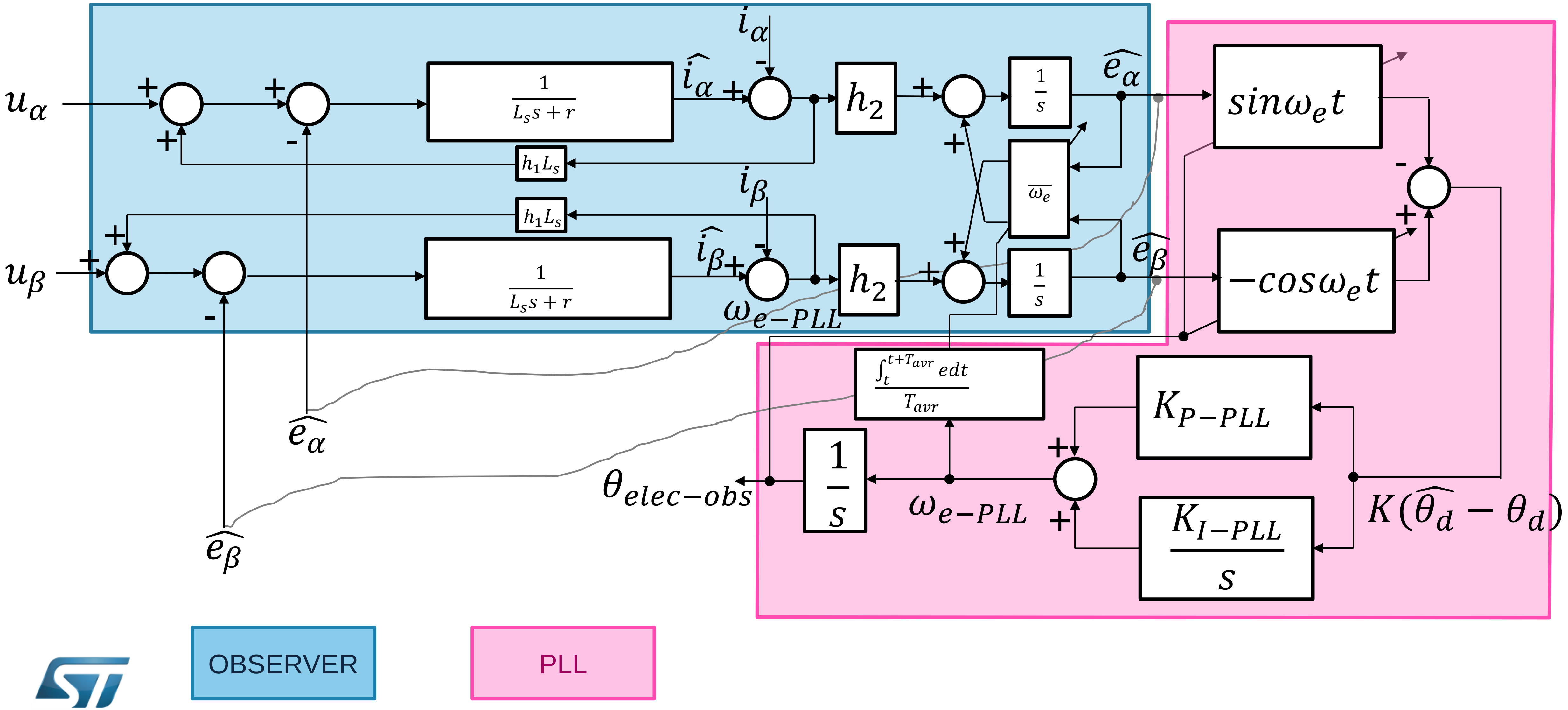
# 位置速度检测 — 观测器(11/13)





# 位置速度检测 — 观测器(12/13)

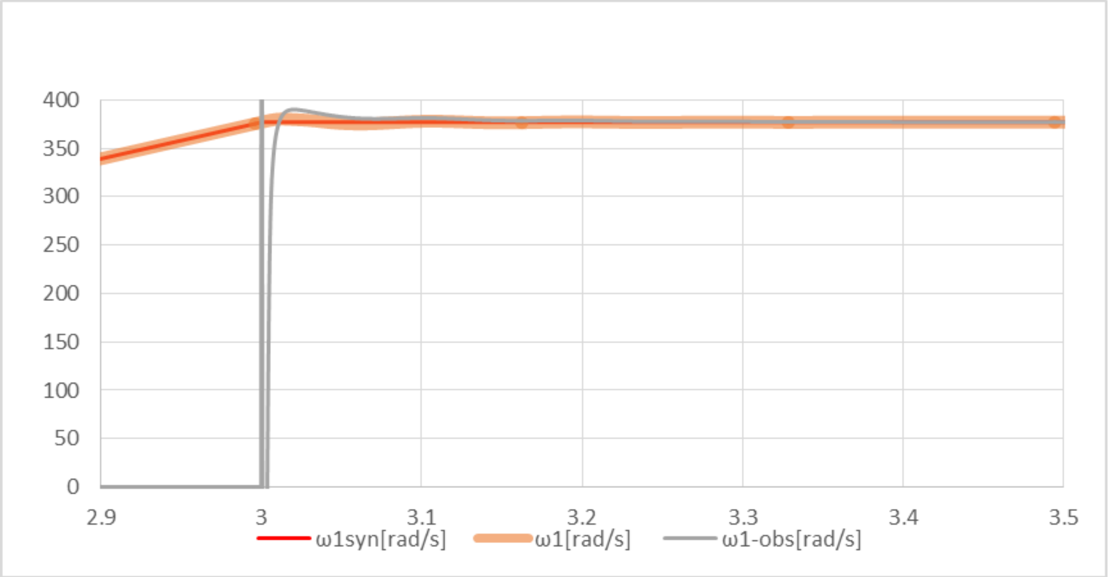


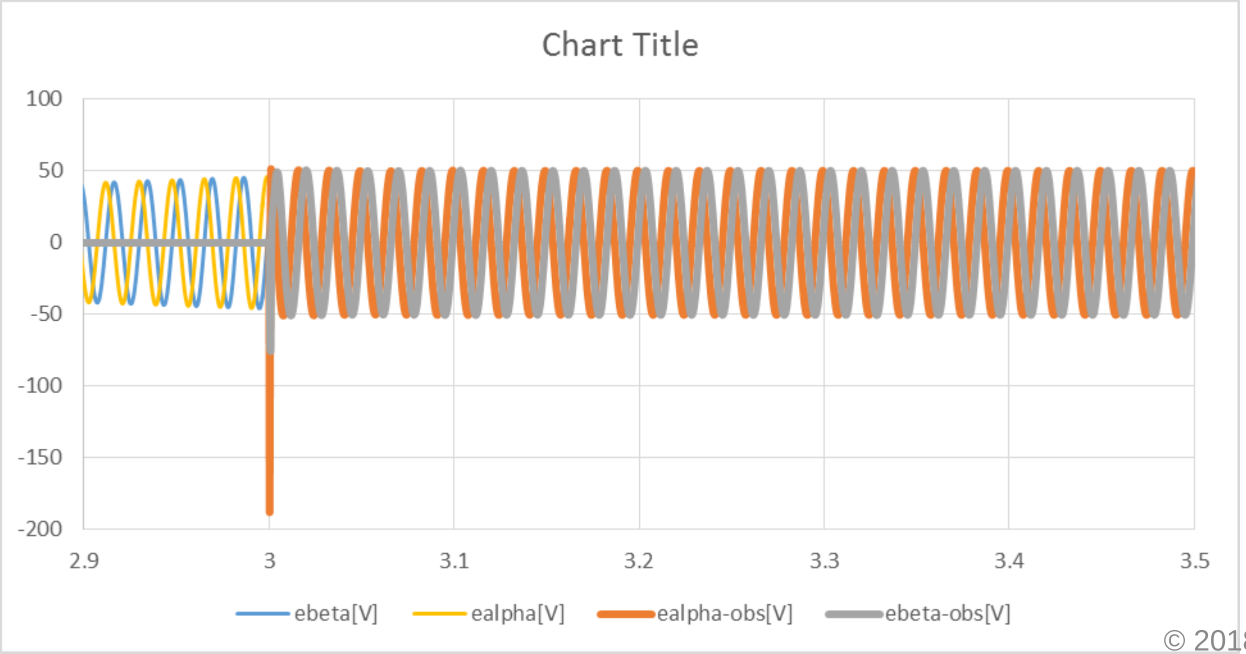


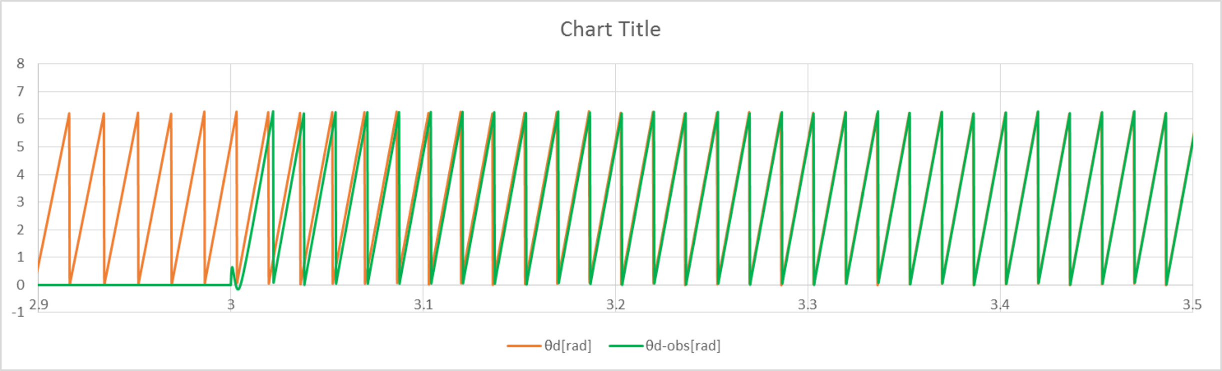
# 位置速度检测 — 观测器(13/13)



$$
\begin{cases}
\hat{i_\alpha}[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right)\hat{i_\alpha}[k-1] - \frac{T_s}{L_s}\widehat{e_\alpha}[k-1] + \frac{T_s}{L_s}u_\alpha[k-1] + h_1T_si_\alpha[k-1] \\
\hat{i_\beta}[k] = \left(1 - \frac{rT_s}{L_s} + h_1T_s\right)\hat{i_\beta}[k-1] - \frac{T_s}{L_s}\widehat{e_\beta}[k-1] + \frac{T_s}{L_s}u_\beta[k-1] + h_1T_si_\beta[k-1] \\
\widehat{e_\alpha}[k] = \widehat{e_\alpha}[k-1] + T_s\overline{\omega_1}\widehat{e_\beta}[k-1] + h_2T_s\left(\hat{i_\alpha}[k-1] - i_\alpha[k-1]\right) \\
\widehat{e_\beta}[k] = \widehat{e_\beta}[k-1] - T_s\overline{\omega_1}\widehat{e_\alpha}[k-1] + h_2T_s\left(\hat{i_\beta}[k-1] - i_\beta[k-1]\right)
\end{cases}
$$



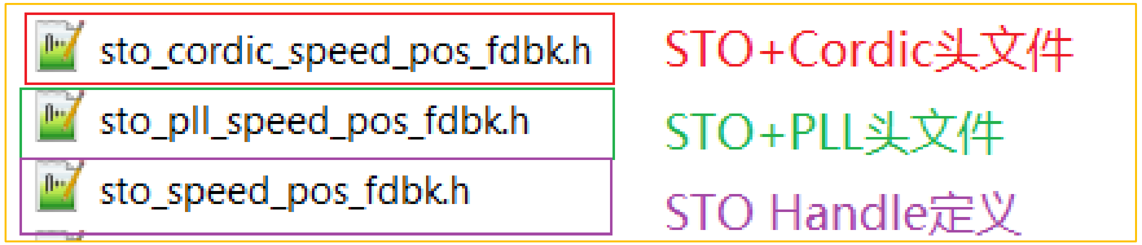



# ST MC SDK5.x 观测器STO的固件



- 对于X-CUBE-MCSDK：观测器的固件以库的形式提供。
  - ✓ xxx\MCSDK_v5.2.0\MotorControl\lib

- 头文件名如下：
  - ✓ sto_cordic_speed_pos_fdbk.h
  - ✓ sto_pll_speed_pos_fdbk.h
  - ✓ sto_speed_pos_fdbk.h

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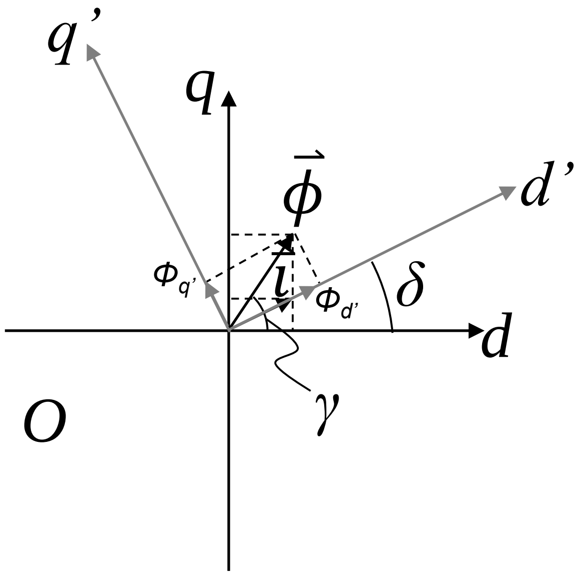
# 位置速度检测 — HFI(1/4)






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

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

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

# 位置速度检测 — HFI(2/4)

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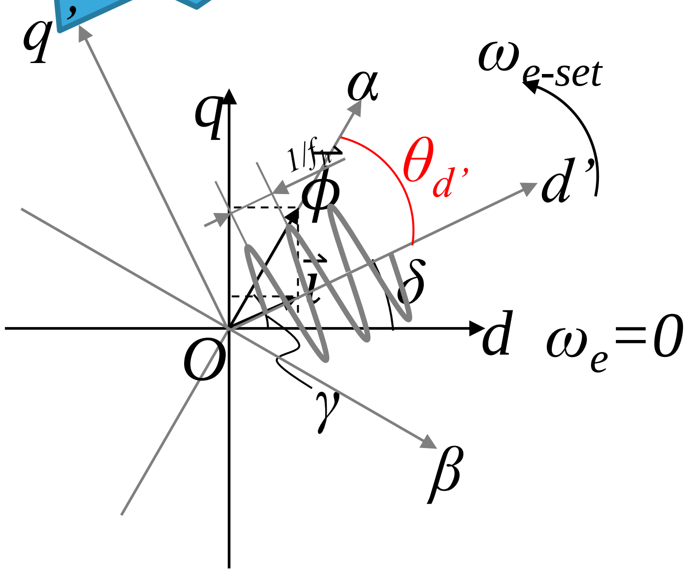
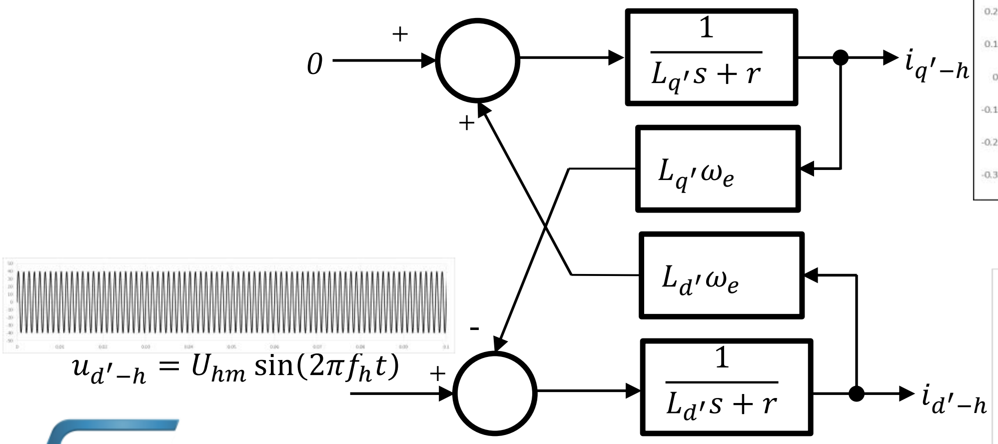
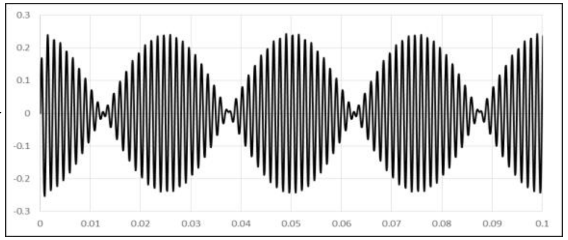
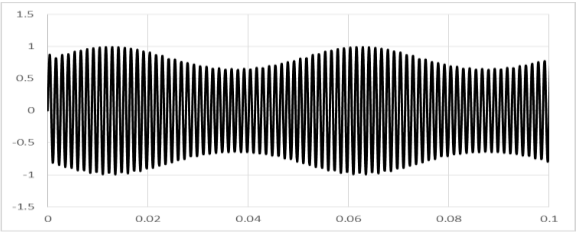


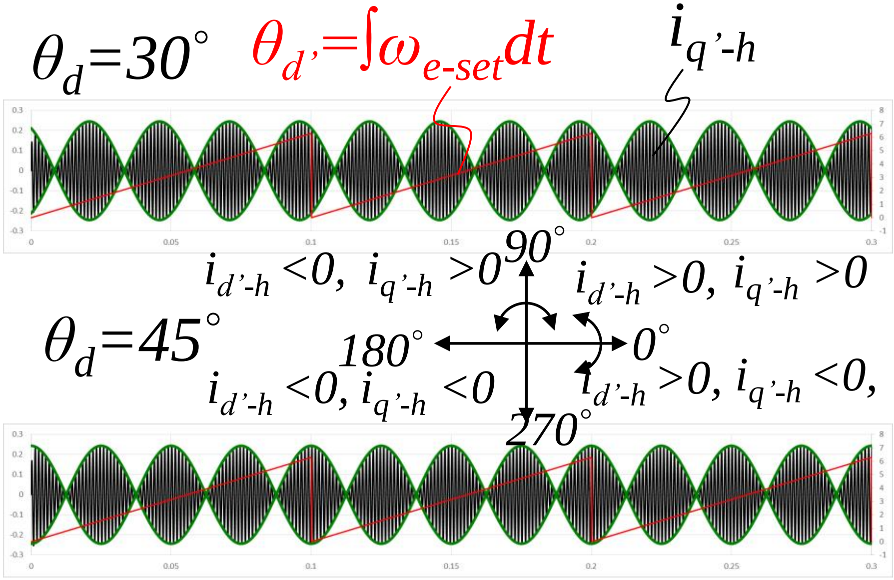

$$|\vec{\phi}| = \sqrt{(L_d I_d)^2 + (L_q I_q)^2} = |\vec{i}|\sqrt{L_d{}^2 + (L_q{}^2 - L_d{}^2)\sin^2\delta}$$

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







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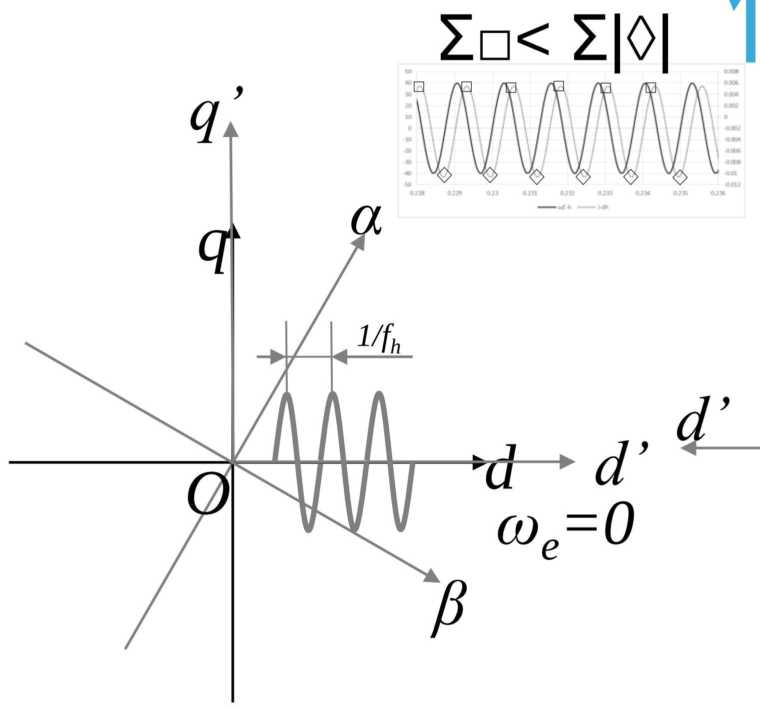
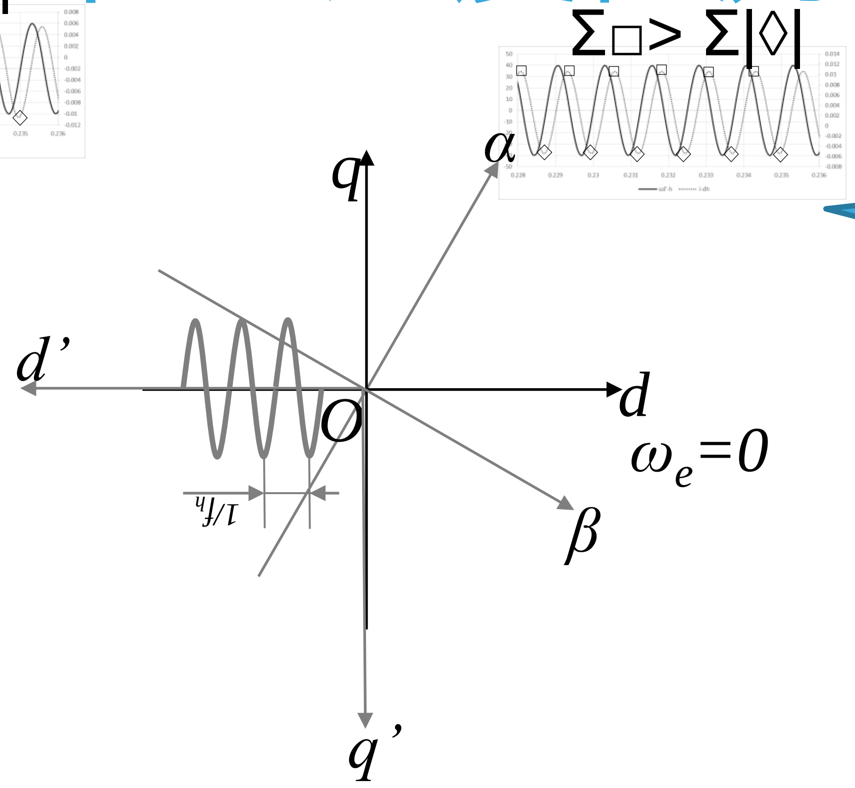
# 位置速度检测 — HFI(3/4)



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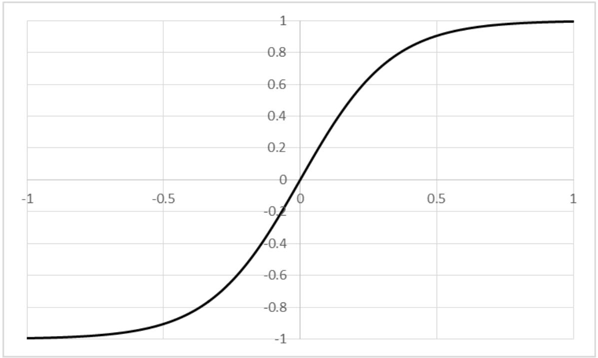
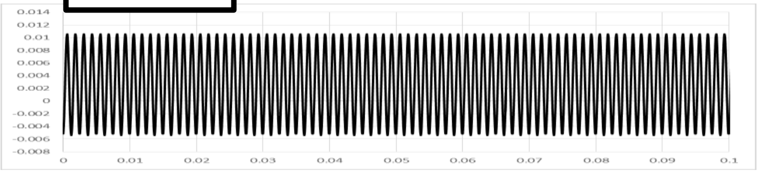


Φ-i 曲线

$u_{d'-h} = U_{hm}\sin(2\pi f_h t) \rightarrow \boxed{\dfrac{1}{L_{d'}s + r}} \rightarrow i_{d'-h}$



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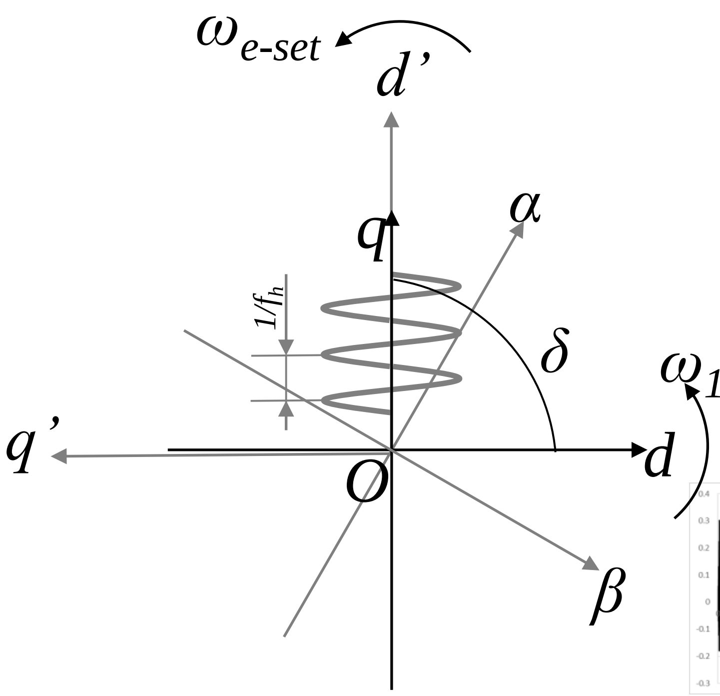
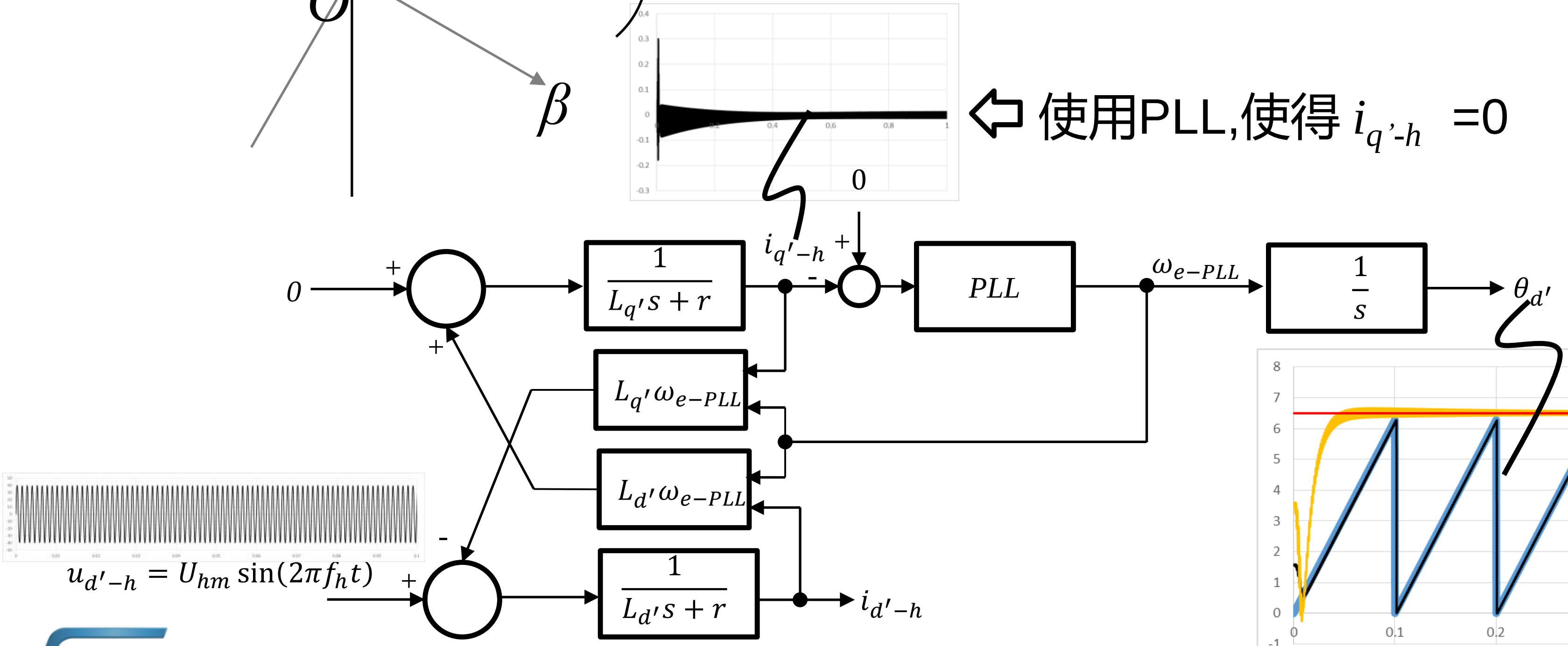
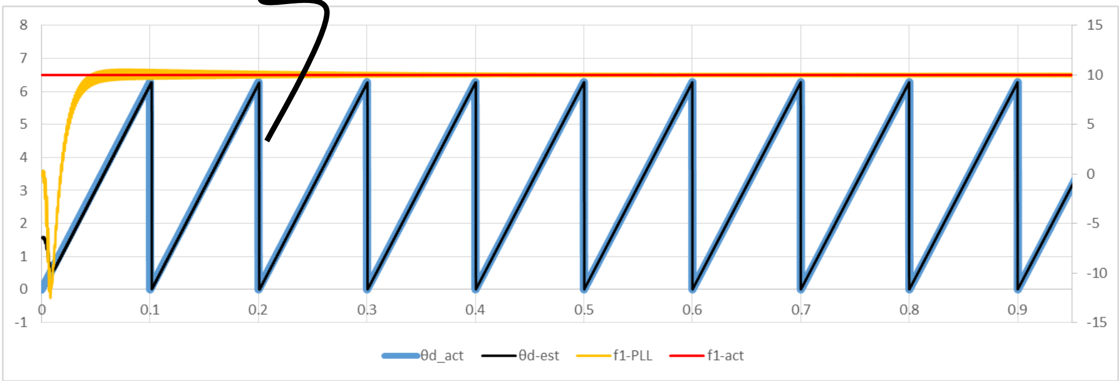
# 位置速度检测 — HFI(4/4)




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




⇦ 使用PLL,使得 $i_{q'\text{-}h}$ =0

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- Thank you -



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