電力電子開發套件

PEK-190

永磁同步馬達驅動器之設計與實作

GW INSTEK
Made to Measure

固緯電子實業股份有限公司

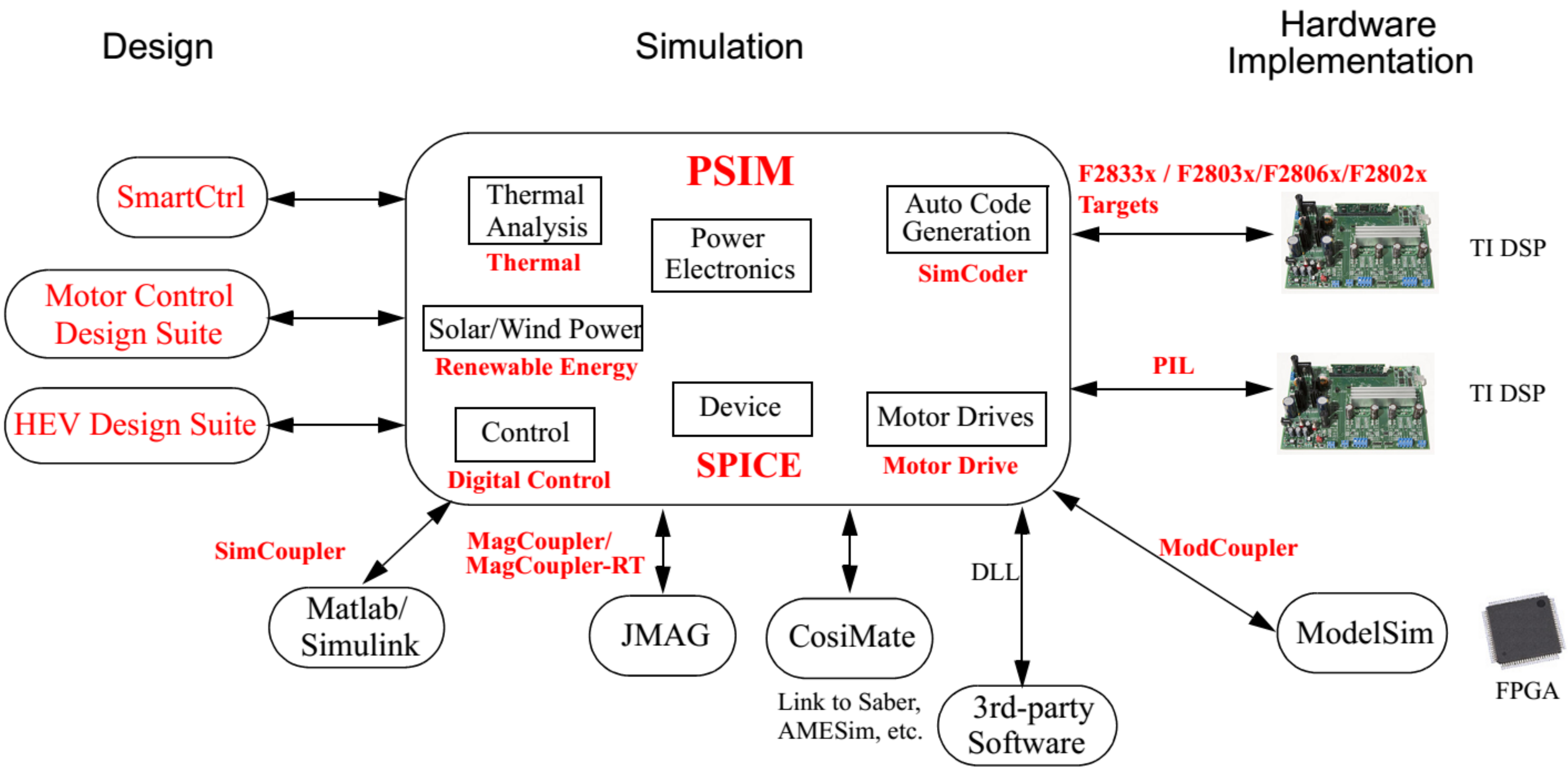
內　容

- PSIM數位控制發展平台、馬達驅動器硬體與PMSM原理介紹
- Lab 1: PMSM之向量控制
- Lab 2: 轉子初始位置檢測及起動
- Lab 3: PMSM參數線上量測與估測
- Lab 4: 無位置傳感器之速度控制(傳統滑模觀測器法)
- Lab 5: 無位置傳感器之速度控制(自適應滑模觀測器法)
- Lab 6: 無位置傳感器之速度控制(模型參考自適應法)

normal

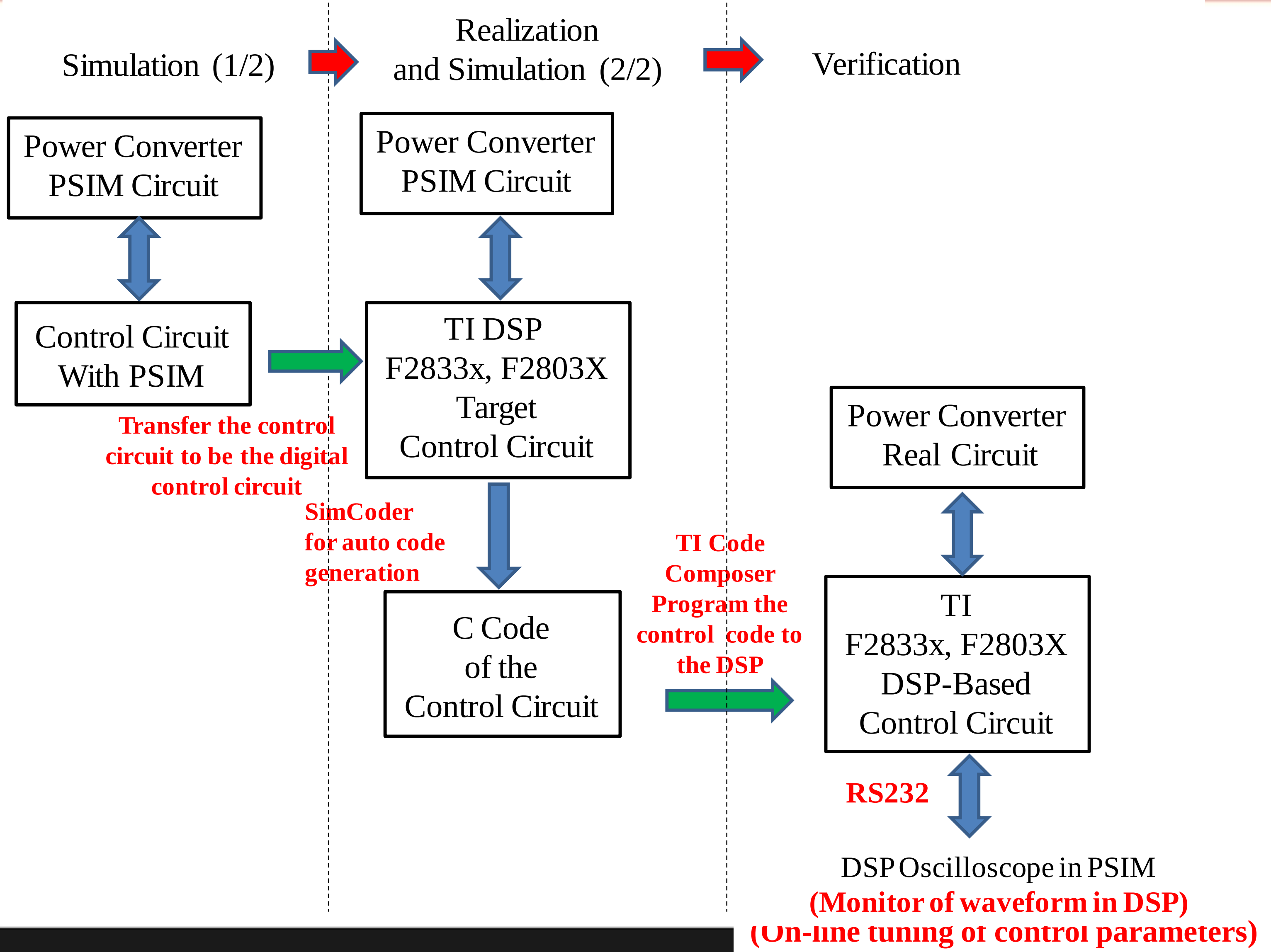
PSIM
數位控制發展平台
介紹

PSIM Functions



Digital Control Implementation

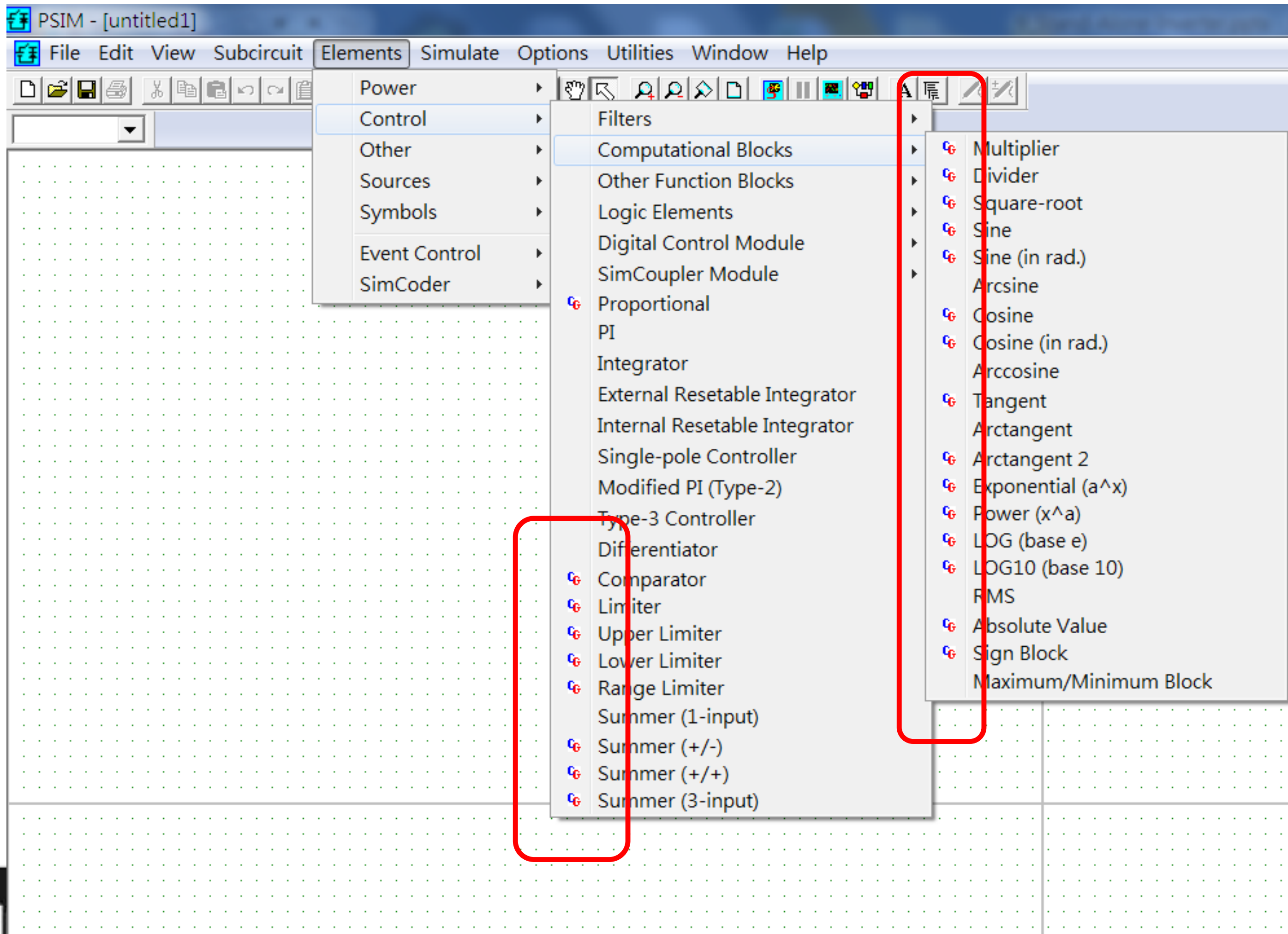
SimCoder + TI DSP Target



normal

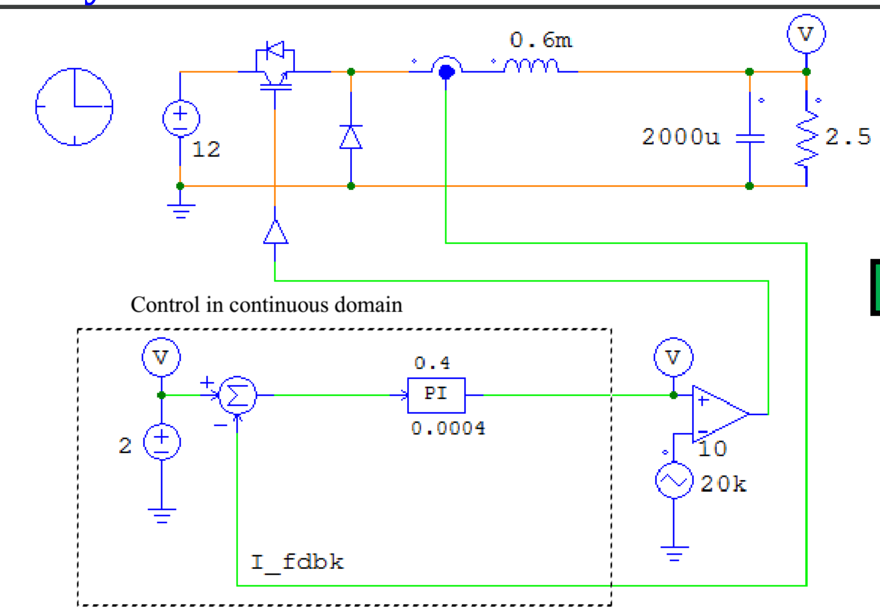
PSIM SimCoder

The element with C_G and T_I on the left column of the element can be used for code generation

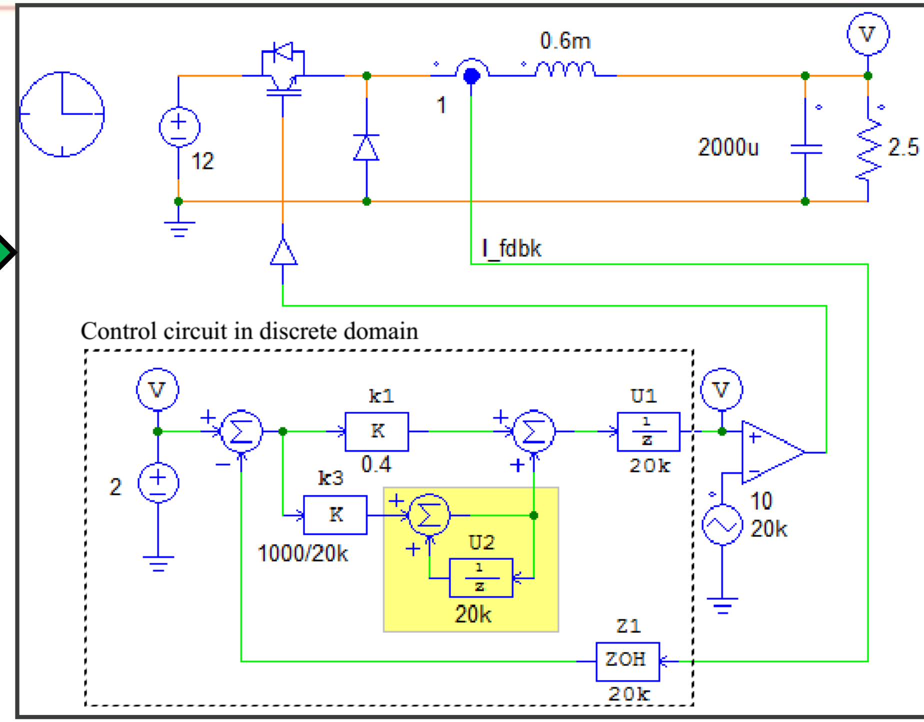


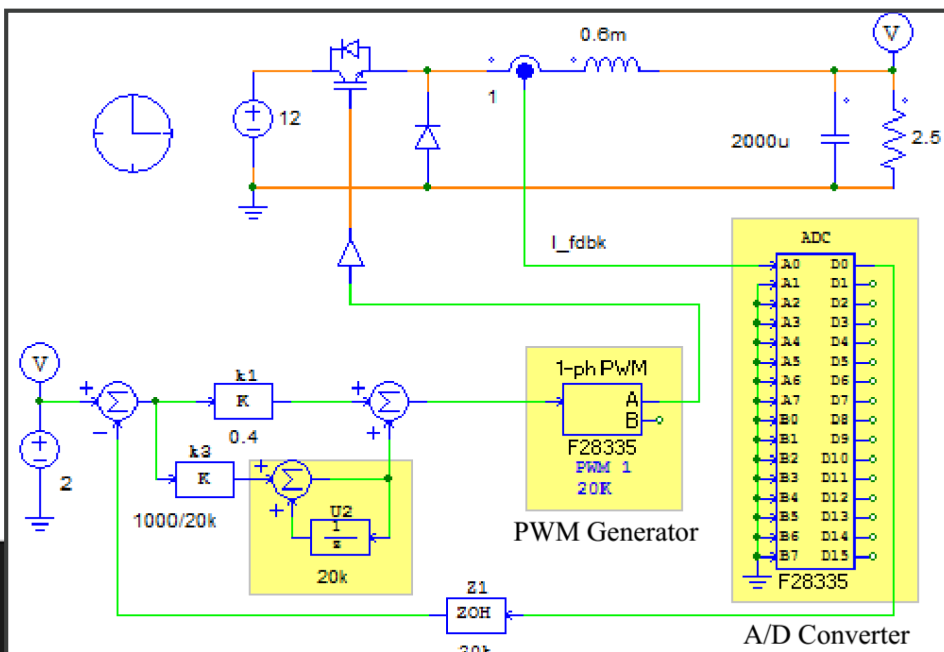
Code Generation - A Step-by-Step Approach

System in Continuous Domain



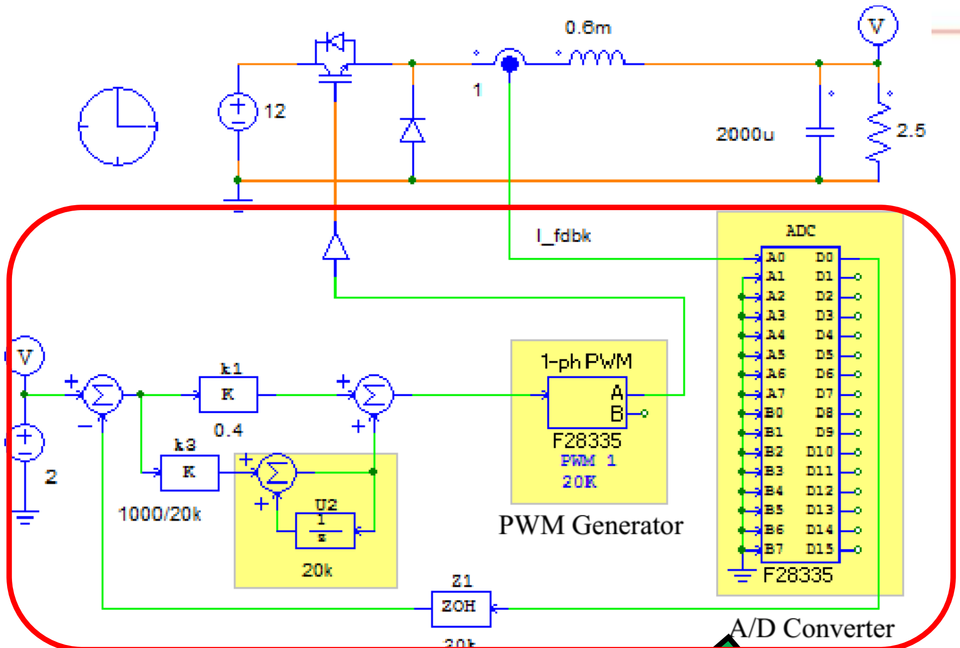
System in Discrete Domain





System with SimCoder for Code Generation of Hardware Target

Code Generation

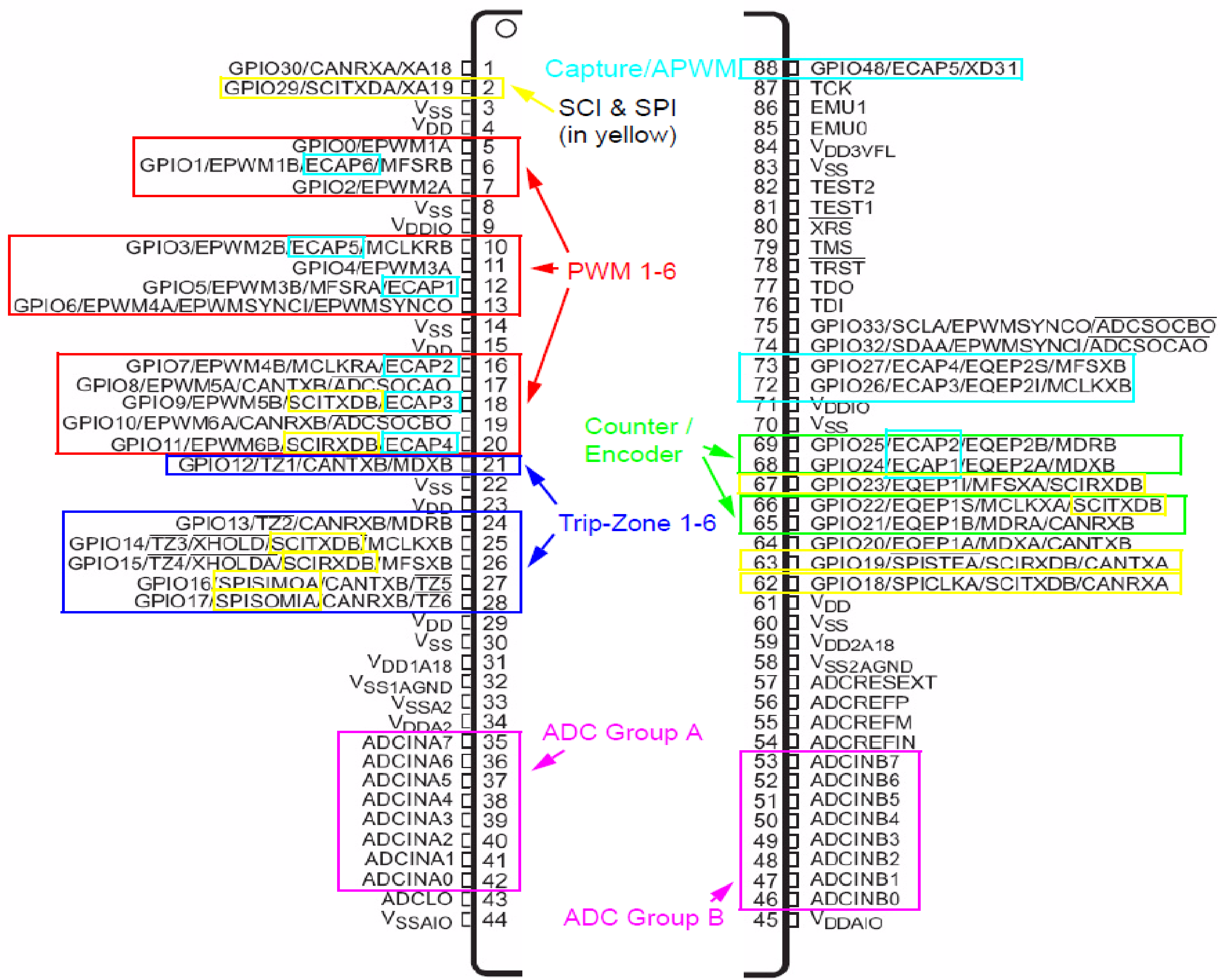


這一部分電路將會被轉成 C code

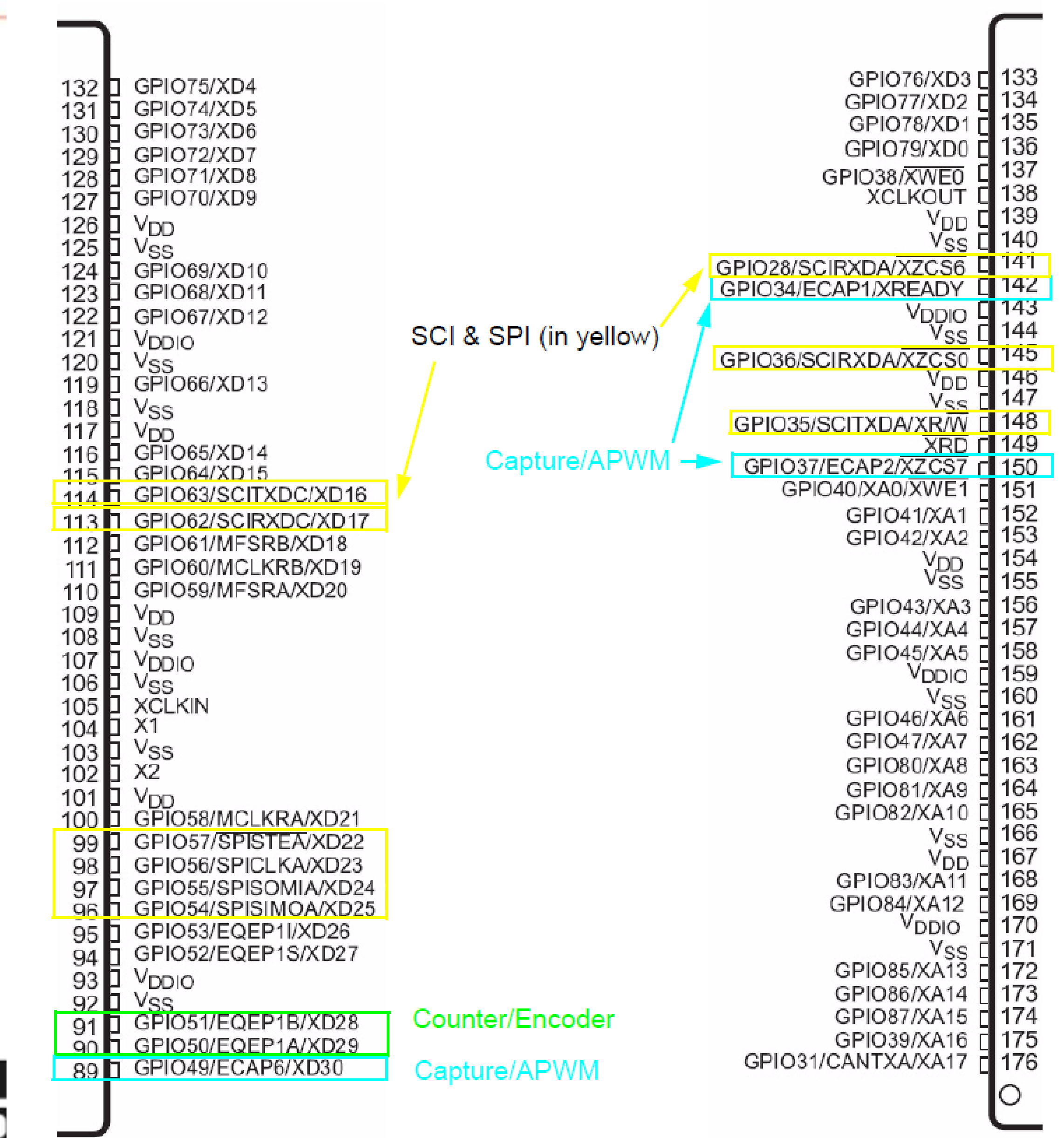
```
#include<math.h>
#include"PS_bios.h"
typedef float DefaultType;
#defineGetCurTime() PS_GetSysTimer()
interrupt void Task();
DefaultTypefGbliref = 0;
DefaultTypefGblU2 = 0;
interrupt void Task()
{
DefaultTypefU2, fSUMP1, fSUMP3, fk3, fk1, fSUM1, fZ1, fTI_ADC1, fVDC2;
PS_EnableIntr();
fU2 = fGblU2;
fTI_ADC1 = PS_GetDcAdc(0);
fVDC2 = 2;
fZ1 = fTI_ADC1;
fSUM1 = fVDC2 - fZ1;
fk1 = fSUM1 * 0.4;
fk3 = fSUM1 * (1000.0/20000);
fSUMP3 = fk3 + fU2;
fSUMP1 = fk1 + fSUMP3;
PS_SetPwm1RateSH(fSUMP1);
#ifdef _DEBUG
fGbliref = fVDC2;
#endif
fGblU2 = fSUMP3;
PS_ExitPwm1General();
}
void Initialize(void)
{
PS_SysInit(30, 10);
PS_StartStopPwmClock(0);
PS_InitTimer(0, 0xffffffff);
PS_InitPwm(1, 0, 20000*1, (4e-6)*1e6, PWM_POSI_ONLY, 42822);// pwnNo,
waveType, frequency, deadtime,
outtype
PS_SetPwmPeakOffset(1, 10, 0, 1.0/10);
PS_SetPwmIntrType(1, ePwmIntrAdc0, 1, 0);
```

```
PS_SetPwmVector(1, ePwmIntrAdc0, Task);
PS_SetPwmTzAct(1, eTZHighImpedance);
PS_SetPwm1RateSH(0);
PS_StartPwm(1);
PS_ResetAdcConvSeq();
PS_SetAdcConvSeq(eAdc0Intr, 0, 1.0);
PS_AdcInit(1, !1);
PS_StartStopPwmClock(1);
}
void main()
{
Initialize();
PS_EnableIntr(); // Enable Global interrupt INTM
PS_EnableDbgm();
for (;;) {
}
}
```

F28335 DSP Port Assignments (Pin 1 - 88)



F28335 DSP Port Assignments (Pin 89 - 176)



DSP Control Board I/O Interface

RS232 JTAG

I/O Interface

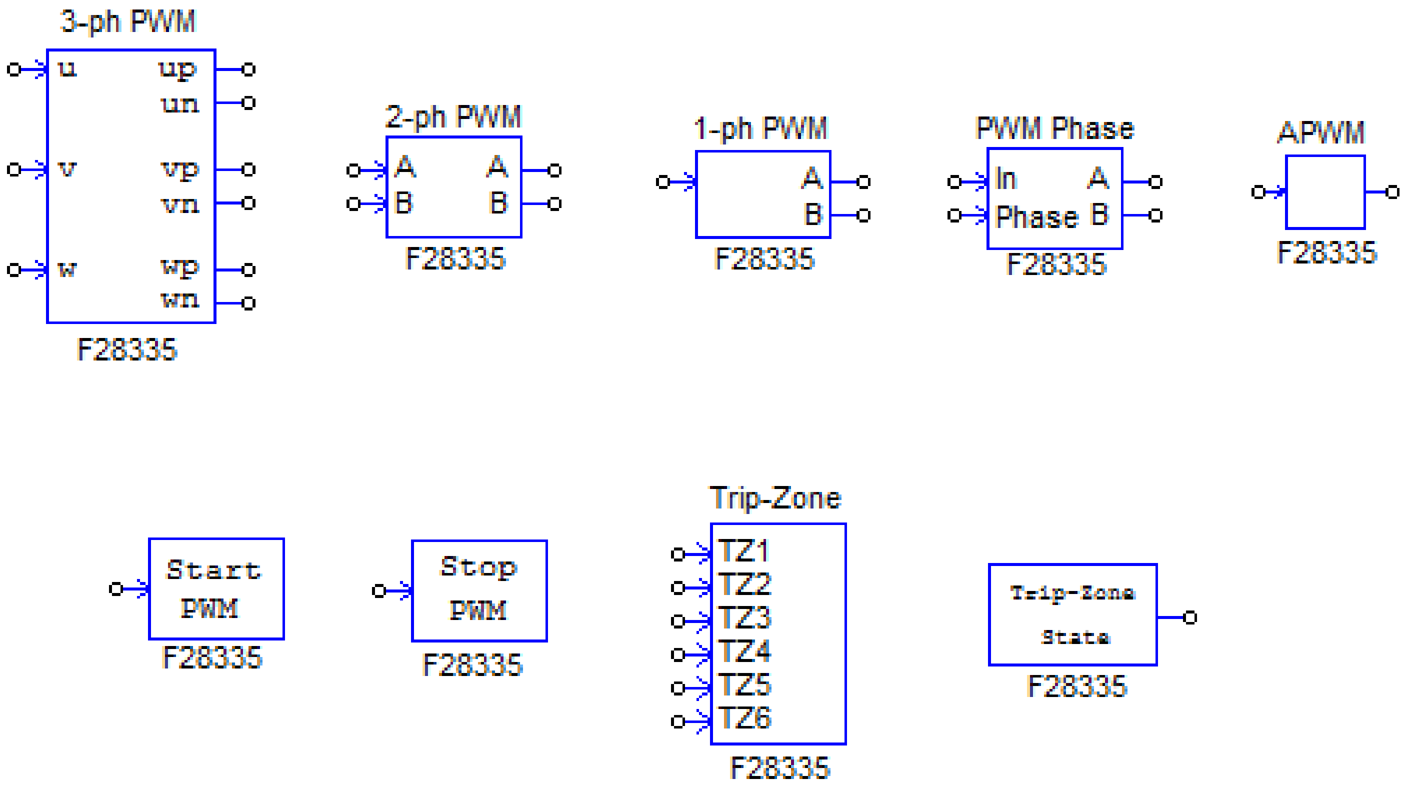
	pin		
+5V in	1	2	+5V in
GND	3	4	GND
GPIO-00 / EPWM	5	6	GPIO-01 / EPWM-1B / MFSR-B
GPIO-02 / EPWM	7	8	GPIO-03 / EPWM-2B / MCLKR-B
GPIO-04 / EPWM	9	10	GPIO-05 / EPWM-3B / MFSR-A / ECAP-1
GPIO-06 / EPWM / SYNCI / SYNCO	11	12	GPIO-07 / EPWM-4B / MCLKR-A / ECAP-2
GPIO-08 / EPWM / CANTX-B / ADCSOC-A	13	14	GPIO-09 / EPWM-5B / SCITX-B / ECAP-3
GPIO-10 / EPWM / CANRX-B / ADCSOC-B	15	16	GPIO-11 / EPWM-6B / SCIRX-B / ECAP-4
GPIO-48 / ECAP5 / XD31 (EMIF)	17	18	GPIO-49 / ECAP6 / XD30 (EMIF)
GPIO-84	19	20	GPIO-85
GPIO-12 / TZ1n / CANTX-B / MDX-B	21	22	GPIO-13 / TZ2n / CANRX-B / MDR-B
GPIO-15 / TZ4n / SCIRX-B / MFSX-B	23	24	GPIO-14 / TZ3n / SCITX-B / MCKX-B
GPIO-24 / ECAP1 / EQEPA-2 / MDX-B	25	26	GPIO-25 / ECAP2 / EQEPB-2 / MDR-B
GPIO-26 / ECAP3 / EQEPI-2 / MCLKX-B	27	28	GPIO-27 / ECAP4 / EQEPS-2 / MFSX-B
GPIO-16 / SPISIMO-A / CANTX-B / TZ-5	29	30	GPIO-17 / SPISOMI-A / CANRX-B / TZ-6
GPIO-18 / SPICLK-A / SCITX-B	31	32	GPIO-19 / SPISTE-A / SCIRX-B
GPIO-20 / EQEP / MDX-A / CANTX-B	33	34	GPIO-21 / EQEP1B / MDR-A / CANRX-B
GPIO-22 / EQEP1S / MCLKX-A / SCITX-B	35	36	GPIO-23 / EQEP1I / MFSX-A / SCIRX-B
GPIO-28 / SCIRX-A / -- / TZ5	37	38	GPIO-29 / SCITX-A / -- / TZ6
GPIO-30 / CANRX-A	39	40	GPIO-31 / CANTX-A
GPIO-32 / I2CSDA / SYNCI / ADCSOCA	41	42	GPIO-33 / I2CSCL / SYNCO / ADCSOCB
ADCIN-B7	43	44	ADCIN-A7
ADCIN-B6	45	46	ADCIN-A6
ADCIN-B5	47	48	ADCIN-A5
ADCIN-B4	49	50	ADCIN-A4
ADCIN-B3	51	52	ADCIN-A3
ADCIN-B2	53	54	ADCIN-A2
ADCIN-B1	55	56	ADCIN-A1
ADCIN-B0	57	58	ADCIN-A0
GND	59	60	GND

SimCoder Elements for TI F2833X Hardware Target

- PWM generators: 3-phase, 2-phase, 1-phase, and APWM
- Variable frequency PWM
- Start/Stop functions for PWM generators
- Trip-zone and trip-zone state
- A/D converter
- Digital input and output
- SCI configuration, input, and output
- SPI configuration, device, input, and output
- CAN configuration, input, and output
- Capture and capture state
- Encoder and encoder state
- Up/Down counter
- Interrupt time
- DSP clock
- Hardware configuration

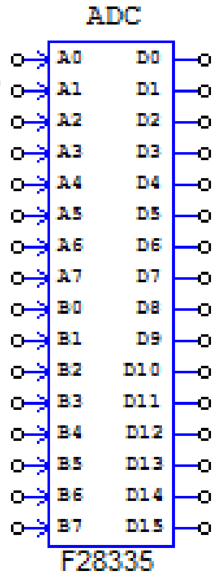
SimCoder Elements for TI F28335 Target

- **PWM**

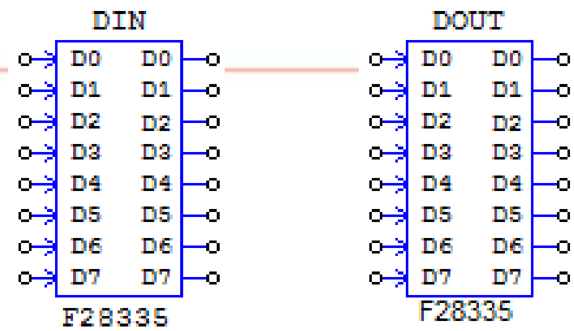


normal

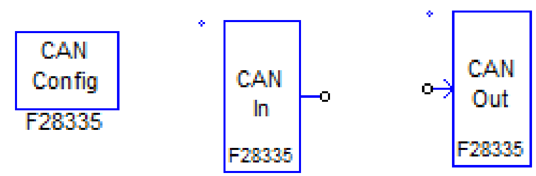
- **A/D Converter**



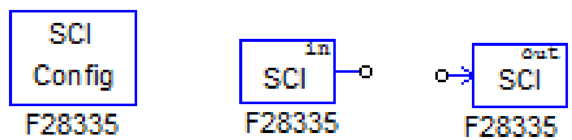
- **Digital I/O**



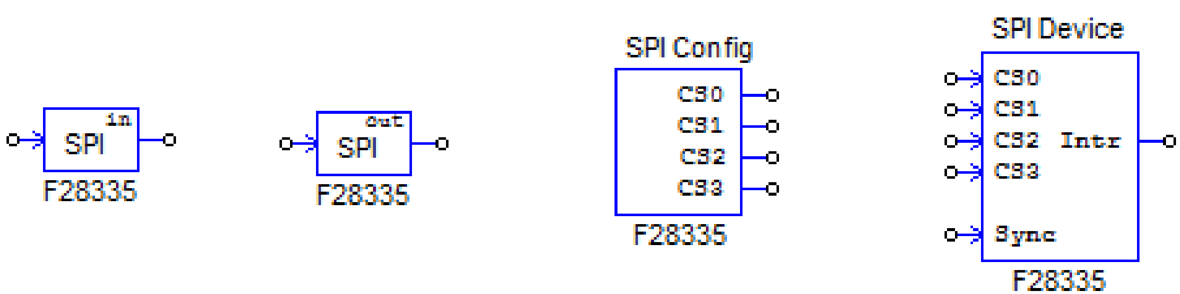
- **CAN**



- **SCI**

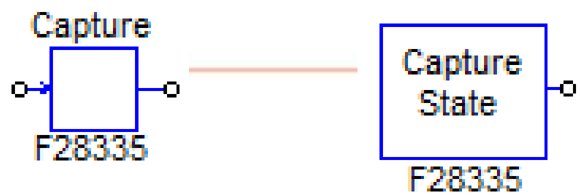


- **SPI**

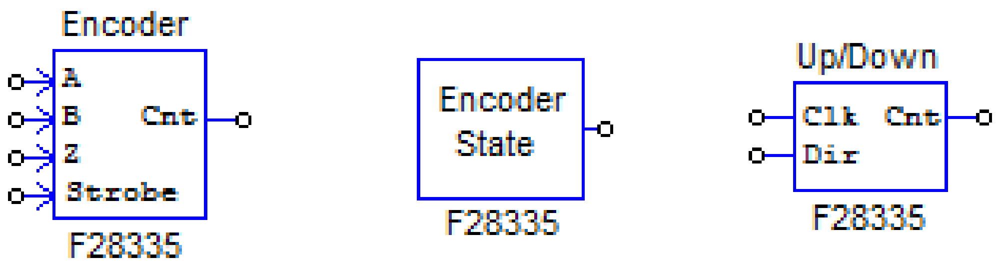


normal

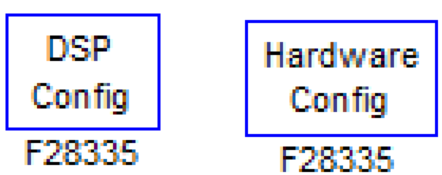
- **Capture**



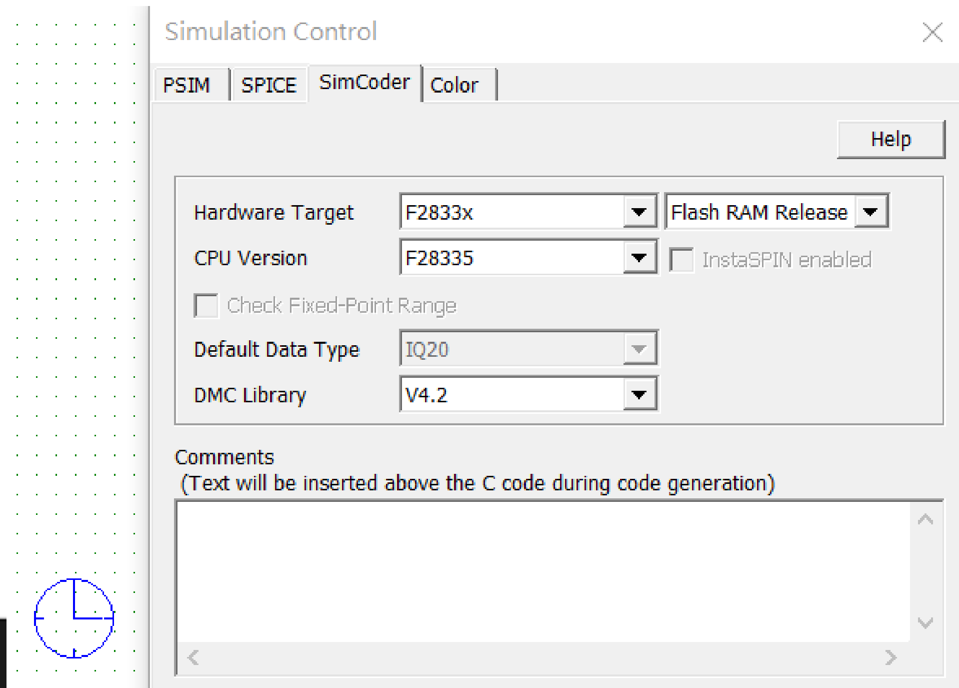
- **Encoder**



- **DSP Configuration**



- **PSIM Simulation Control**

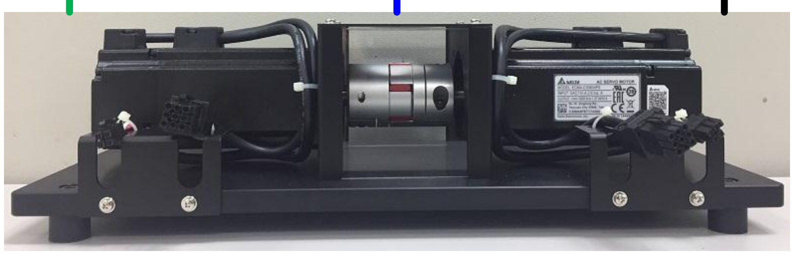


PEK-190
馬達驅動器硬體
介紹

Experimental System

PEK-190 Motor Drive

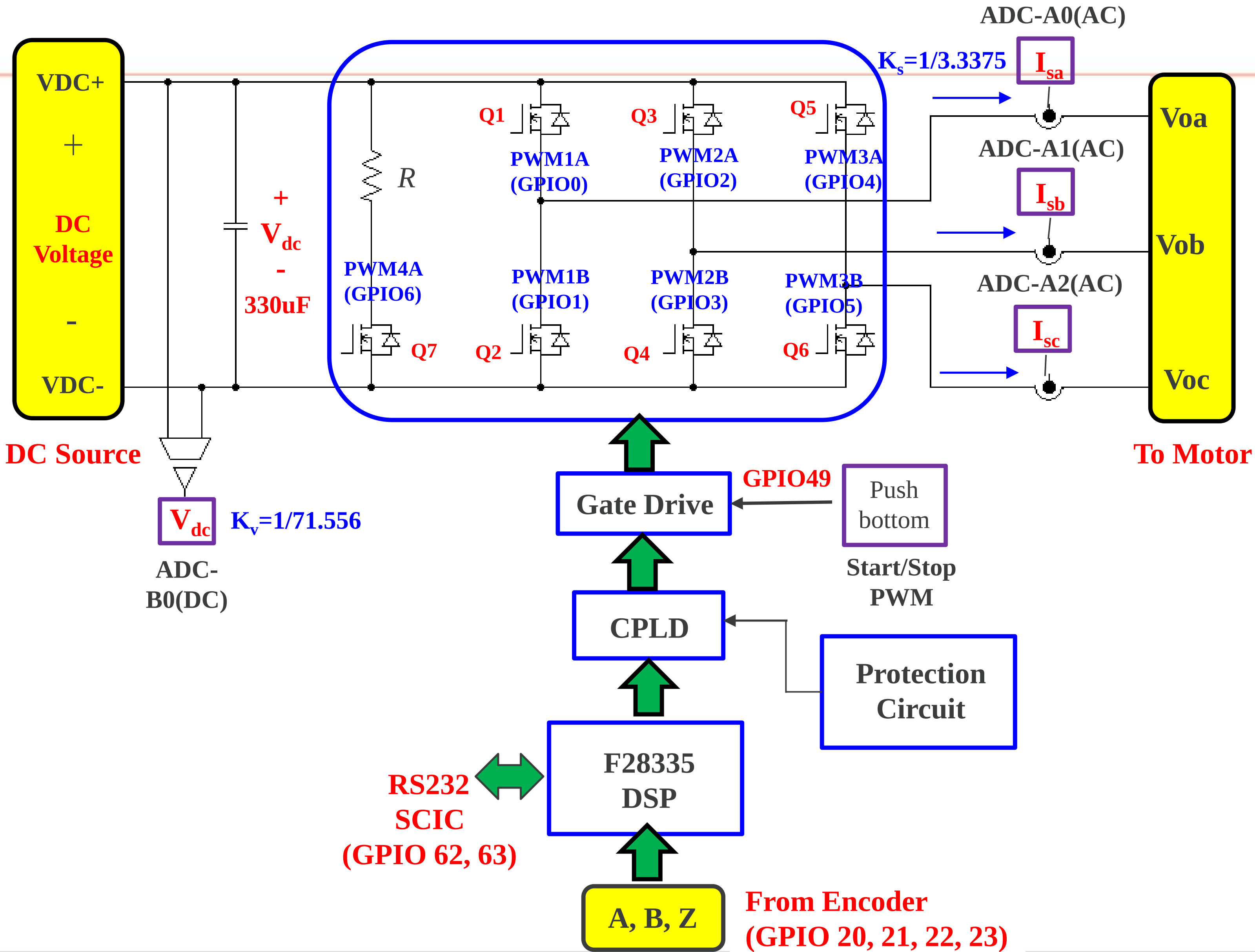
Power Wire | Encoder Wire | Load Wire



M-G Set

PTS-3000

電路及 I/O規劃



VDC+
+
DC Voltage
-
VDC-
DC Source
+
V_{dc}
-
330uF
R
V_{dc}
K_v=1/71.556
ADC-B0(DC)
Q1
Q3
Q5
PWM1A (GPIO0)
PWM2A (GPIO2)
PWM3A (GPIO4)
PWM4A (GPIO6)
PWM1B (GPIO1)
PWM2B (GPIO3)
PWM3B (GPIO5)
Q7
Q2
Q4
Q6
ADC-A0(AC)
K_s=1/3.3375
I_{sa}
ADC-A1(AC)
I_{sb}
ADC-A2(AC)
I_{sc}
Voa
Vob
Voc
To Motor
Gate Drive
GPIO49
Push bottom
Start/Stop PWM
CPLD
Protection Circuit
F28335 DSP
RS232 SCIC (GPIO 62, 63)
A, B, Z
From Encoder (GPIO 20, 21, 22, 23)

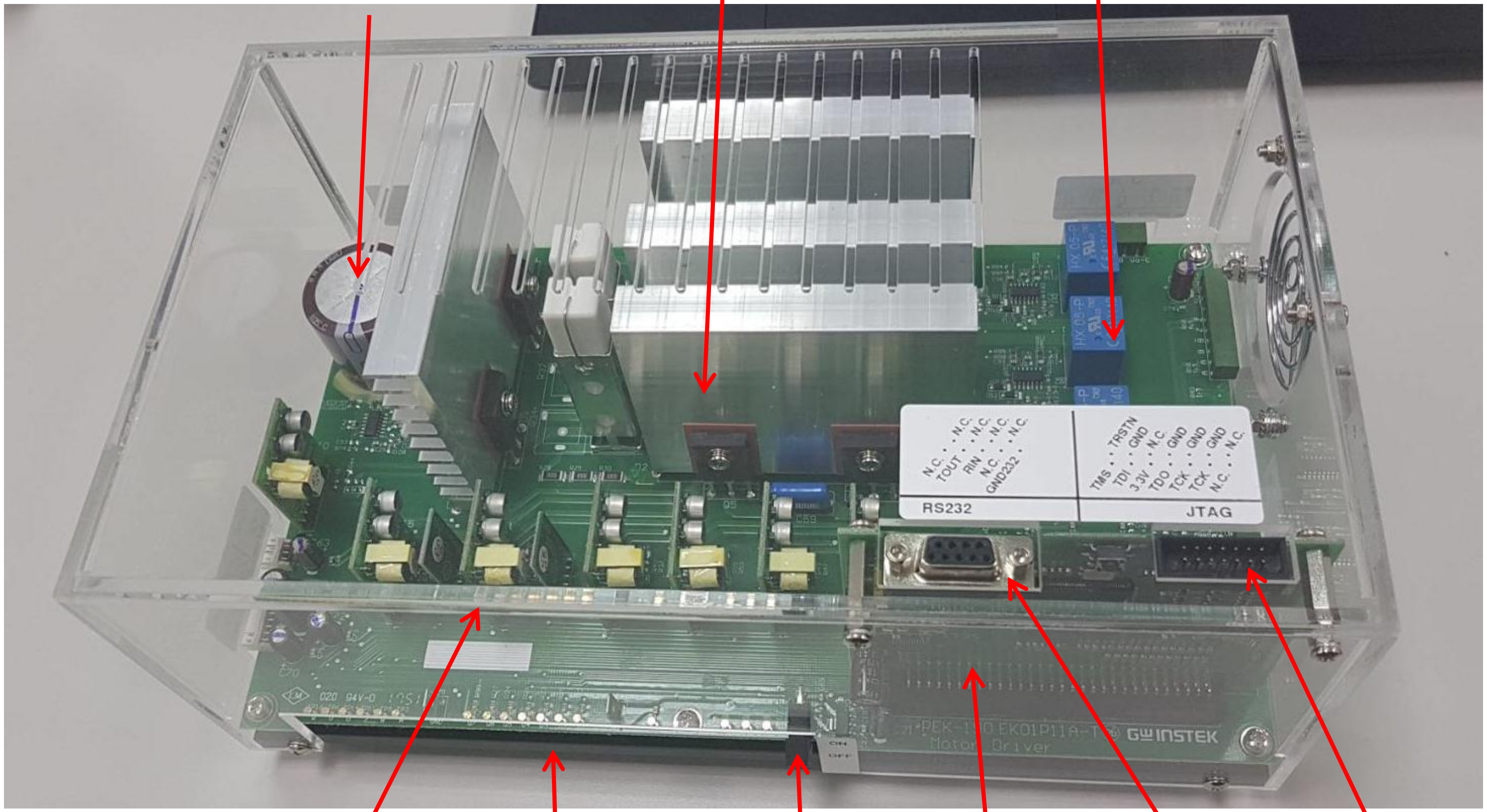
電路外觀

normal

Hall
Current Sensor

DC
Capacitor

MOSFET



Gate Drive
Circuit

Test Points

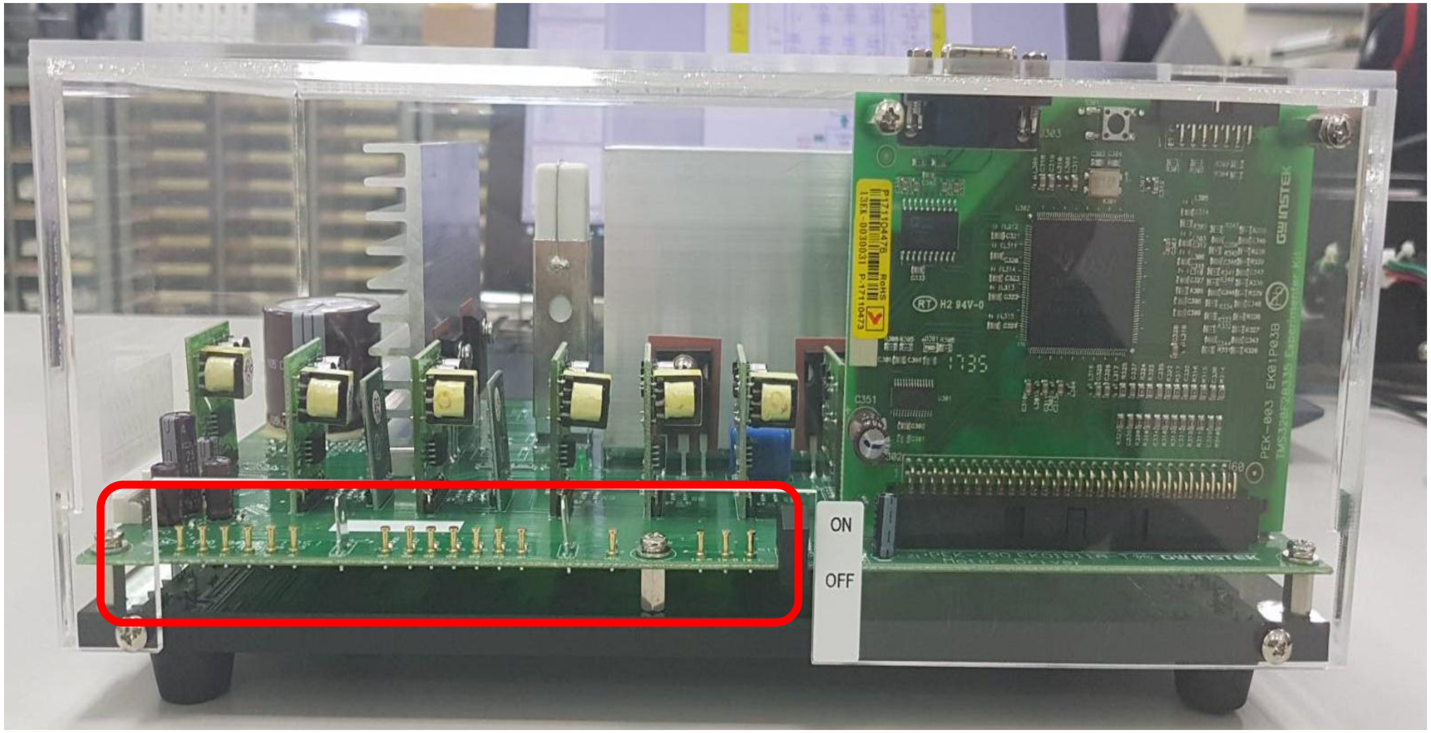
ON/OFF
Push Bottom

F28335 DSP
Control Board

RS232

JTAG

Test Points

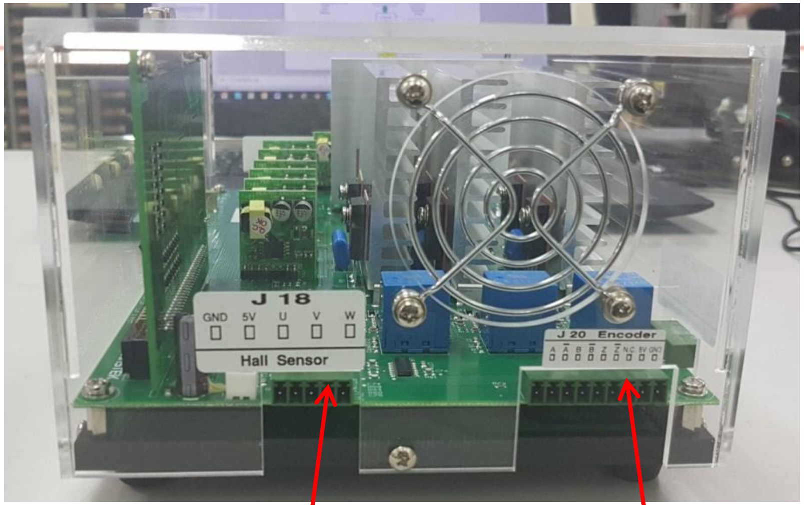


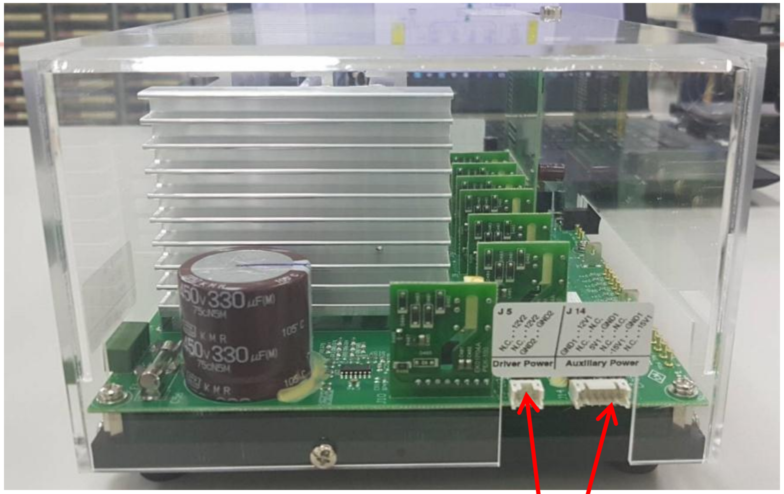
- Q1, Q2, Q3, Q4, Q5: PWM signal
- I_{sa}, I_{sb}, I_{sc}: sensor factor = 1/3.3375
- V_{dc}: sensing factor = 1/71.556

normal

Connections

normal

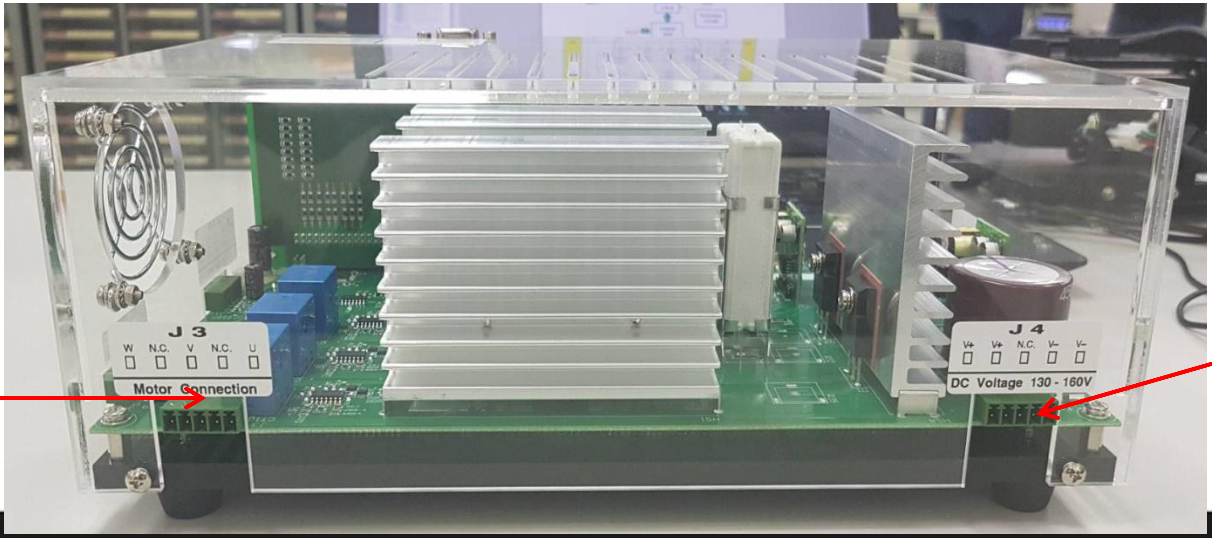




Hall Sensor Input

Encoder

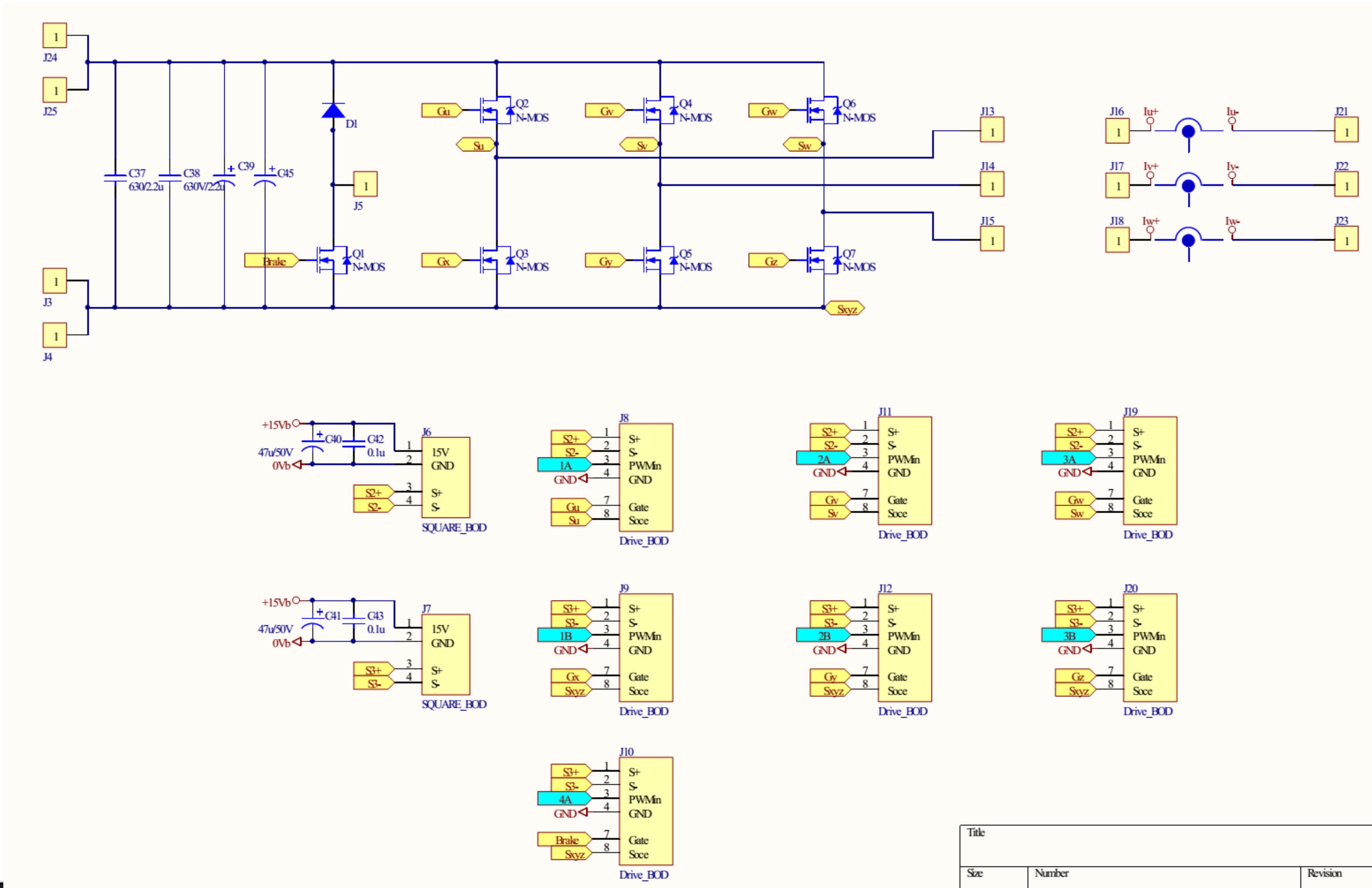
Auxiliary Power Supply Input



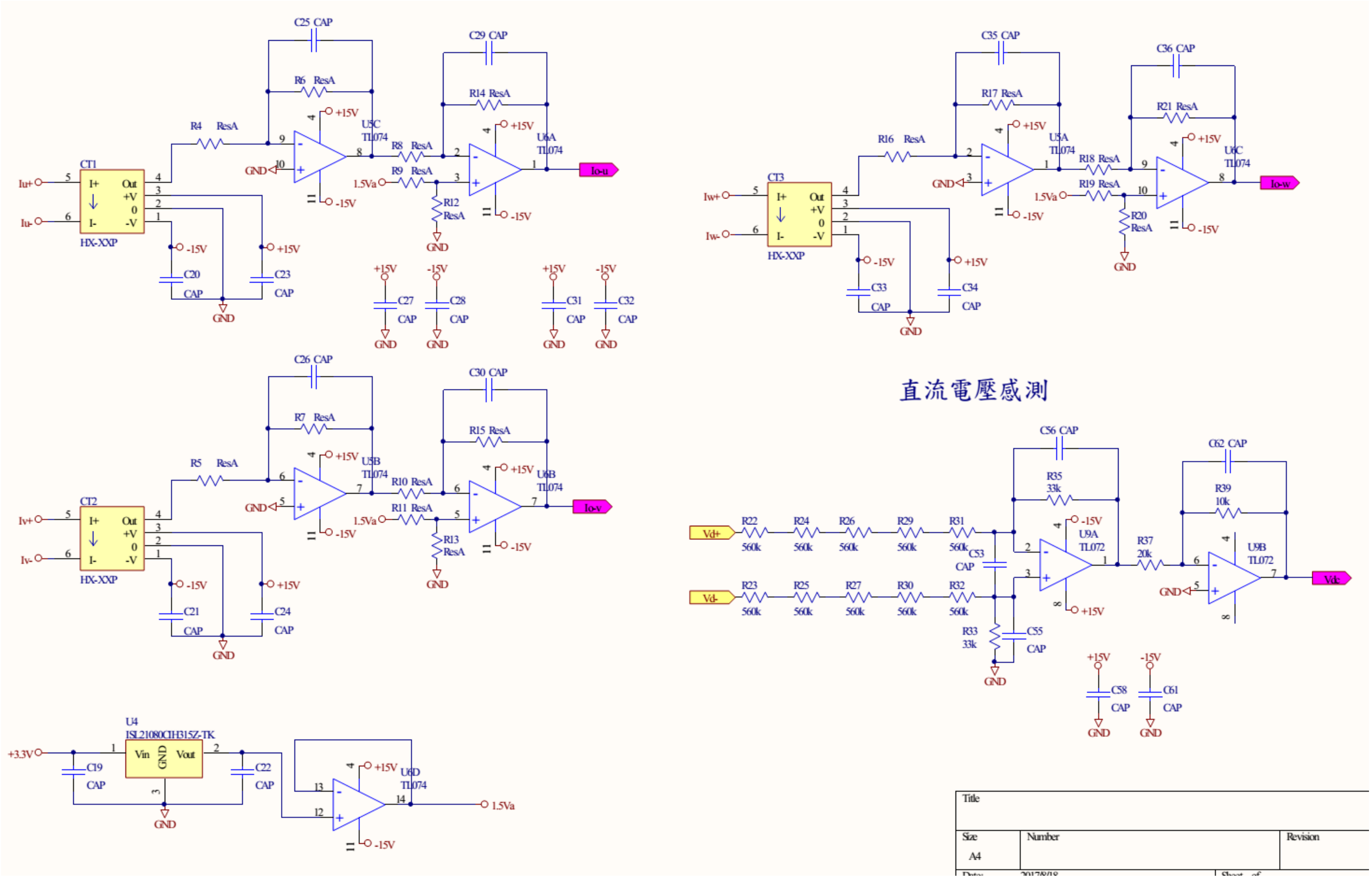
Motor Connection

DC Voltage

主電路

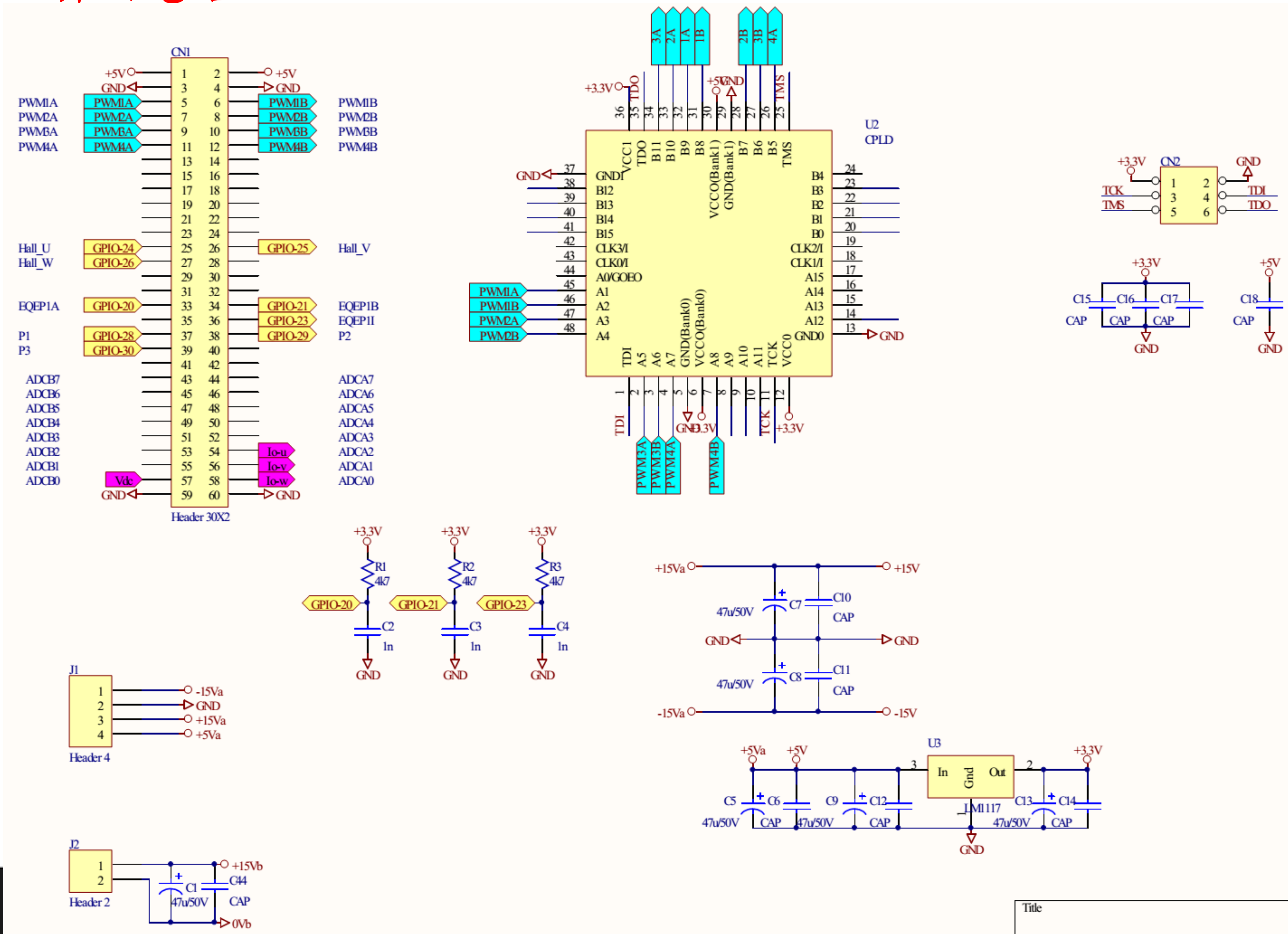

J24
J25
J3
J4
C37 630/2.2u
C38 630V/2.2u
C39
C45
D1
J5
Brake
Q1 N-MOS
Gu
Q2 N-MOS
Su
Gx
Q3 N-MOS
Gv
Q4 N-MOS
Sv
Gy
Q5 N-MOS
Gw
Q6 N-MOS
Sw
Gz
Q7 N-MOS
Sxyz
J13
J14
J15
J16 Iu+ Iu- J21
J17 Iv+ Iv- J22
J18 Iw+ Iw- J23
+15Vb
47u/50V
0Vb
C40
C42 0.1u
J6
15V
GND
S2+
S2-
S+
S-
SQUARE_BOD
J8
S+
S-
PWMin
GND
Gate
Soce
1A
GND
Gu
Su
Drive_BOD
J11
2A
Gv
Sv
Drive_BOD
J19
3A
Gw
Sw
Drive_BOD
+15Vb
47u/50V
0Vb
C41
C43 0.1u
J7
S3+
S3-
SQUARE_BOD
J9
1B
Gx
Sxyz
Drive_BOD
J12
2B
Gy
Sxyz
Drive_BOD
J20
3B
Gz
Sxyz
Drive_BOD
J10
4A
Brake
Sxyz
Drive_BOD
Title
Size
A4
Number
Revision

電壓及電流感測電路



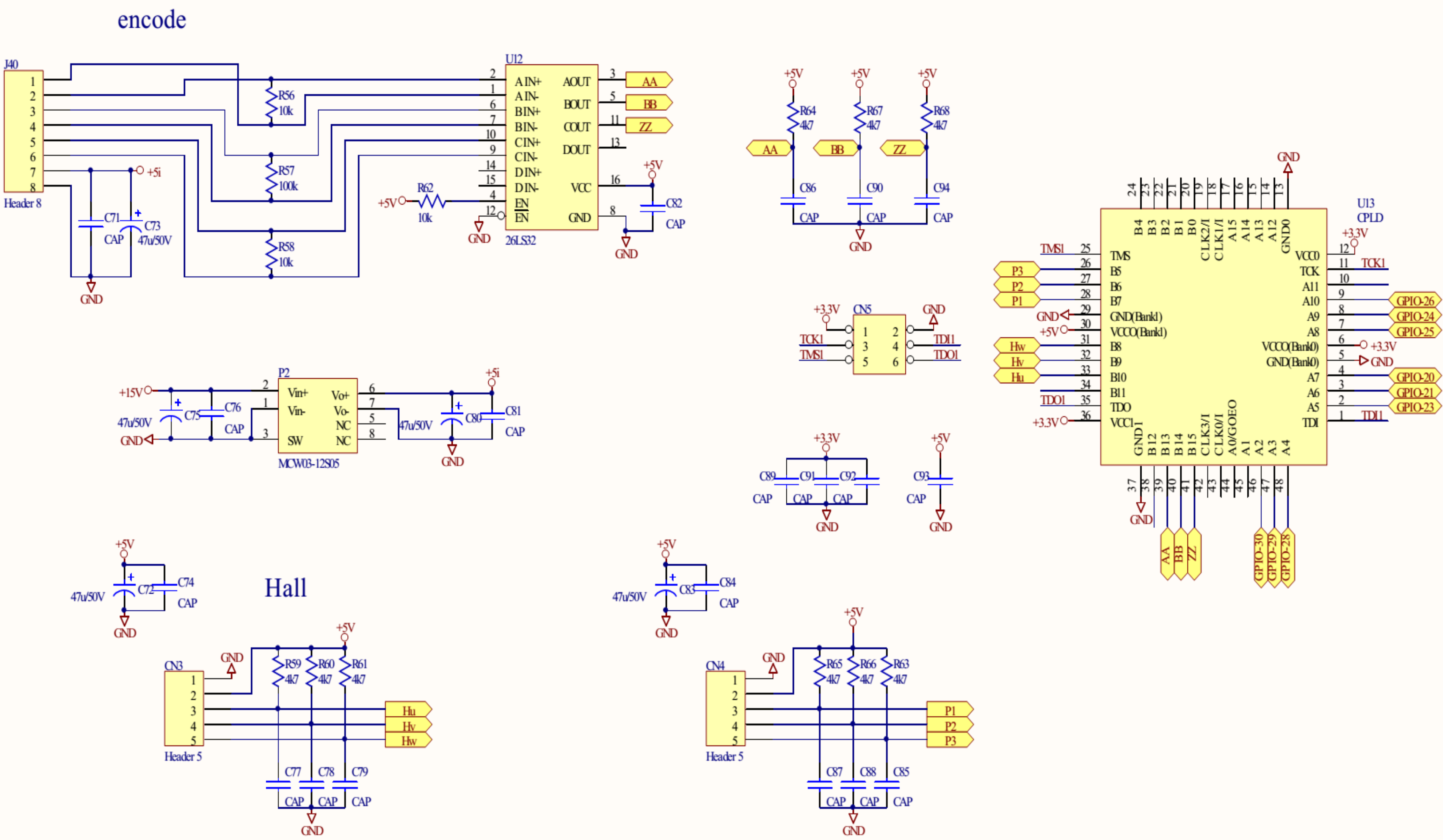
normal

介面電路



CN1
Header 30X2
PWM1A
PWM2A
PWM3A
PWM4A
PWM1B
PWM2B
PWM3B
PWM4B
Hall_U
Hall_W
Hall_V
GPIO-24
GPIO-26
GPIO-25
EQEP1A
EQEP1B
EQEP1I
GPIO-20
GPIO-21
GPIO-23
GPIO-28
GPIO-29
GPIO-30
P1
P2
P3
ADCB7
ADCB6
ADCB5
ADCB4
ADCB3
ADCB2
ADCB1
ADCB0
ADCA7
ADCA6
ADCA5
ADCA4
ADCA3
ADCA2
ADCA1
ADCA0
Io-u
Io-v
Io-w
Vdc
+5V
GND
+3.3V
U2
CPLD
TDI
TDO
TCK
TMS
CN2
C15
C16
C17
C18
CAP
R1
R2
R3
4k7
C2
C3
C4
1n
+15Va
+15V
-15Va
-15V
C7
C8
C10
C11
47u/50V
J1
Header 4
+5Va
J2
Header 2
+15Vb
0Vb
C1
C44
U3
In
Gnd
Out
LM1117
C5
C6
C9
C12
C13
C14
Title

位置迴授電路



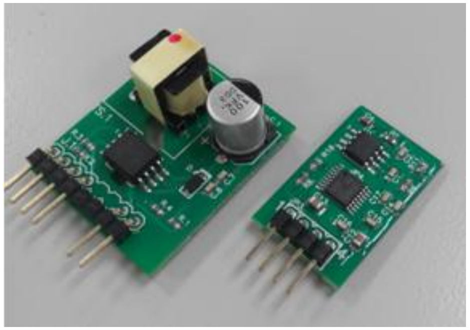
normal

Auxiliary Circuits

DSP Control Board (with Isolated RS232 port)

Flyback Auxiliary Power Supply

Switch Drive Power and Drive Circuit

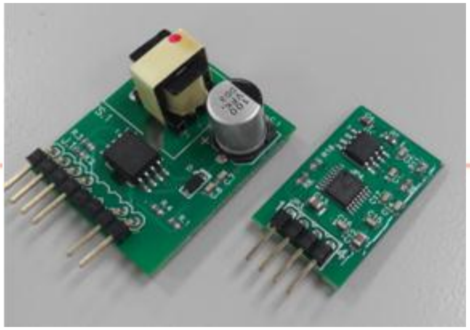


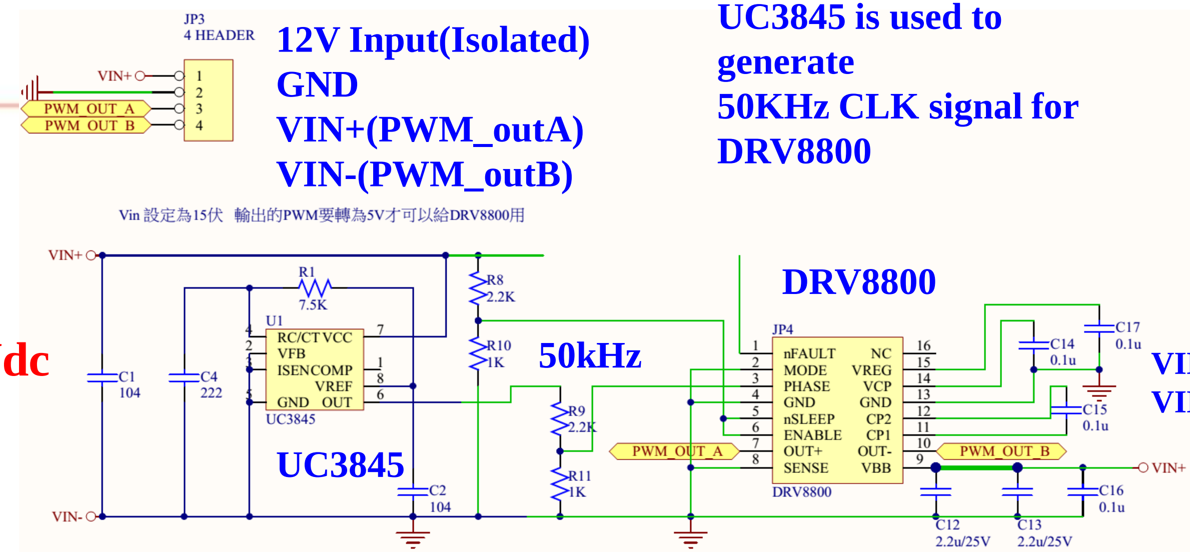
JTAG Module

Gate Drive Power Circuit

12V Input(Isolated)
GND
VIN+(PWM_outA)
VIN-(PWM_outB)

UC3845 is used to generate 50KHz CLK signal for DRV8800





12Vdc

50kHz

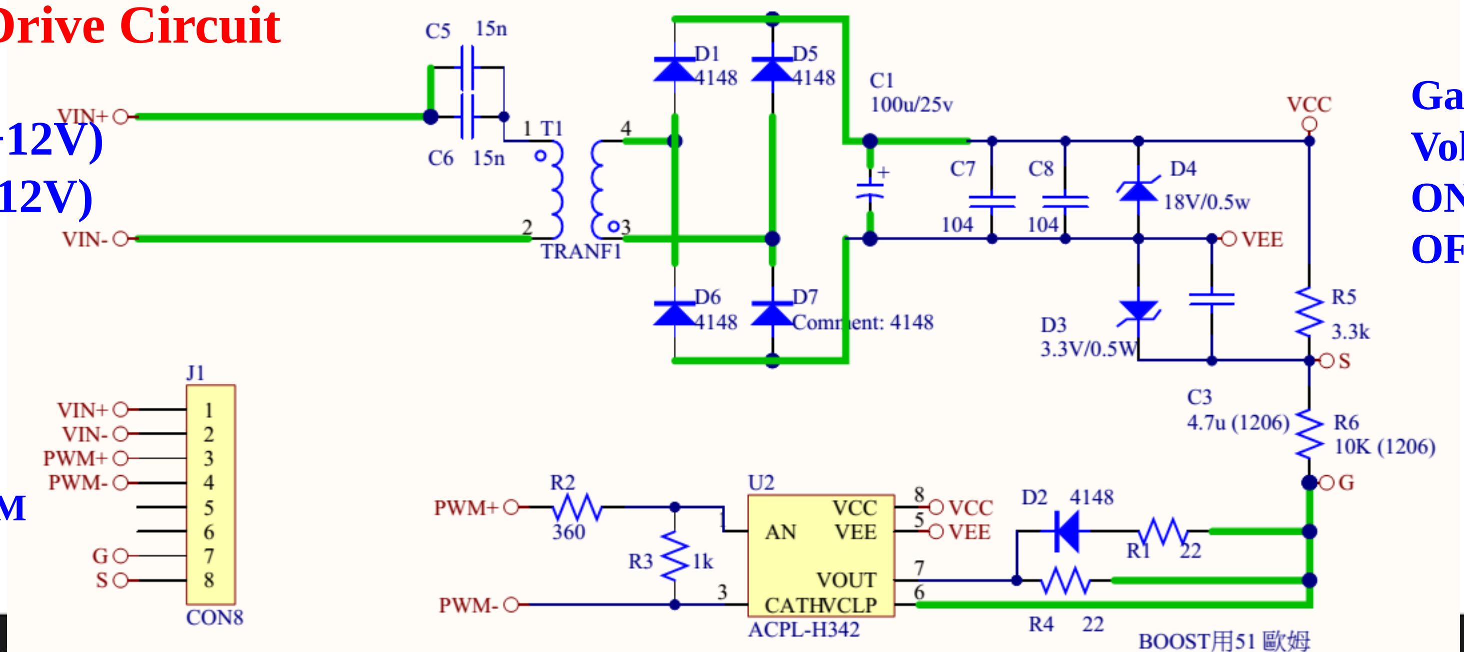
UC3845

DRV8800

VIN+(PWM_outA)
VIN-(PWM_outB)

Gate Drive Circuit

VIN+(+12V)
VIN- (-12V)



Gate Drive Voltage
ON: +12V
OFF: -3.3V

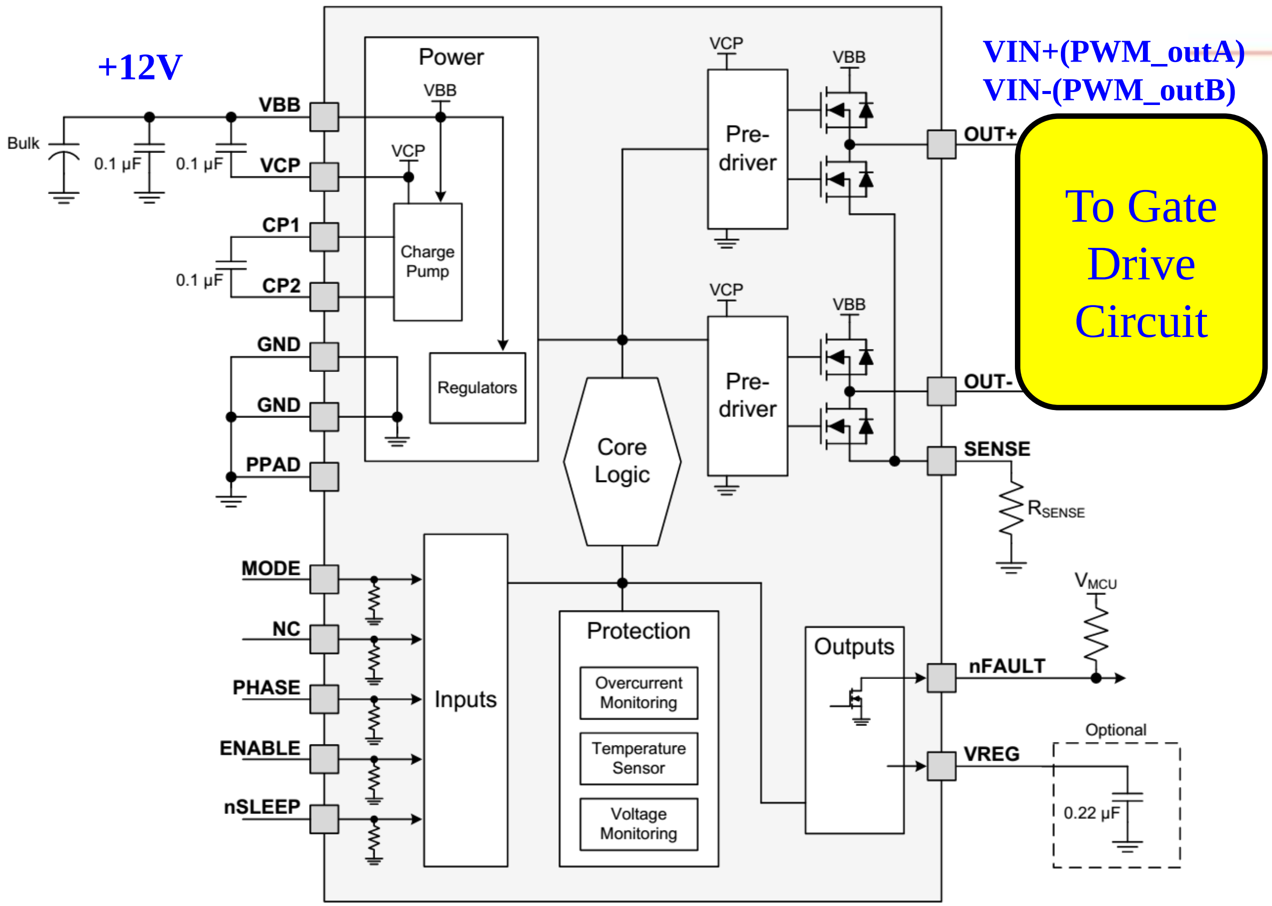
From PWM (CPLD)

Photo couple MOSFET Driver

normal

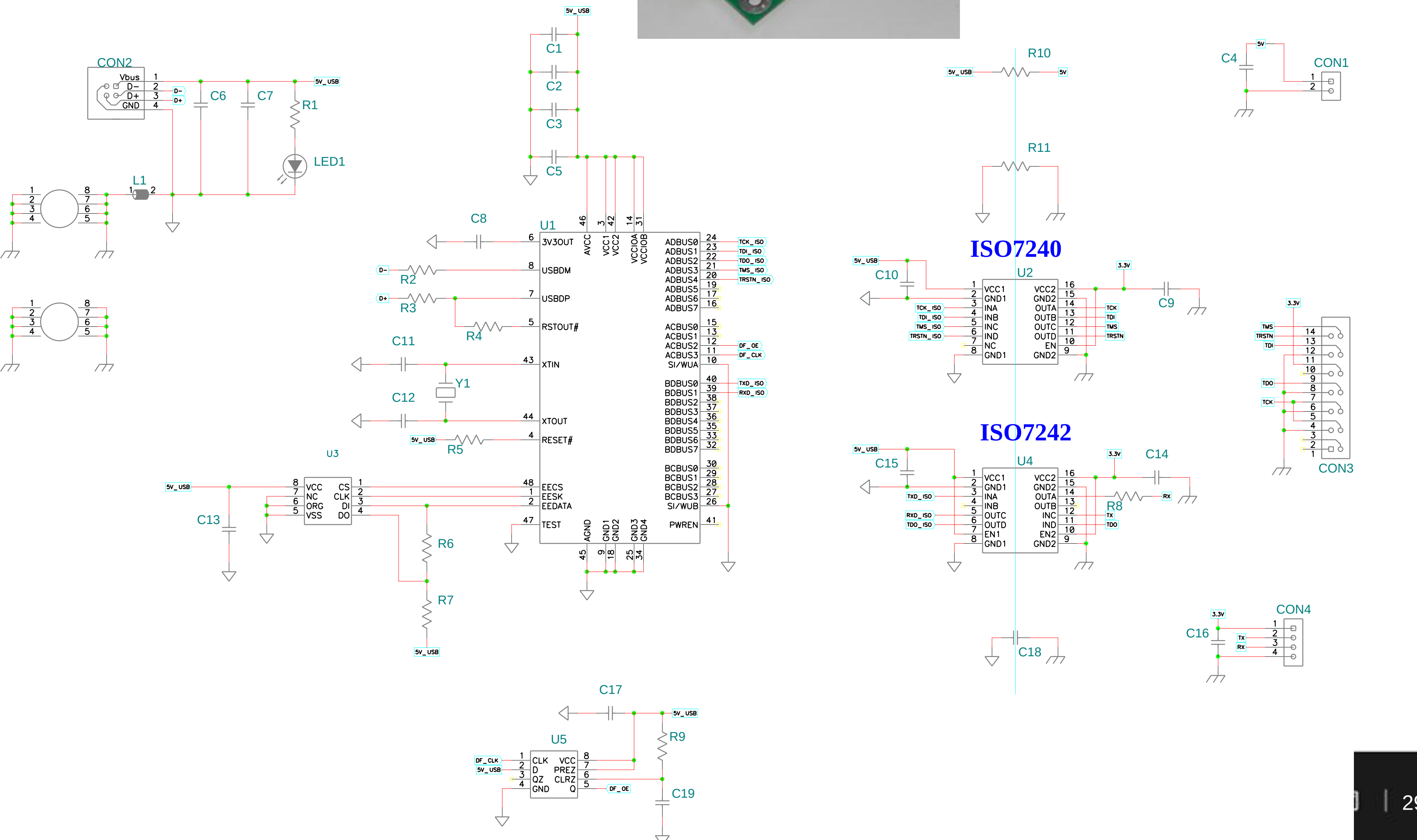
DRV8800 IC

- To Generate ±12V square wave voltage for gate drive power
- It can provide 2.8A output current



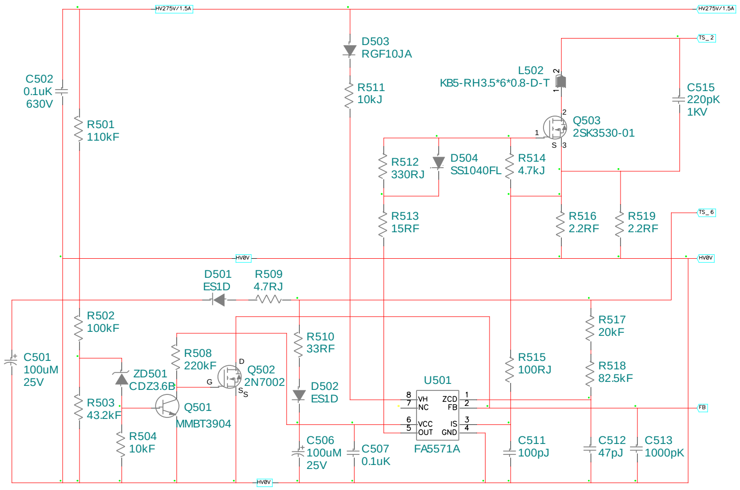
		MIN	MAX	UNIT
VBB	Load supply voltage (2)	–0.3	40	V
	Output current	–2.8	2.8	A
V_{Sense}	Sense voltage	–500	500	mV
	VBB to OUTx		36	V
	OUTx to SENSE		36	V
VDD	Logic input voltage (2)	–0.3	7	V
	Continuous total power dissipation	See *Thermal Information*		
T_A	Operating free-air temperature	–40	85	°C
T_J	Maximum junction temperature		150	°C
T_{stg}	Storage temperature	–40	125	°C

USB_JTAG電路

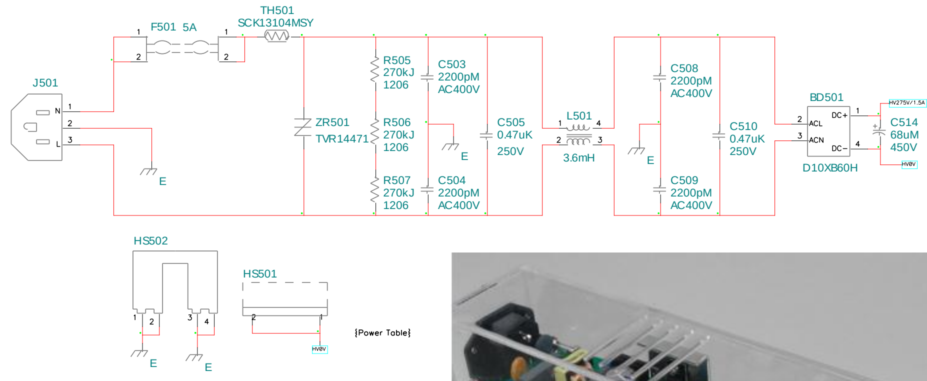


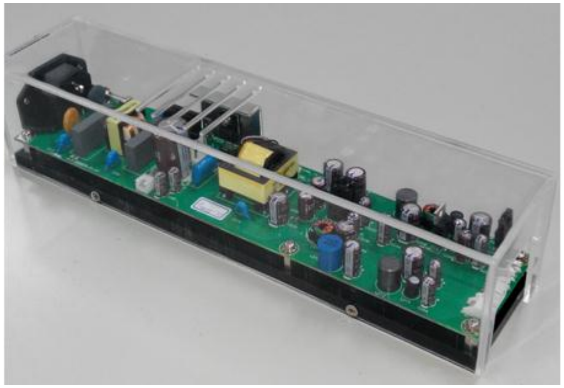
ISO7240
ISO7242
U1
U2
U3
U4
U5
CON1
CON2
CON3
CON4
Y1
L1
LED1
5V_USB
3.3V

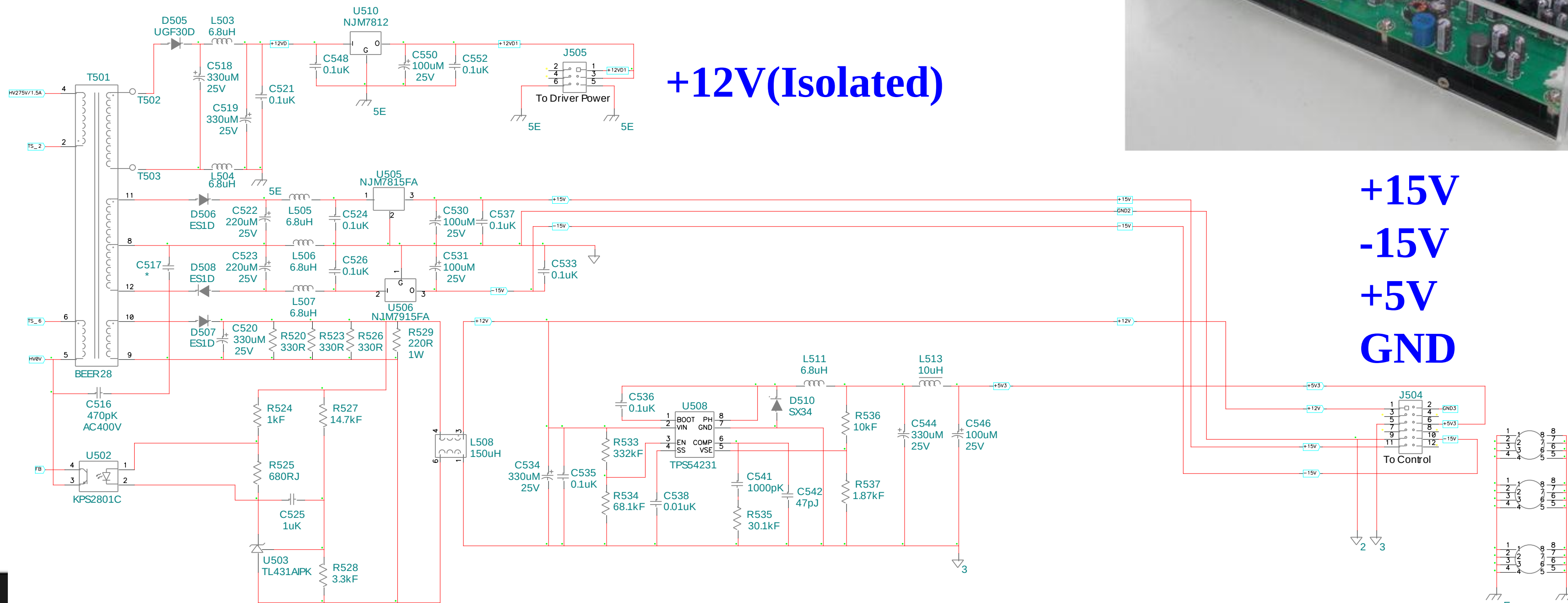
Auxiliary Power Supply (Flyback with multiple outputs and linear regulators)



AC Input
90Vac~264Vac







+12V(Isolated)

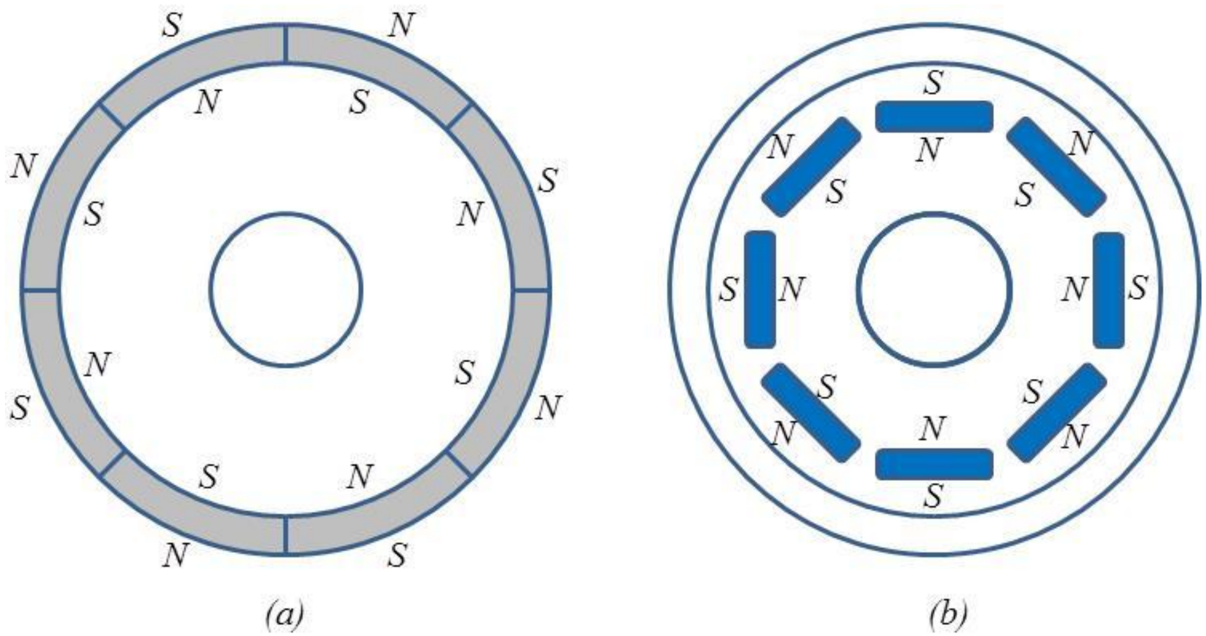
+15V
-15V
+5V
GND

normal

PMSM原理

介紹

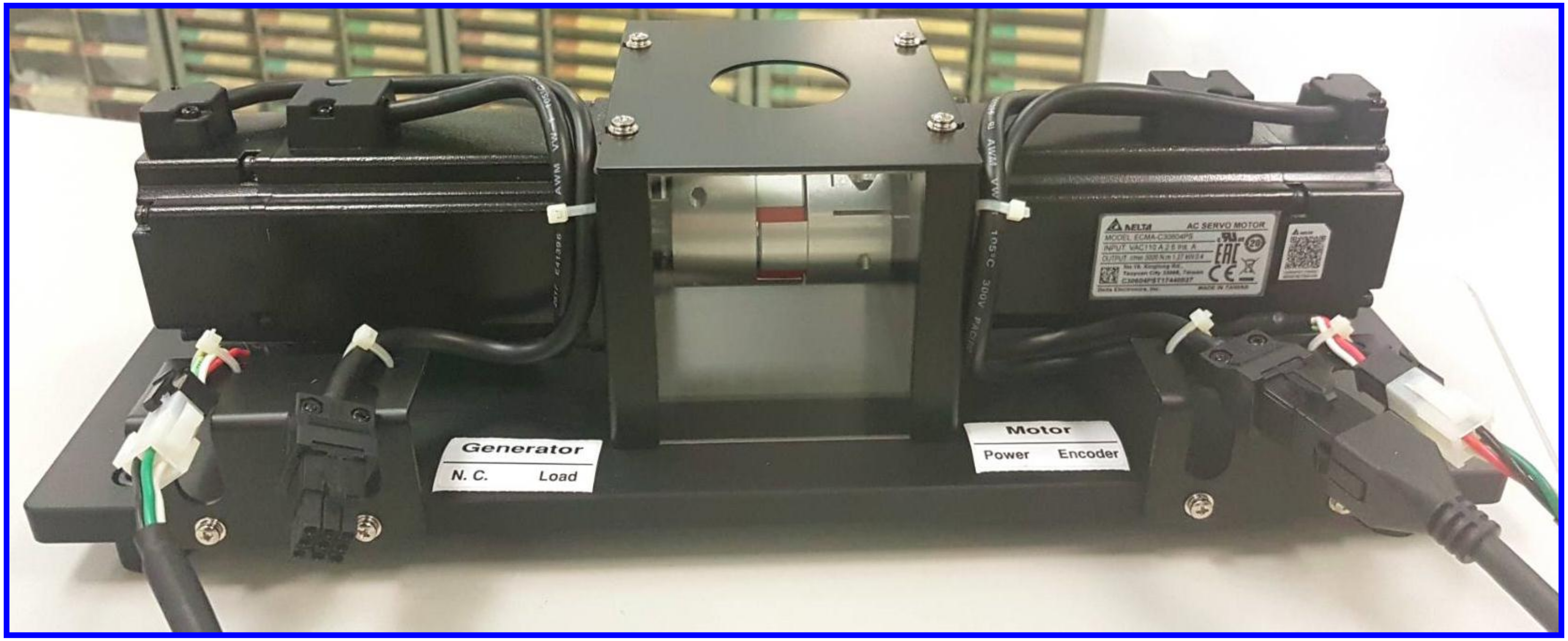
永磁同步馬達(PMSM)結構



外貼式SPMSM

內藏式IPMSM

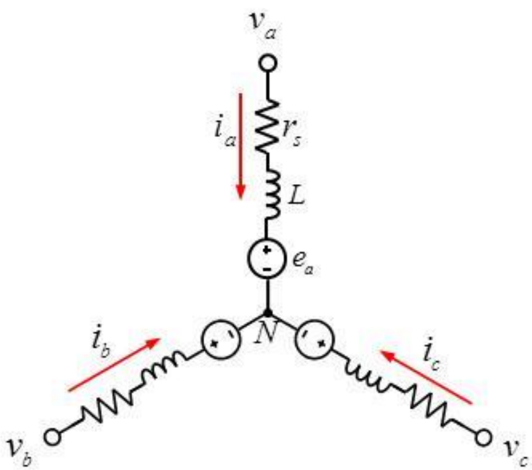
PMSM馬達-發電機組 (400W, 3000rpm)



normal

PMSM等效電路

abc座標軸上之定子電壓方程式：



$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix}$$

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \lambda_{pm} \begin{bmatrix} \cos\theta_{re} \\ \cos(\theta_{re} - 120°) \\ \cos(\theta_{re} + 120°) \end{bmatrix}$$

λ_{pm} ：馬達轉子側等效至定子側之磁通鏈

$$\begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} = \begin{bmatrix} L_{ls} + L_o + L_m \cos 2\theta_{re} & \frac{-L_o}{2} + L_m \cos(2\theta_{re} - \frac{2\pi}{3}) & \frac{-L_o}{2} + L_m \cos(2\theta_{re} + \frac{2\pi}{3}) \\ \frac{-L_o}{2} + L_m \cos(2\theta_{re} - \frac{2\pi}{3}) & L_{ls} + L_o + L_m \cos(2\theta_{re} + \frac{2\pi}{3}) & \frac{-L_o}{2} + L_m \cos 2\theta_{re} \\ \frac{-L_o}{2} + L_m \cos(2\theta_{re} + \frac{2\pi}{3}) & \frac{-L_o}{2} + L_m \cos 2\theta_{re} & L_{ls} + L_o + L_m \cos(2\theta_{re} - \frac{2\pi}{3}) \end{bmatrix}$$

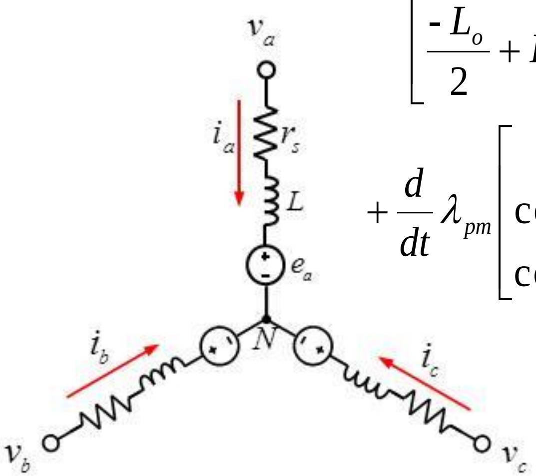
normal

PMSM於ABC軸之等效電路方程式

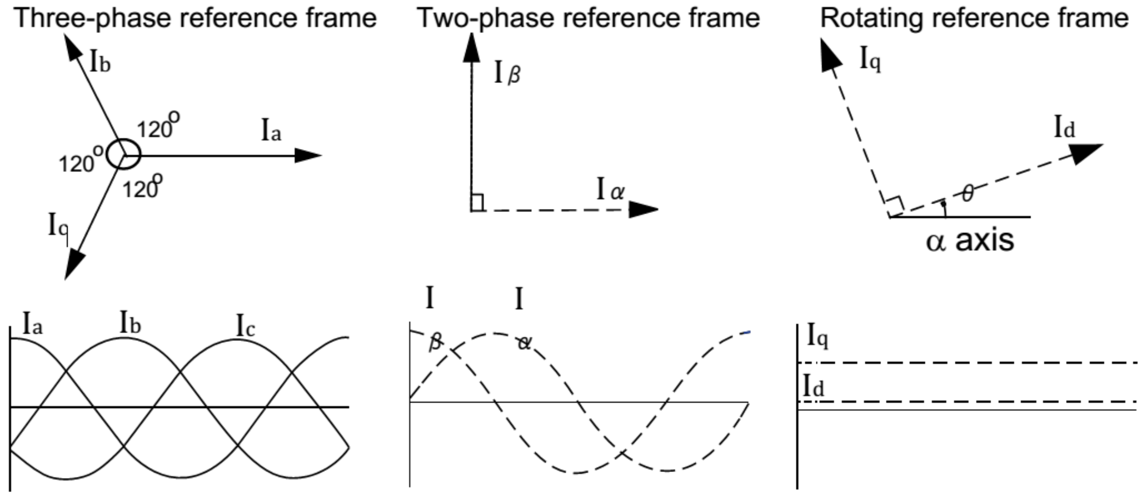
$$
\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} +
$$

$$
\frac{d}{dt}\begin{bmatrix} L_{ls}+L_o+L_m\cos 2\theta_{re} & \frac{-L_o}{2}+L_m\cos(2\theta_{re}-\frac{2\pi}{3}) & \frac{-L_o}{2}+L_m\cos(2\theta_{re}+\frac{2\pi}{3}) \\ \frac{-L_o}{2}+L_m\cos(2\theta_{re}-\frac{2\pi}{3}) & L_{ls}+L_o+L_m\cos(2\theta_{re}+\frac{2\pi}{3}) & \frac{-L_o}{2}+L_m\cos 2\theta_{re} \\ \frac{-L_o}{2}+L_m\cos(2\theta_{re}+\frac{2\pi}{3}) & \frac{-L_o}{2}+L_m\cos 2\theta_{re} & L_{ls}+L_o+L_m\cos(2\theta_{re}-\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}
$$

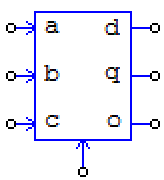
$$
+\frac{d}{dt}\lambda_{pm}\begin{bmatrix} \cos\theta_{re} \\ \cos(\theta_{re}-120^\circ) \\ \cos(\theta_{re}+120^\circ) \end{bmatrix}
$$



座標軸轉換

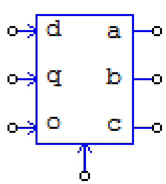


abc to dqo



$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

dqo to abc

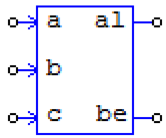


$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \cdot \begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix}$$

normal

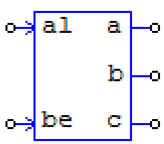
Clarke and Inverse Clarke Transformation

abc to αβ

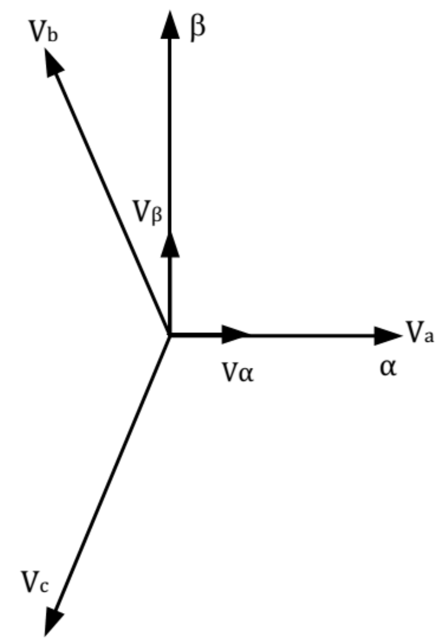


$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

αβ to abc



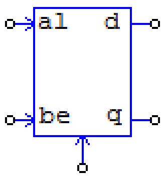
$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$



normal

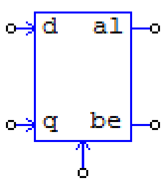
Park and Inverse Park Transformation

αβ to dq

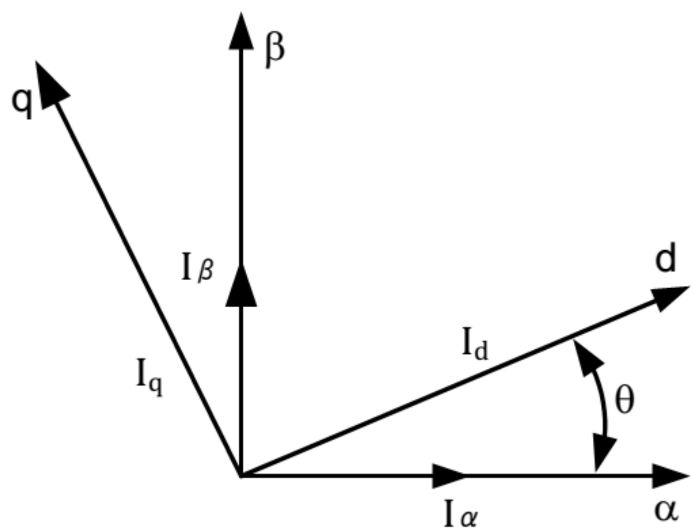


$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

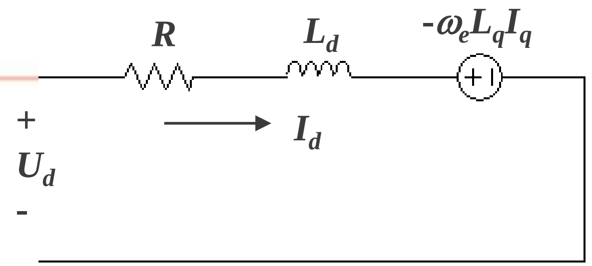
dq to αβ

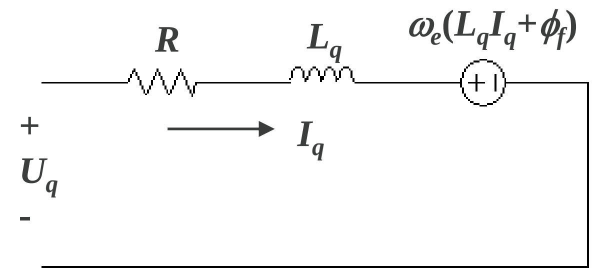


$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$



PMSM於DQ軸之等效電路方程式





$$U_d = RI_d + \frac{d}{dt}\varphi_d - \omega_e\varphi_q$$

$$U_q = RI_q + \frac{d}{dt}\varphi_q + \omega_e\varphi_d$$

$$\varphi_d = L_d I_d + \varphi_f$$

$$\varphi_q = L_q I_q$$

$$U_d = RI_d + L_d\frac{d}{dt}I_d - \omega_e L_q I_q$$

$$U_q = RI_q + L_q\frac{d}{dt}I_q + \omega_e(L_d I_d + \varphi_f)$$

$$T_e = \frac{3}{2}p_n I_q[I_d(L_d - L_q) + \varphi_f]$$

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m$$

$$\omega_e = p_n\omega_m$$

p_n is the motor pole-pair number

$$\omega_m = \frac{N}{60}2\pi \quad \text{(rad/s)}$$

$$N = \frac{30}{\pi}\omega_m \quad \text{(rpm)}$$

$$\theta_e = \int \omega_e dt$$

Experimental Motor

AC Servo System 伺服馬達標準規格(ECMA系列)

機型 ECMA	C304	C306		C308		C310	
	01	02	04	04	07	10	20
額定功率 (kW)	0.1	0.2	0.4	0.4	0.75	1.0	2.0
額定扭矩 (N.m)	0.32	0.64	1.27	1.27	2.39	3.18	6.37
最大扭矩 (N.m)	0.96	1.92	3.82	3.82	7.16	9.54	19.11
額定轉速 (r/min)	3000						
最高轉速 (r/min)	5000						
額定電流 (A)	0.9	1.55	2.6	2.6	5.1	7.3	12.05
瞬時最大電流 (A)	2.7	4.65	7.8	7.8	15.3	21.9	36.15
每秒最大功率 (kW/s)	27.7	22.4	57.6	24.0	50.4	38.1	90.6
轉子慣量 ($kg.m^2$)	0.037E-4	0.177E-4	0.277E-4	0.68E-4	1.13E-4	2.65E-4	4.45E-4
機械常數 (ms)	0.75	0.80	0.53	0.74	0.63	0.74	0.61
扭矩常數-KT (N.m/A)	0.36	0.41	0.49	0.49	0.47	0.43	0.53
電壓常數-KE (mV/min^{-1})	13.6	16	17.4	18.5	17.2	16.8	19.2
電機阻抗 (Ohm)	9.3	2.79	1.55	0.93	0.42	0.20	0.13
電機感抗 (mH)	24	12.07	6.71	7.39	3.53	1.81	1.50
電氣常數 (ms)	2.58	4.3	4.3	7.96	8.37	9.3	11.4

P_{rated}=400W, N_{rated}=3000rpm

T_{rated}=1.27Nm (=$P_{rated}/\omega_{m,rated}$)

R = 1.55Ω, L_q=L_d=6.71mH

J = 27.7u, Shaft time constant (J/B) = 0.53

Pole = 10

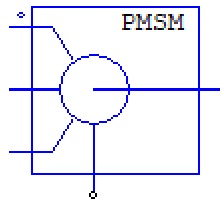
V_f = Vpk/krpm = 17.4 * 1.414

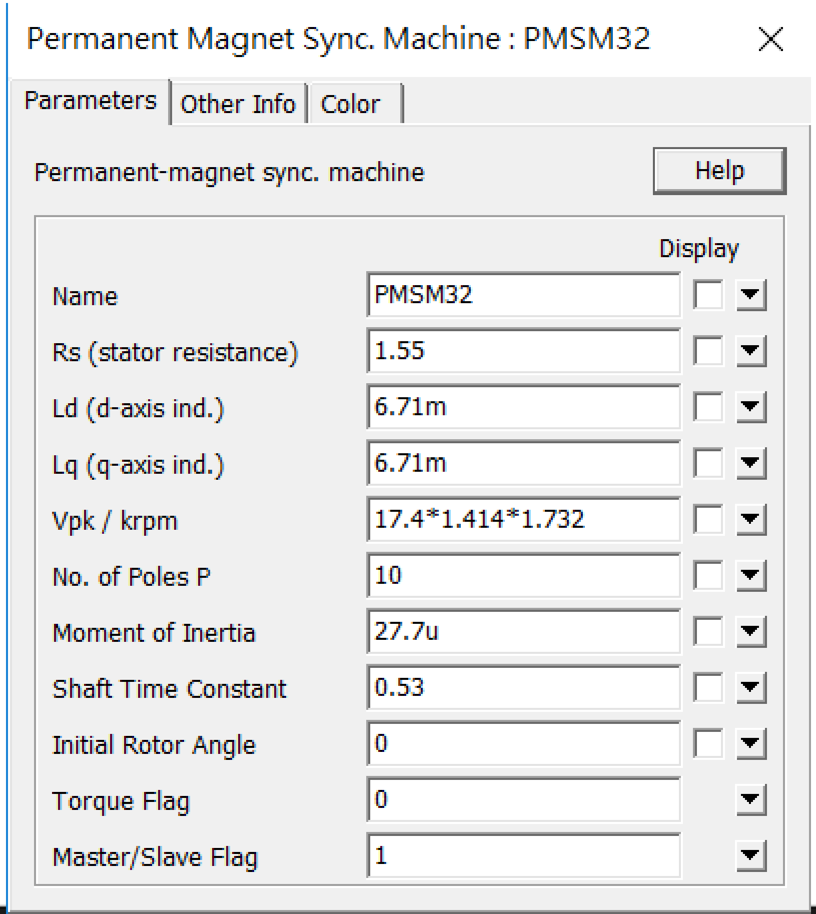
$$\omega_{m,rated} = \frac{3000}{60} 2\pi = 314.16 \text{(rad/s)}$$

$$\omega_{e,rated} = (P/2) * \omega_{m,rated} = 1570.8 \text{(rad/s)}$$

$$\varphi_f = \frac{V_f(3000rpm)}{\omega_e(3000rpm)} = 47m$$

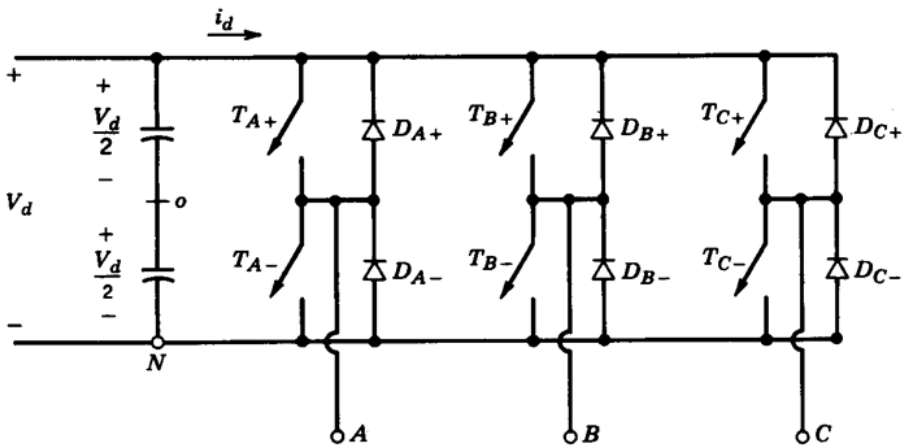
Motor Parameters in PSIM





normal

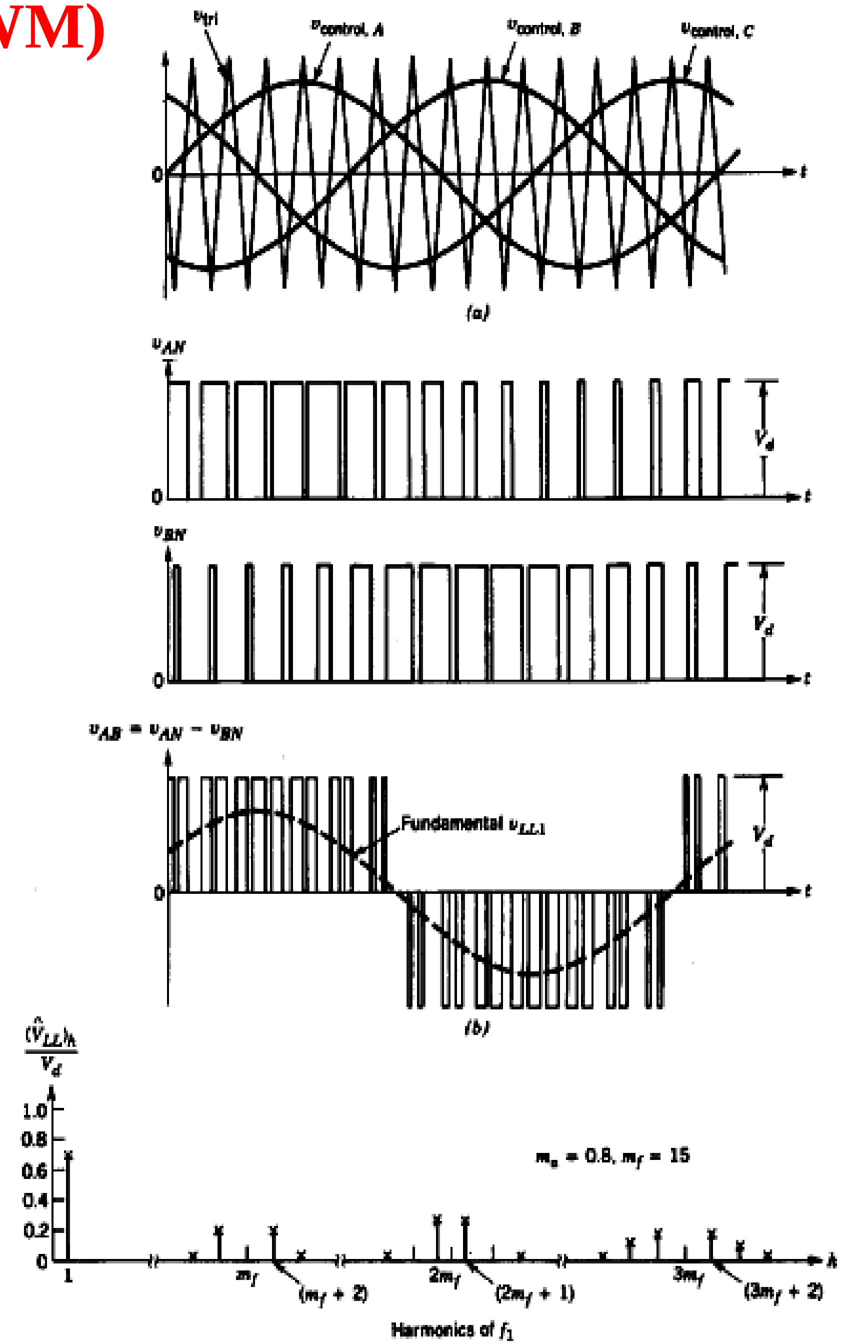
Three-phase Sinusoidal PWM (SPWM)



$$m_a = \frac{\hat{V}_{\text{control}}}{\hat{V}_{\text{tri}}} \qquad m_f = \frac{f_s}{f_1}$$

$$(\hat{V}_{AN})_1 = m_a \frac{V_d}{2}$$

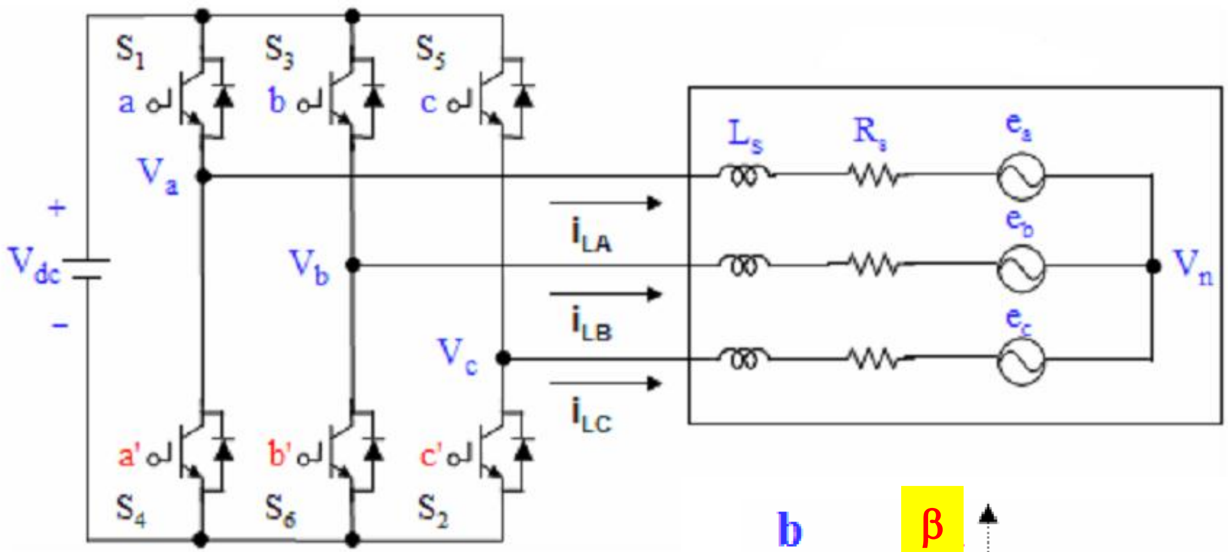
$$\underset{\text{(line-line, rms)}}{V_{LL_1}} = \frac{\sqrt{3}}{\sqrt{2}}(\hat{V}_{AN})_1 = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d \simeq 0.612 m_a V_d \qquad (m_a \le 1.0)$$



normal

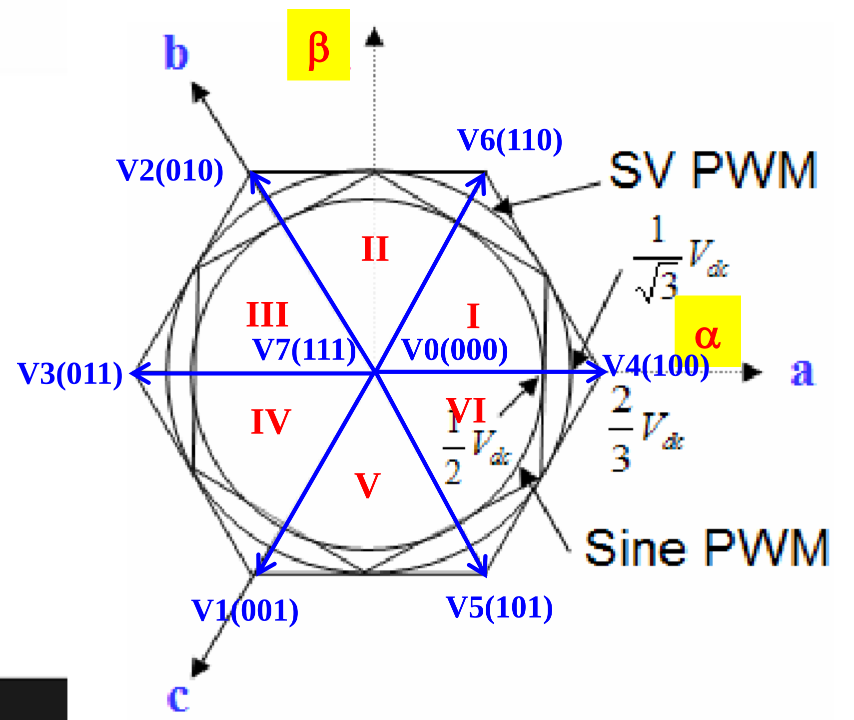
GW INSTEK

Space Vector PWM (SVPWM)



$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

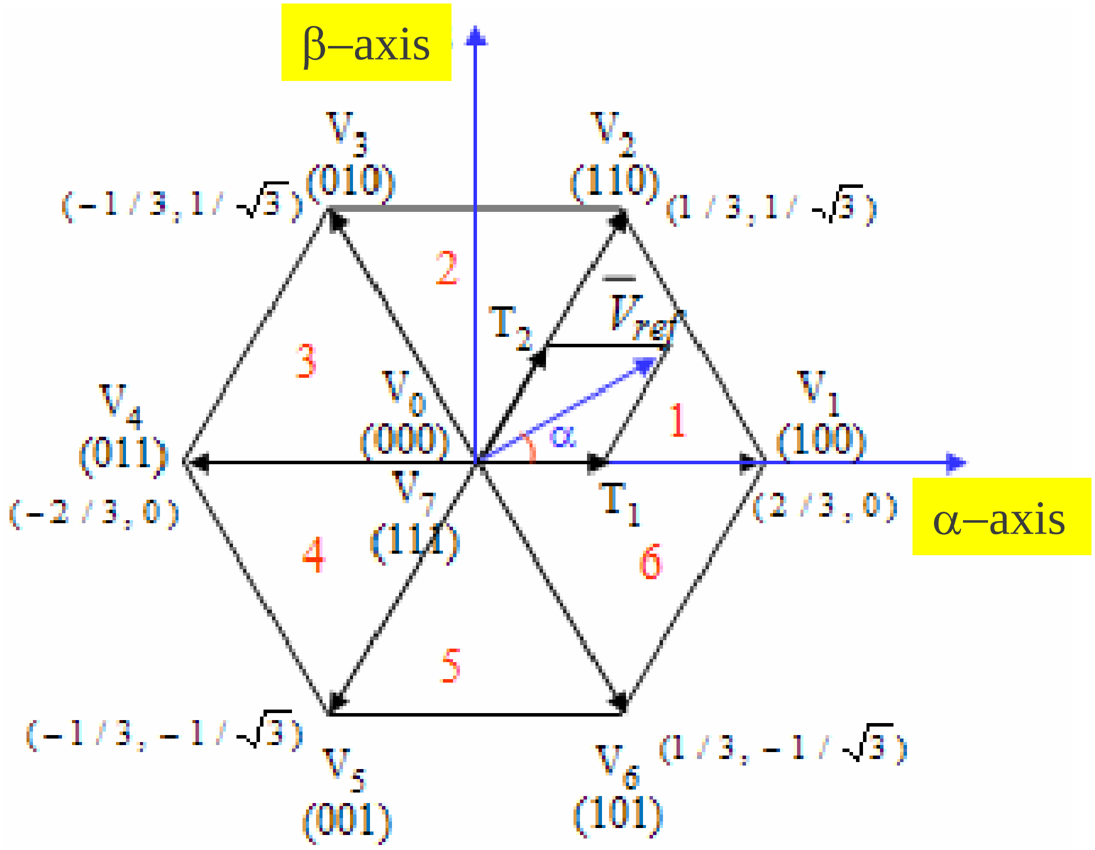
$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$



SVPWM Voltage Vector

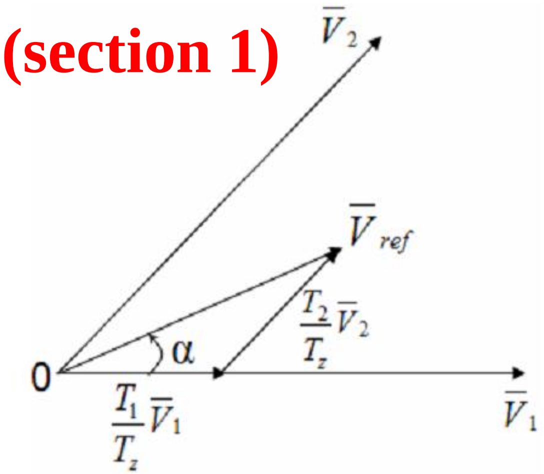
Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

Voltage Vector of the Space Voltage PWM



- Vector space can be divided into 6 sections
- V_{ref} can be constructed with the adjacent vectors located in the same section and the zero vector

Conduction Time Interval of the Voltage Vector (section 1)

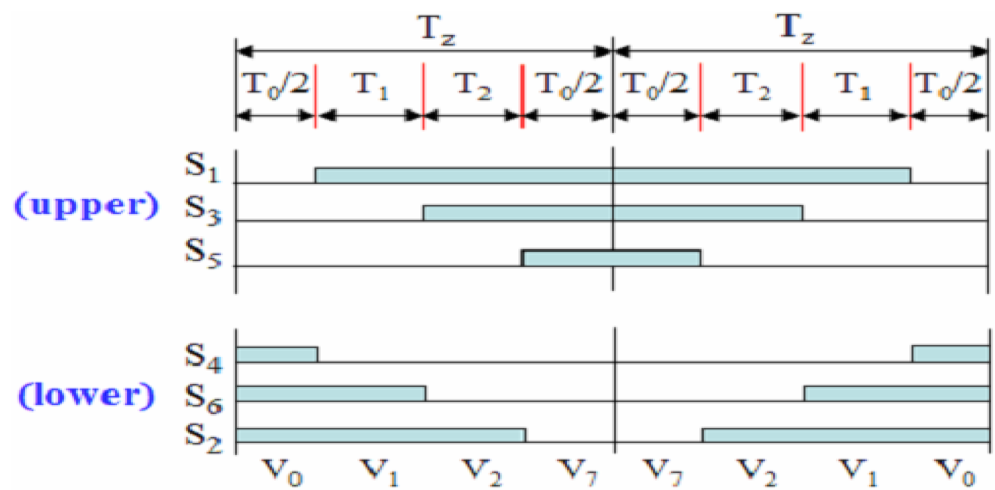


$$\int_0^{T_z} \overline{V}_{ref} = \int_0^{T_1} \overline{V}_1 dt + \int_{T1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_z} \overline{V}_0$$

$$\therefore T_z \cdot \overline{V}_{ref} = (T_1 \cdot \overline{V}_1 + T_2 \cdot \overline{V}_2)$$

$$\Rightarrow T_z \cdot \left|\overline{V}_{ref}\right| \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

(where, $0 \le \alpha \le 60°$)



$$\therefore T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

$$\therefore T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$\therefore T_0 = T_z - (T_1 + T_2), \quad \left(\text{where,} \quad T_z = \frac{1}{f_z} \quad \text{and} \quad a = \frac{\left|\overline{V}_{ref}\right|}{\frac{2}{3} V_{dc}} \right)$$

Conduction Time Interval of the Voltage Vectors (section 2~6)

$$\therefore T_1 = \frac{\sqrt{3}\cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}}\left(\sin\left(\frac{\pi}{3}-\alpha+\frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}\cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}}\left(\sin\frac{n}{3}\pi-\alpha\right)$$

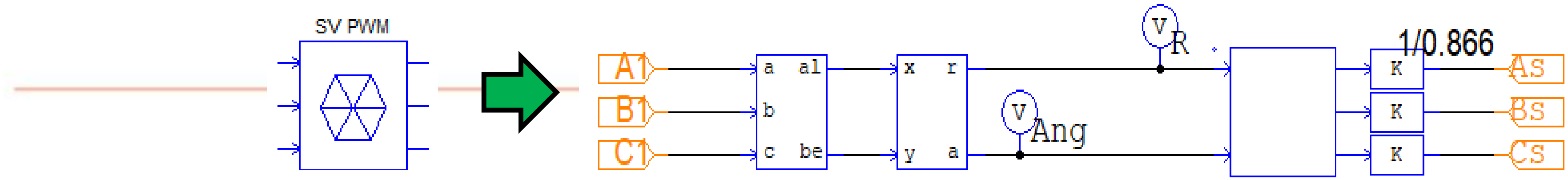
$$= \frac{\sqrt{3}\cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}}\left(\sin\frac{n}{3}\pi\cos\alpha-\cos\frac{n}{3}\pi\sin\alpha\right)$$

$$\therefore T_2 = \frac{\sqrt{3}\cdot T_z \cdot \left|\overline{V}ref\right|}{V_{dc}}\left(\sin\left(\alpha-\frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}\cdot T_z \left|\overline{V}ref\right|}{V_{dc}}\left(-\cos\alpha\cdot\sin\frac{n-1}{3}\pi+\sin\alpha\cdot\cos\frac{n-1}{3}\pi\right)$$

$$\therefore T_0 = T_z - T_1 - T_2, \quad \left(\begin{array}{c}\text{where, n = 1 through 6 (that is, Sector1 to 6)}\\ 0 \le \alpha \le 60^\circ\end{array}\right)$$

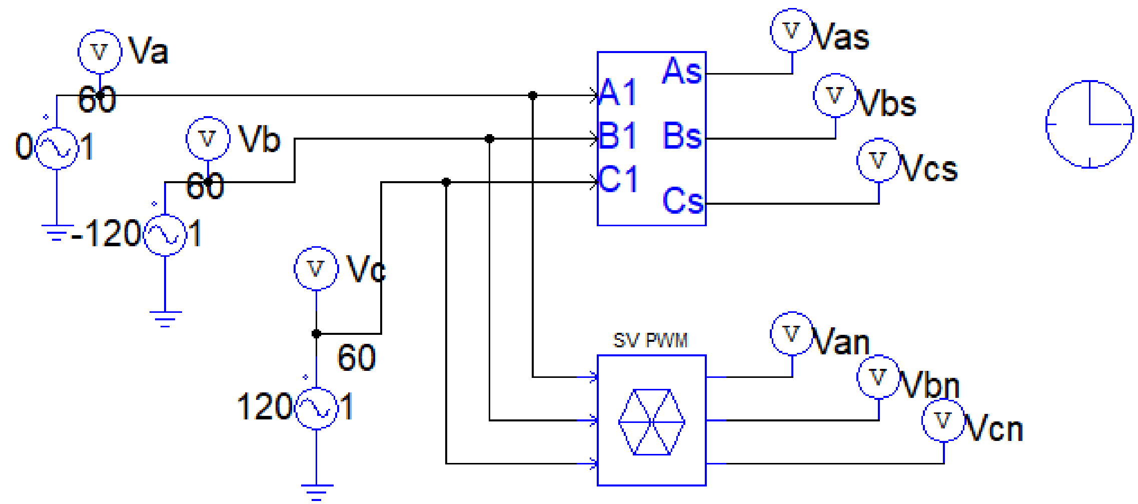
SVPWM之實現

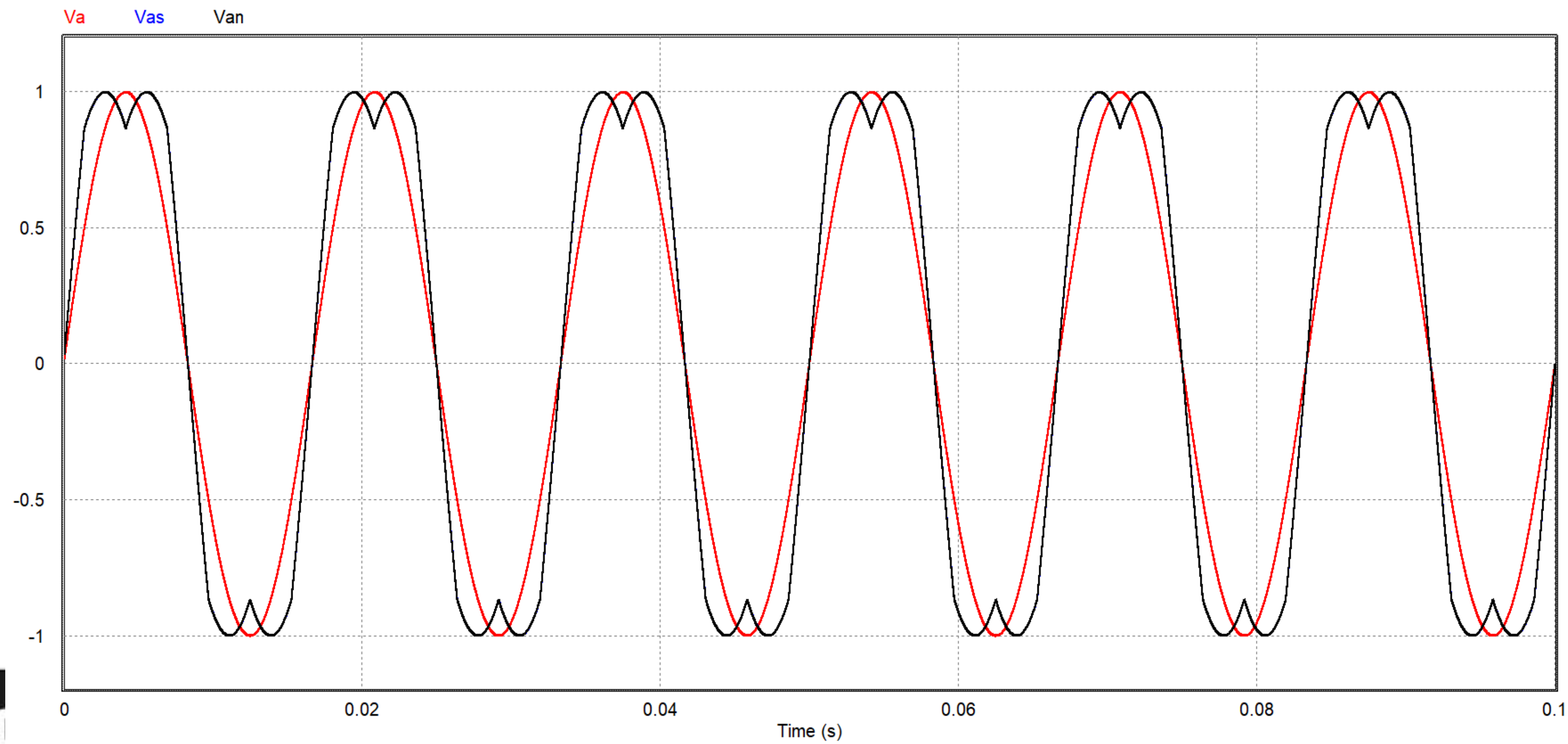



```
float PI = 3.1416;
float K1 = 1.732/2;
float K2 = 1.5;
float P120=3.1416/3*2;
//0 0~60
if ((x2>0) && (x2<=PI/3))
{
  y1 = K1 * x1 * cos(x2 - PI/6);
  y3=K1 * x1 * cos(x2 + PI/6 +P120);
  y2= K2 * x1 * cos(x2-P120);
  }
//1  60~120
if ((x2>PI/3) && (x2<=2*PI/3))
{
  y1 = K2 * x1 * cos(x2);
  y3= K1 * x1 * cos(x2 - PI/6 +P120);
  y2= K1 * x1 * cos(x2 + PI/6-P120);
  }
//2 120~180
if ((x2>2*PI/3) && (x2<=PI))
{
  y1 = K1 * x1 * cos(x2 + PI/6);
  y3= K2 * x1 * cos(x2+P120);
  y2= K1 * x1 * cos(x2 - PI/6-P120);
 }
```

```
//3 180~240
if ((x2>-PI) && (x2<=-2*PI/3))
{
  y1 = K1 * x1 * cos(x2 - PI/6);
  y3= K1 * x1 * cos(x2 + PI/6+P120);
  y2= K2 * x1 * cos(x2-P120);
 }
//4  240~300
if ((x2>-2*PI/3) && (x2<=-PI/3))
{
  y1 = K2 * x1 * cos(x2);
  y3= K1 * x1 * cos(x2 - PI/6+P120);//y2= K2 * x1 *
cos(x2+P120);
  y2= K1 * x1 * cos(x2 + PI/6-P120);
 }
//5 300~360
if ((x2>-PI/3) && (x2<=0))
{
  y1 = K1 * x1 * cos(x2 + PI/6);
  y3= K2 * x1 * cos(x2+P120);
  y2= K1 * x1 * cos(x2 - PI/6-P120);
 }
```

SVPWM模擬

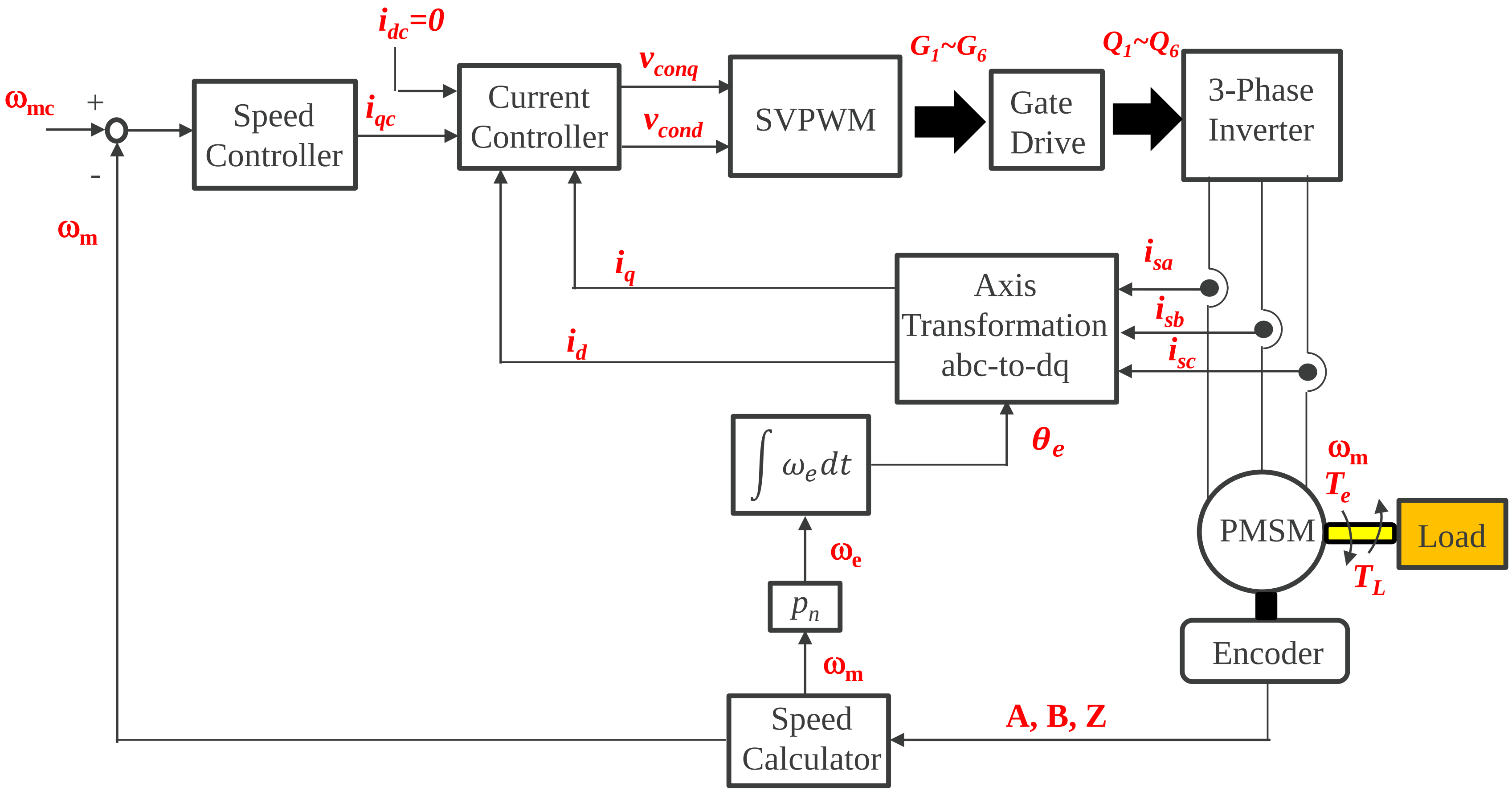

Va
60
0
1
Vb
60
-120
1
Vc
60
120
1
A1
B1
C1
As
Bs
Cs
Vas
Vbs
Vcs
SV PWM
Van
Vbn
Vcn


Va
Vas
Van
1
0.5
0
-0.5
-1
0
0.02
0.04
0.06
0.08
0.1
Time (s)

Lab 1: PMSM之向量控制

$$\omega_m = \frac{N}{60} \cdot 2\pi \qquad \theta_e = \int \omega_e dt$$

$$\omega_e = \frac{P}{2}\omega_m$$



Current Loop Control Scheme

where $U_d = K_{pwm}V_{cond}$

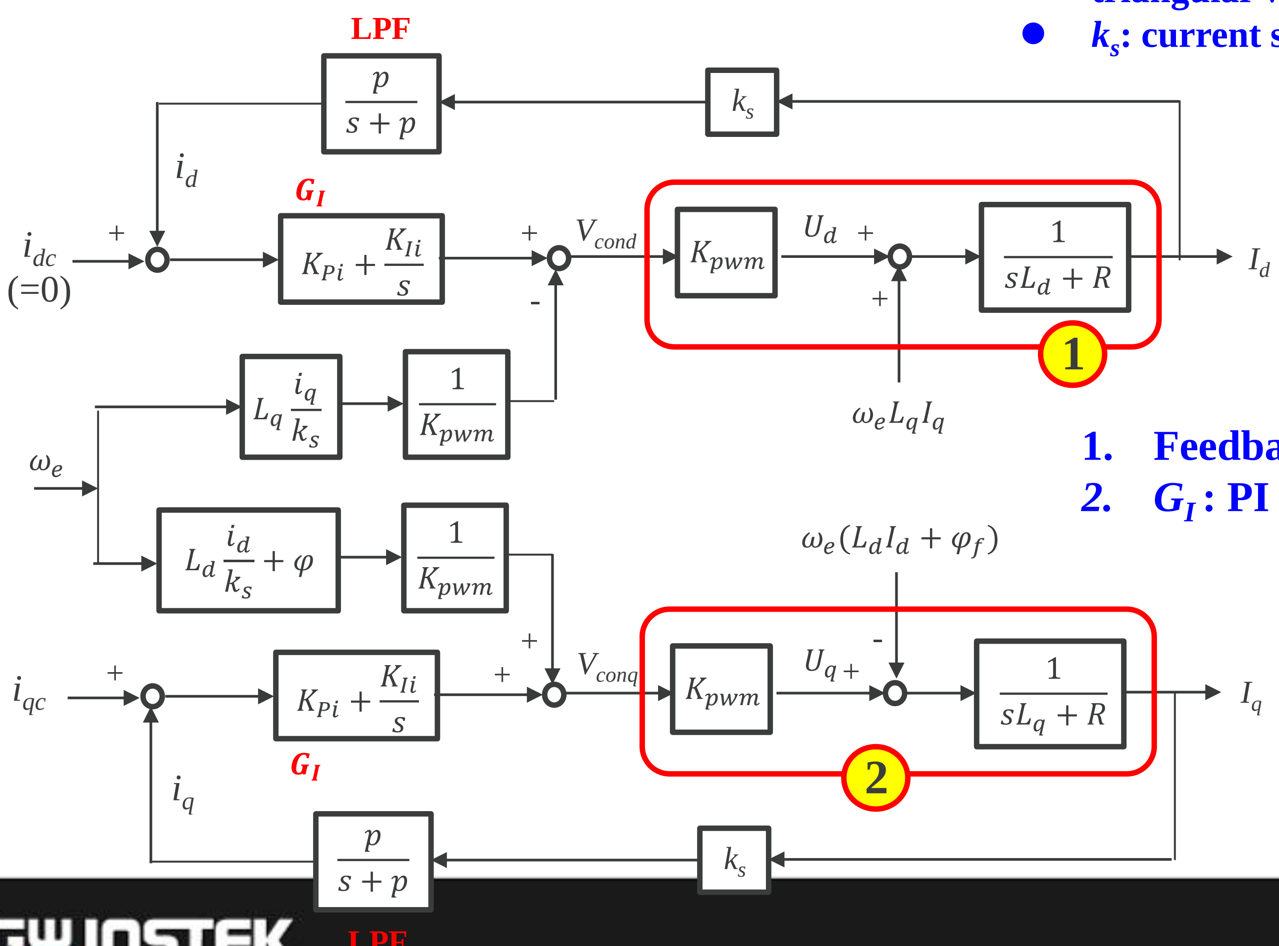
$U_q = K_{pwm}V_{conq}$

$K_{pwm} = \dfrac{V_d}{2V_{tm}}$

(1) $$L_d\frac{dI_d}{dt} + RI_d = U_d + \omega_e L_q I_q$$

(2) $$L_q\frac{dI_q}{dt} + RI_q = U_q - \omega_e(L_d I_d + \varphi_f)$$

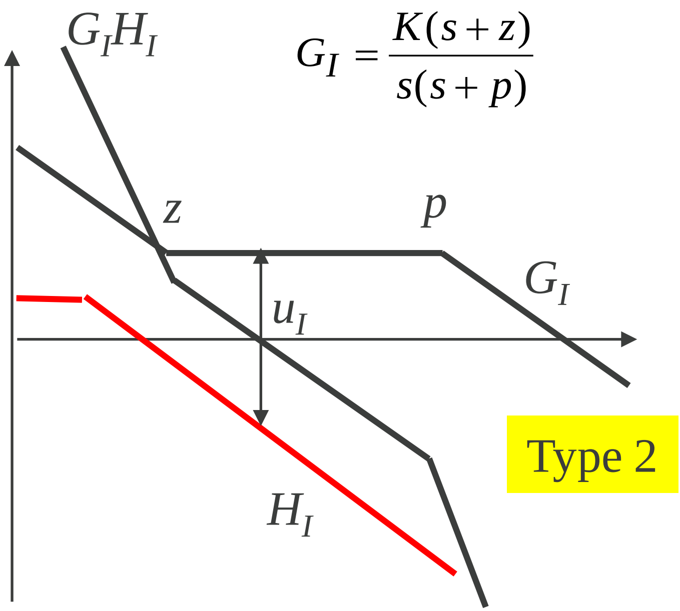
- **K_{pwm}: Inverter voltage gain**
- **V_{tm} : the amplitude of PWM triangular waveform**
- **k_s: current sense gain**



1. **Feedback + Feedforward Control**
2. **G_I : PI + LPF = Type 2 regulator**

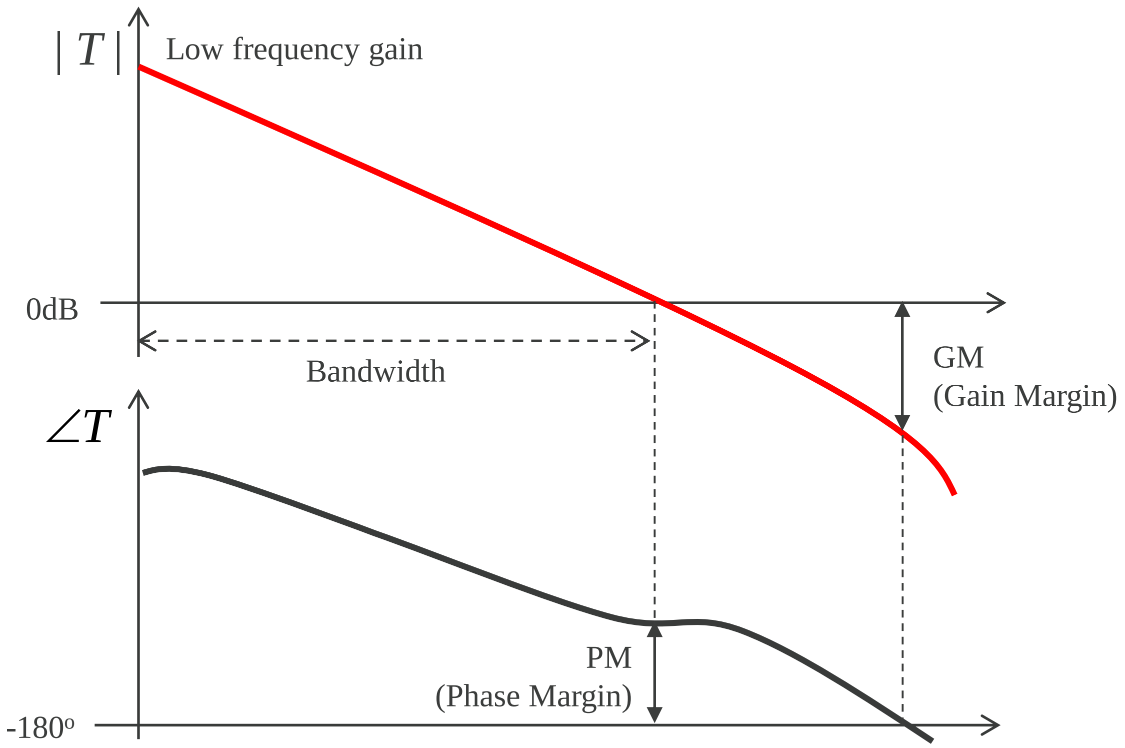
Current Regulator Design

Bode plot of current loop



1. Set u_I to be 1/8~1/10 of the switching frequency(f_s)
2. Set $z = u_I/3$
3. Set $p = f_s/(4\pi)$
4. Find K

Requirement of Loop Gain

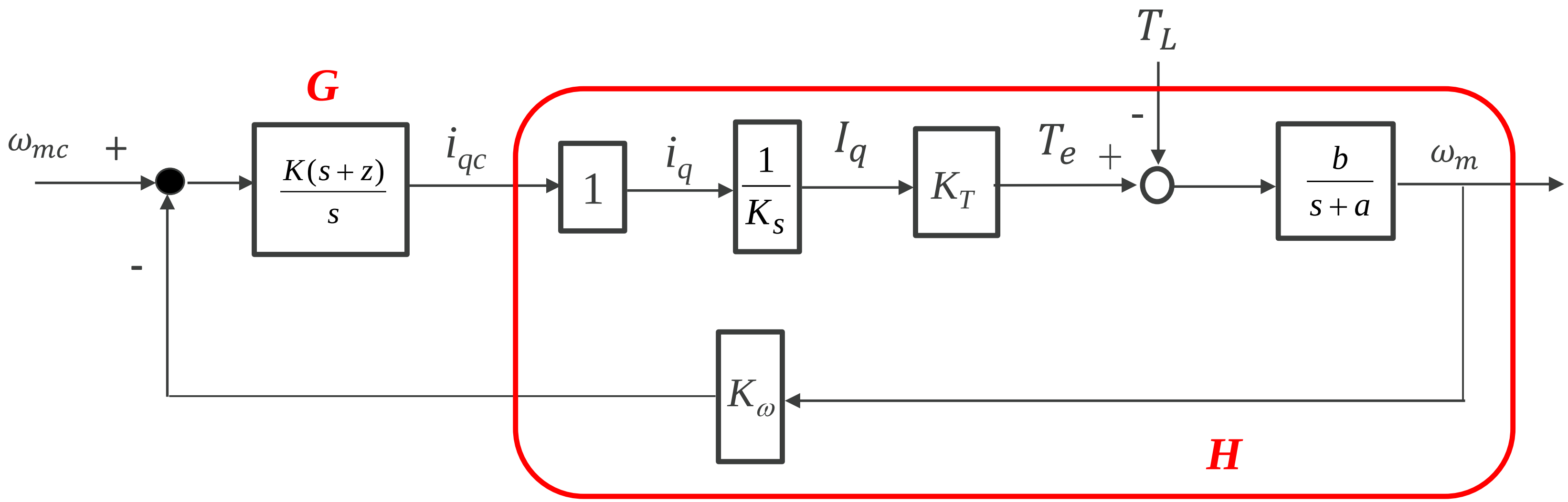


- **High low-frequency gain for good regulation accuracy**
- **Wide bandwidth for fast response**
- **Enough phase margin PM>45º**
- **Enough gain margin GM>10~20dB**

Speed Regulation

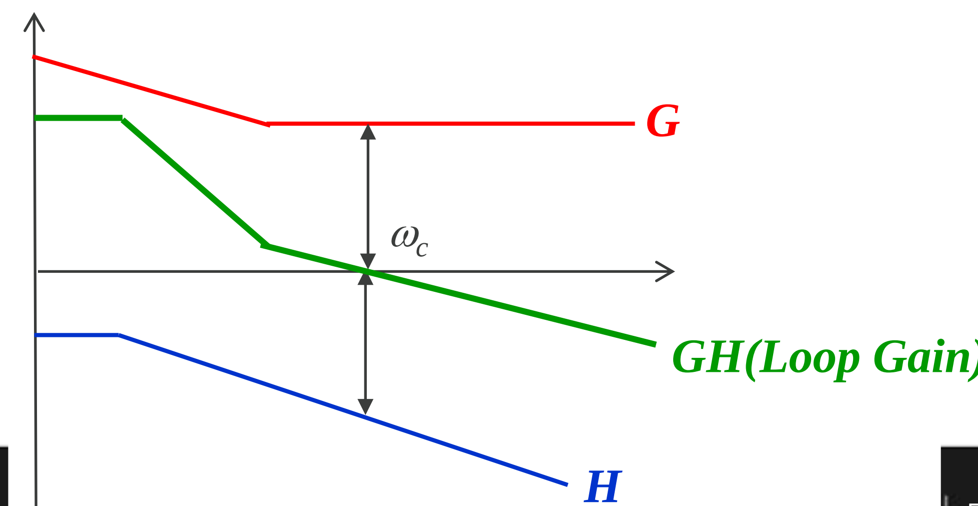
$$T_e = \frac{3}{2} p_n I_q [I_d (L_d - L_q) + \varphi_f] = \frac{3}{2} p_n I_q \varphi_f = K_T I_q$$

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \qquad a = \frac{B}{J} \qquad b = \frac{1}{J}$$

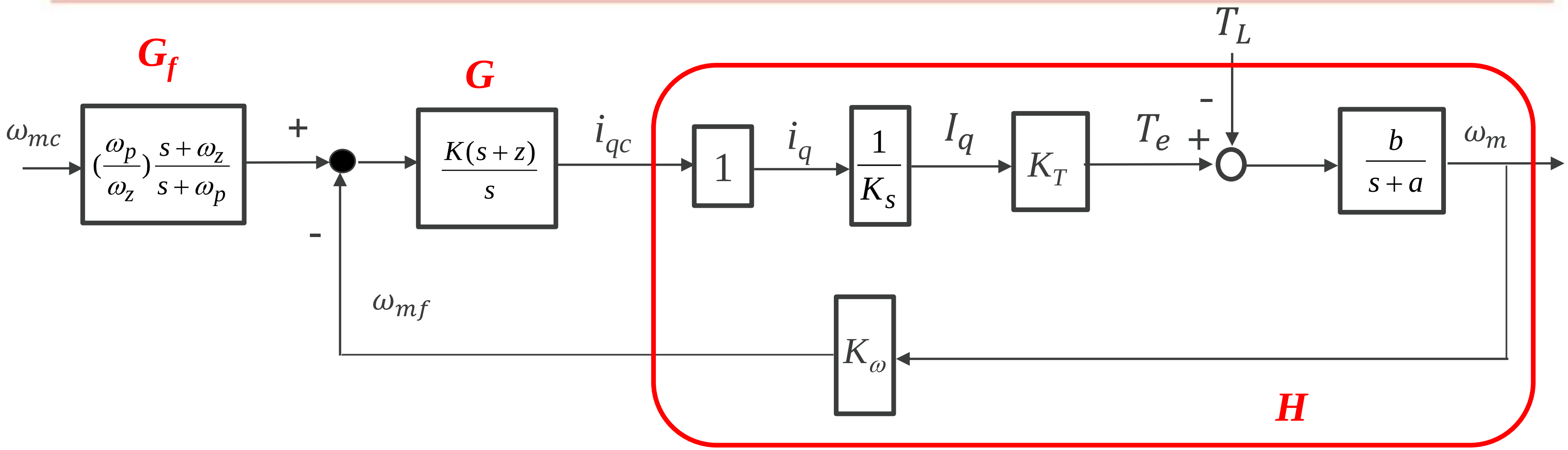


Speed regulator design

- Usually PI is adopted as the speed regulator
- The crossover frequency (ω_c) can be assigned to be 1/10 ~ 1/4 of the current loop



Speed Tracking

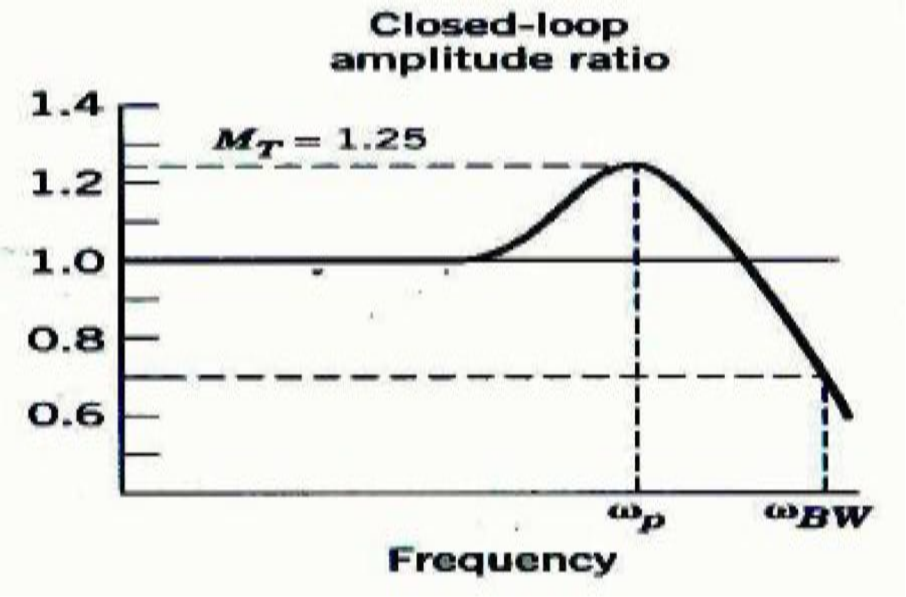


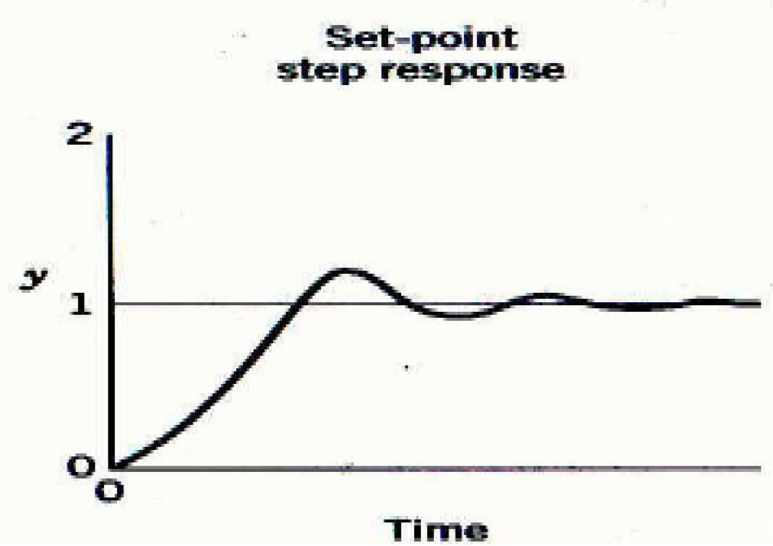
Feedforward Controller (G_f)

$$\frac{\omega_{mf}}{\omega_{mc}} = M = \frac{G_f GH}{1 + GH} = G_f L$$

$$L = \frac{GH}{1+GH}$$

Requirement of M





- M_T is the peak value of M
- M_T should be selected so that $1.0 < M_T < 1.5$
- The bandwidth ω_{BW} and the frequency ω_p at which M_T occurs, should be as large as possible. Large values result in the fast closed-loop responses

normal

System Parameters

DC Voltage $V_d = 130V$

$f_s = 20kHz$, $V_{tri} = 5V_{pp}$ (PWM)

$C_d = 330uF$

$L_s = 6.71mH$, $R_s=1.55\Omega$, $\phi_f=47m\ V/rad/s$

$K_s = 1/3.375$ (current sensing factor)

$K_v = 1/71.556$ (DC voltage sensing), $K_s = 1/3.3375$ (current sensing)

Max Speed=2000rpm

Max torque = 1.27Nm

P = 10

$K_t = 0.3524$ Nm/A

Current loop bandwidth $f_{coi} = 750Hz$

Speed loop bandwidth $f_{co} = 50Hz$

Matlab Controller Design (1/2)

```
% PMSM Vector Control
clf;
clc;
PI = 3.1416;
% Motor parameters
Po = 400;
Nrated = 3000;
P = 10;
Wmrated = 3000/60 * 2 * PI;
Werated = Wmrated * P/2;
Tn = Po/Wmrated
Ls = 6.71e-3;
Rs = 1.55;
Vf = 17.4 * 1.414 * Nrated/1000;
F = Vf/Werated
J = 0.227e-6;
Tu = 0.53;
B = J/Tu;
Kt = 3/2 * P/2 * F
% Inverter parameters
Vd = 130;
fs = 20e3;
ws = 2 * PI * fs;
ks = 1/3.3375;
kv = 1/71.556;
Vtm = 5;
kpwm = Vd/(2*Vtm);
```

```
% current regulator design
% Gi : PI=K1(s+z)/s
p = 10e3 * 2 * PI;
numLR = 1;
denLR = [Ls  Rs];
HLR=tf(numLR, denLR);
numLPF = p;
denLPF = [1  p];
LPF=tf(numLPF, denLPF);
Hi = kpwm * ks * series(HLR,
LPF);
fcoi = 750
wcoi = 2 * PI* fcoi;
Hir = freqresp(Hi, wcoi);
GainHi = abs(Hir);
z = wcoi/5;
ti = 1/z
numGi1 = [1 z];
denGi = [1 0];
Gi1=tf(numGi1, denGi);
Gi1r = freqresp(Gi1, wcoi);
GainGi1r = abs(Gi1r);
K1 = 1/(GainHi*GainGi1r)
Gi = K1 * Gi1;
GiHi = series(Gi, Hi);
wmin = 100 * 2* PI;
wmax = 50e3 * 2 *PI;
figure(1);
bode(Hi, Gi, GiHi, {wmin,
wmax});
grid;
```

Matlab Controller Design (2/2)

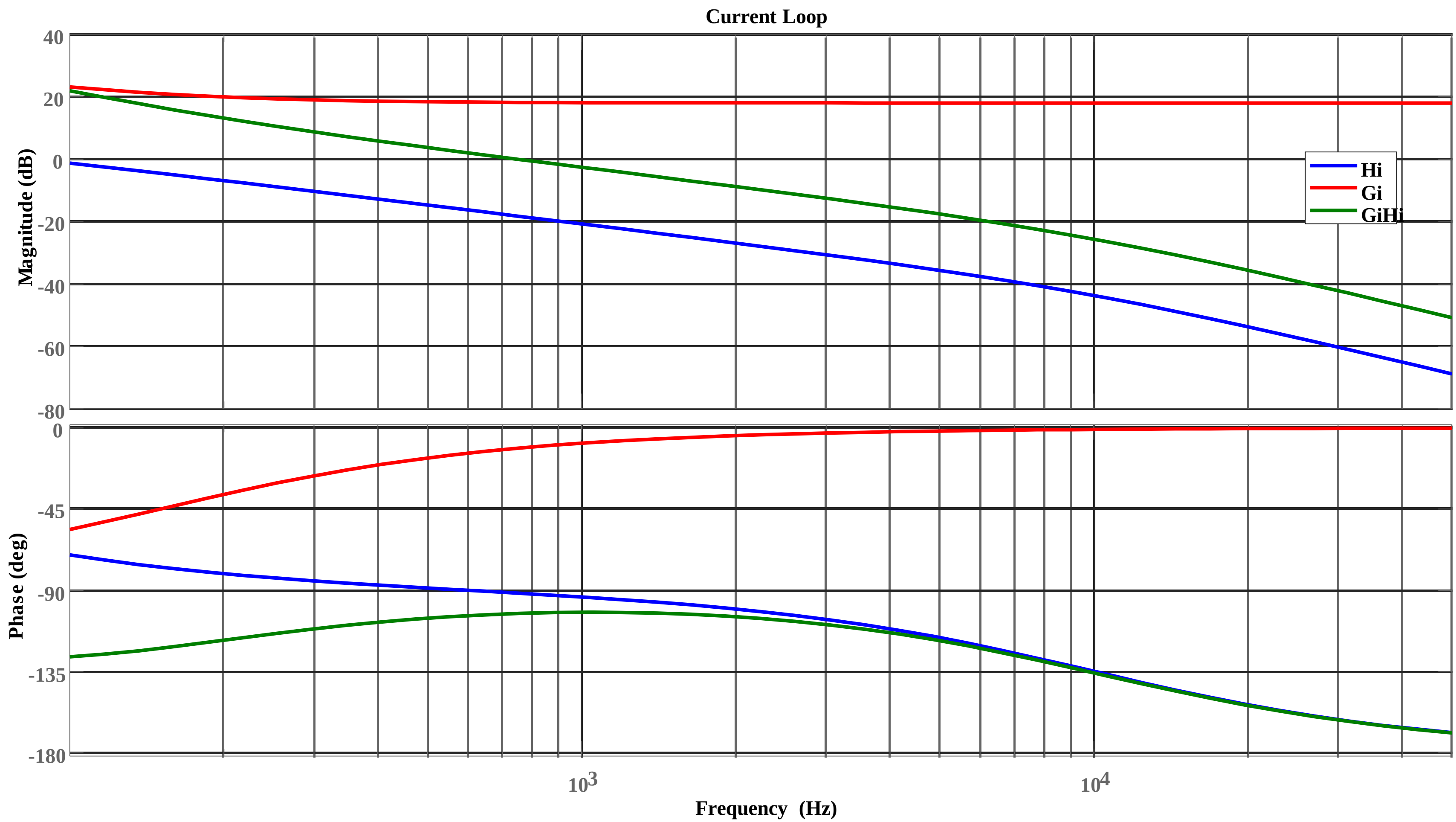
normal

```
% Speed regulator design
J = 100e-6;
B = J/Tu;
a = B/J;
b = 1/J;
Kw = 1/100;
numH = Kt/ks * Kw *b;
denH = [1  a];
H=tf(numH, denH);
fco = 75
wco = 2*PI*fco;
Hr = freqresp(H, wco);
GainH = abs(Hr);
z = wco/5;
tw = 1/z
numG1 = [1 z];
denG = [1 0];
G1=tf(numG1, denG);
G1r = freqresp(G1, wco);
GainG1r = abs(G1r);
K2 = 1/(GainH * GainG1r)
G = K2 * G1;
GH = series(G, H);
figure(2);
bode(H, G, GH);
grid;
```

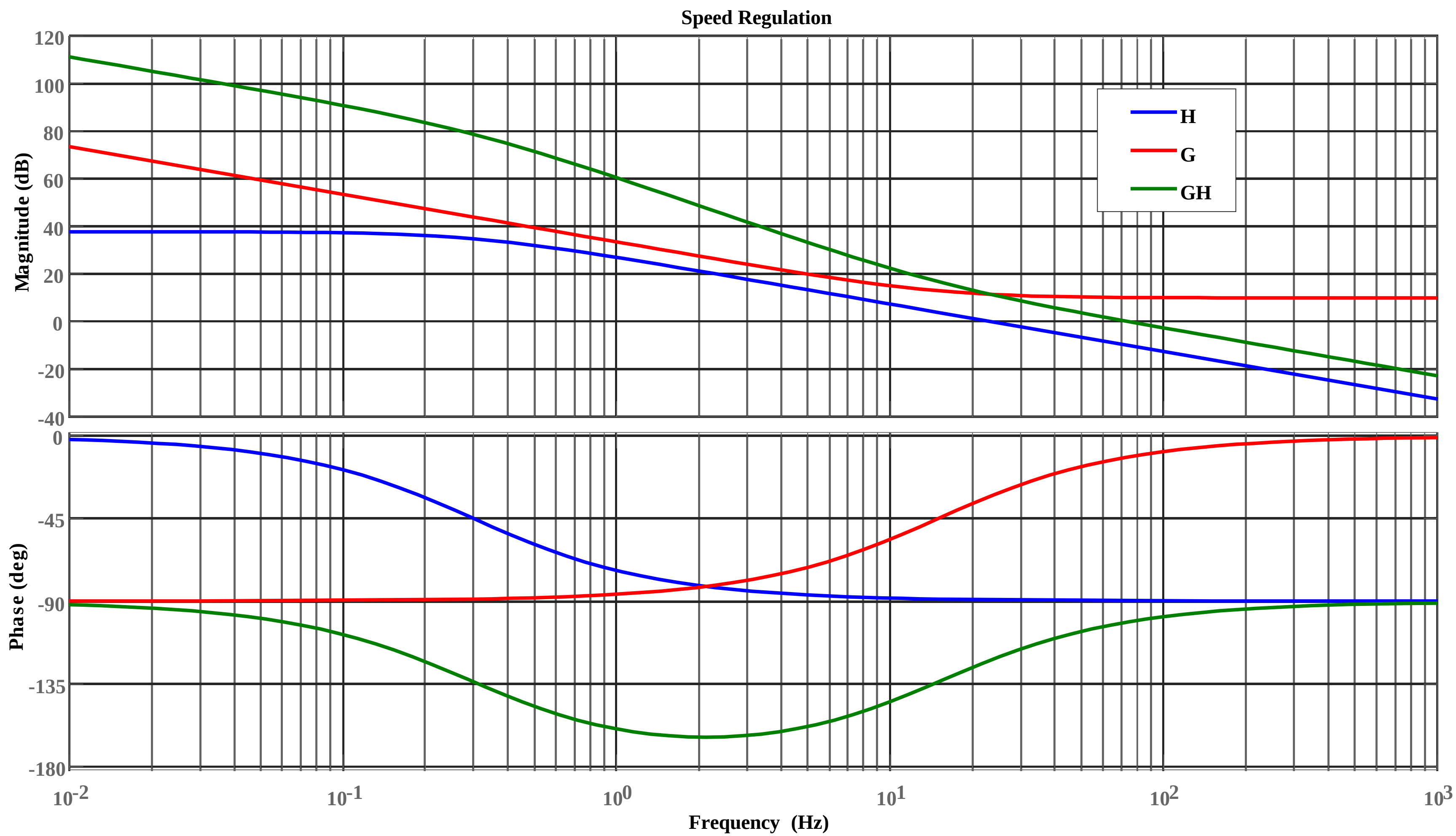
```
% Speed tracking controller
design
p = 100;
z = 250;
numGf = p/z * [1 z];
denGf = [1 p];
Gf=tf(numGf, denGf);
L = GH/(1+GH);
M = Gf * L;
figure(3);
bode(L, M);
grid
```

Tn = 1.2732
F = 0.0470
Kt =
0.3524
fcoi = 750
ti = 0.001
K1 = 2
fco = 75
tw = 0.01
K2 = 2

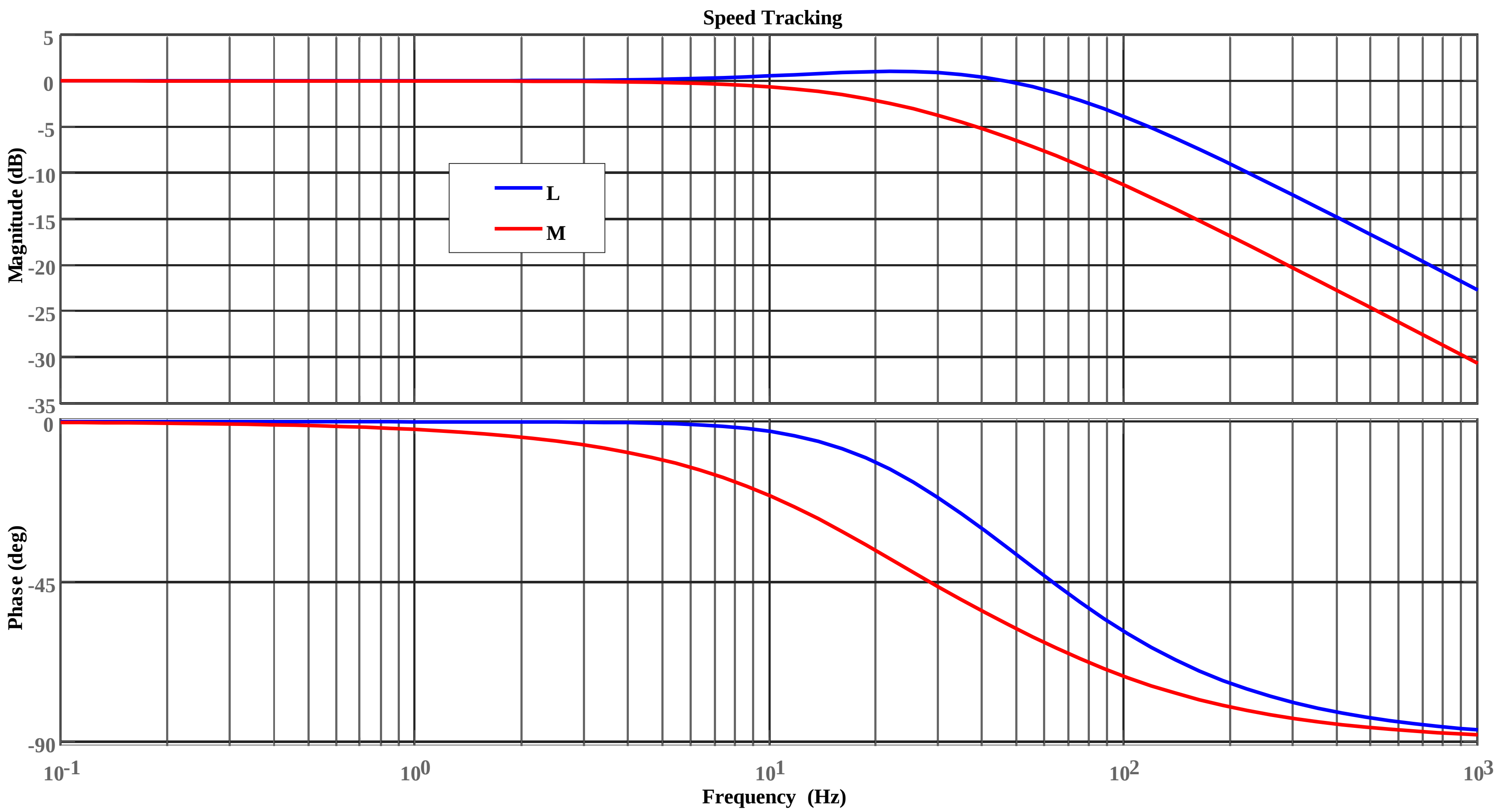
Bode Plot of Current Loop



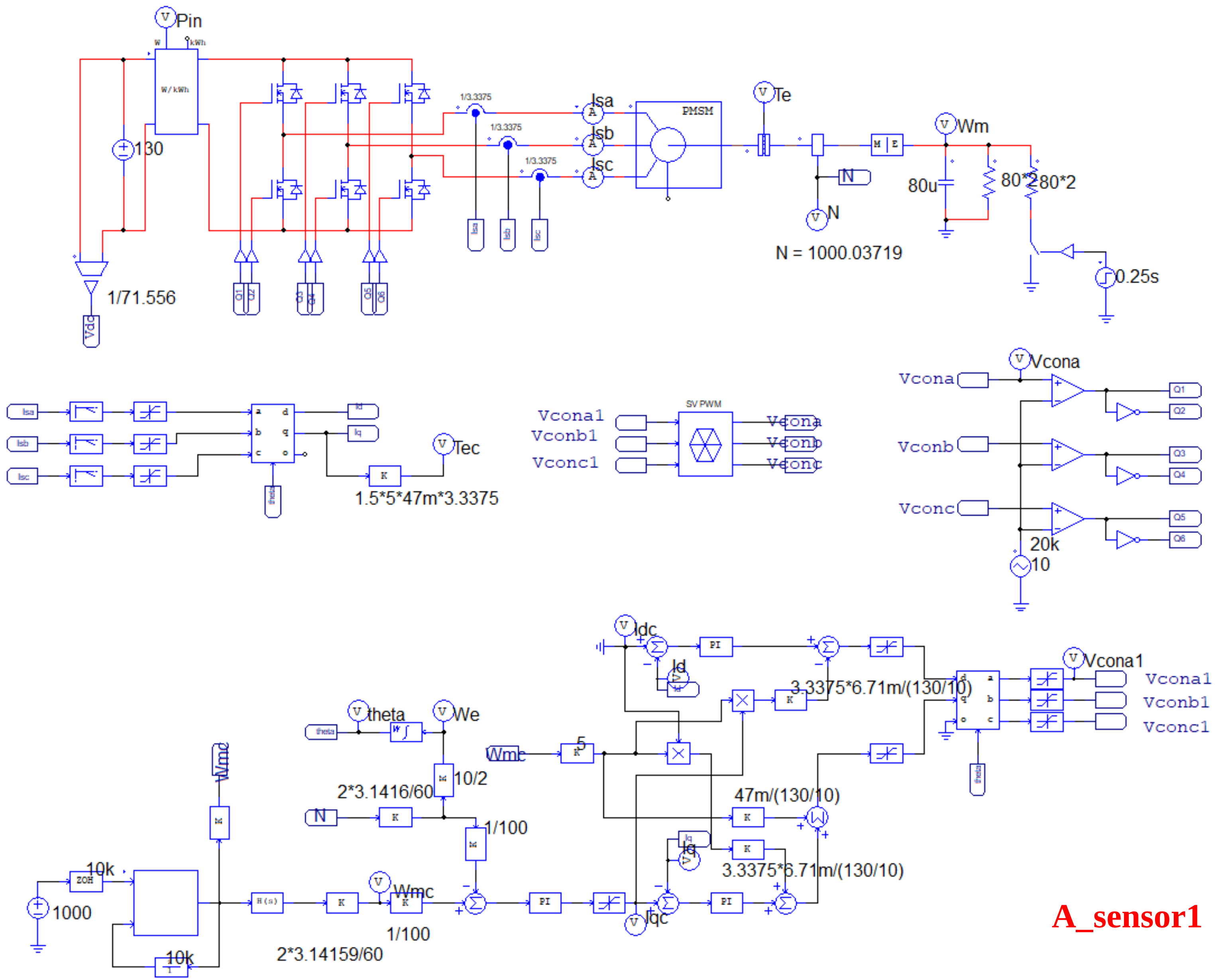
Bode Plot of Speed Regulation Loop



Bode Plot of Speed Tracking Loop

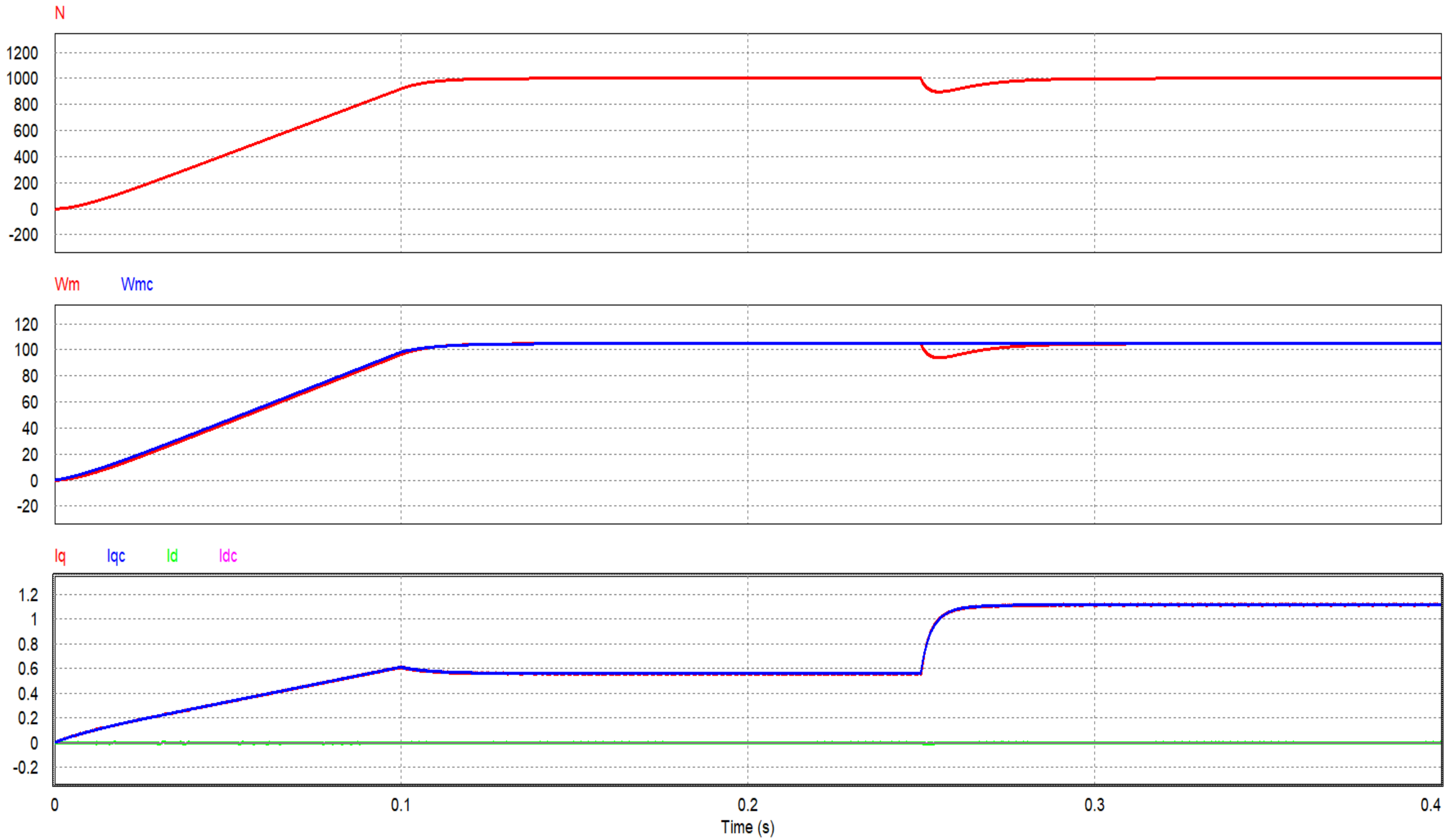


Simulation Circuit

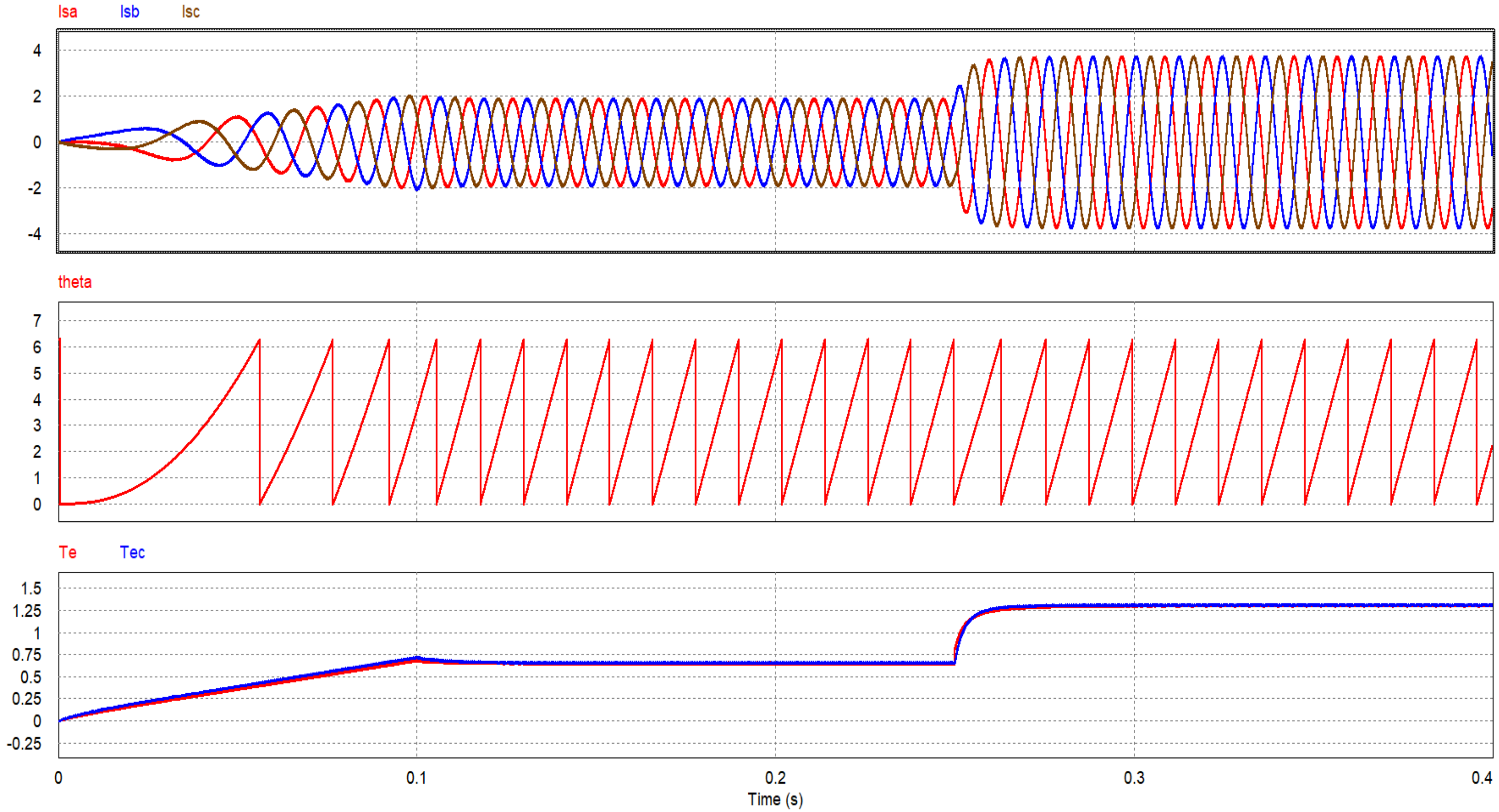


A_sensor1

Simulation Result (1/3)

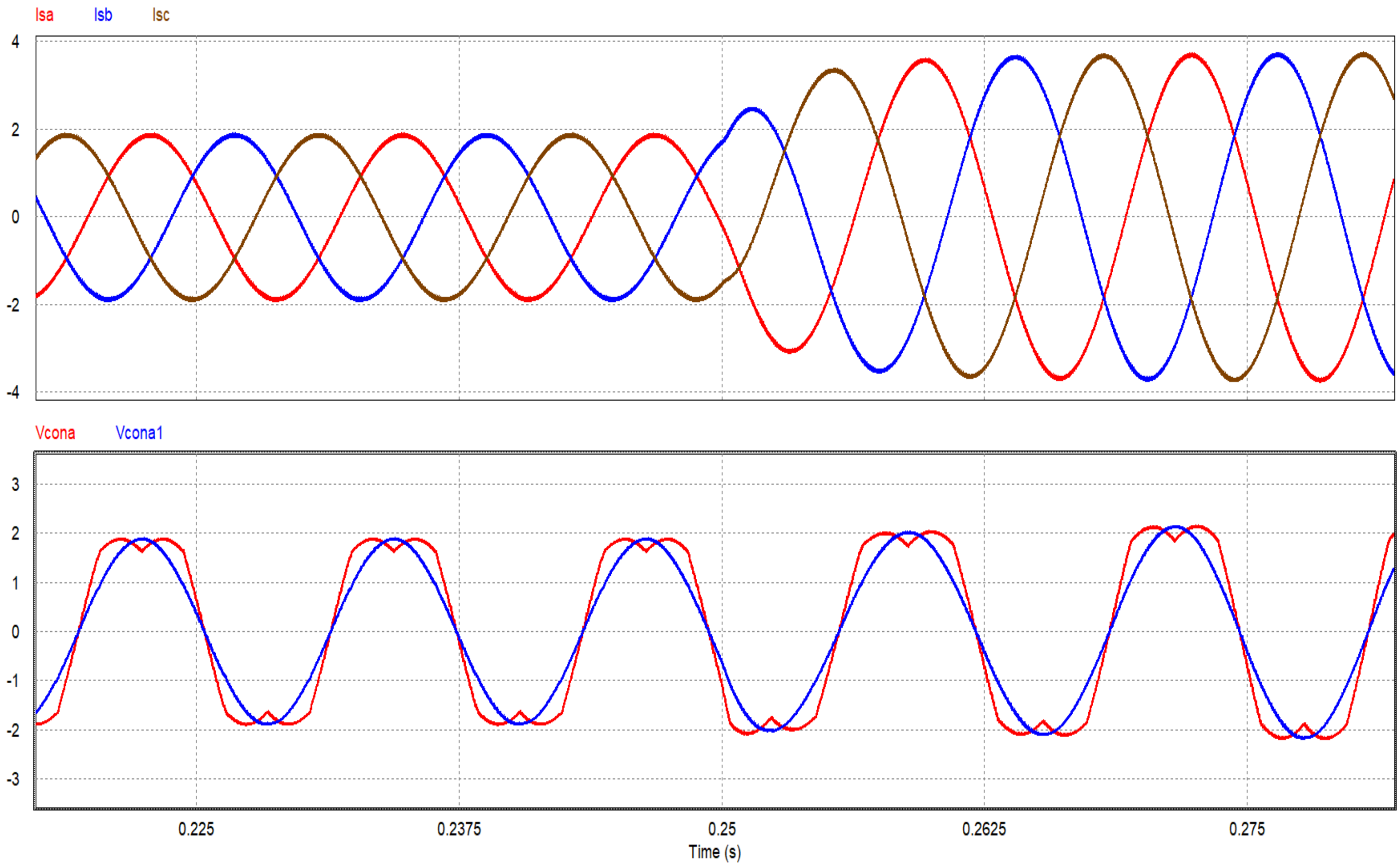


Simulation Result (2/3)

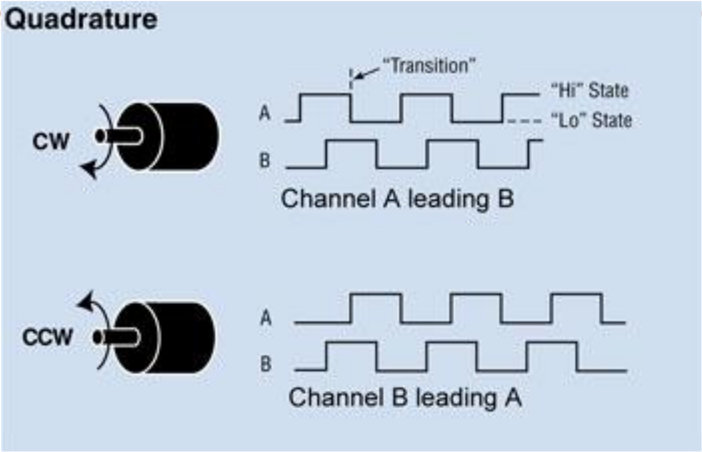


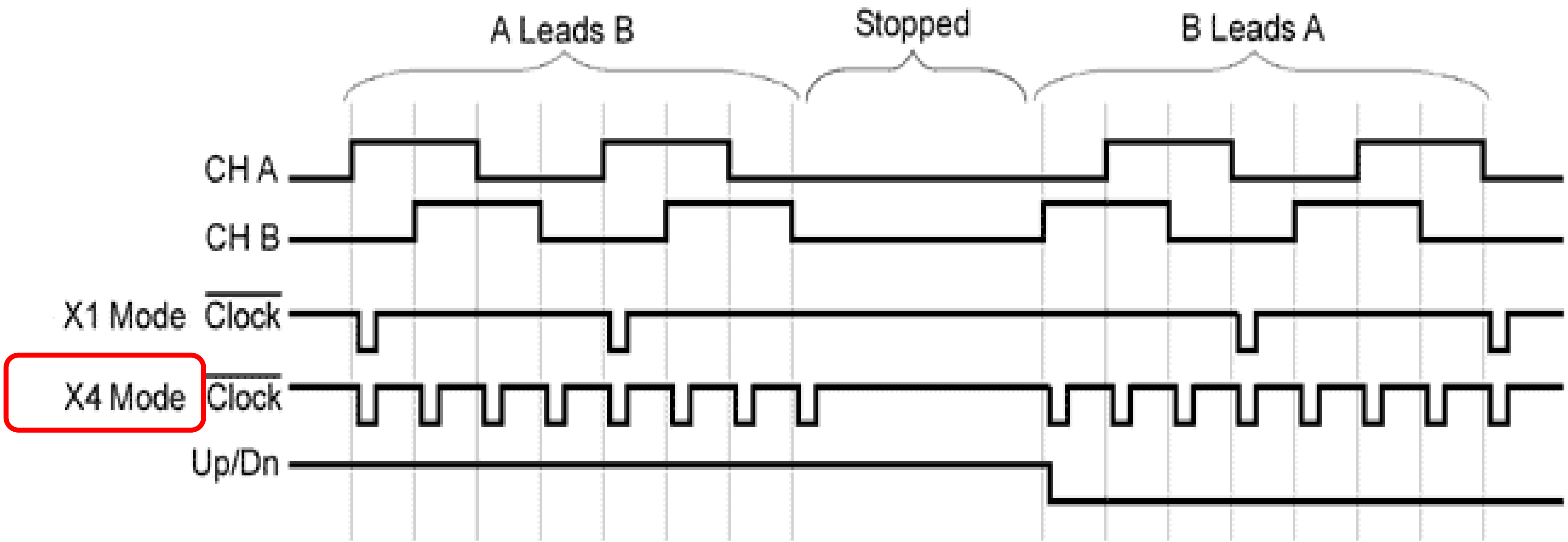
Simulation Result (3/3)

normal



Speed Measurement with Incremental Encoder

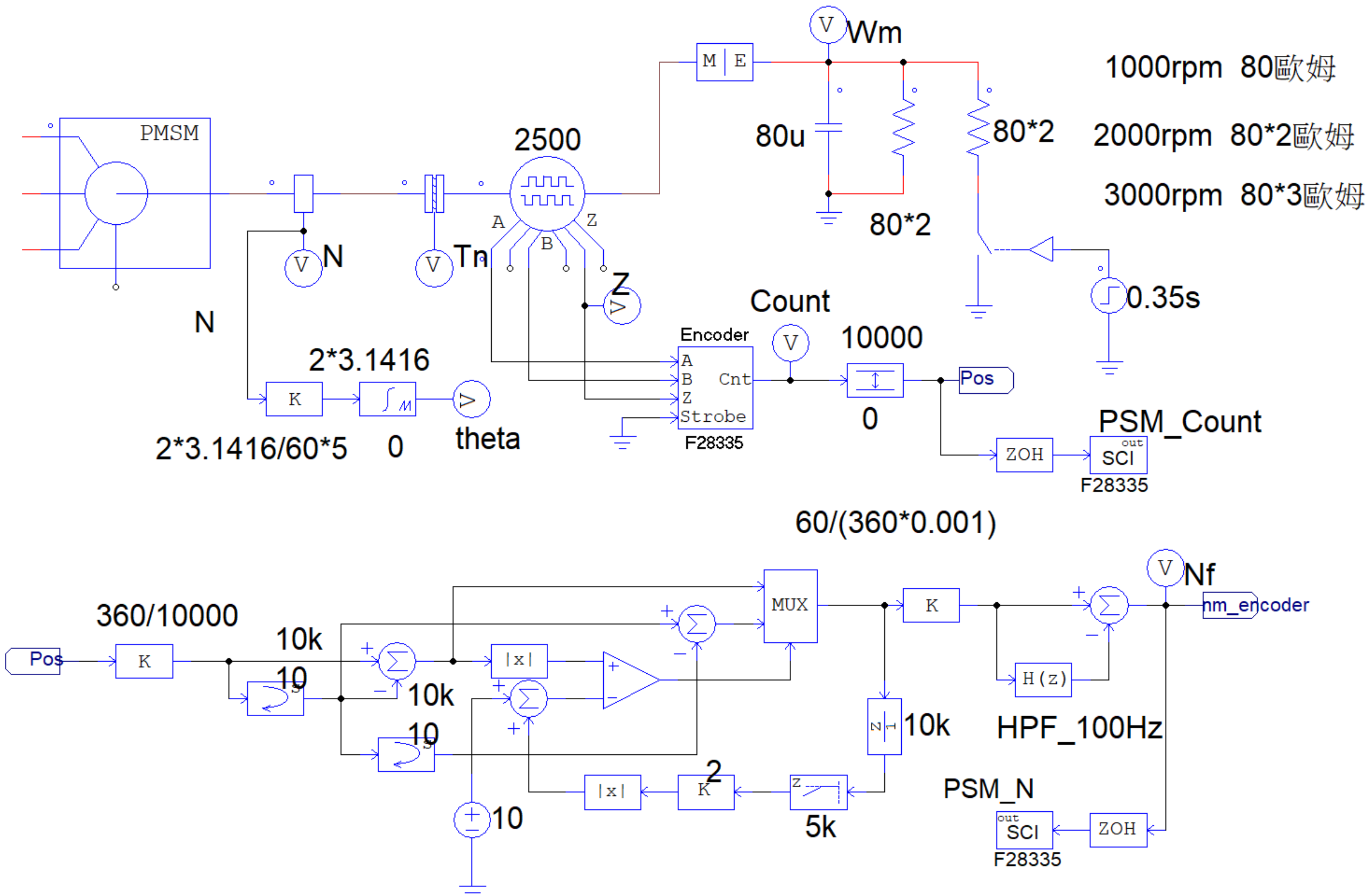




轉速及角度計算(1/2)

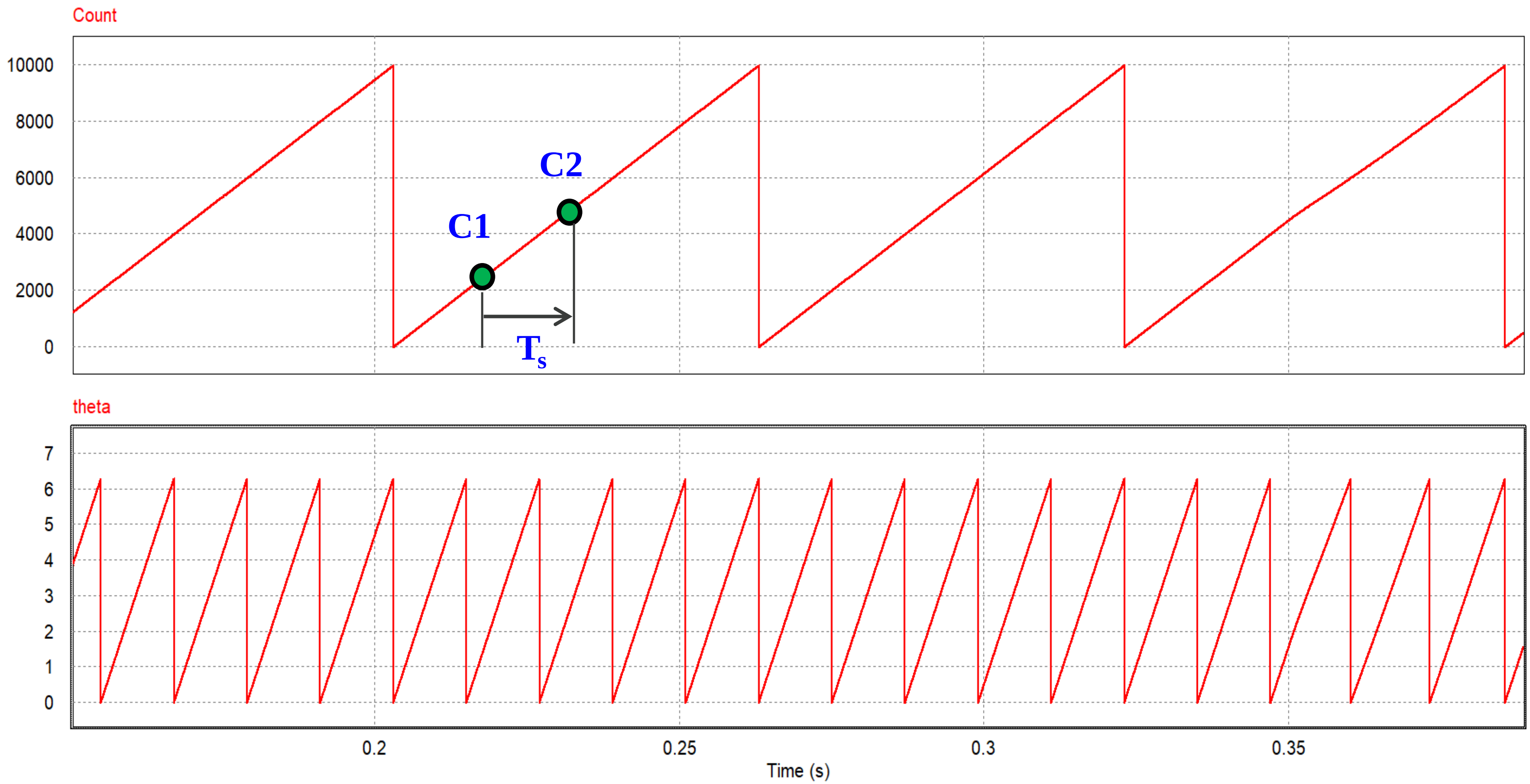
Encoder = 2500 ps/rev

Count = =2500 x 4 = 10000 ps/rev



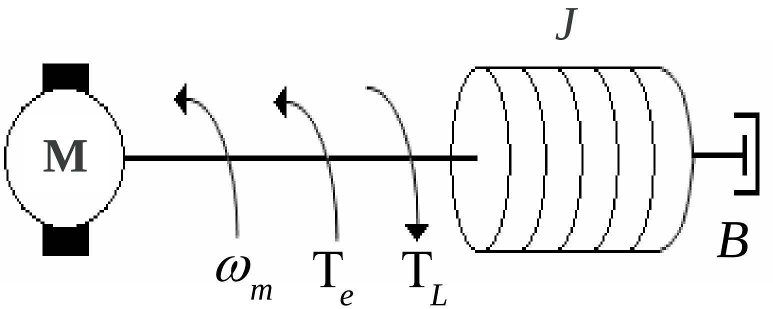
轉速及角度計算(2/2)

$$N = \frac{C2-C1}{T_s}\frac{60}{10000}(rpm)$$

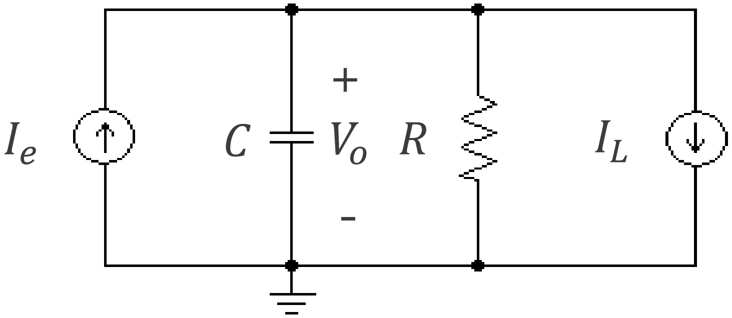


電與機械具有對耦關係

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L$$

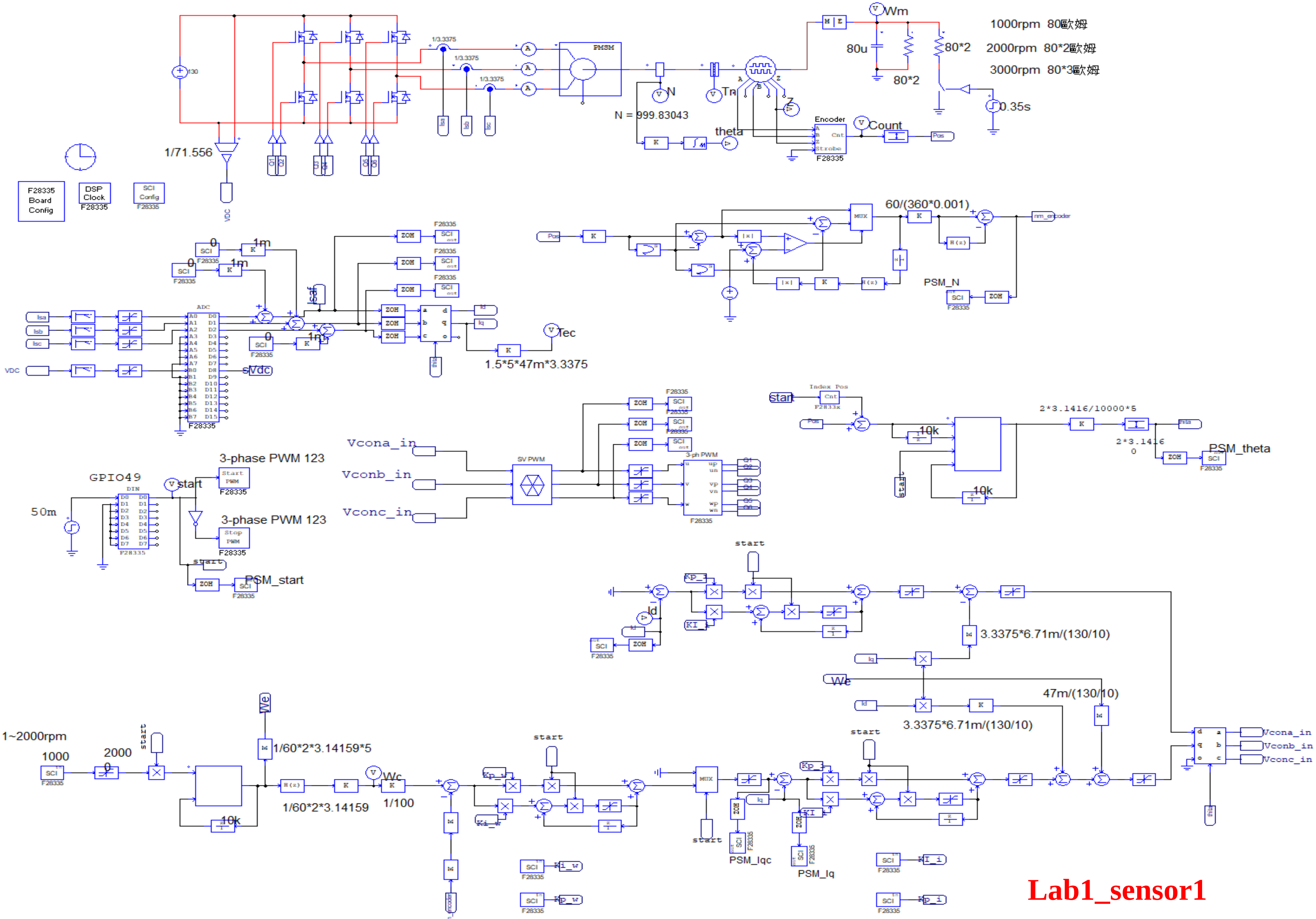


$$I_e = C\frac{dV_o}{dt} + \frac{1}{R}V_o + I_L$$



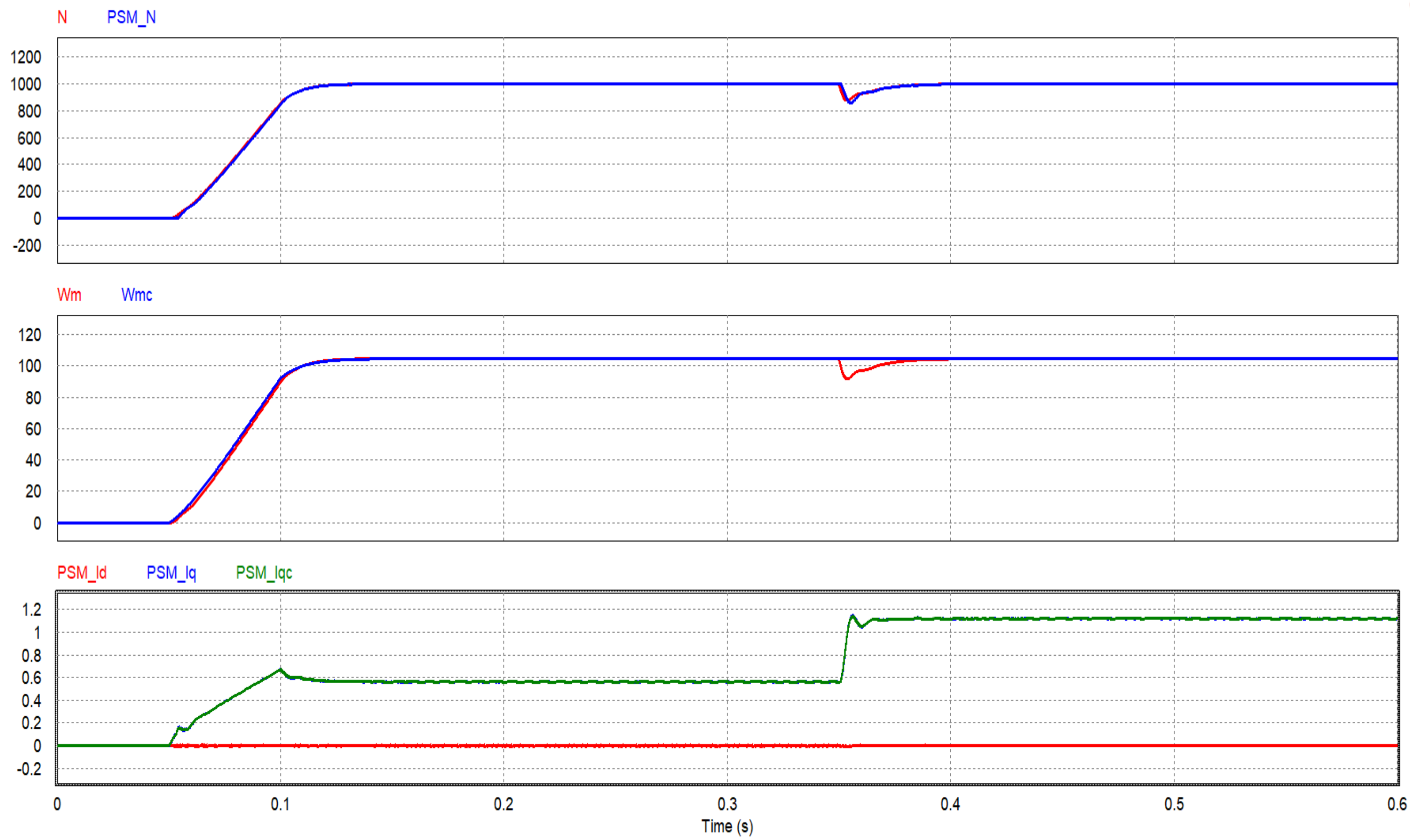
可利用此方式建立模擬電路的機械模型

Control Circuit Realized with SimCoder

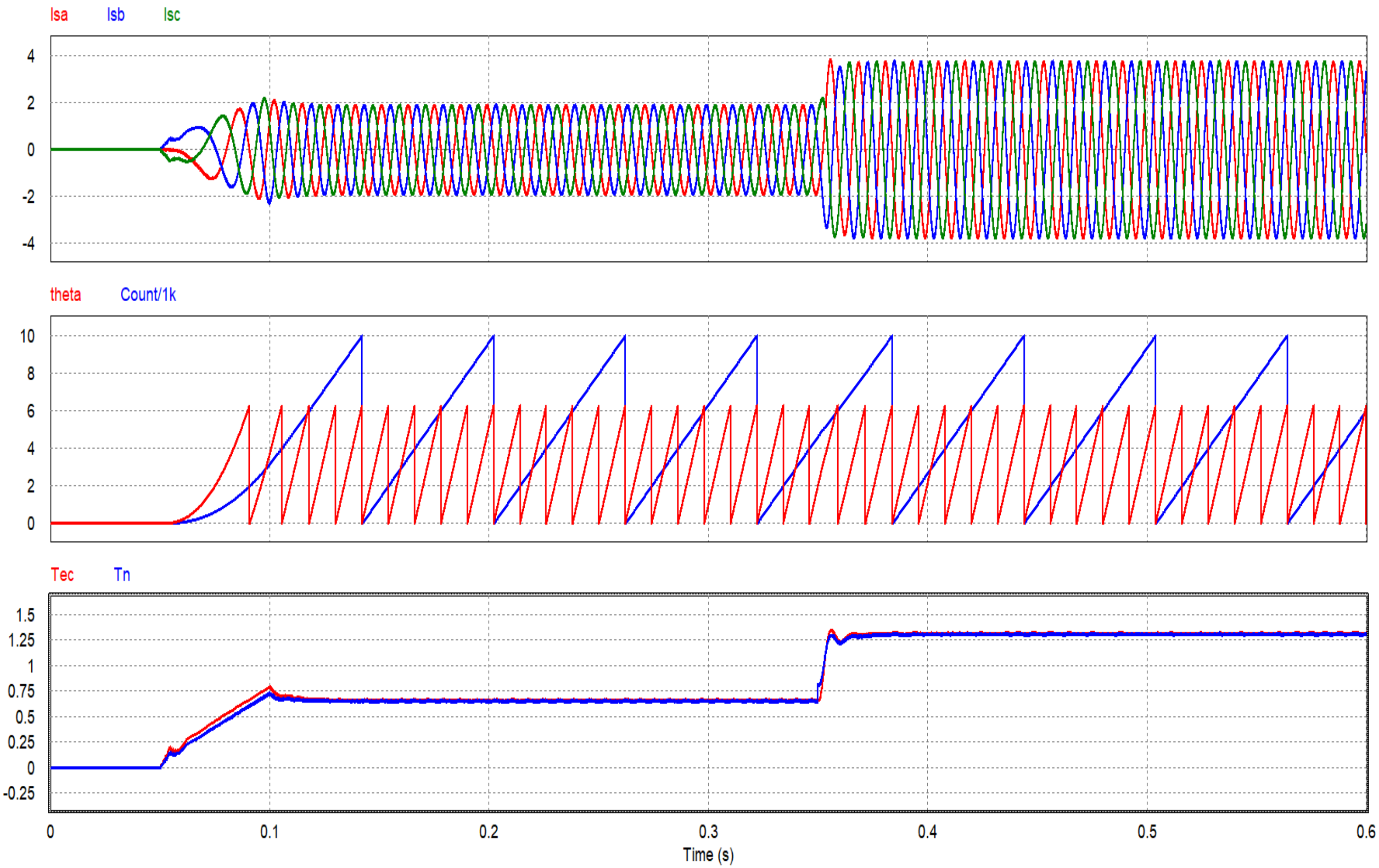


Lab1_sensor1

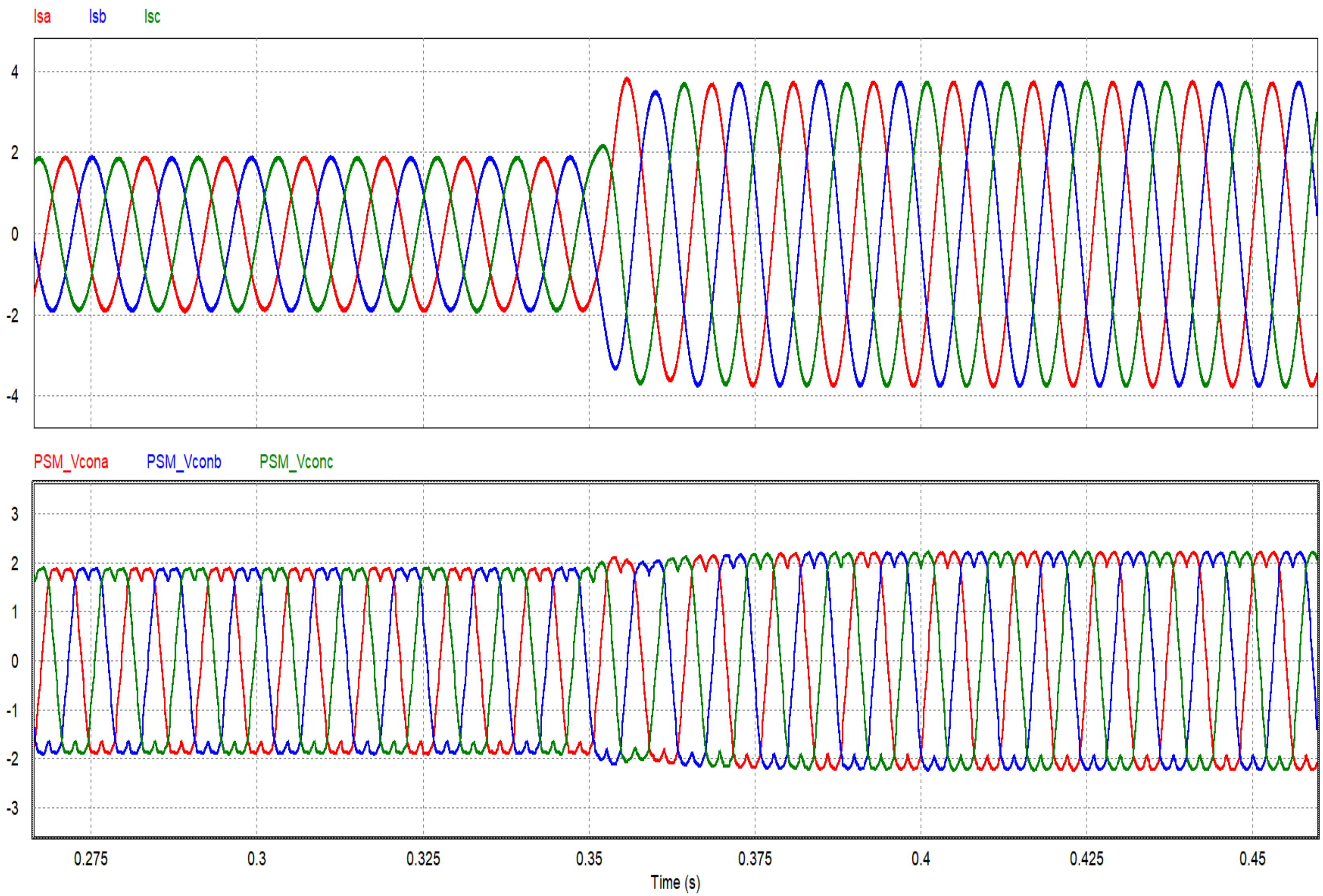
Simulation Result (1/3)



Simulation Result (2/3)



Simulation Result (3/3)



normal

Lab 2: 轉子初始位置檢測及起動

利用

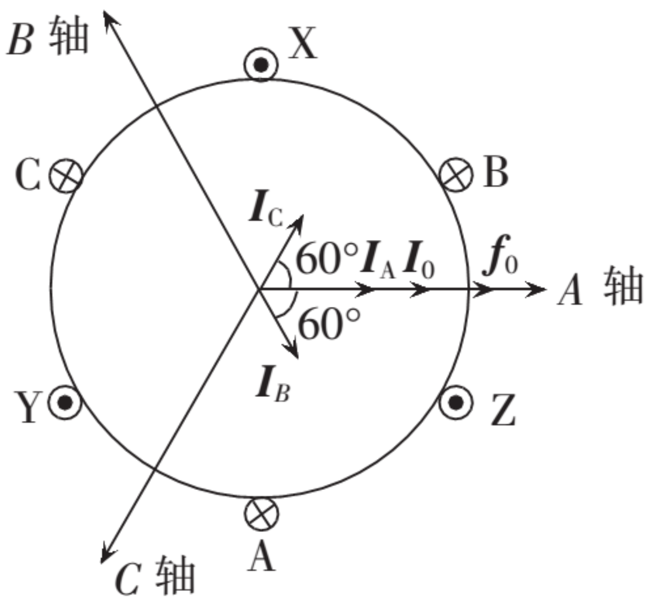
$$\begin{cases} i_A = I_m \\ i_B = -I_m/2 \\ i_C = -I_m/2 \end{cases}$$

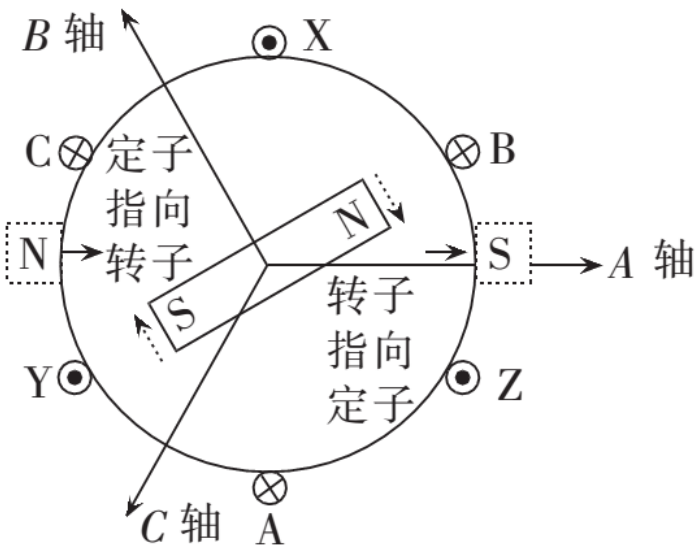
相當於

$$\begin{cases} i_d = i_\alpha \cos\theta + i_\beta \sin\theta \\ i_q = i_\beta \cos\theta - i_\alpha \sin\theta \end{cases}$$

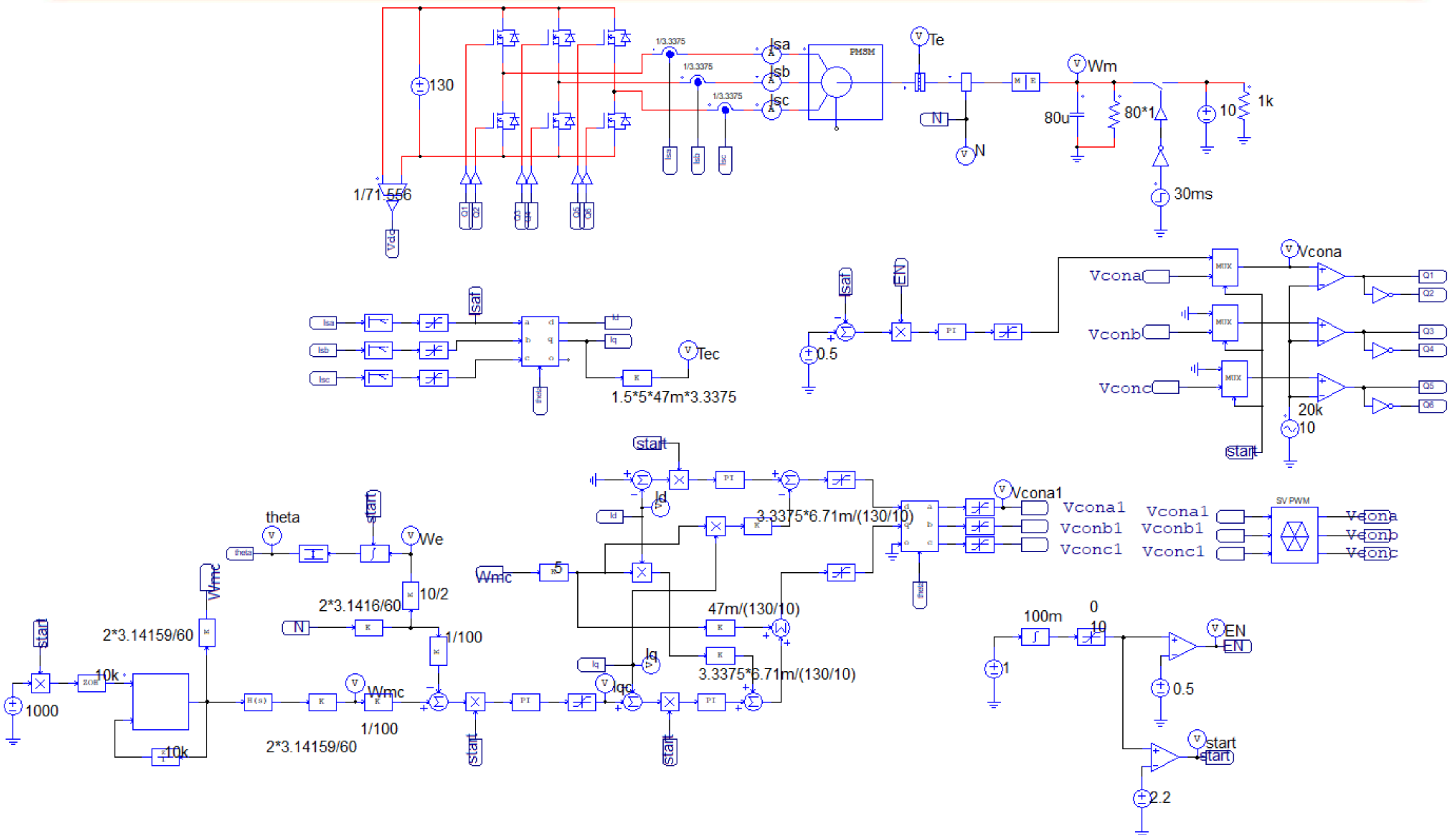
$$i_d = I_m, i_q = 0$$

可將轉子的N極
復歸至零度位置





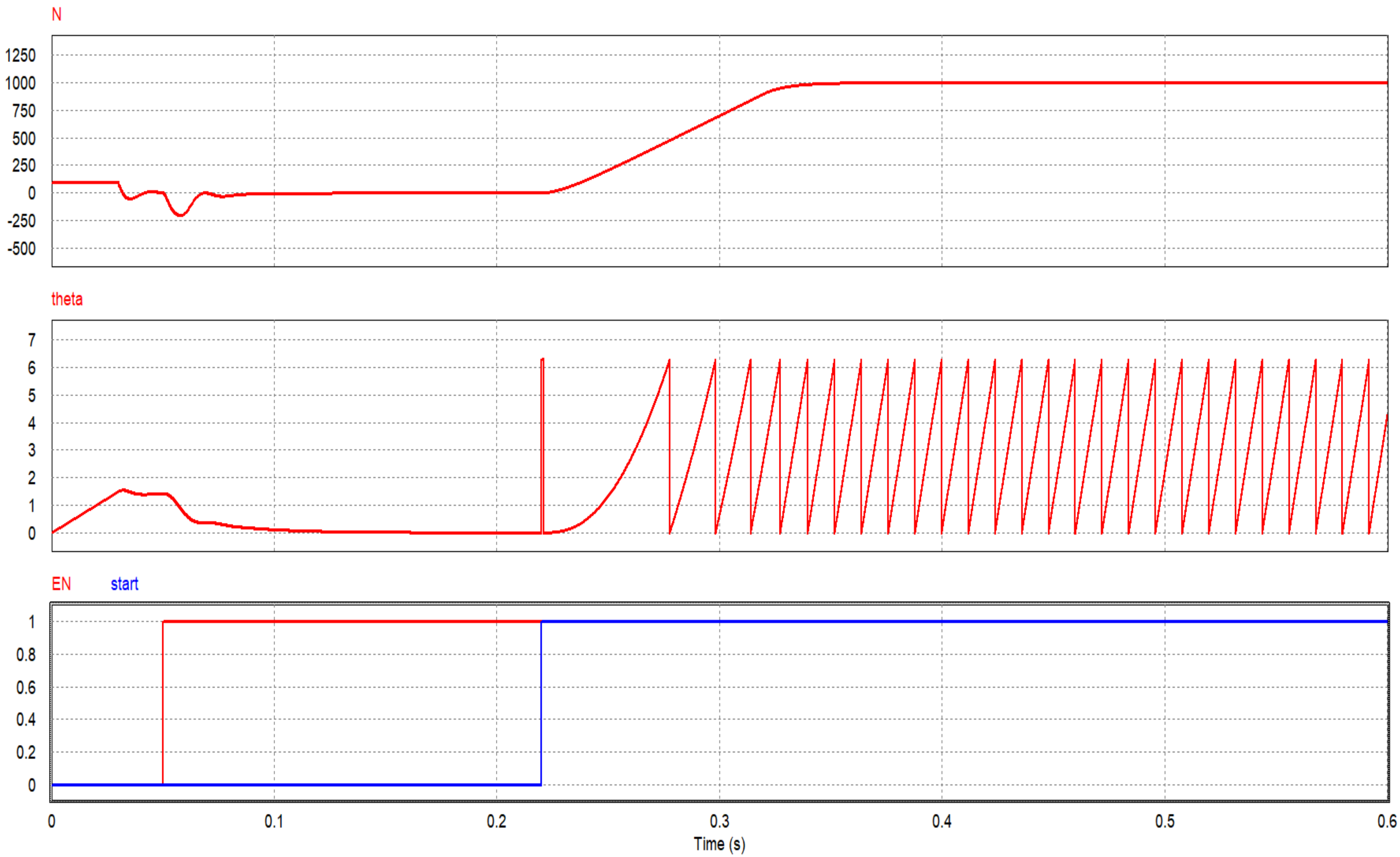
Simulation Circuit



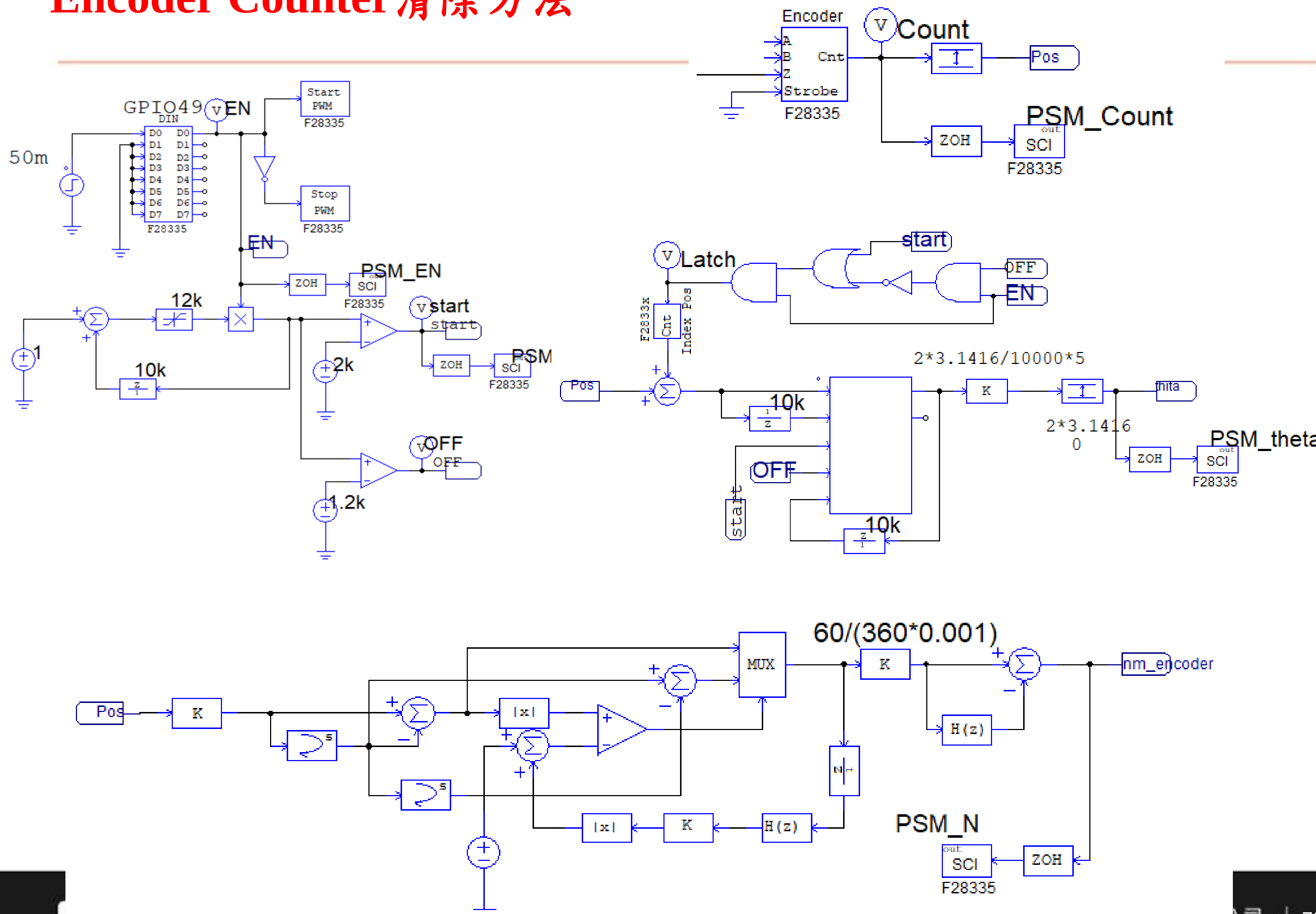
A_sensor_start1

Simulation Result

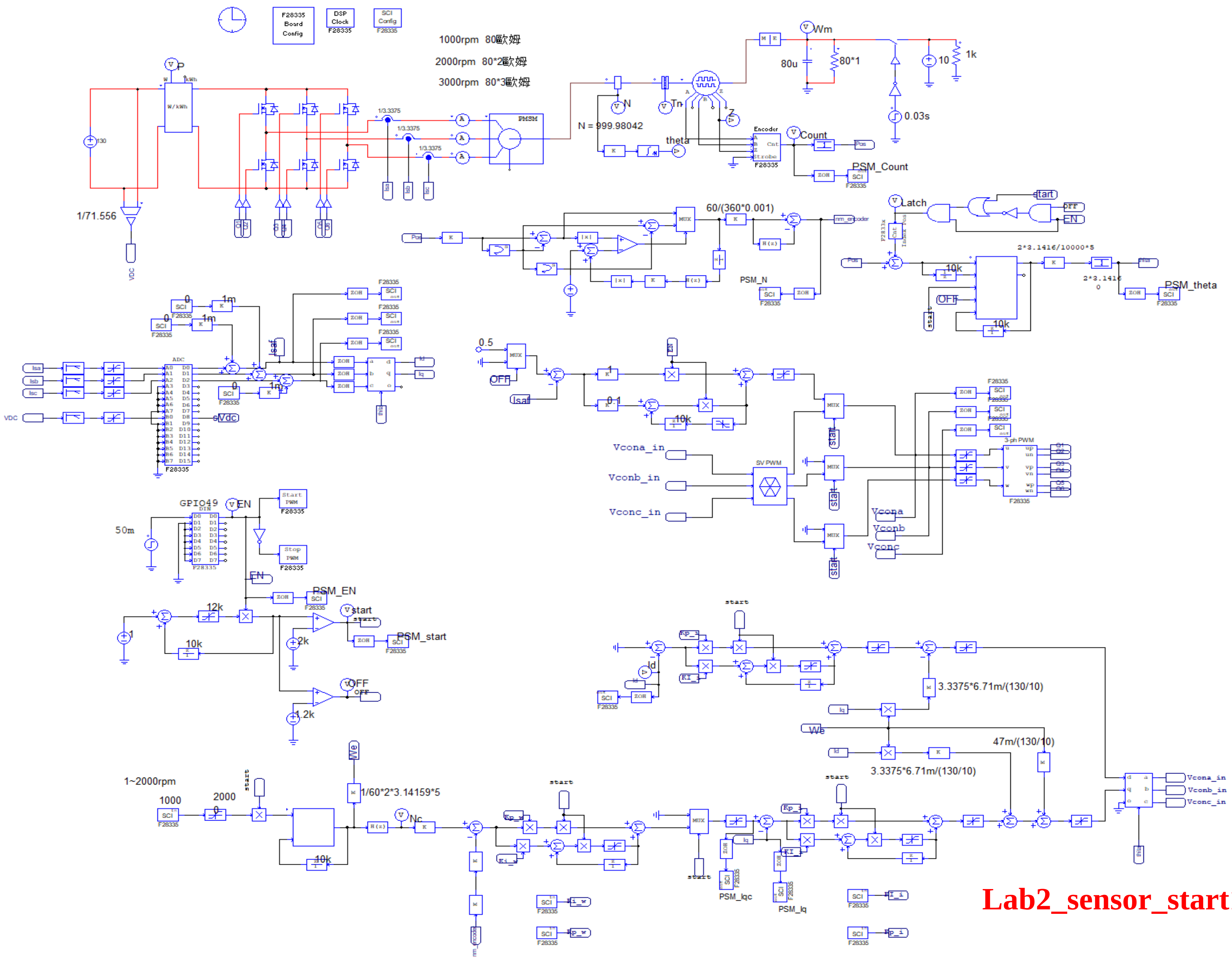
normal



Encoder Counter清除方法

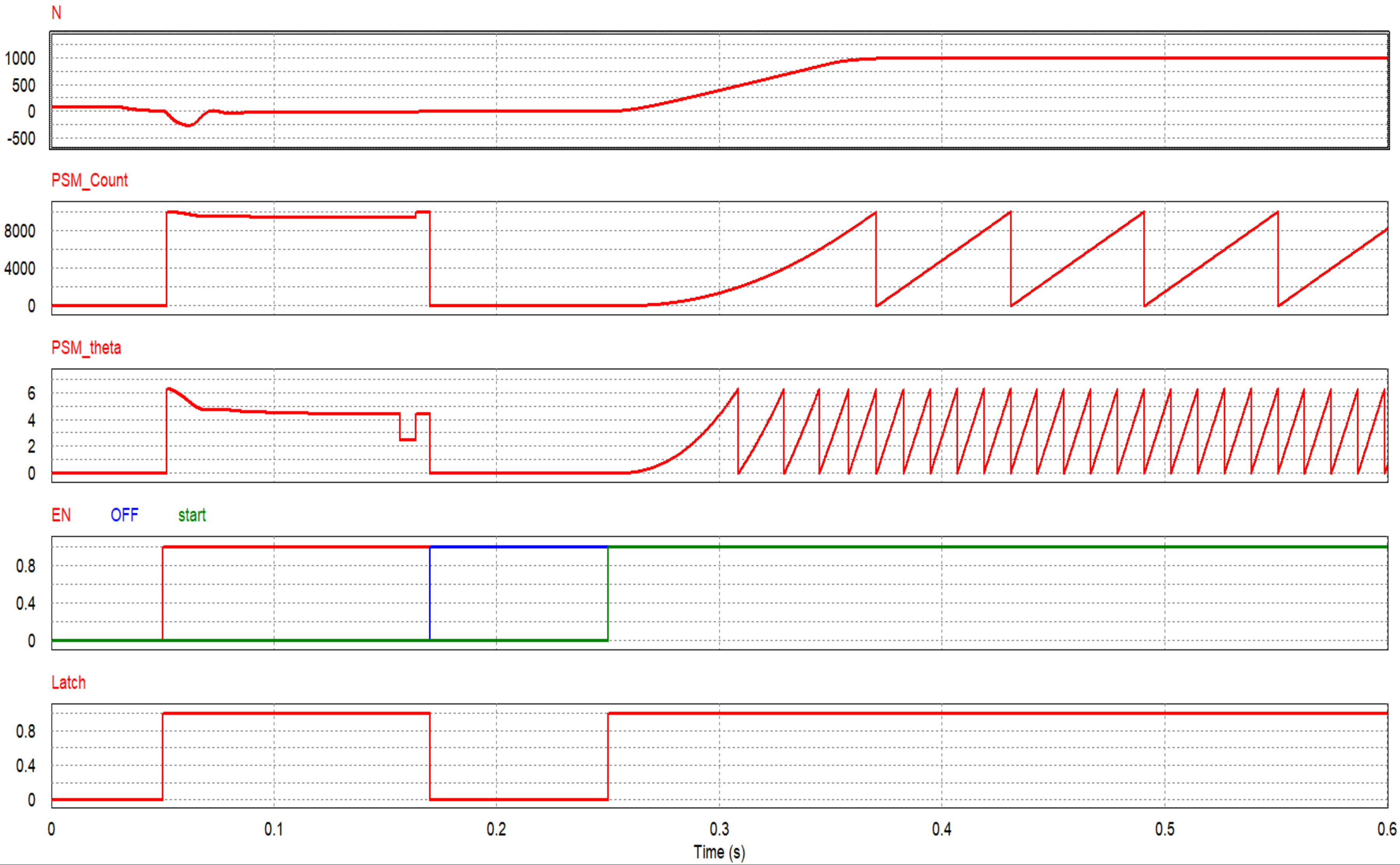


Control Circuit Realized with SimCoder



Lab2_sensor_start1

Simulation Result

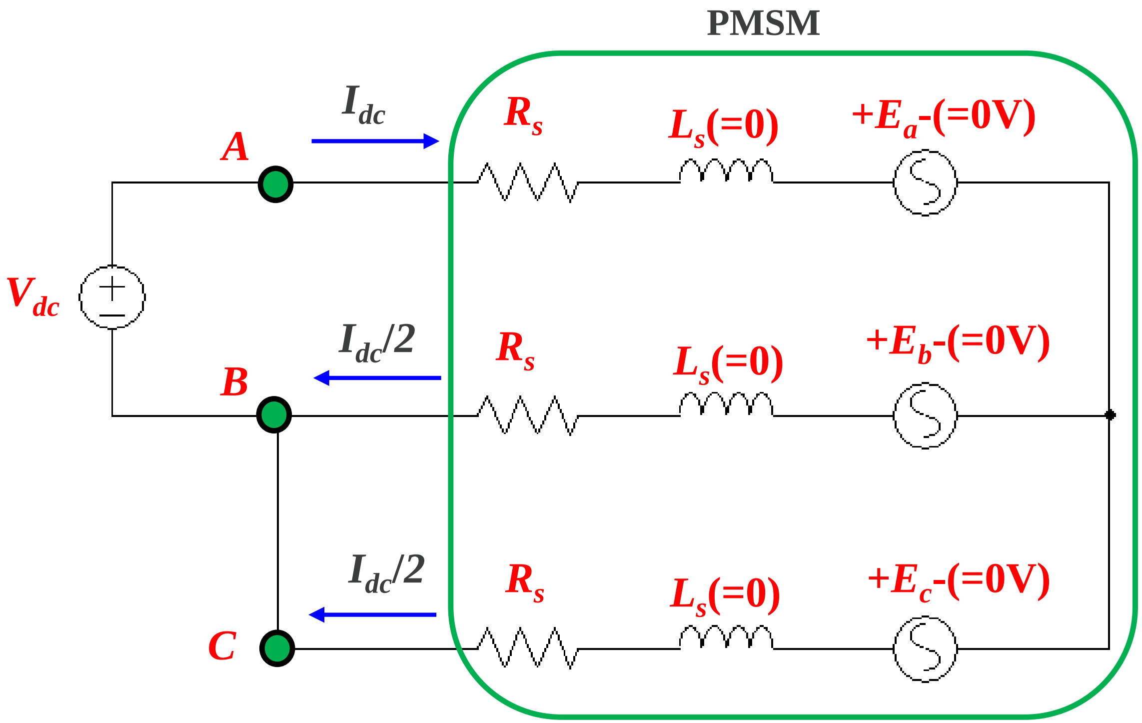


Lab 3: 馬達參數線上量測與估測

- R_s量測

PMSM通入DC電壓，馬達不會轉動，其速度電壓為零，馬達線圈電感電壓在直流下亦為零

$$I_{dc} = \frac{V_{dc}}{\frac{3}{2}R_s} \Rightarrow R_s = \frac{2}{3}\frac{V_{dc}}{I_{dc}}$$



實現方法

- 透過Inverter閉迴路電流控制以獲得精確之電流I_{dc}
- V_{dc}可由PWM控制電壓V_{cona}間接計算獲得

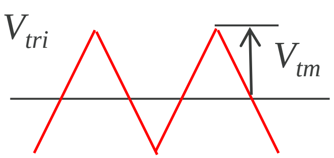
$$i_{dcr} = i_{dc} = K_s I_{dc}$$

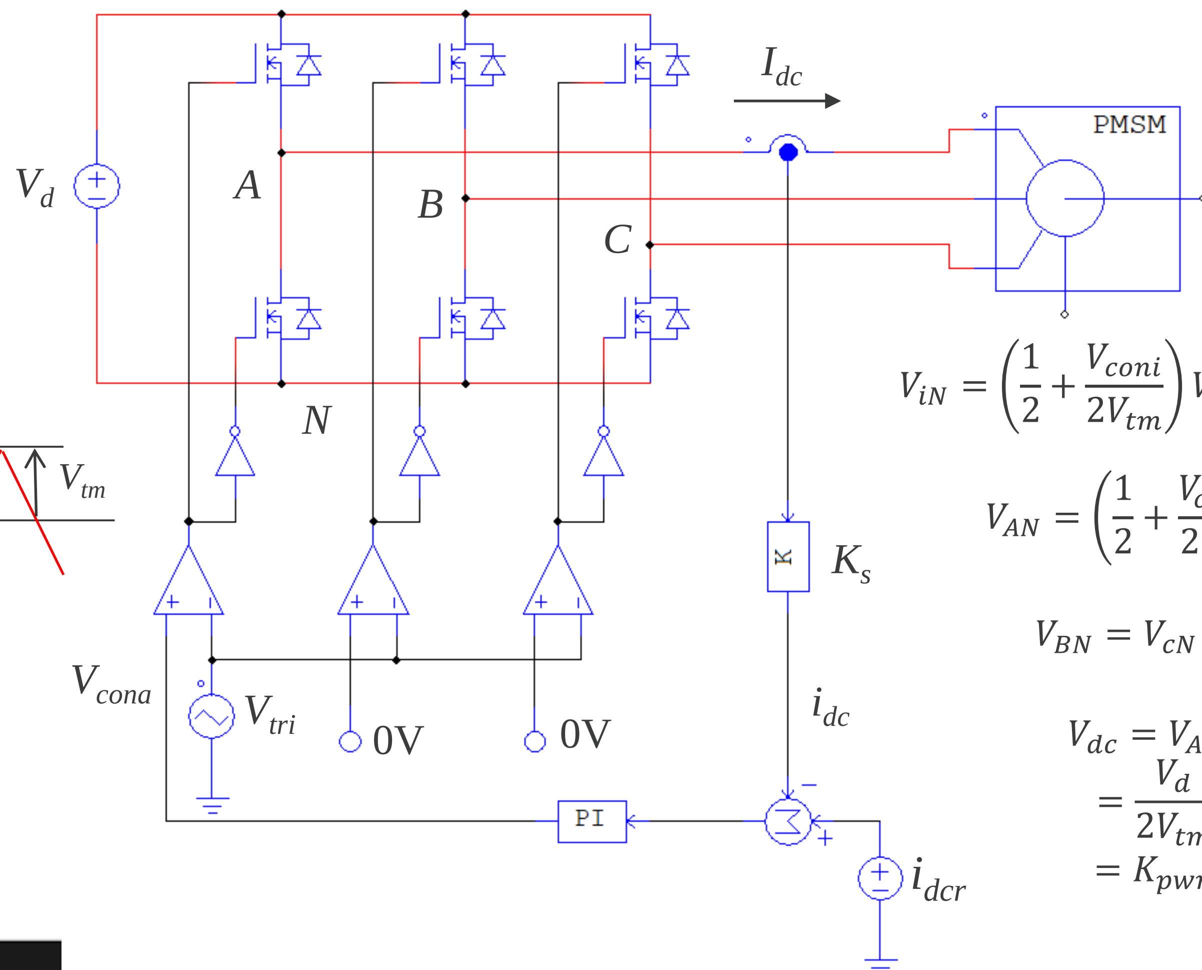
$$V_{dc} = K_{pwm} V_{cona} = \frac{V_d}{2V_{tm}} V_{cona}$$

V_{tm} is the amplitude of V_{tri}

$$R_s = \frac{2}{3}\frac{V_{dc}}{I_{dc}} = \frac{1}{3}\frac{V_d}{V_{tm}}\frac{K_s}{i_{dcr}} V_{cona}$$

$$K_{pwm} = \frac{V_d}{2V_{tm}}$$





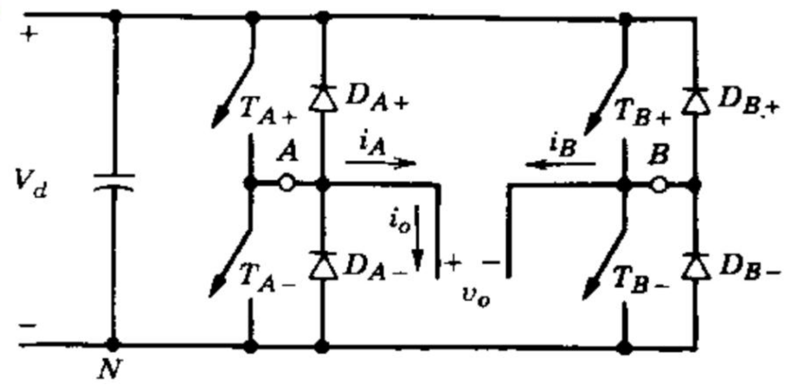
$$V_{iN} = \left(\frac{1}{2} + \frac{V_{coni}}{2V_{tm}}\right) V_d \text{ , } i = A, B, C$$

$$V_{AN} = \left(\frac{1}{2} + \frac{V_{cona}}{2V_{tm}}\right) V_d$$

$$V_{BN} = V_{cN} = \frac{1}{2} V_d$$

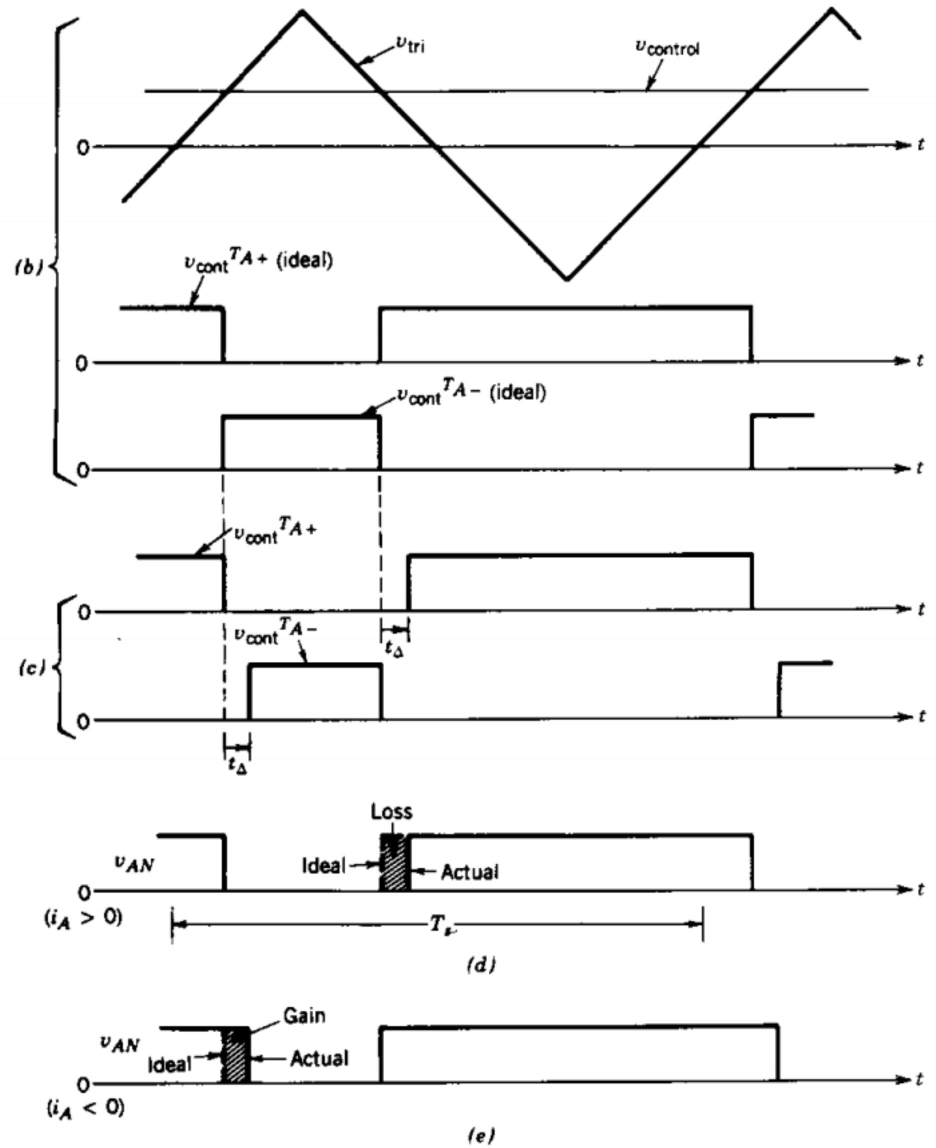
$$V_{dc} = V_{AN} - V_{BN} = \frac{V_d}{2V_{tm}} V_{cona} = K_{pwm} V_{cona}$$

Dead-time對於各臂輸出電壓的影響



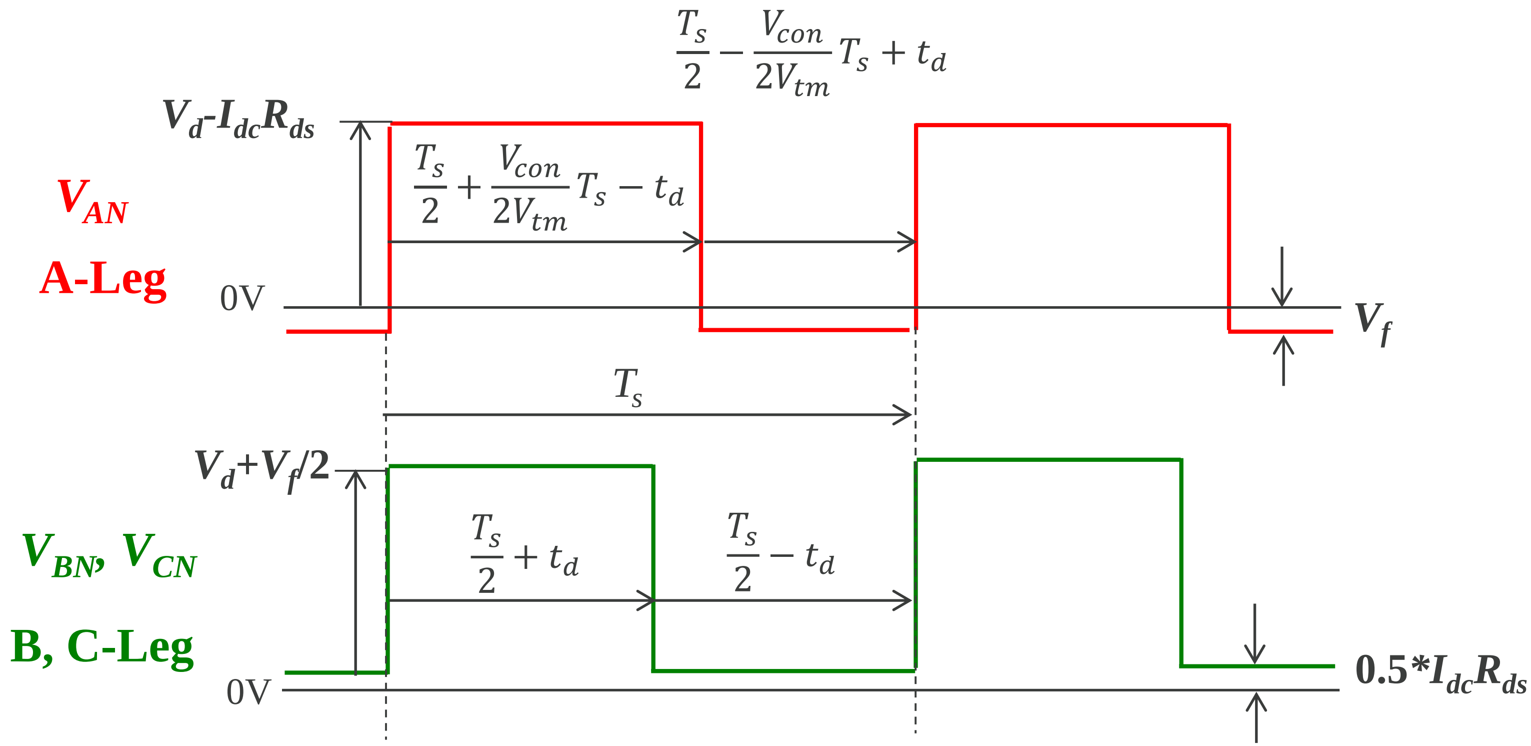
$$\Delta V_{AN} = \begin{cases} +\dfrac{t_\Delta}{T_s} V_d & i_A > 0 \\ -\dfrac{t_\Delta}{T_s} V_d & i_A < 0 \end{cases}$$

$$\Delta V_{BN} = \begin{cases} -\dfrac{t_\Delta}{T_s} V_d & i_A > 0 \\ +\dfrac{t_\Delta}{T_s} V_d & i_A < 0 \end{cases}$$



精確計算電阻需考慮事項

由於V_{dc}電壓相當低，欲精確計算電阻需要考慮Inverter的dead-time(t_d)以及開關的導通壓降

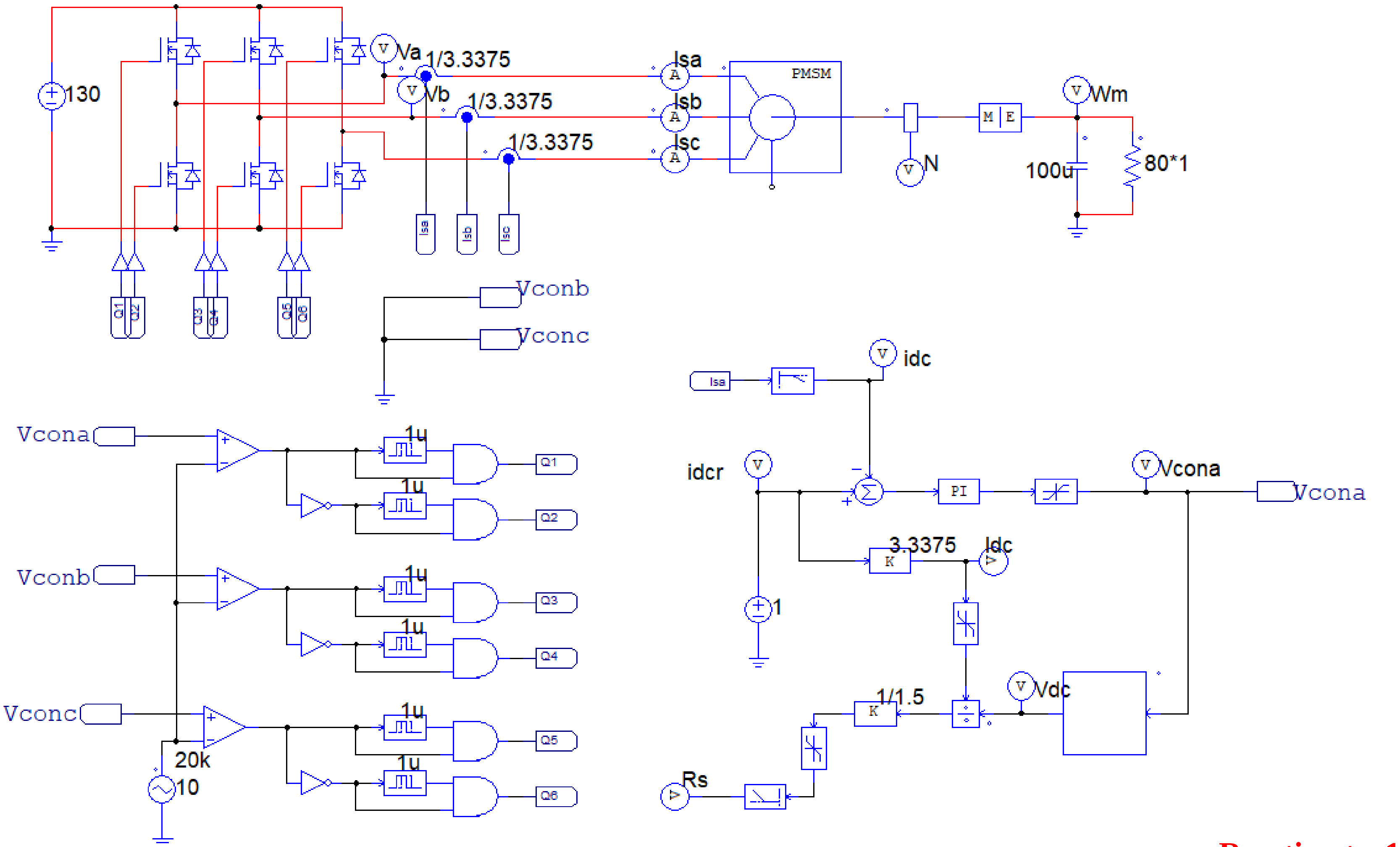


$$V_{AN(avg)} = \left\{ (V_d - I_{dc}R_{ds}) \left(\frac{T_s}{2} + \frac{V_{con}}{2V_{tm}} T_s - t_d \right) - V_f \left(\frac{T_s}{2} - \frac{V_{con}}{2V_{tm}} T_s + t_d \right) \right\} / T_s$$

$$V_{BN(avg)} = \left\{ (V_d + V_f/2) \left(\frac{T_s}{2} + t_d \right) + \frac{I_{dc}R_{ds}}{2} \left(\frac{T_s}{2} - t_d \right) \right\} / T_s$$

$$V_{dc} = V_{AN(avg)} - V_{BN(avg)}$$

Simulation Circuit

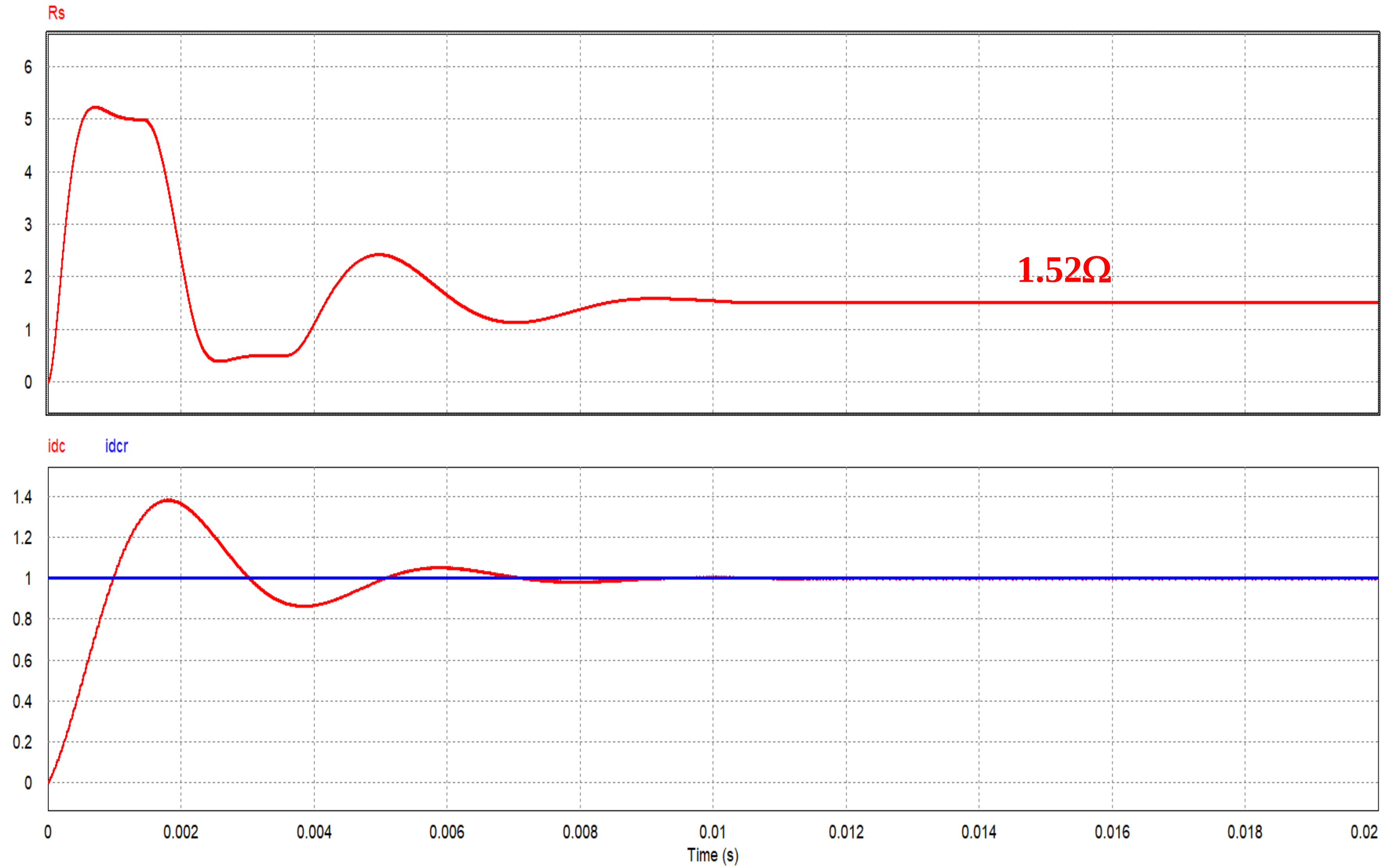


R_estimate_1

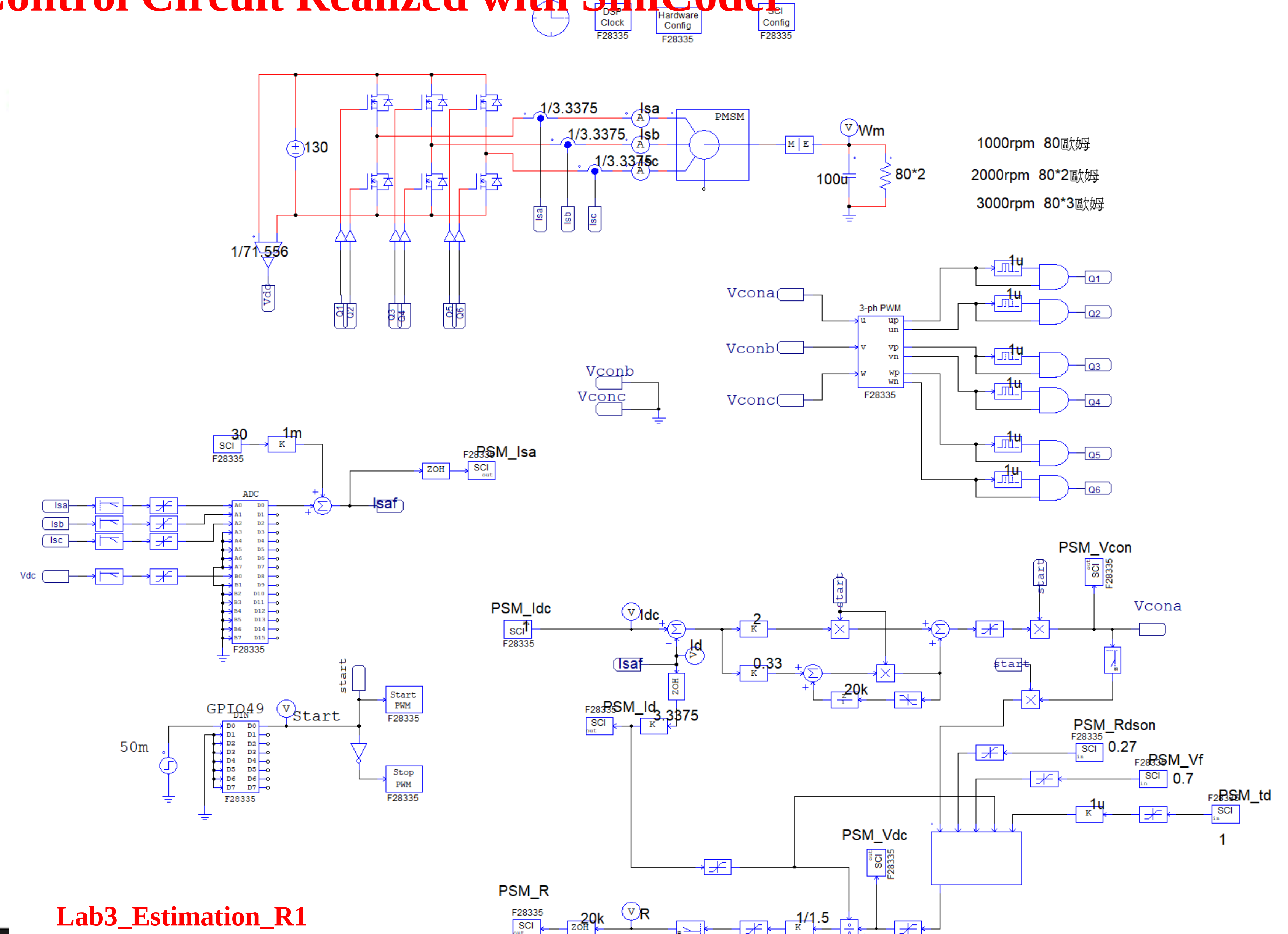
static float Va, Vb, Rds=0.27, Vf=0.7, Vcon, Ts=50e-6, td=1e-6, vtm=5, Vd=130, Idc=3.3375;
Vcon = x1;
Va = (Vd - Rds * Idc) * (Ts/2 + Ts * Vcon/(2*vtm) - td) - (Ts/2 + td - Ts * Vcon/(2*vtm)) * Vf;
Vb = (Vd + Vf/2) * (Ts/2 + td) + Rds/2 * Idc * (Ts/2 - td) ;
y1 = (Va - Vb)/Ts;

Simulation Result

normal



Control Circuit Realized with SimCoder



Lab3_Estimation_R1

normal

normal

L_s與ϕ_f量測原理

利用PMSM在dq軸的模型

$$U_q = RI_q + L_q \frac{d}{dt} I_q + \omega_e (L_d I_d + \varphi_f)$$

利用穩態下微分為零且I_d=0可得：

(1) $\omega_e \varphi_f = U_q - RI_q$ ➡ φ_f

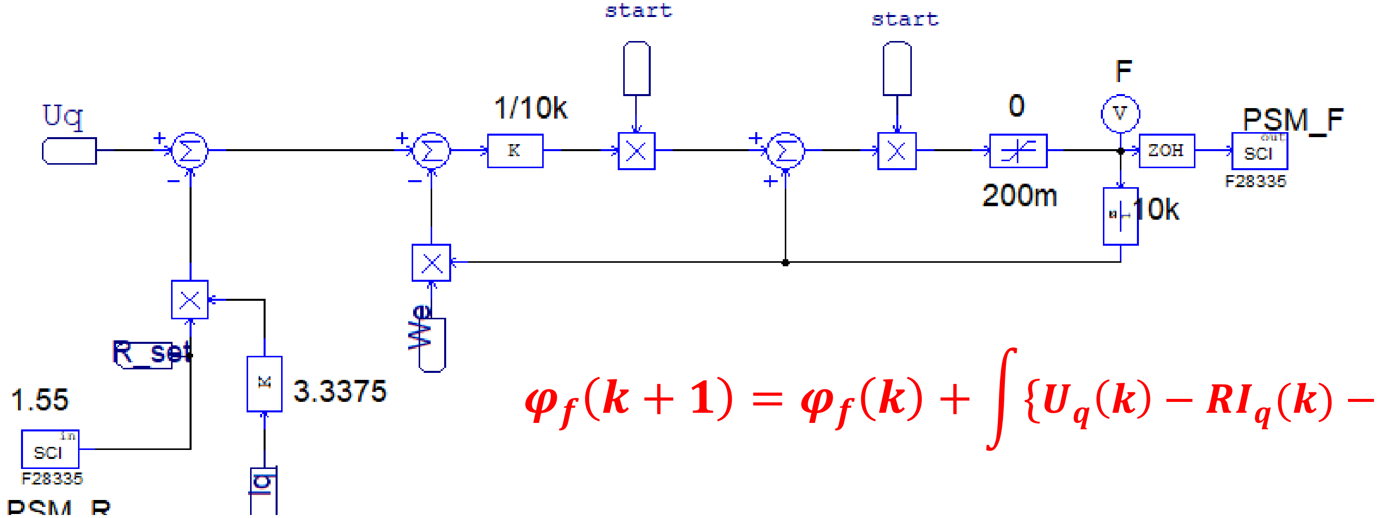
$$U_d = RI_d + L_d \frac{d}{dt} I_d - \omega_e L_q I_q$$

重新整理可得

(2) $L_d \frac{d}{dt} I_d = U_d - RI_d + \omega_e L_q I_q$ ➡ L_d

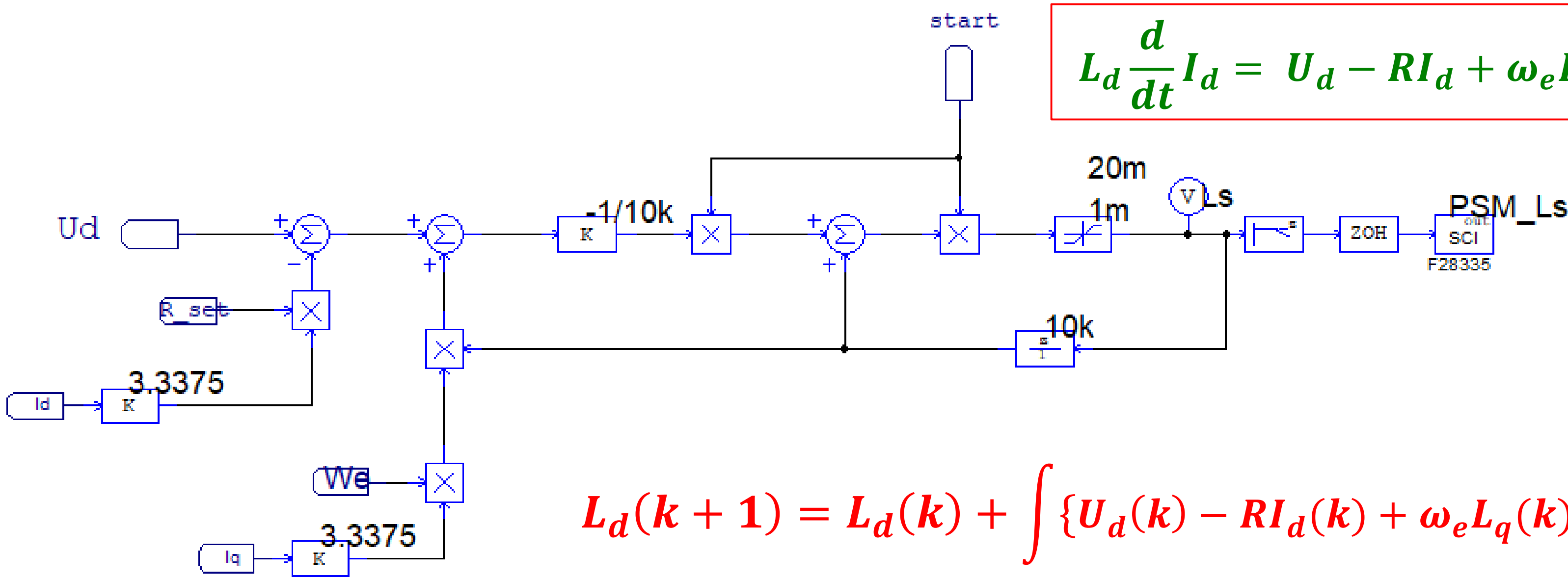
● L_s與ϕ_f量測之實現方法

$$\omega_e \varphi_f = U_q - RI_q$$



$$\varphi_f(k+1) = \varphi_f(k) + \int \{U_q(k) - RI_q(k) - \omega_e \varphi_f(k)\}$$

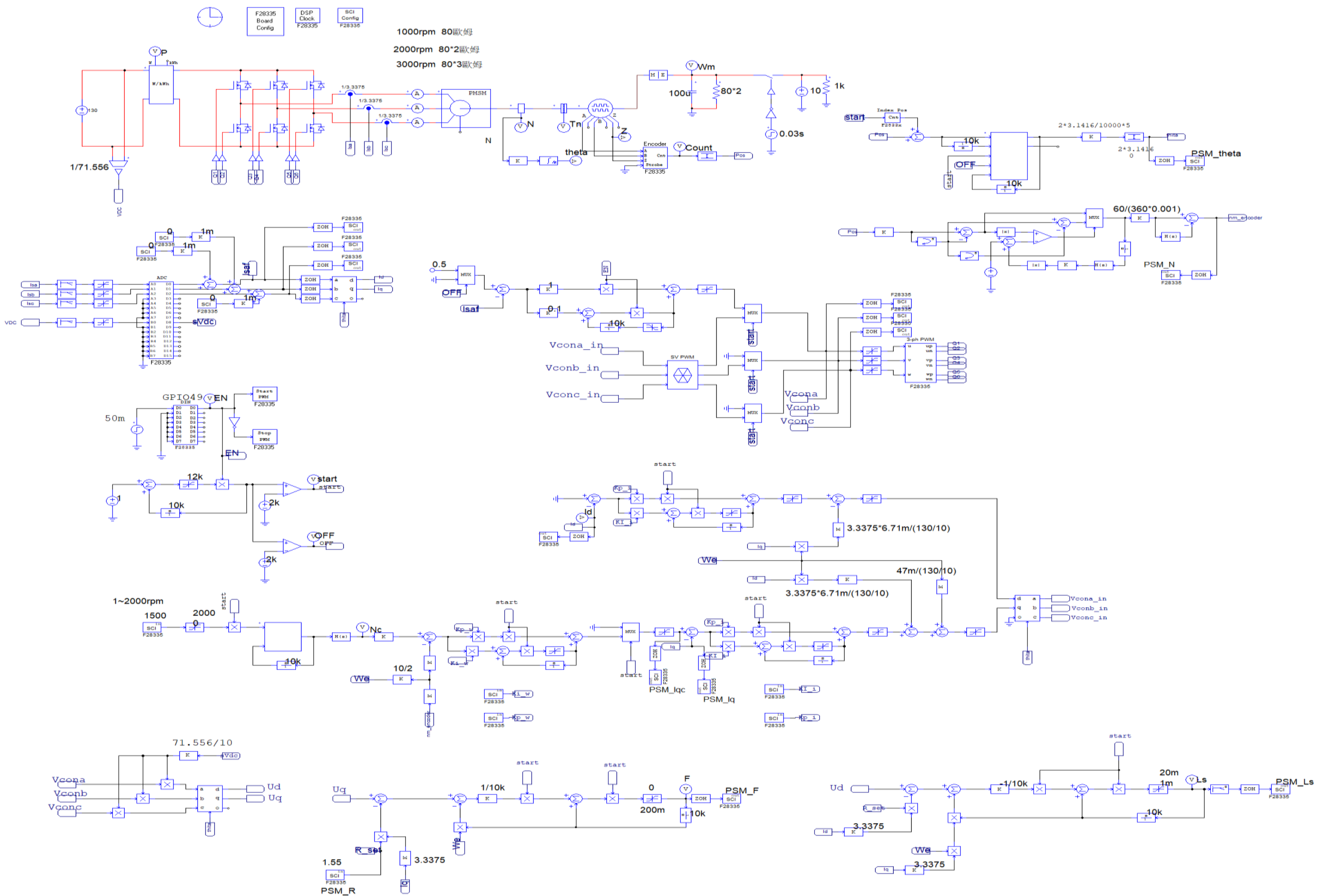
$$L_d \frac{d}{dt} I_d = U_d - RI_d + \omega_e L_q I_q$$



$$L_d(k+1) = L_d(k) + \int \{U_d(k) - RI_d(k) + \omega_e L_q(k) I_q(k)\}$$

Control Circuit Realized with SimCoder

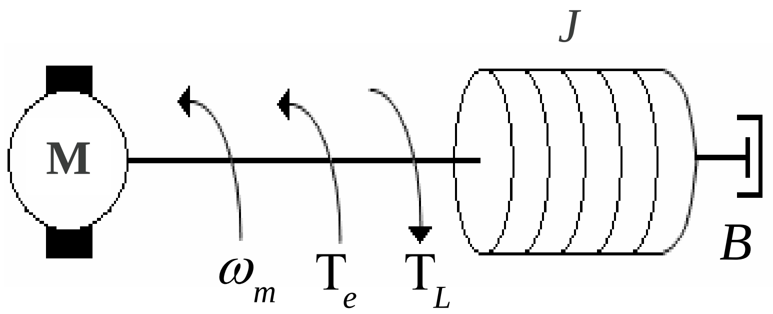
normal



Lab3_Estimation_LF1

● 馬達機械參數線上估測

機械方程式
$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - B\omega_m - T_L)$$



在無載下
$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - B\omega_m)$$

估測模型
$$\frac{d\widetilde{\omega_m}}{dt} = \frac{1}{\tilde{J}}(T_e - \tilde{B}\widetilde{\omega_m})$$

估測誤差
$$e = \omega_m - \widetilde{\omega_m}$$

估測誤差方程式
$$\frac{de}{dt} = ae + bT_e + c\widetilde{\omega_m}$$

$$a = -\frac{B}{J} \qquad b = \frac{1}{J} - \frac{1}{\tilde{J}} \qquad c = \frac{\tilde{B}}{\tilde{J}} - \frac{B}{J}$$

$$\tilde{J} = \frac{1}{\frac{1}{J_0} + \int eT_e edt} \qquad \tilde{B} = \tilde{J}\left(\frac{B_0}{J_0} - \int e\widetilde{\omega_m}dt\right)$$

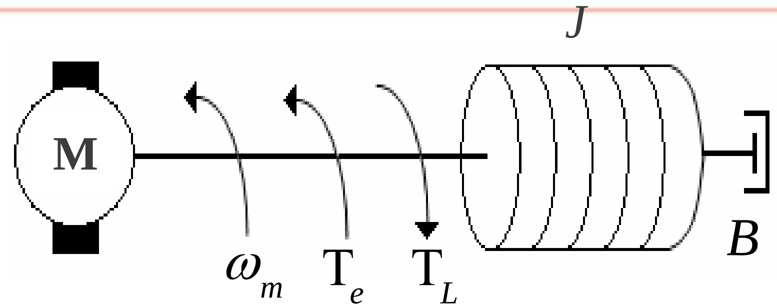
J_0及B_0為前一次估計值

normal

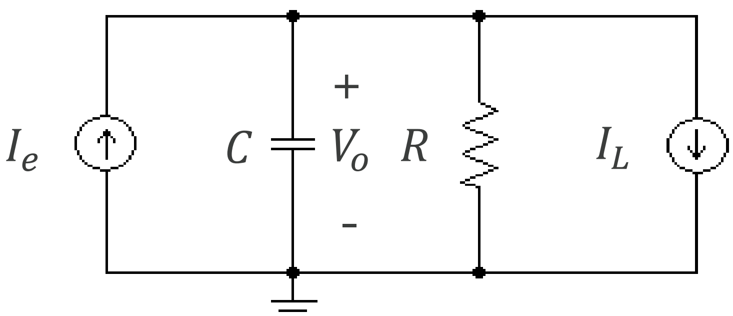
● 馬達機械參數線上估測的實現方法

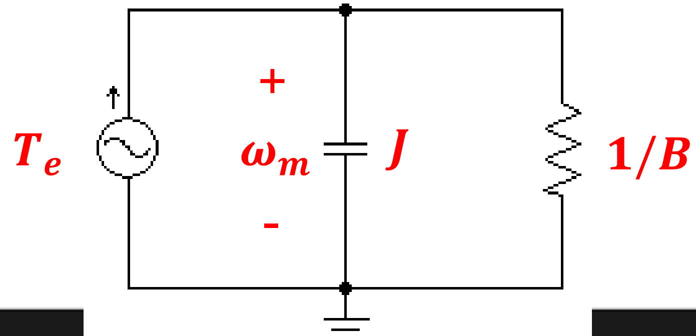
電與機械具有對耦關係

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L$$



$$I_e = C\frac{dV_o}{dt} + \frac{1}{R}V_o + I_L$$





在空載下利用交流轉矩執行以下估測

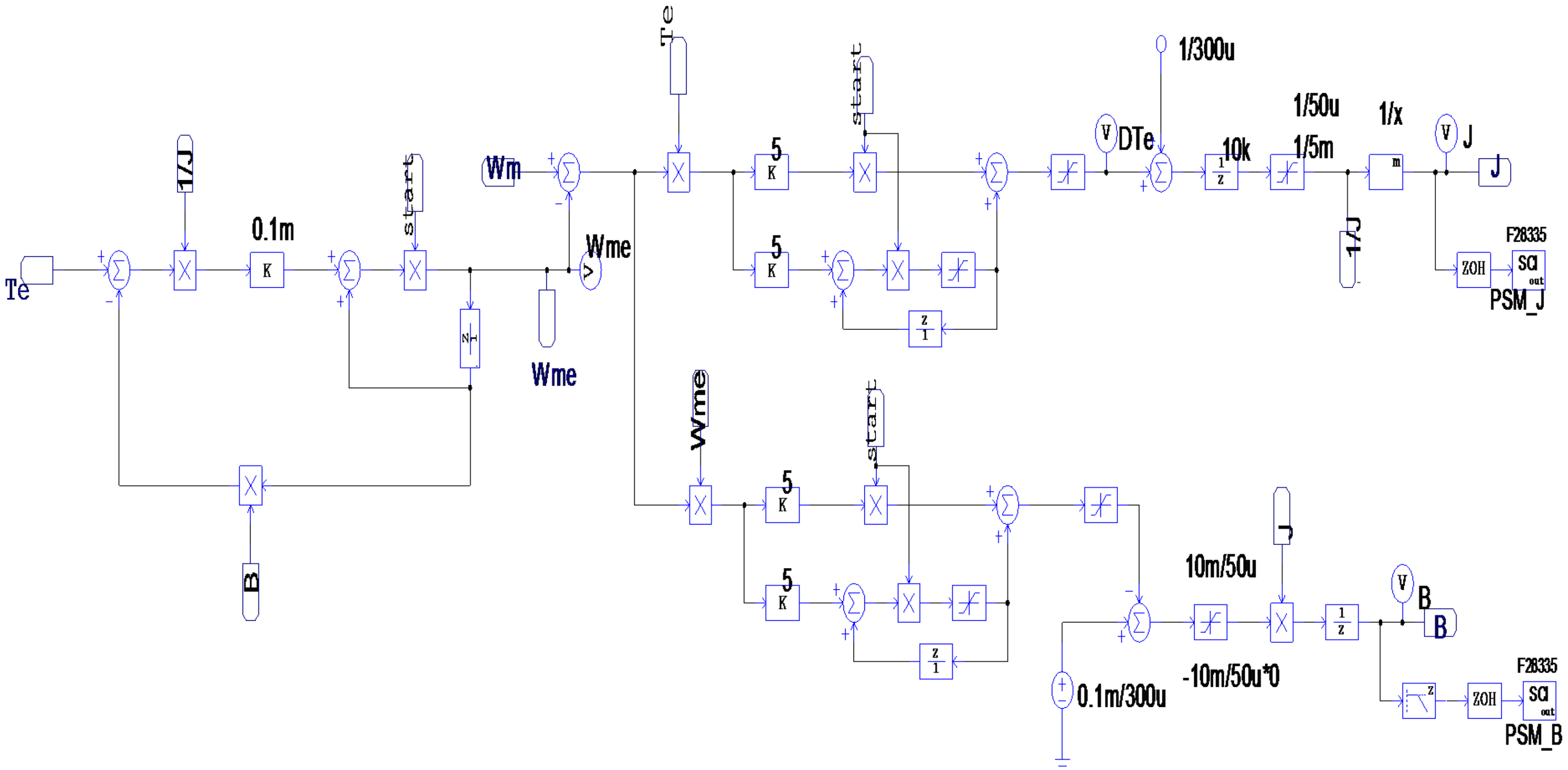
$$\tilde{J} = \frac{1}{\frac{1}{J_0} + \int eT_e e dt}$$

$$\tilde{B} = \tilde{J}\left(\frac{B_0}{J_0} - \int e\widetilde{\omega_m} dt\right)$$

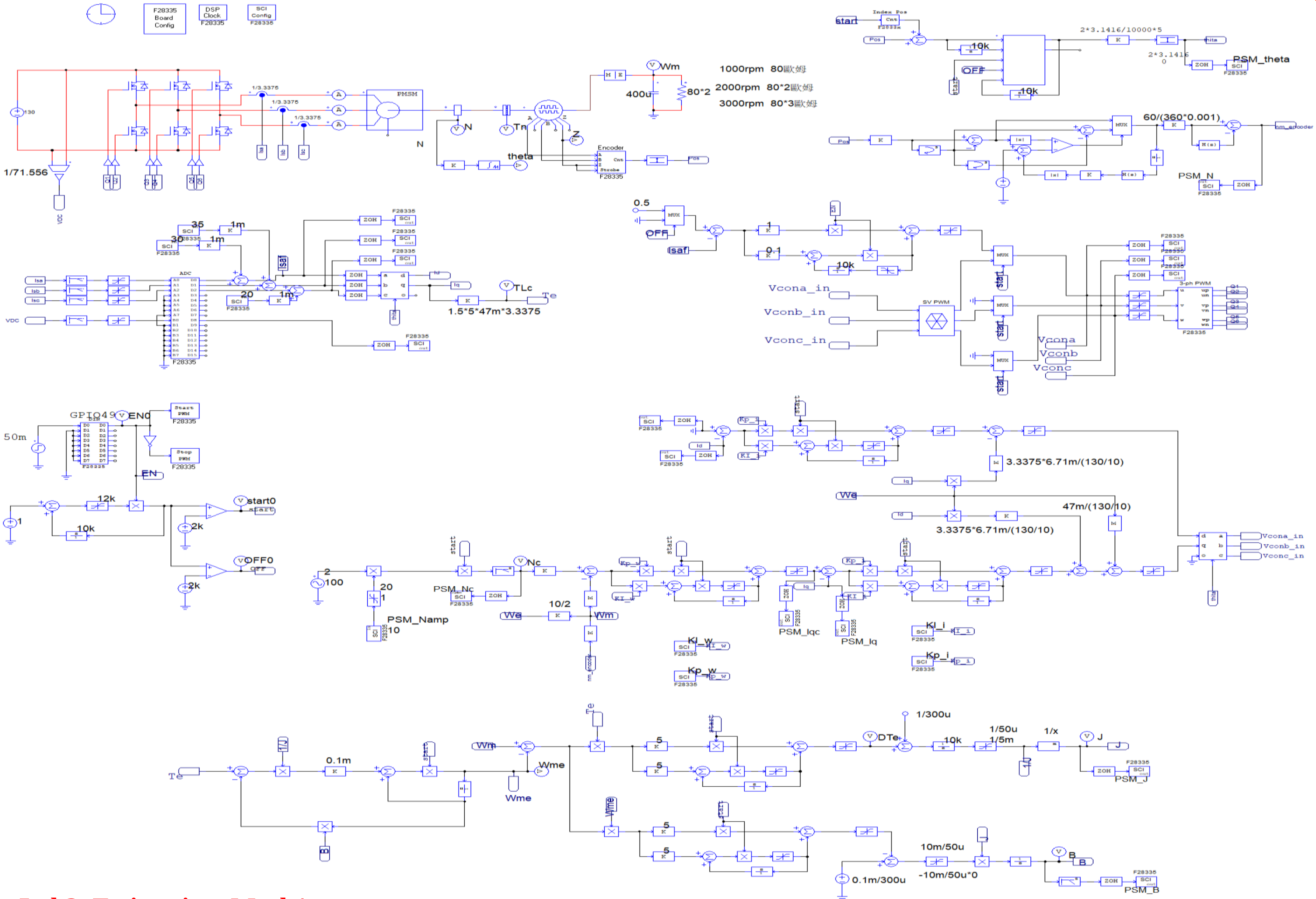
實現方法

$$\tilde{J} = \frac{1}{\frac{1}{J_0} + \int eT_e e dt}$$

$$\tilde{B} = \tilde{J}\left(\frac{B_0}{J_0} - \int e\widetilde{\omega_m} dt\right)$$



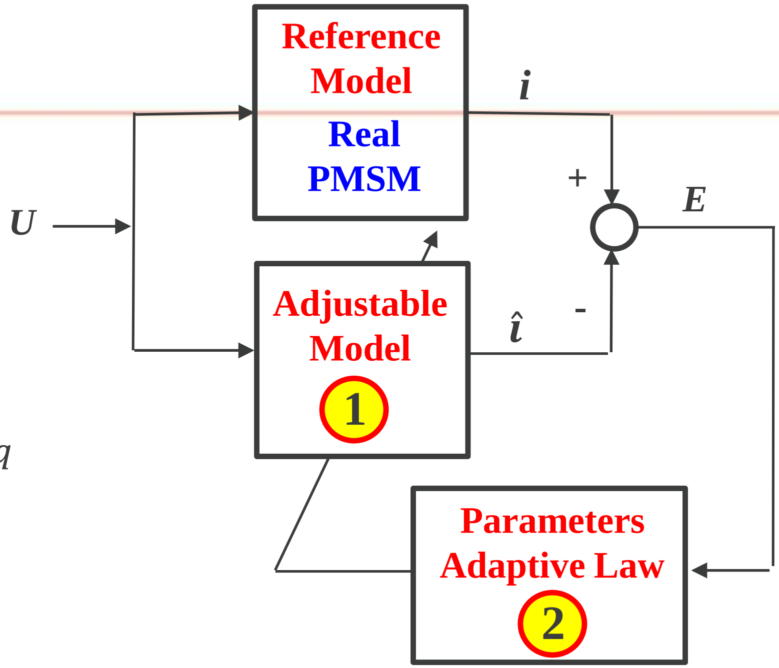
Control Circuit Realized with SimCoder



Lab3_Estimation_Mech1

馬達參數線上估測

normal



1

$$\frac{d}{dt}I_d = -\frac{R}{L_s}I_d + \omega_e I_q + \frac{1}{L_s}U_d$$

$$\frac{d}{dt}I_q = -\frac{R}{L_s}I_q - \omega_e I_d - \frac{\varphi_f}{L_s}\omega_e + \frac{1}{L_s}U_q$$

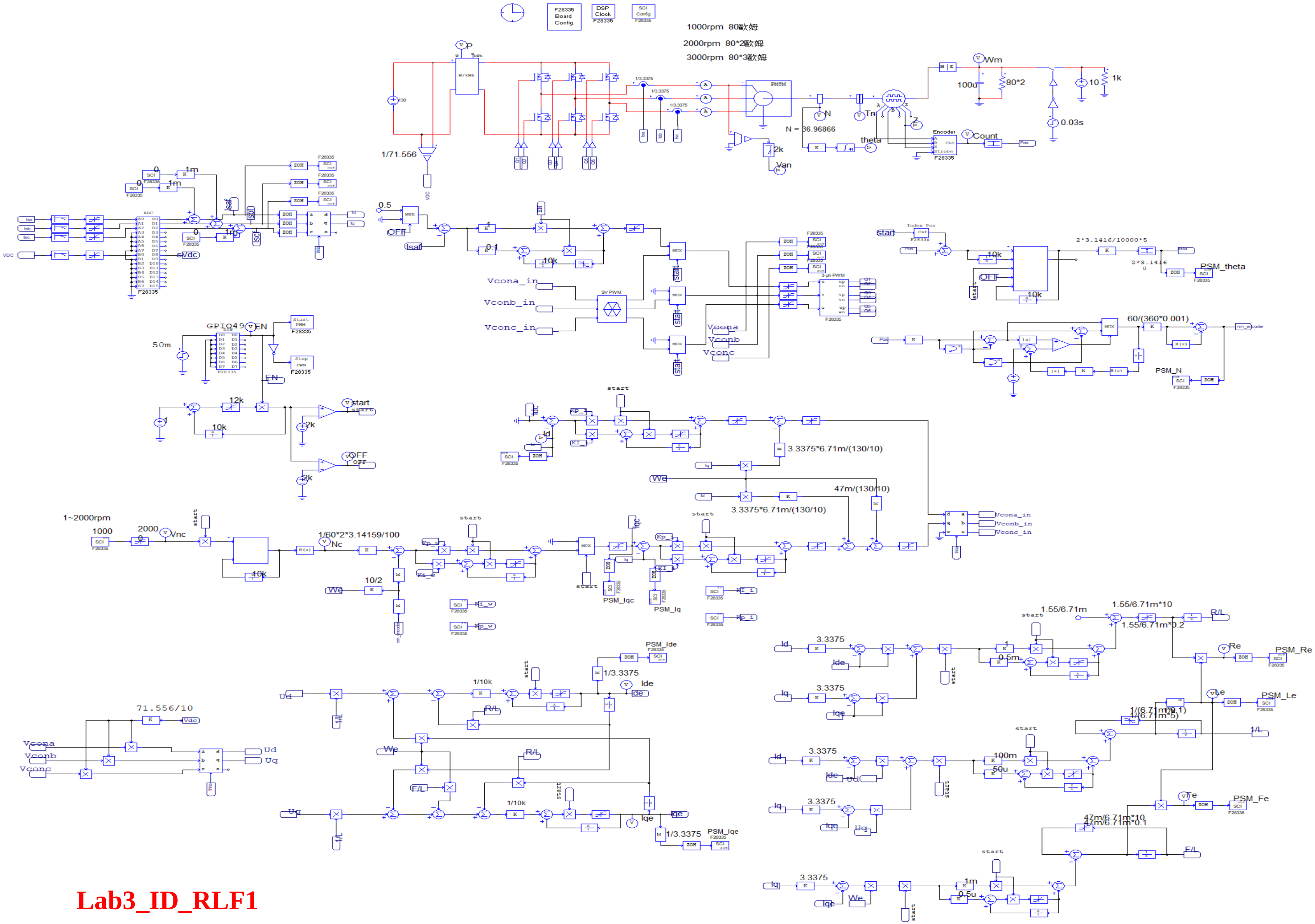
2

$$\frac{\widehat{R_s}}{\widehat{L_s}} = \frac{R_s}{L_s} - K_i\int_0^t\left((I_d-\widehat{I_d})\widehat{I_d} + (I_q-\widehat{I_q})\widehat{I_q}\right)d\tau - K_p((I_d-\widehat{I_d})\widehat{I_d} + (I_q-\widehat{I_q}))$$

$$\frac{1}{\widehat{L_s}} = \frac{1}{L_s} + K_i\int_0^t\left(U_d(I_d-\widehat{I_d}) + U_q(I_q-\widehat{I_q})\right)d\tau + K_p((I_d-\widehat{I_d})\widehat{I_d} + (I_q-\widehat{I_q}))$$

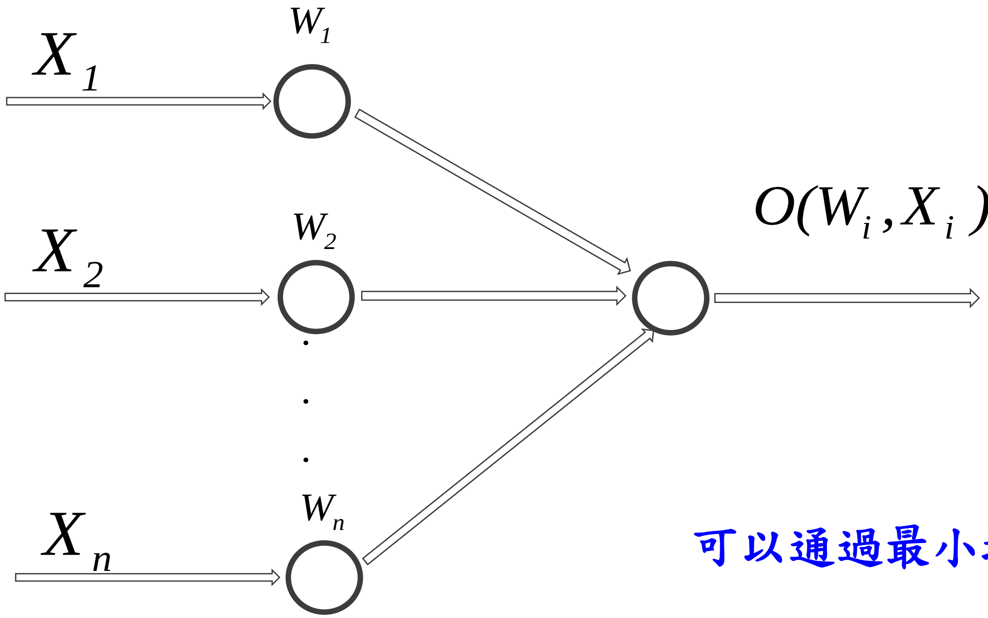
$$\frac{\widehat{\varphi_f}}{\widehat{L_s}} = \frac{\varphi_f}{L_s} - K_i\int_0^t \omega_e(I_q-\widehat{I_q})d\tau - K_p\omega_e(I_q-\widehat{I_q})$$

Control Circuit Realized with SimCoder



Lab3_ID_RLF1

採用自適應類神經之參數量測方法



$$O(W_i, X_i) = \sum_{i=0}^{n} W_i X_i$$

可以通過最小均方根來調整權重:

$$W_i(k+1) = W_i(k) + 2\eta X_i(d(k) - O)$$

其中η為收斂速度因子

考慮Dead-time之非線性PMSM模型

$$u_d^* = Ri_d - L_q \omega i_q + L_d \frac{di_d}{dt} - D_d V_{dead}$$

$$u_q^* = Ri_q + L_d \omega i_d + \psi_m \omega + L_q \frac{di_q}{dt} - D_d V_{dead}$$

其中 $$V_{dead} = \frac{1}{6}\left(\frac{T_{off} - T_{on} - T_d}{T_s} V_{dc} - V_{ce0} - V_{d0}\right)$$

Ton/Toff:開關上升與下降時間
Td:死區時間
Vce0:IGBT導通壓降
Vd0:二極體導通壓降

$$\begin{bmatrix} D_d \\ D_q \end{bmatrix} = 2 \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} sign(i_{as}) \\ sign(i_{bs}) \\ sign(i_{cs}) \end{bmatrix}$$

定子電阻Rs量測

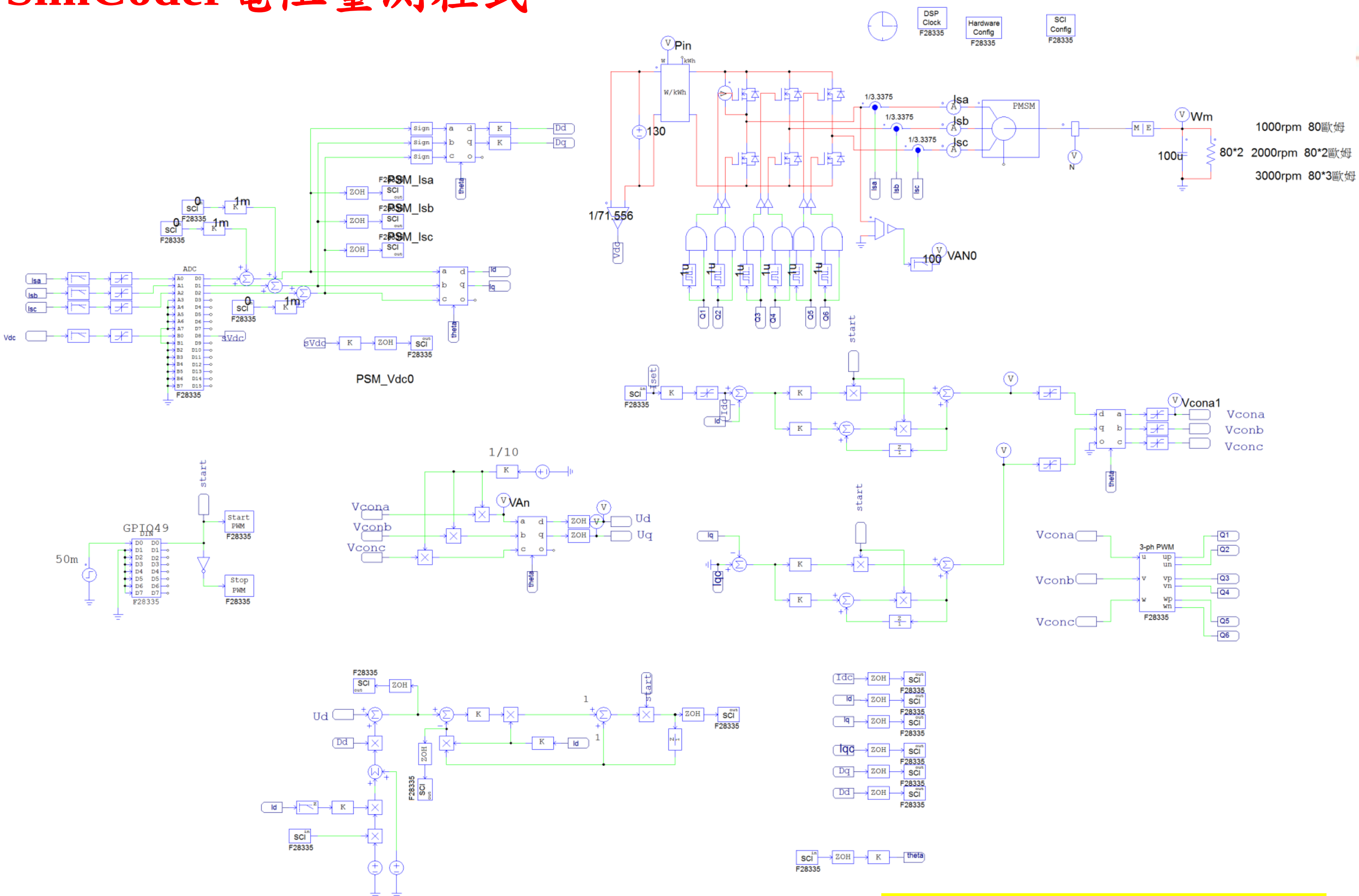
將iq=0穩定狀態下，將式子改寫成:

$$u^*{}_d(k) = Ri_d(k) - D_d(k)V_{dead}$$

利用自適應神經元方法，可以利用下式求得定子電阻R_s:

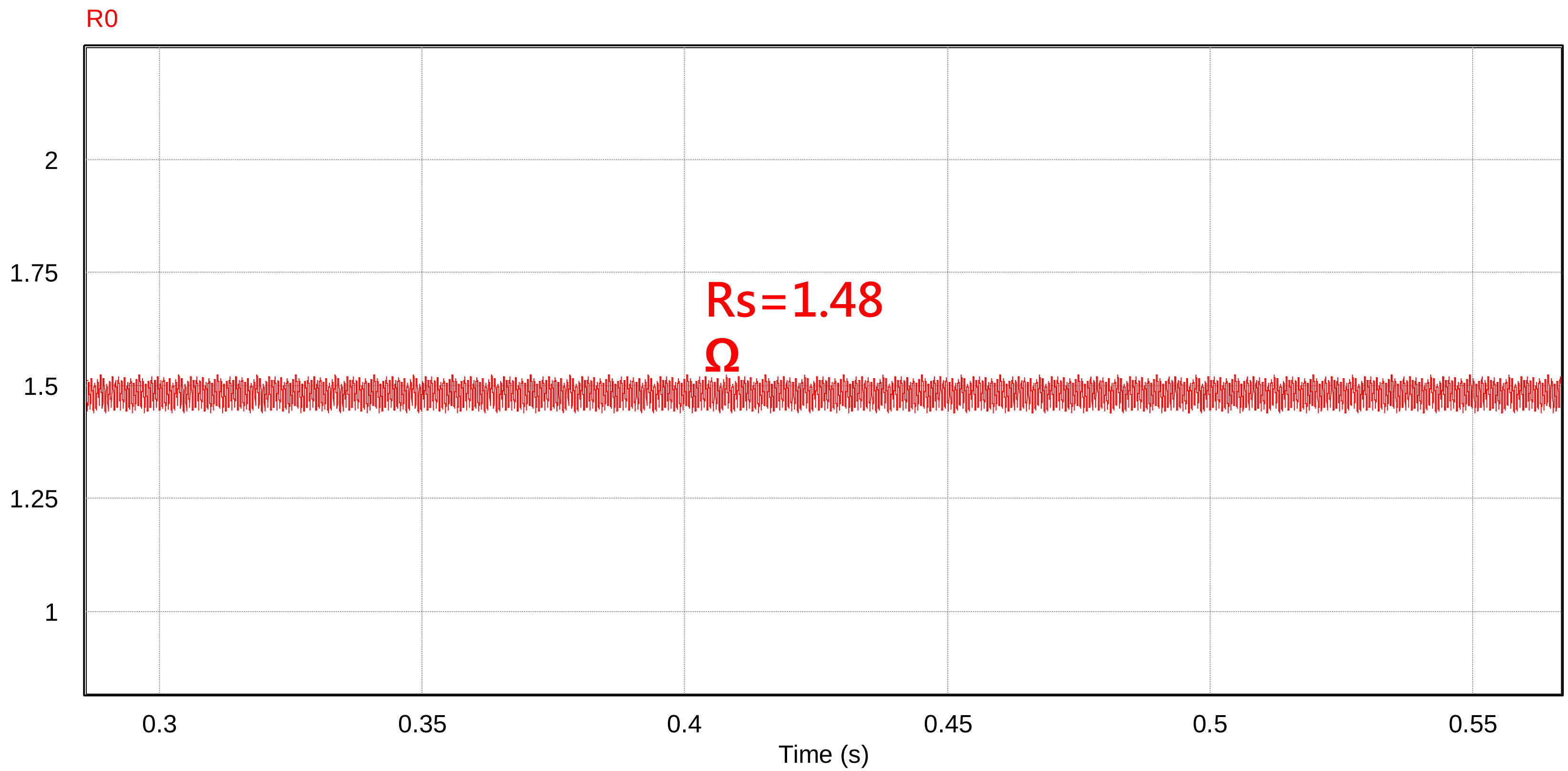
$$\hat{R}(k+1) = \hat{R}(k) + 2\eta i_d(k)(u^*{}_d(k) + D_d(k)\hat{V}_{dead}(k) - \hat{R}(k)i_d(k))$$

SimCoder電阻量測程式



PEK-190_Estimation_R2

仿真結果(電阻量測)



normal

電感Ld及Lq量測

將i_q及i_d注入高頻電流，因為機械系統的時間常數較大，在高頻電流下不會轉動，將式子改寫如下:

$$u_d^* = Ri_d + L_d \frac{d_i}{dt} - D_d V_{dead}$$

$$u_q^* = Ri_q + L_q \frac{di_q}{dt} - D_q V_{dead}$$

利用自適應神經元方法，可以利用下式求得電感L_d及L_q:

$$\hat{L}_d(k+1) = \hat{L}_d(k) + 2\eta \frac{i_d(k) - i_d(k-1)}{T_s}(u_d^*(k))$$

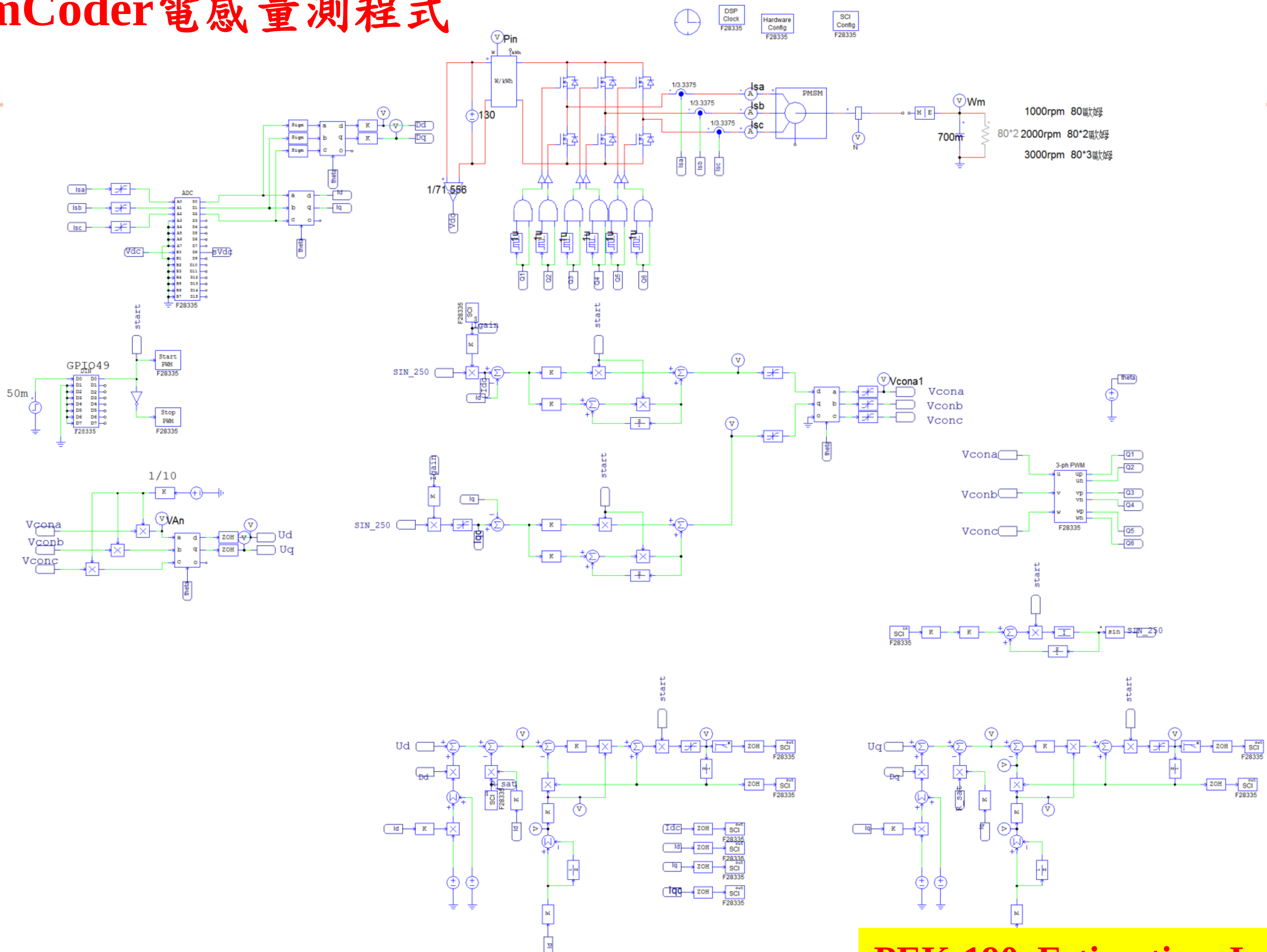
$$+ D_d(k)\hat{V}_{dead} - \hat{R}i_d(k) - \frac{i_d(k) - i_d(k-1)}{T_s}\hat{L}_d(k))$$

$$\hat{L}_q(k+1) = \hat{L}_q(k) + 2\eta \frac{i_q(k) - i_q(k-1)}{T_s}(u_q^*(k))$$

$$+ D_q(k)\hat{V}_{dead} - \hat{R}i_q(k) - \frac{i_q(k) - i_q(k-1)}{T_s}\hat{L}_q(k))$$

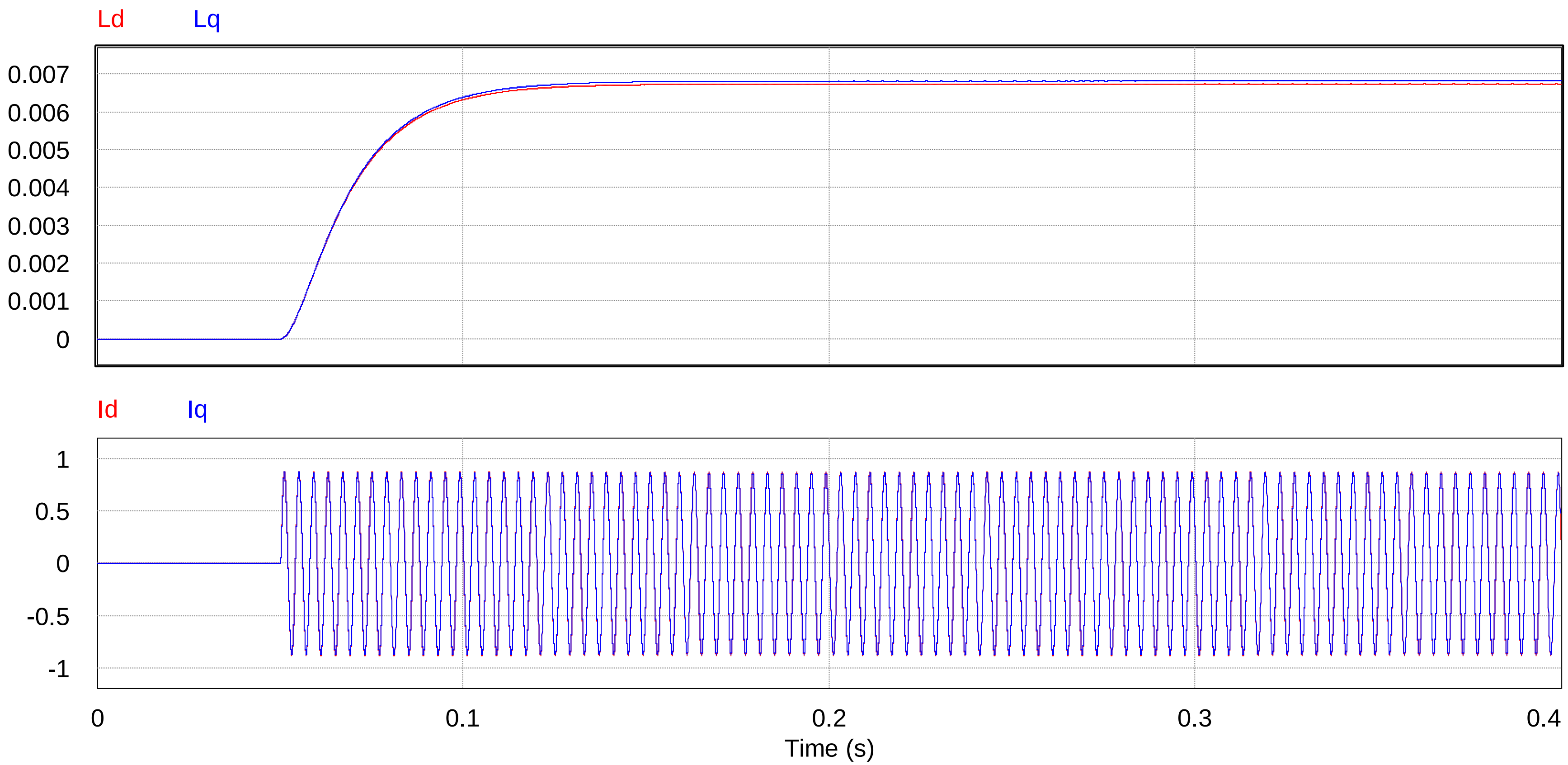
SimCoder電感量測程式

normal



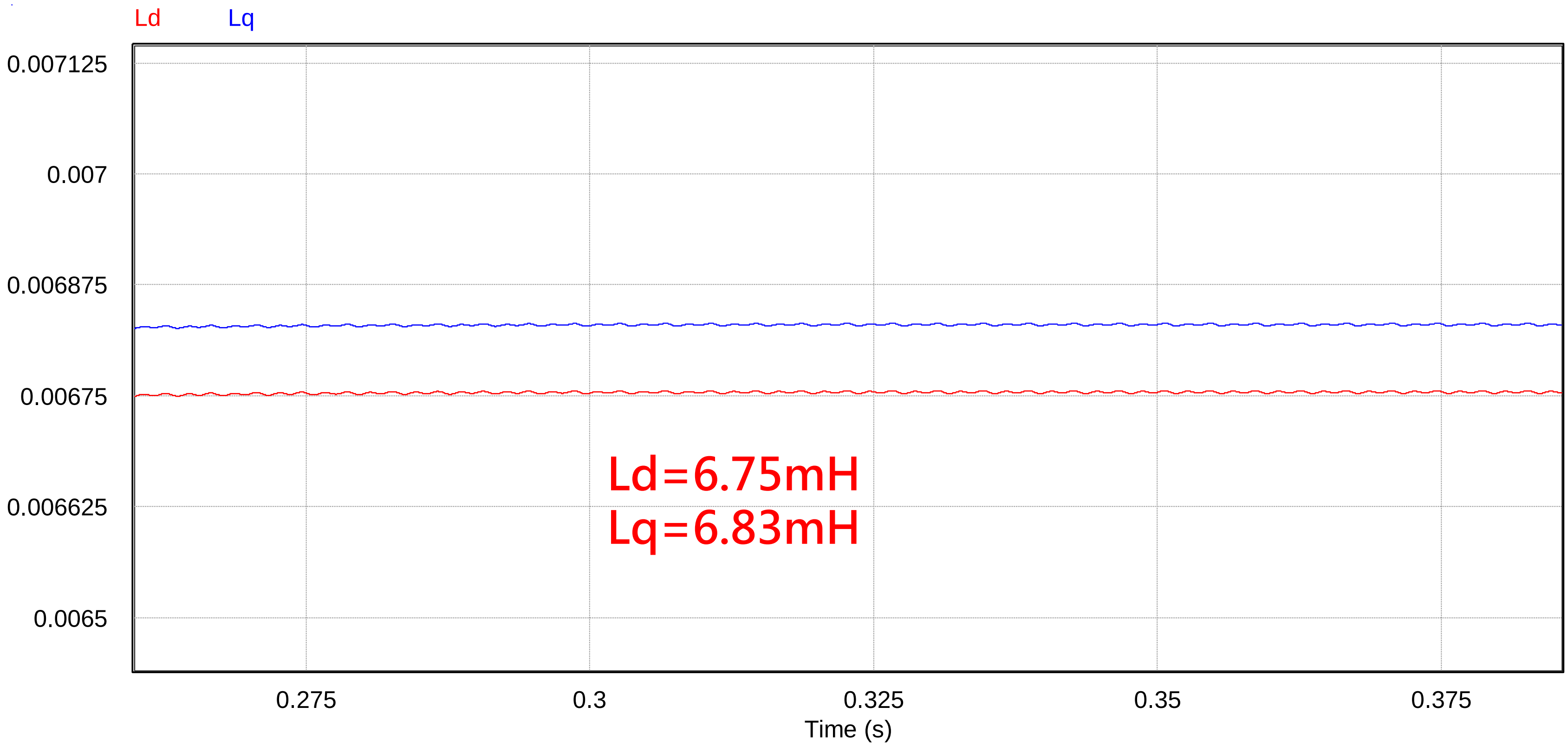
PEK-190_Estimation_L

仿真結果



Ld
Lq
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Id
Iq
1
0.5
0
-0.5
-1
0
0.1
0.2
0.3
0.4
Time (s)

仿真結果(電感量測)



normal

反電勢Ψm量測

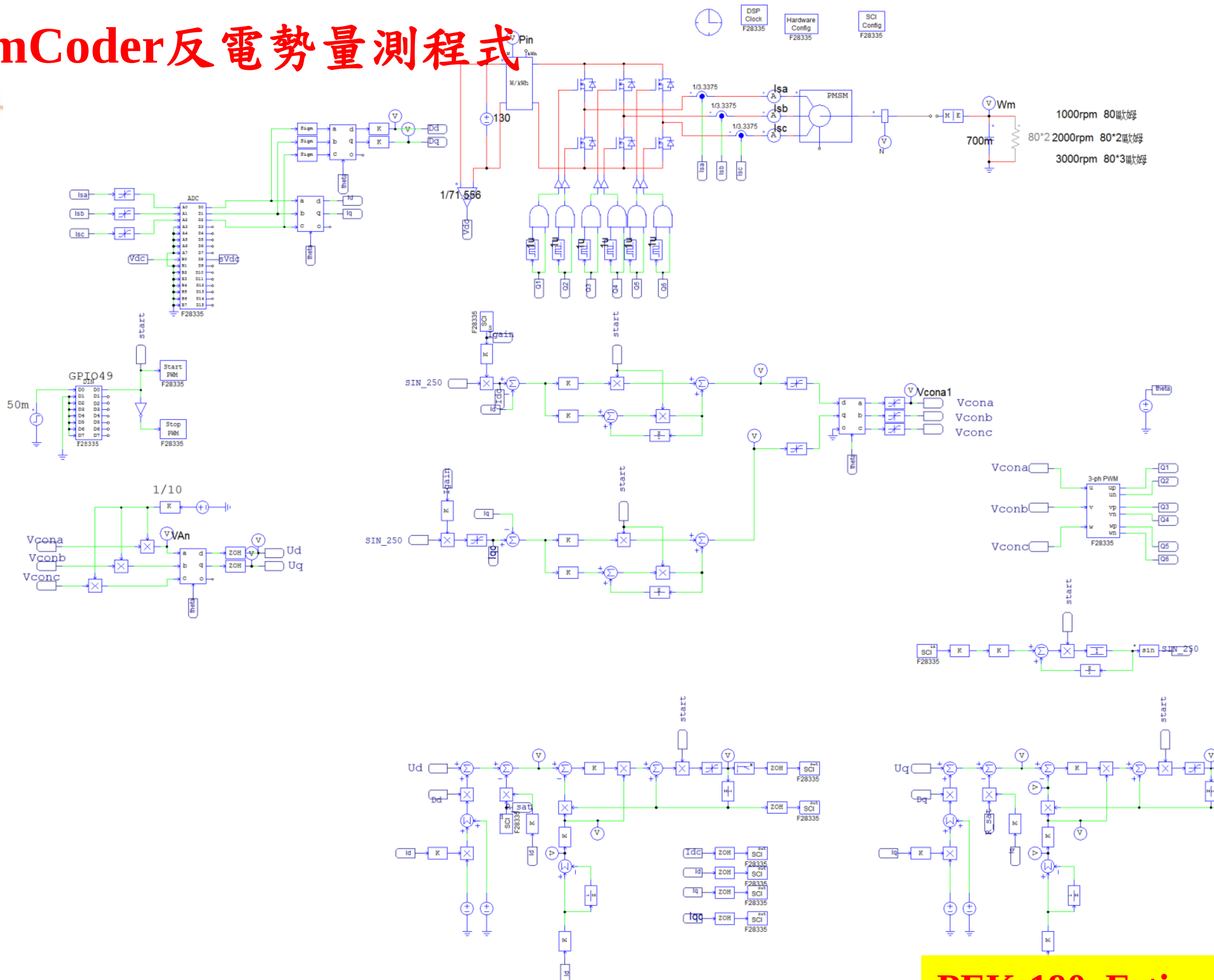
在馬達運轉穩定無載情況下(i_d=0)，將式子改寫成:

$$u_q^*(k) + D_q(k)V_{dead} = Ri_q(k) + \psi_m\omega(k)$$

利用自適應神經元方法，可以利用下式求得反電勢Ψm :

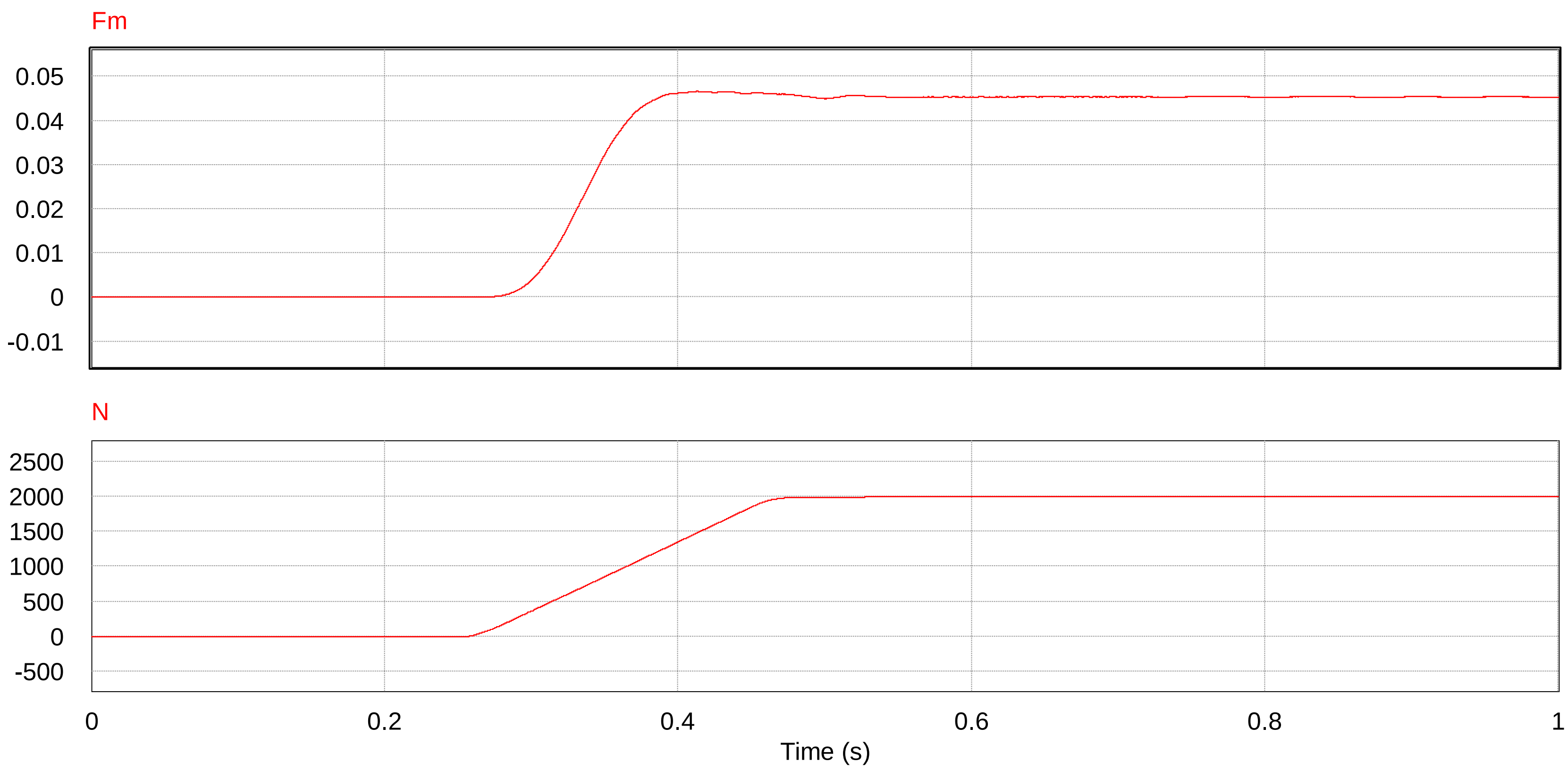
$$\hat{\psi}_m(k+1) = \hat{\psi}_m(k) + 2\eta\omega(k)(u_q^*(k) + D_q(k)\hat{V}_{dead}(k) - \hat{R}i_q(k) - \hat{\psi}_m(k)\omega(k))$$

SimCoder反電勢量測程式

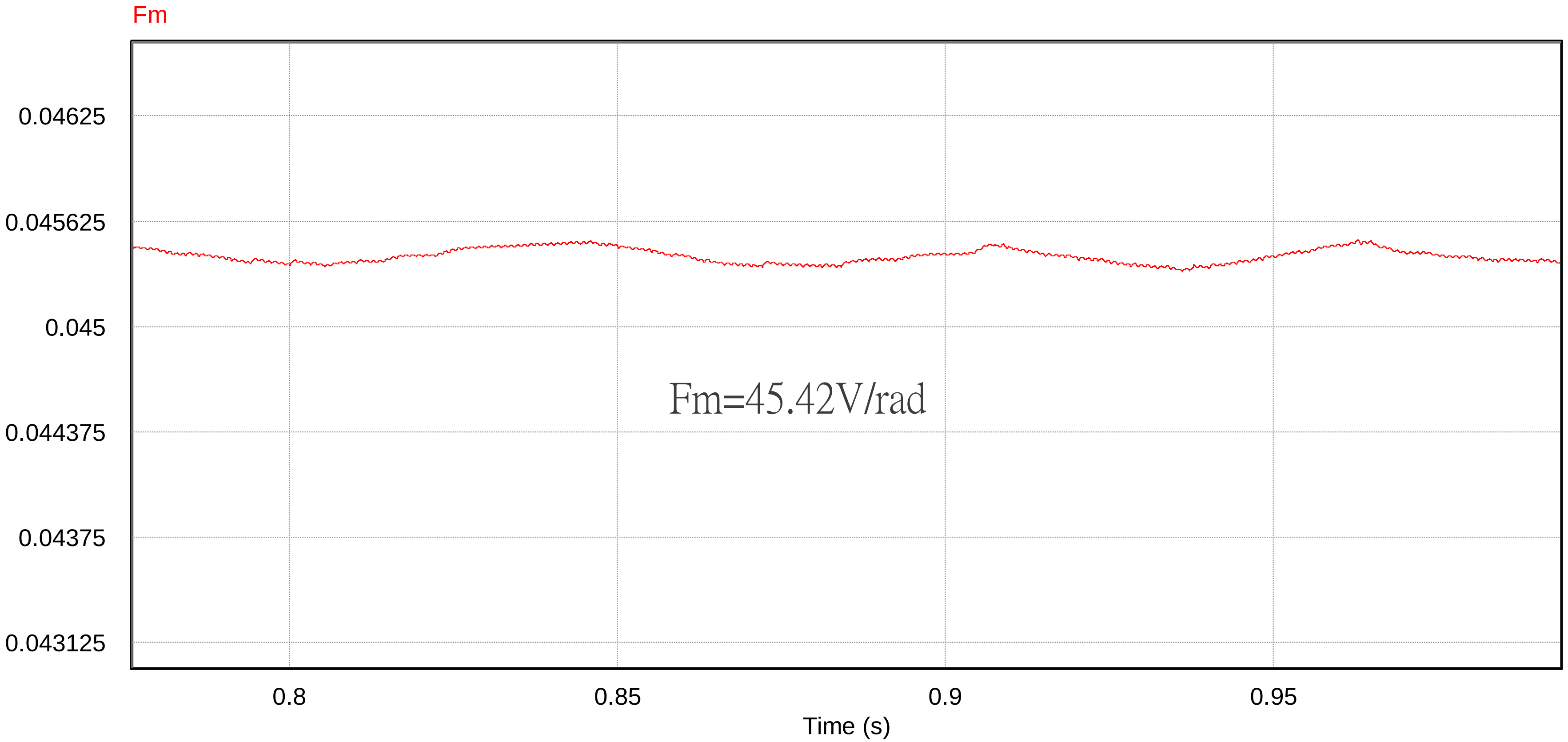


PEK-190_Estimation_F

仿真結果

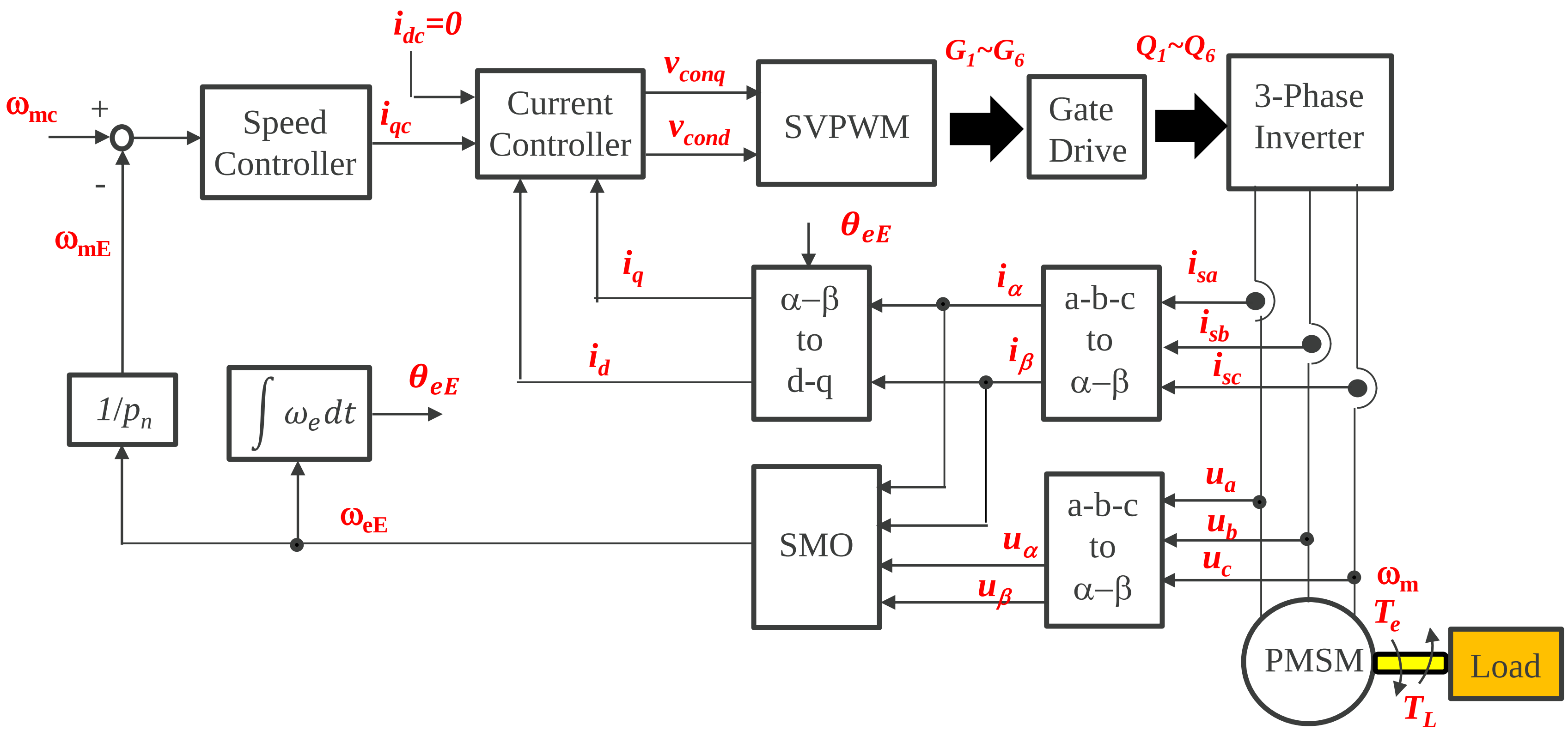

Fm
0.05
0.04
0.03
0.02
0.01
0
-0.01
N
2500
2000
1500
1000
500
0
-500
0
0.2
0.4
0.6
0.8
1
Time (s)

仿真結果(反電勢)



Fm
0.04625
0.045625
0.045
0.044375
0.04375
0.043125
Fm=45.42V/rad
0.8
0.85
0.9
0.95
Time (s)

Lab 4: 無位置傳感器之速度控制(滑模觀測器法) (Sliding Mode Observer, SMO)



SMO Fundamental

Consider the system of the form:

$$\dot{x} = Ax + Bu + f(x,t) + d(t)$$

$f(x,t)$ and $d(t)$ represent the nonlinear uncertainty and external disturbance

- **Switching Surface**

Define a surface function $\sigma(x) = Hx$

The equation $\sigma(x)=0$ defines a linear surface (hyperplane), which is called the switching surface S.

- **Equivalent Control**

Consider the unperturbed system

$$\dot{x} = Ax + Bu$$

$$u_{eq} = -(HB)^{-1} HAx$$

The equivalent control, which is found from the constrains $\sigma(x)=0$ and $\dot{\sigma}(x)=0$.

- **Sliding Dynamics**

$$\dot{x} = [A - B(HB)^{-1} HA]x$$

$$\equiv A_c x$$

Reaching Control

In case the system states do not locate on the switching surface due to parameter variation and disturbance, an additional control called reaching control should be augmented on the control input to force the system states to reach the switching surface

$$u = u_{eq} + u_R$$

The condition to guarantee the hitting of trajectory of the system upon the switching surface from arbitrary initial state is

$$\sigma\dot{\sigma} < 0$$

$$\Rightarrow \quad u_R = -(HB)^{-1} k(x,t) sign(\sigma)$$

$$k(x,t) > \left| Hf(x,t) + Hd(t) \right|_{\max}$$

Sliding Mode Observer (SMO)

PMSM Model in α–β

$$\begin{bmatrix}U_\alpha\\U_\beta\end{bmatrix}=\begin{bmatrix}R+pL_s & 0\\0 & R+pL_s\end{bmatrix}\begin{bmatrix}I_\alpha\\I_\beta\end{bmatrix}+\begin{bmatrix}E_\alpha\\E_\beta\end{bmatrix}\qquad \begin{bmatrix}E_\alpha\\E_\beta\end{bmatrix}=\omega_e\varphi_f\begin{bmatrix}-\sin\theta_e\\ \cos\theta_e\end{bmatrix}$$

$$\frac{d}{dt}\begin{bmatrix}I_\alpha\\I_\beta\end{bmatrix}=A\begin{bmatrix}I_\alpha\\I_\beta\end{bmatrix}+\frac{1}{L_s}\begin{bmatrix}U_\alpha\\U_\beta\end{bmatrix}-\frac{1}{L_s}\begin{bmatrix}E_\alpha\\E_\beta\end{bmatrix}\qquad A=\frac{1}{L_s}\begin{bmatrix}-R & 0\\0 & -R\end{bmatrix}$$

$$U_s=\begin{bmatrix}U_\alpha\\U_\beta\end{bmatrix}\qquad I_s=\begin{bmatrix}I_\alpha\\I_\beta\end{bmatrix}\qquad E_s=\begin{bmatrix}E_\alpha\\E_\beta\end{bmatrix}$$

Sliding surface function

$$\sigma=\tilde{I_s}=\hat{I_s}-I_s=\begin{bmatrix}\tilde{I_\alpha}\\\tilde{I_\beta}\end{bmatrix}$$

Observer

$$\frac{d}{dt}\begin{bmatrix}\hat{I_\alpha}\\\hat{I_\beta}\end{bmatrix}=A\begin{bmatrix}\hat{I_\alpha}\\\hat{I_\beta}\end{bmatrix}+\frac{1}{L_s}\begin{bmatrix}U_\alpha\\U_\beta\end{bmatrix}-\frac{1}{L_s}\begin{bmatrix}V_\alpha\\V_\beta\end{bmatrix}$$

Error equation

$$\frac{d}{dt}\begin{bmatrix}\tilde{I_\alpha}\\\tilde{I_\beta}\end{bmatrix}=A\begin{bmatrix}\tilde{I_\alpha}\\\tilde{I_\beta}\end{bmatrix}-\frac{1}{L_s}\begin{bmatrix}E_\alpha-V_\alpha\\E_\beta-V_\beta\end{bmatrix}$$

$$\begin{bmatrix}V_\alpha\\V_\beta\end{bmatrix}=\begin{bmatrix}Ksign(\hat{I_\alpha}-I_\alpha)\\Ksign(\hat{I_\beta}-I_\beta)\end{bmatrix}\qquad K>max\{-R|\tilde{I_\alpha}|+E_\alpha sign(\hat{I_\alpha}),R|\tilde{I_\beta}|+E_\beta sign(\hat{\beta})\}$$

As enter into and stay on the sliding surface, it will be $\sigma=\dot{\sigma}=0$

$$\frac{d}{dt}\tilde{I_s}=\tilde{I_s}=0\qquad \begin{bmatrix}E_\alpha\\E_\beta\end{bmatrix}=\begin{bmatrix}V_\alpha\\V_\beta\end{bmatrix}_{eq}=\begin{bmatrix}Ksign(\tilde{I_\alpha})_{eq}\\Ksign(\tilde{I_\beta})_{eq}\end{bmatrix}$$

normal

Conventional Angle Calculation Method

$$\begin{bmatrix}\dot{\widehat{E_\alpha}}\\ \dot{\widehat{E_\beta}}\end{bmatrix} = \begin{bmatrix}(-\widehat{E_\alpha} + K \cdot sign(\widetilde{I_\alpha}))/\tau\\ (-\widehat{E_\beta} + K \cdot sign(\widetilde{I_\beta}))/\tau\end{bmatrix}$$

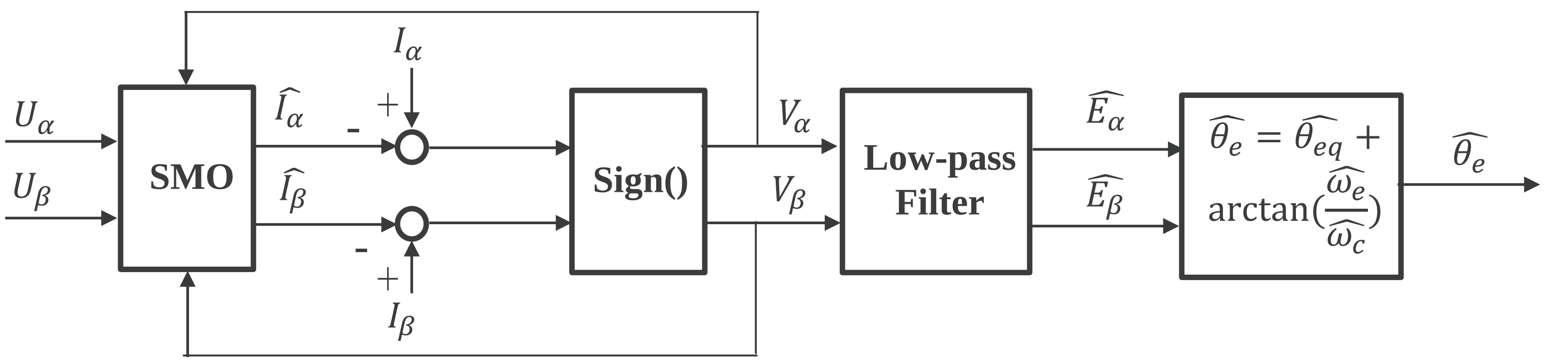
- **Low-pass filter is employed to reduce the switching signal**
- **The low pass filter will introduce a series phase delay of the rotor angle**
- **A compensated angle is required to compensate the angle delay**

$$\widehat{\theta_{eq}} = -\arctan\left(\frac{\widehat{E_\alpha}}{\widehat{E_\beta}}\right)$$

$$\widehat{\theta_e} = \widehat{\theta_{eq}} + \arctan\left(\frac{\widehat{\omega_e}}{\omega_c}\right)$$

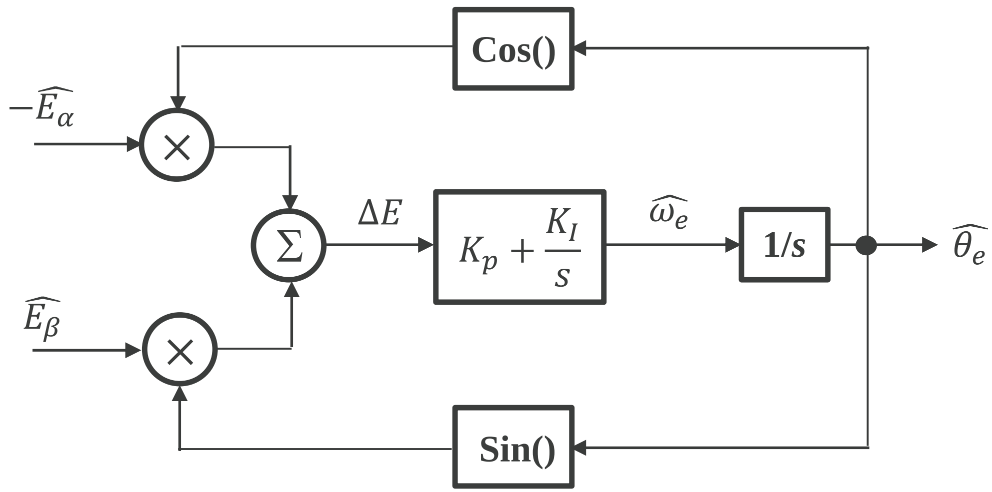
$$\widehat{\omega_e} = \frac{\sqrt{\widehat{E_\alpha^2} + \widehat{E_\beta^2}}}{\varphi_f}$$

ω_c is the cut-off frequency of the low pass filter



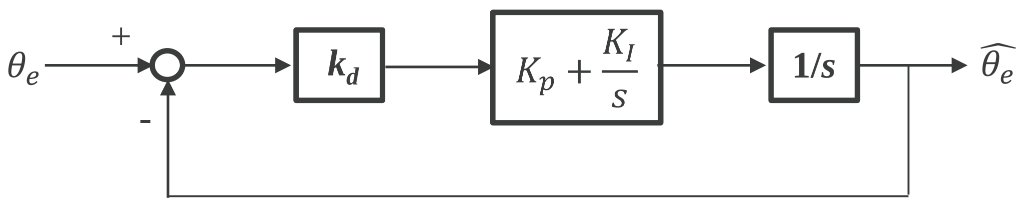
Phase-Lock-Loop (PLL)

$$\Delta E = -\widehat{E_\alpha}cos\widehat{\theta_e} - \widehat{E_\beta}sin\widehat{\theta_e} = kdsin\theta_e cos\widehat{\theta_e} - k_d cos\theta_e sin\widehat{\theta_e}$$
$$= k_d sin(\theta_e - \widehat{\theta_e}) = kd(\theta_e - \widehat{\theta_e})$$



- **PLL omit the complex computation of arctan function**
- **It also omit the low-pass filter that may cause a series phase delay**

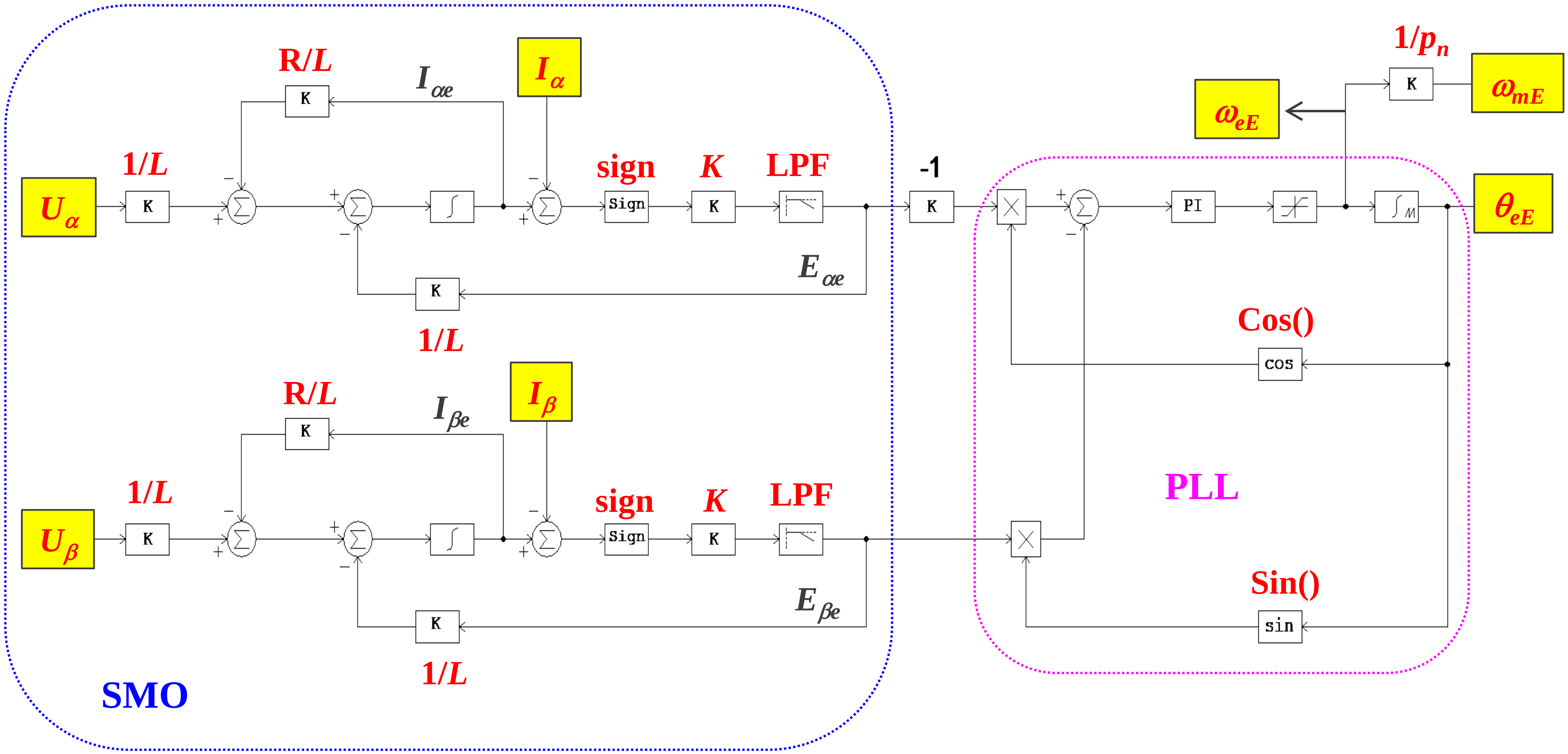
Equivalent control loop



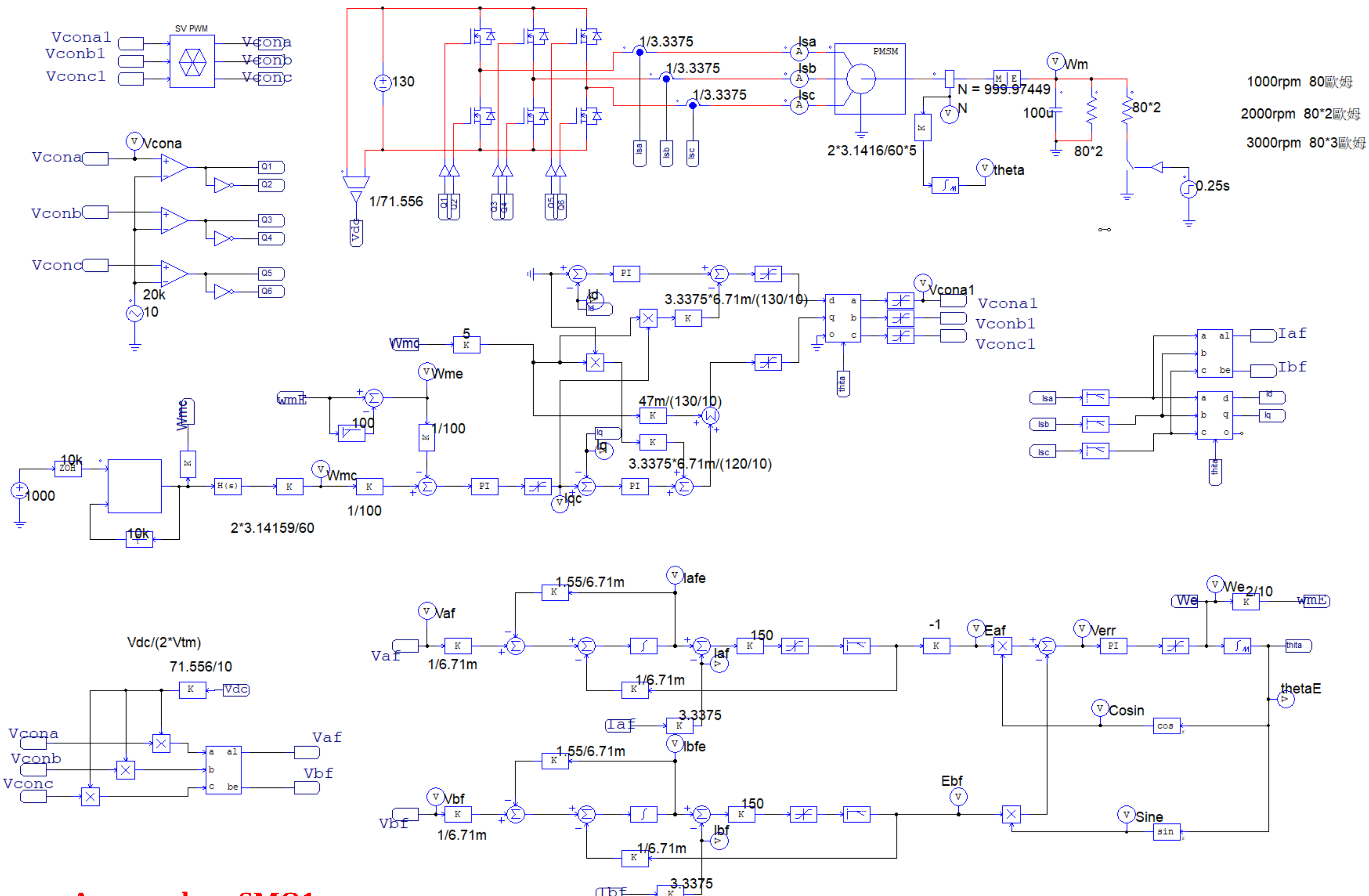
$$\frac{\widehat{\theta_e}}{\theta_e} = \frac{s^2}{s^2 + kdK_p s + k_d K_I}$$

$$k_d = (L_q - L_d)(\omega_e I_d - pI_q) + \omega_e \varphi_f = \omega_e \varphi_f$$

SMO+PLL Speed Observer



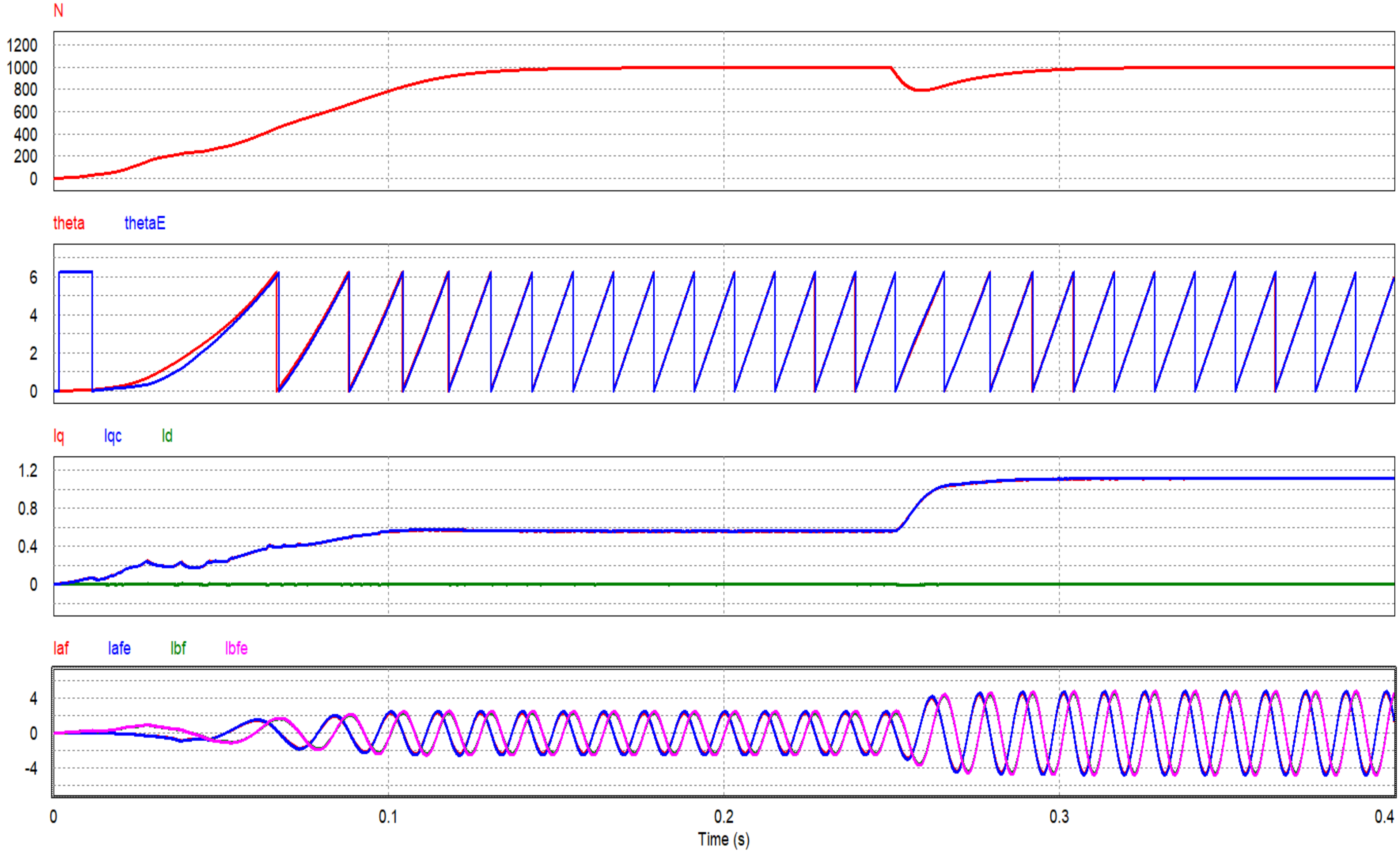
Simulation Circuit



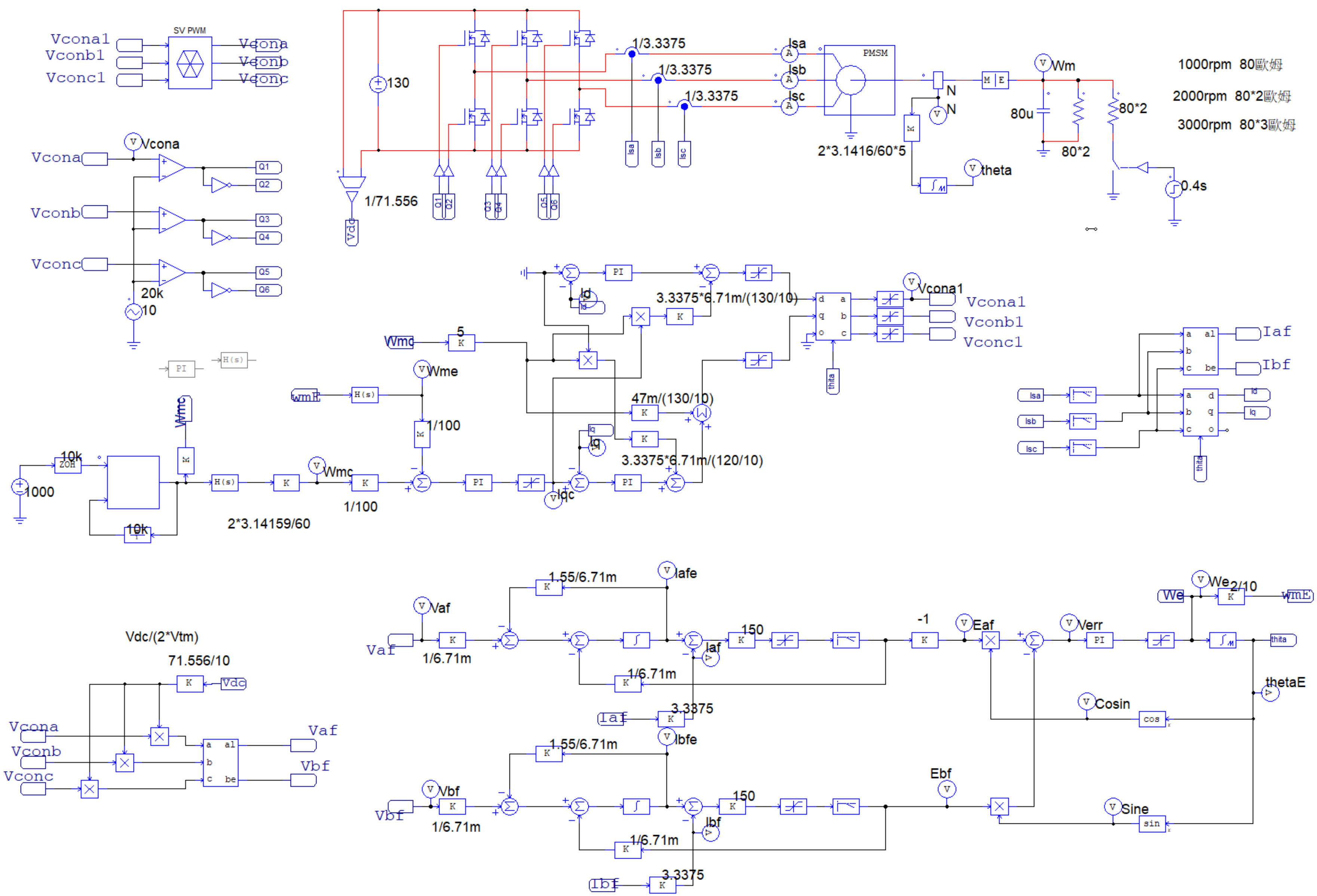
A_sensorless_SMO1

Simulation Result

normal

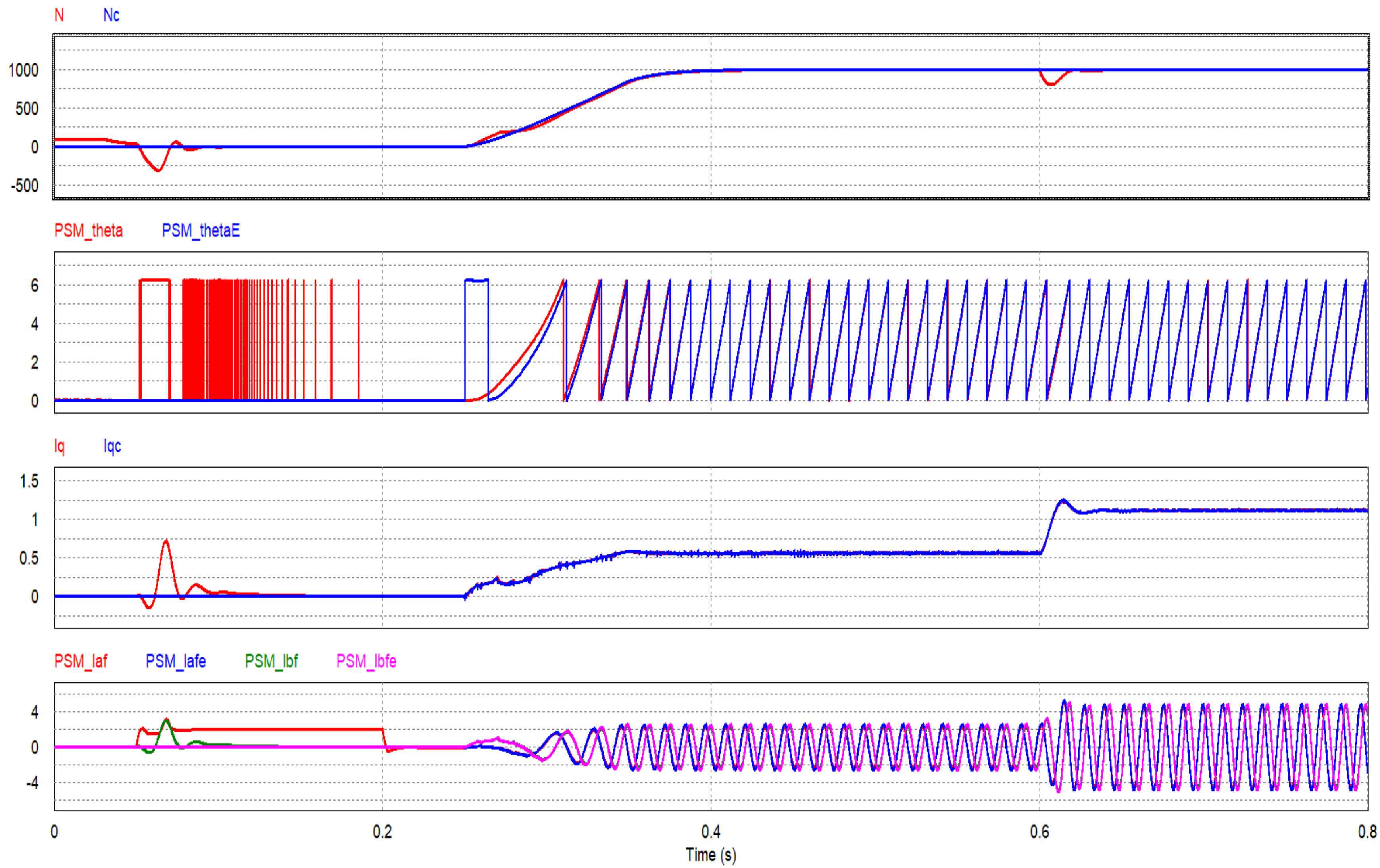


Control Circuit Realized with SimCoder

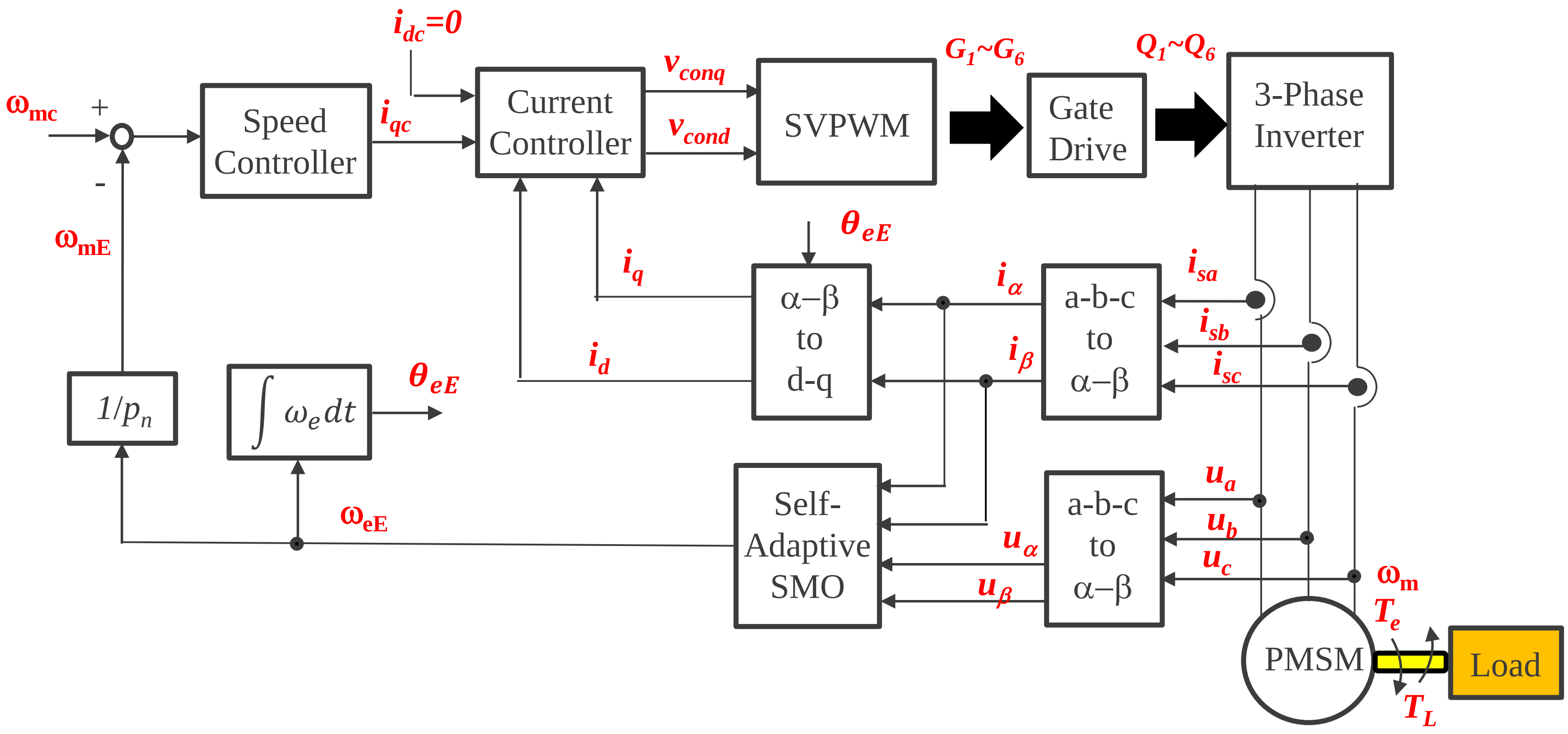


Lab4_sensorless_SMO1

Simulation Result



Lab 5: 無位置傳感器之速度控制(自適應滑模觀測器法)



Sliding Mode Observer (SMO)

$$\frac{d}{dt}I_s = AI_s + BU_s + K_eE_s \qquad I_s = \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad U_s = \begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} \qquad E_s = \begin{bmatrix} -\varphi_f\omega_e sin\theta_e \\ \varphi_f\omega_e cos\theta_e \end{bmatrix}$$

$$A = \begin{bmatrix} -\frac{R}{L_s} & 0 \\ 0 & -\frac{R}{L_s} \end{bmatrix} \qquad B = \begin{bmatrix} -\frac{1}{L_s} & 0 \\ 0 & -\frac{1}{L_s} \end{bmatrix} \qquad K_e = \begin{bmatrix} -\frac{1}{L_s} & 0 \\ 0 & -\frac{1}{L_s} \end{bmatrix}$$

$$\dot{E}_s = \omega_e \begin{bmatrix} -\varphi_f\omega_e cos\theta_e \\ -\varphi_f\omega_e sin\theta_e \end{bmatrix} = \omega_e \begin{bmatrix} -E_\beta \\ E_\alpha \end{bmatrix}$$

PMSM Model in α–β

Sliding surface function

$$s = \widetilde{I_s} = \widehat{I_s} - I_s = \begin{bmatrix} \widetilde{I_\alpha} \\ \widetilde{I_\beta} \end{bmatrix}$$

Control law

$$\frac{d}{dt}\widehat{I_s} = A\widehat{I_s} + BU_s + K_e\widehat{E_s} + Ksign(s) \qquad K = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix}$$

$$k < \min[-\frac{R}{L_s}|\widetilde{I_s}| - \frac{1}{L_s}|\widetilde{E_\alpha}|, -\frac{R}{L_s}|\widetilde{I_\beta}| - \frac{1}{L_s}|\widetilde{E_\beta}|] \qquad \widehat{E_s} = \begin{bmatrix} -\varphi_f\widehat{\omega_e} sin\widehat{\theta_e} \\ \varphi_f\widehat{\omega_e} cos\widehat{\theta_e} \end{bmatrix}$$

Error equation

$$\frac{d}{dt}\widetilde{I_s} = A\widetilde{I_s} + K_e\widetilde{E_s} + Ksign(s)$$

As enter into and stay on the sliding surface, it will be

$$\frac{d}{dt}\widetilde{I_s} = \widetilde{I_s} = 0 \qquad \widetilde{E_s} = -K_e^{-1}Ksign(s)$$

Self-adaptive Law and PLL

$$\frac{d}{dt}\widehat{E_\alpha} = -\widehat{\omega_e}\widehat{E_\beta} - l\widetilde{E_\alpha}$$

$$\frac{d}{dt}\widehat{E_\beta} = \widehat{\omega_e}\widehat{E_\alpha} - l\widetilde{E_\beta}$$

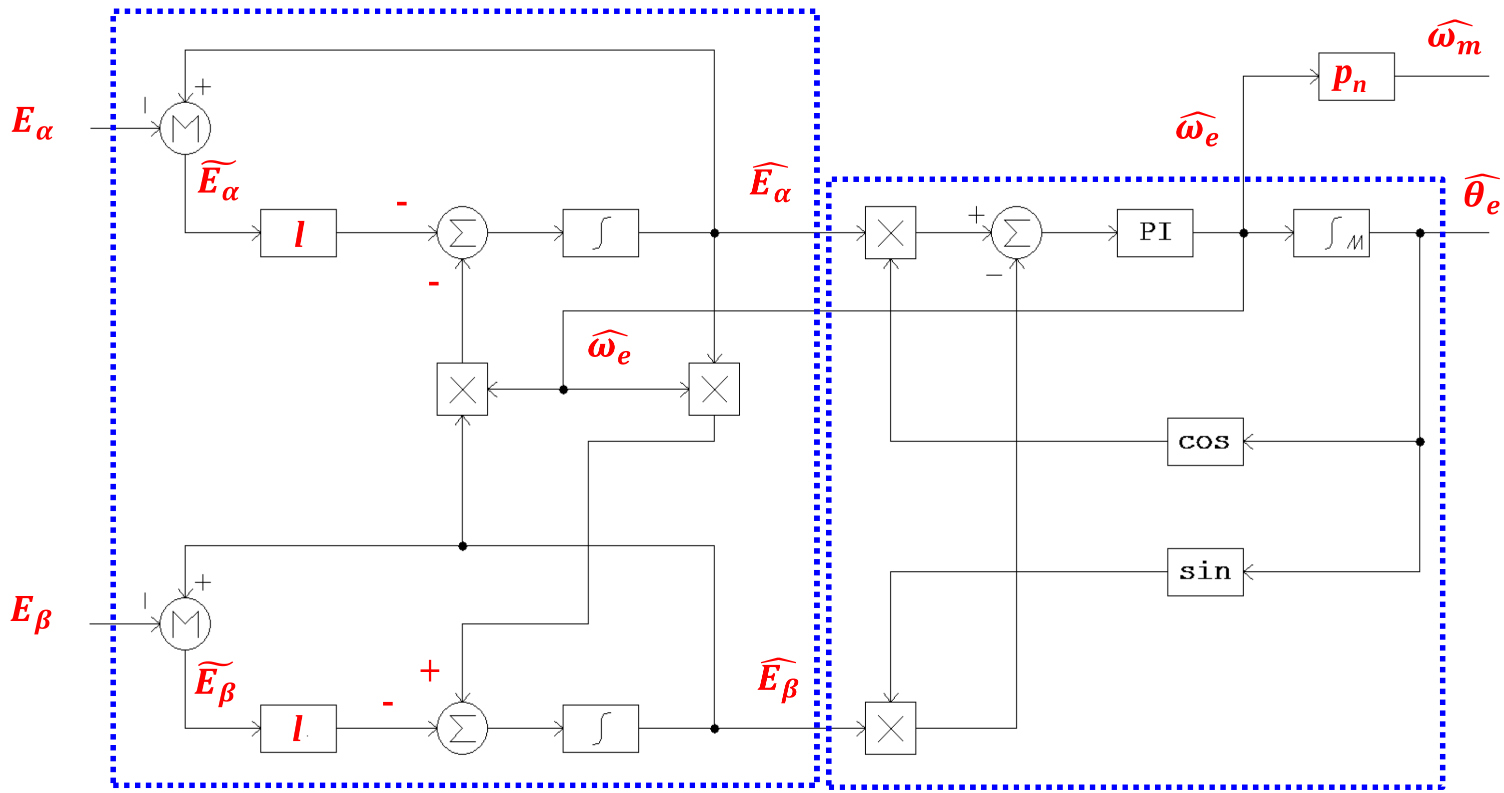
$$\frac{d}{dt}\widetilde{\omega_e} = \widetilde{E_\alpha}\widehat{E_\beta} - \widehat{E_\alpha}\widetilde{E_\beta}$$

Select Lyapunov function

$$V = \frac{1}{2}(\widetilde{E_\alpha^2} + \widetilde{E_\beta^2} + \widetilde{\omega_e^2})$$

$$\dot{V} = \widetilde{E_\alpha}\dot{\widetilde{E_\alpha}} + \widetilde{E_\beta}\dot{\widetilde{E_\beta}} + \widetilde{\omega_e}\dot{\widetilde{\omega_e}} = -l(\widetilde{E_\alpha^2} + \widetilde{E_\beta^2}) \leq 0$$

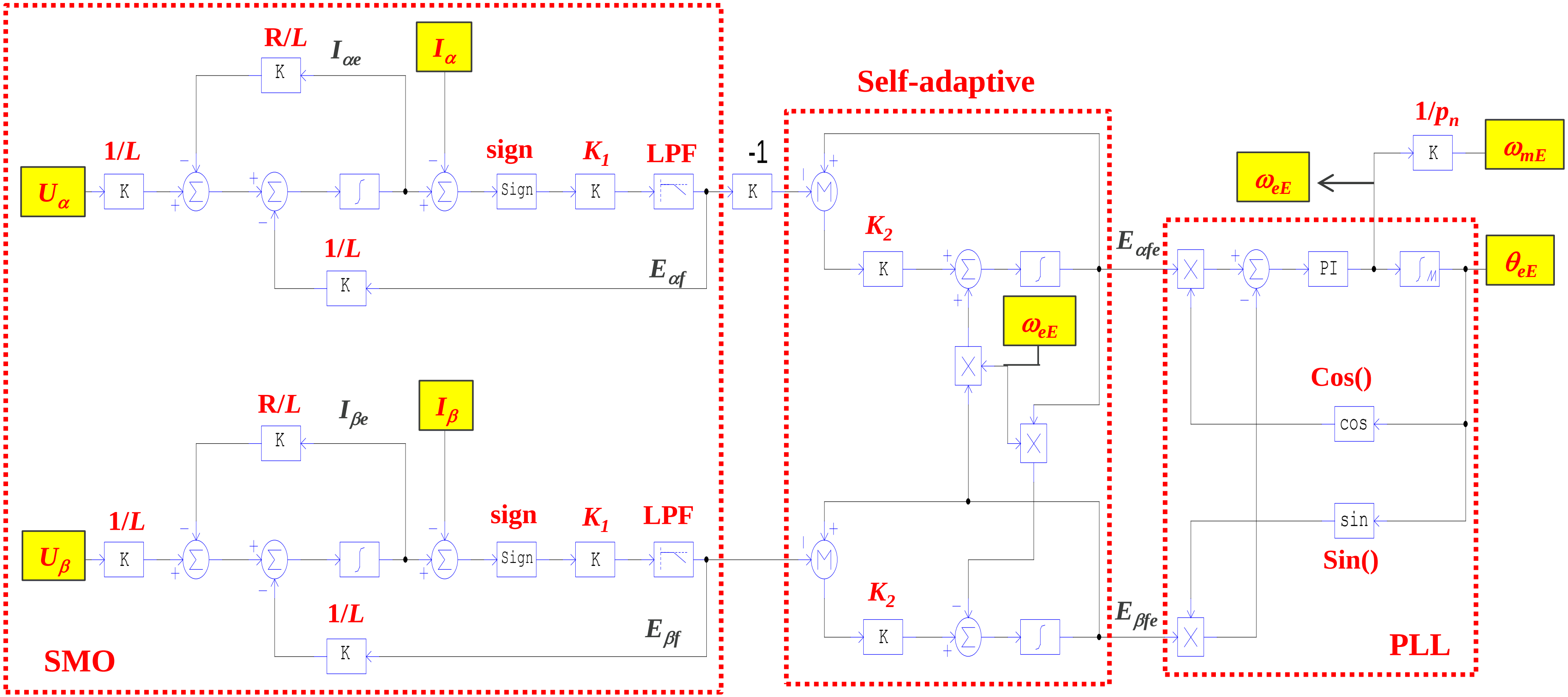
Stability of the system is guaranteed



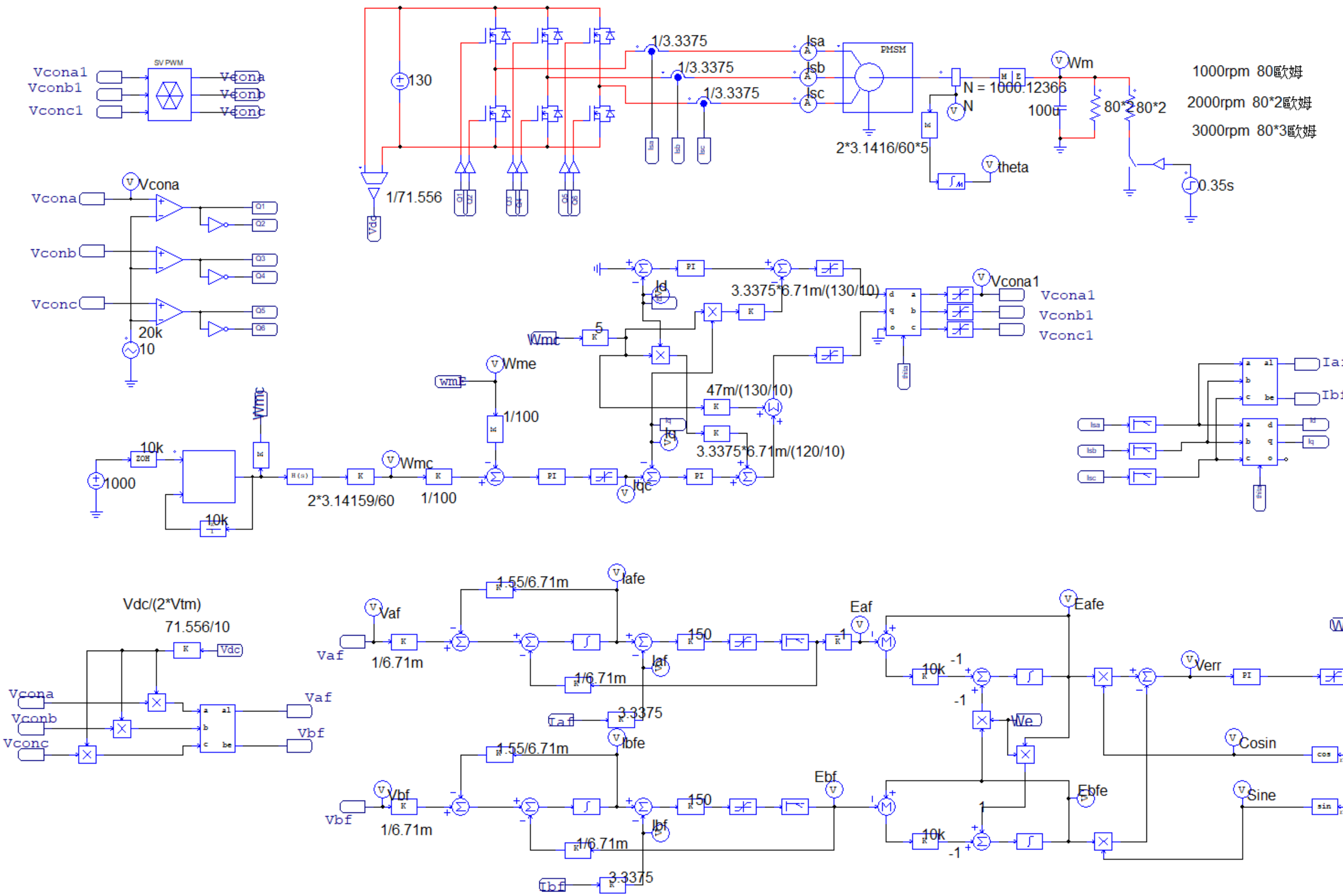
Self-adaptive

PLL

SMO+Self-adaptive+PLL

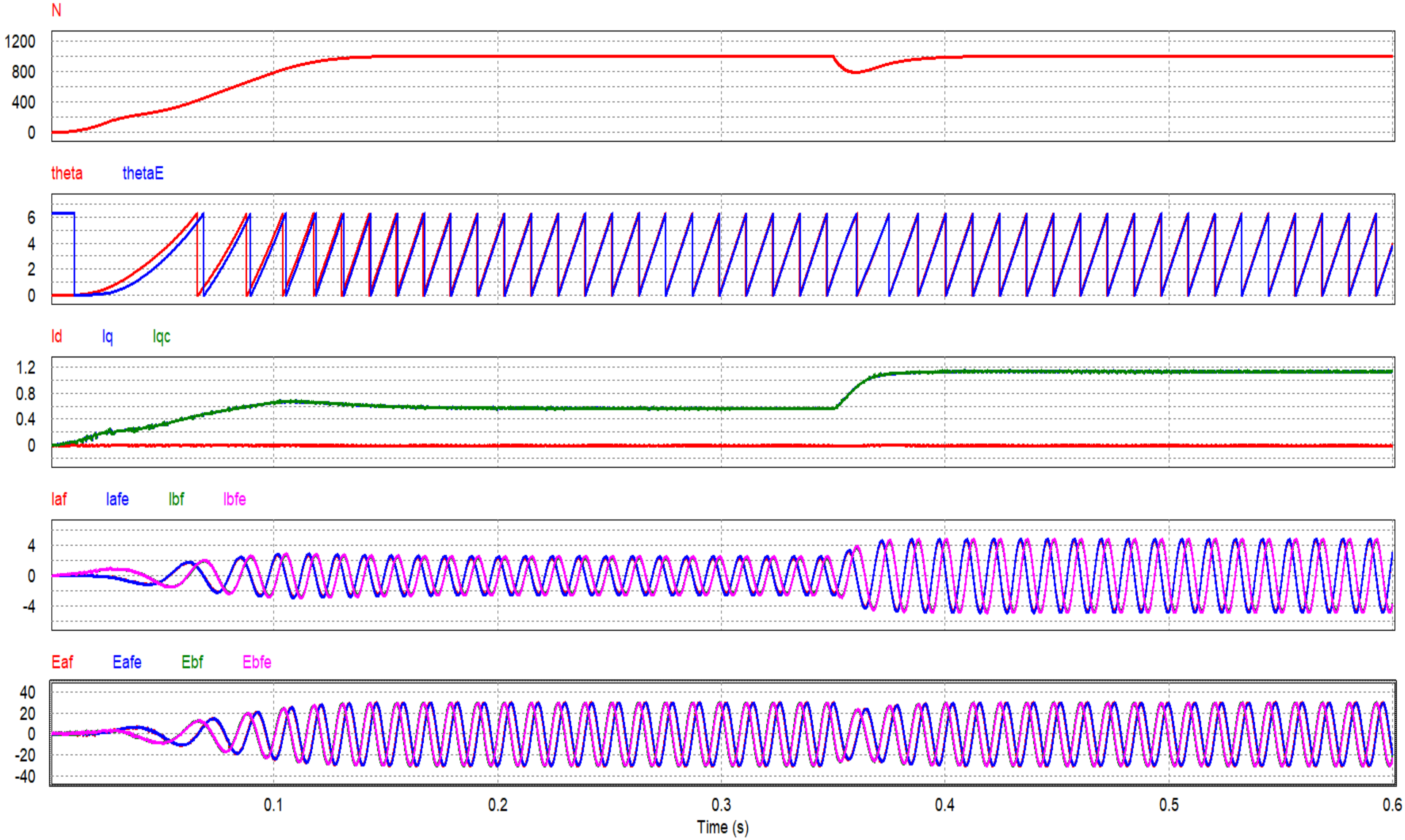


Simulation Circuit

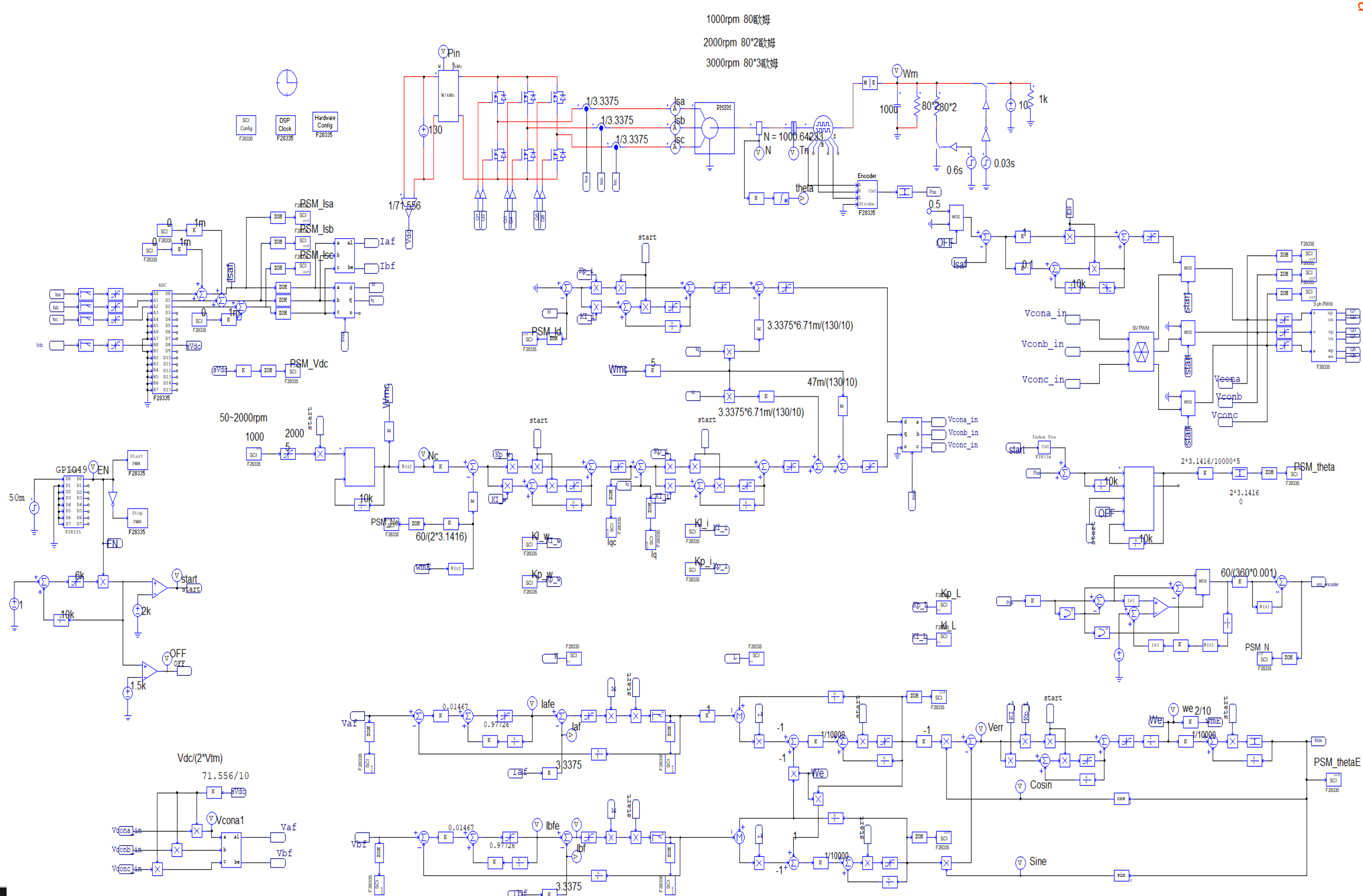


A_sensorless_SMO_apt1

Simulation Result

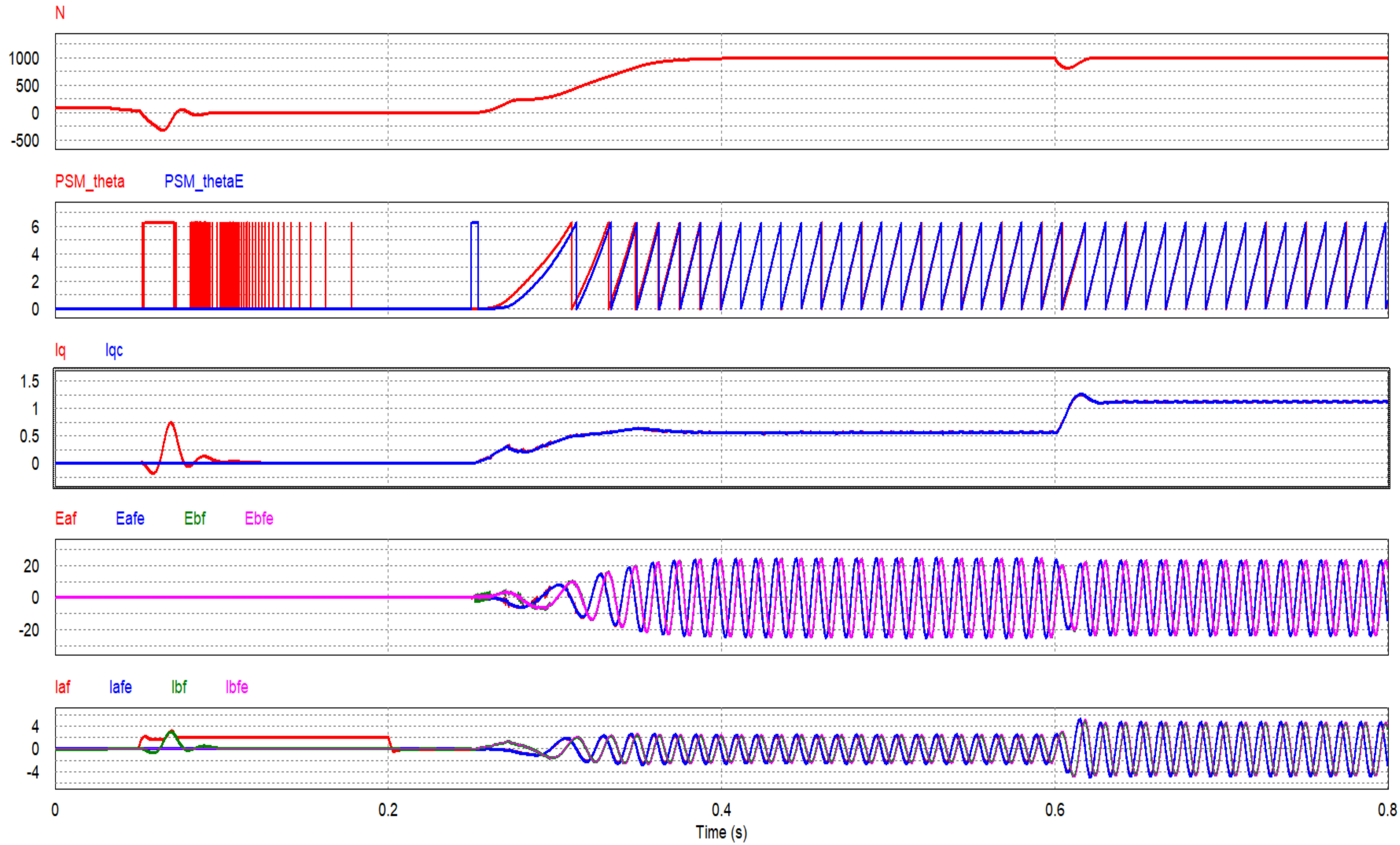


Control Circuit Realized with SimCoder

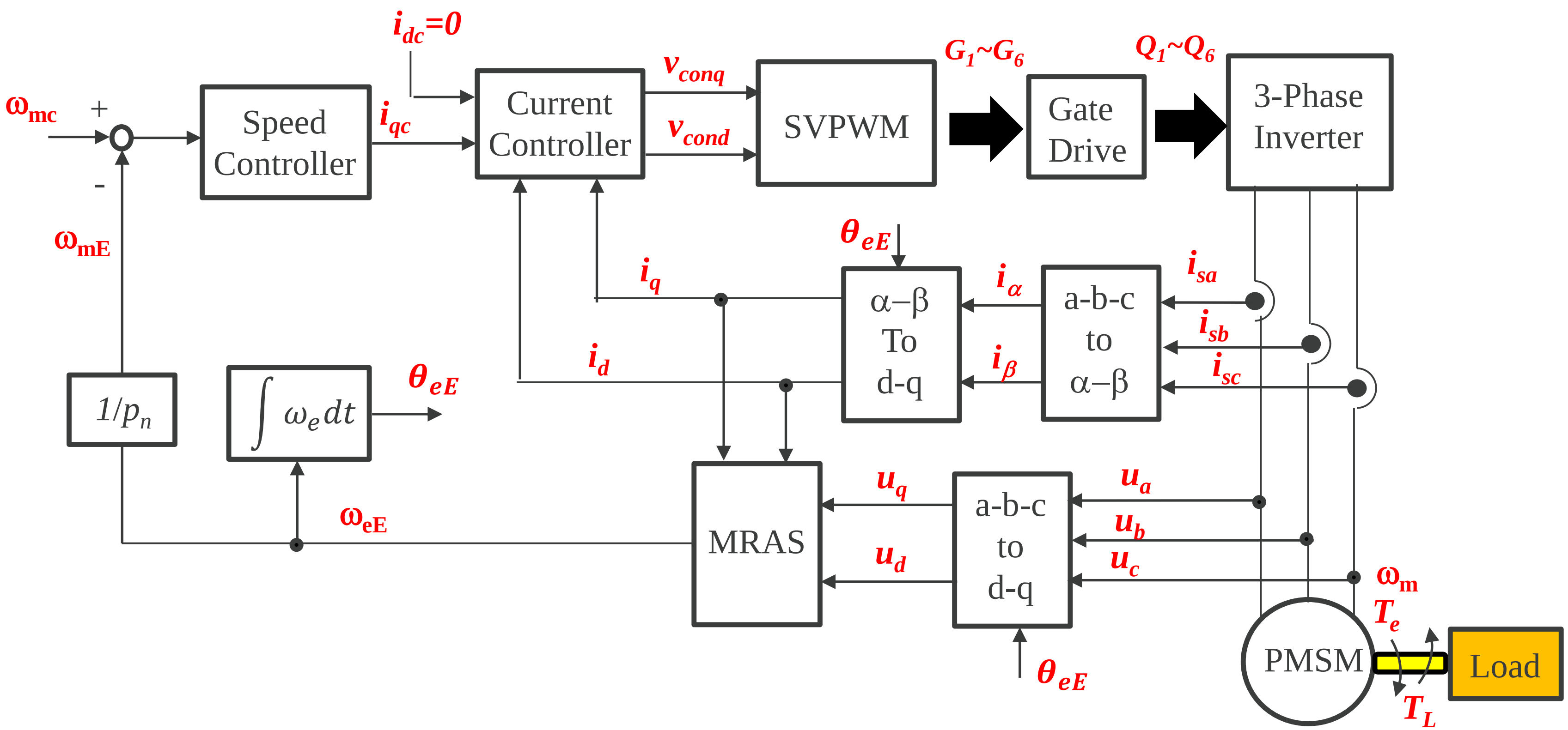


Lab5_sensorless_SMO_apt1

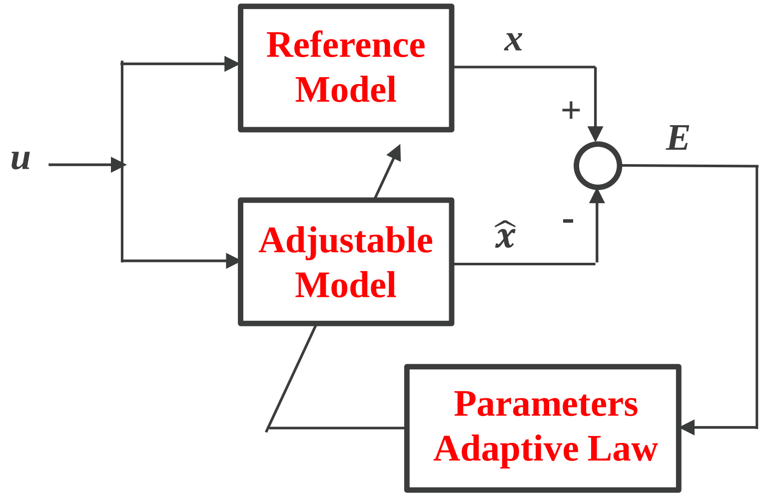
Simulation Result



Lab 6: 無位置傳感器之速度控制 (Model Reference Adaptive System, MRAS)



Model Reference Adaptive System



Reference Model

d-q Model of PMSM

$$U_d = RI_d + L_d \frac{d}{dt} I_d - \omega_e L_q I_q$$

$$U_q = RI_q + L_q \frac{d}{dt} I_q + \omega_e (L_d I_d + \varphi_f)$$

Expressed with state equation of current

$$\frac{d}{dt} I_d = -\frac{R}{L_s} I_d + \omega_e I_q + \frac{1}{L_s} U_d$$

$$\frac{d}{dt} I_q = -\frac{R}{L_s} I_q - \omega_e I_d - \frac{\varphi_f}{L_s} \omega_e + \frac{1}{L_s} U_q$$

Rearrange

$$\frac{d}{dt}(I_d + \frac{\varphi_f}{L_s}) = -\frac{R}{L_s}(I_d + \frac{\varphi_f}{L_s}) + \omega_e I_q + \frac{1}{L_s}(U_d + \frac{R\varphi_f}{L_s})$$

$$\frac{d}{dt} I_q = -\frac{R}{L_s} I_q - \omega_e (I_d + \frac{\varphi_f}{L_s}) + \frac{1}{L_s} U_q$$

$$I'_d = I_d + \frac{\varphi_f}{L_s}$$

$$I'_q = I_q$$

$$U'_d = U_d + \frac{R}{L_s} \varphi_f$$

$$U'_q = U_q$$

Reference Model

$$\frac{d}{dt} I'_d = -\frac{R}{L_s} I'_d + \omega_e I'_q + \frac{1}{L_s} U'_d$$

$$\frac{d}{dt} I'_q = -\frac{R}{L_s} I'_q - \omega_e I'_d + \frac{1}{L_s} U'_q$$

R

Adjustable Model

$$\frac{d}{dt}I' = AI' + BU'$$

$$I' = \begin{bmatrix} I'_d \\ I'_q \end{bmatrix} \quad U' = \begin{bmatrix} U'_d \\ U'_q \end{bmatrix} \quad A = \begin{bmatrix} -\frac{R}{L_s} & \omega_e \\ -\omega_e & -\frac{R}{L_s} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix}$$

$$\frac{d}{dt}\widehat{I'_d} = -\frac{R}{L_s}\widehat{I'_d} + \omega_e\widehat{I'_q} + \frac{1}{L_s}U'_d$$

$$\frac{d}{dt}\widehat{I'_q} = -\frac{R}{L_s}\widehat{I'_q} - \omega_e\widehat{I'_d} + \frac{1}{L_s}U'_q$$

B

$$\frac{d}{dt}\widehat{I'} = \hat{A}\widehat{I'} + BU' \quad \widehat{I'} = \begin{bmatrix} \widehat{I'_d} \\ \widehat{I'_q} \end{bmatrix} \quad \hat{A} = \begin{bmatrix} -\frac{R}{L_s} & \widehat{\omega_e} \\ \widehat{\omega_e} & -\frac{R}{L_s} \end{bmatrix}$$

$$err = I' - \widehat{I'}$$

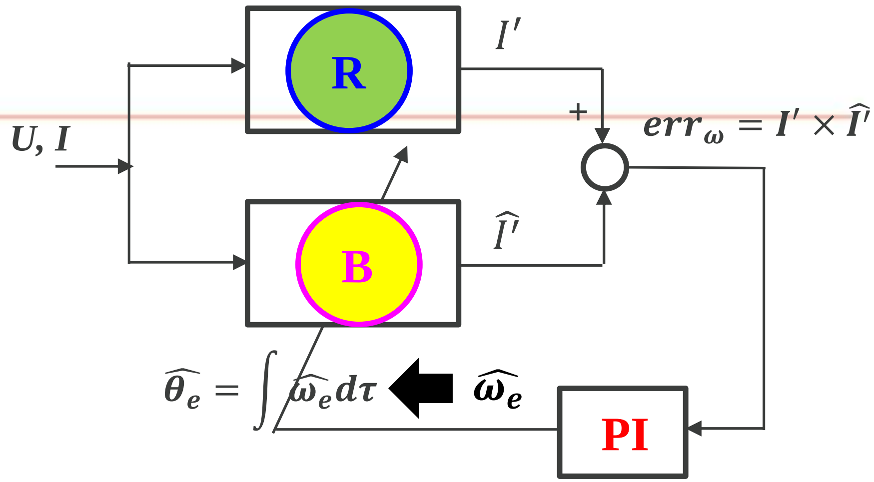
Error equation

$$\frac{d}{dt}\begin{bmatrix} \widetilde{err_d} \\ \widetilde{err_q} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & \omega_e \\ \omega_e & -\frac{R}{L_s} \end{bmatrix}\begin{bmatrix} \widetilde{err_d} \\ \widetilde{err_q} \end{bmatrix} - J(\omega_e - \widehat{\omega_e})\begin{bmatrix} \widehat{I'_d} \\ \widehat{I'_q} \end{bmatrix} \quad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Adaptation Law

$$\frac{d}{dt}err = A_e err - W$$

$$A_e = \begin{bmatrix} -\frac{R}{L_s} & \omega_e \\ -\omega_e & -\frac{R}{L_s} \end{bmatrix} \qquad W = J(\omega_e - \widehat{\omega_e})\widehat{I'}$$



According to Popov stability criterion:

(1) $H(s)=(sI-A_e)^{-1}$ is strictly positive real;

(2) $\eta(0, t_1)=\int_0^t V^T W dt \geq -\gamma_o^2, \forall t_1 \geq 0, \gamma_o^2$ is positive and $\lim_{t\to\infty} err(t) = 0$, so MRAS is asymptotically stable

$$\widehat{\omega_e} = \int_0^t K_i(I'_d\widehat{I'_q} - \widehat{I'_d}I'_q)d\tau + K_p(I'_d\widehat{I'_q} - \widehat{I'_d}I'_q)$$

(Derived from the solution of Popov inequality)

$$\widehat{\omega_e} = \left(\frac{K_i}{s} + K_p\right) err_\omega$$

$$err_\omega = I'_d\widehat{I'_q} - \widehat{I'_d}I'_q = I' \times \widehat{I'}$$

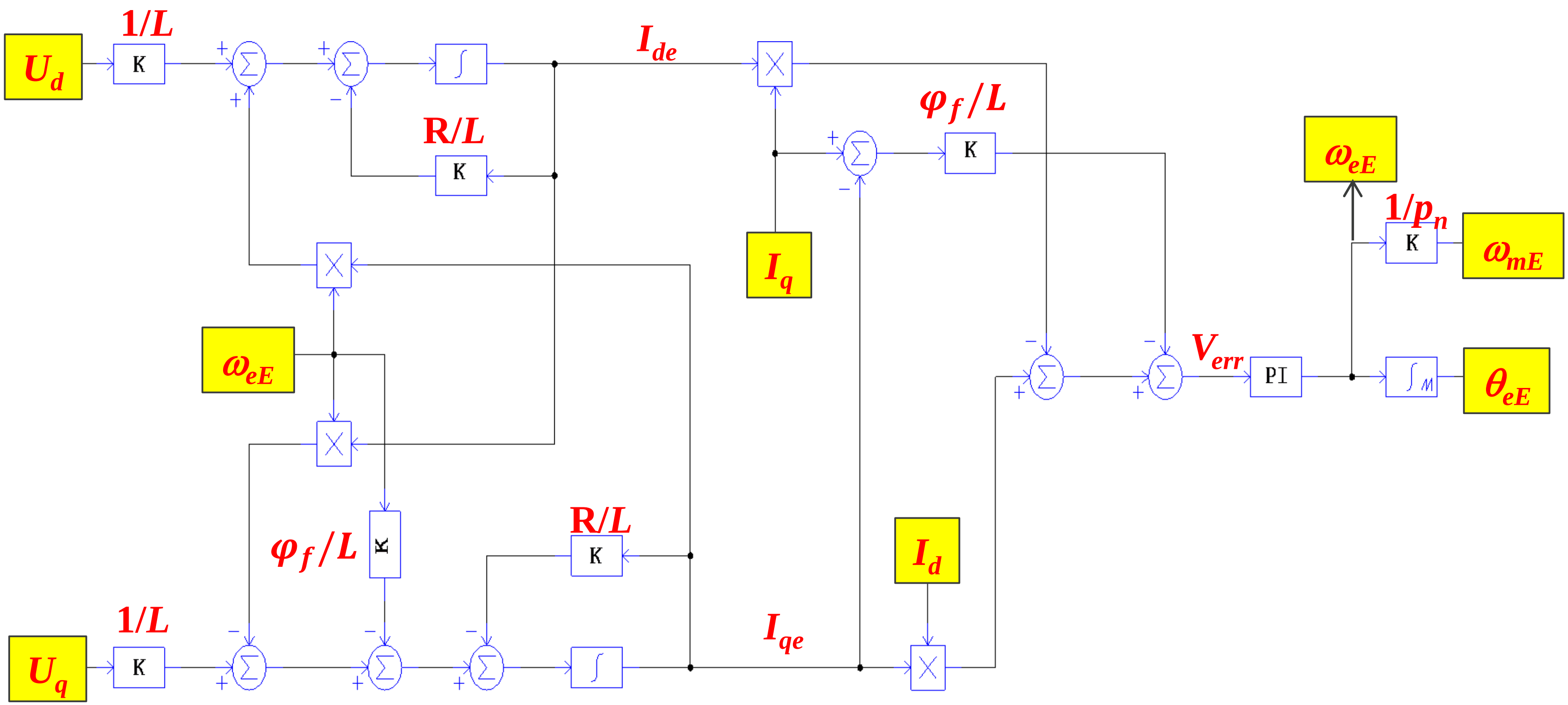
Rearrange ⇨

$$\widehat{\omega_e} = \left(\frac{K_i}{s} + K_p\right)[I_d\widehat{I_q} - \widehat{I_d}I_q - \frac{\varphi_f}{L_s}(I_q - \widehat{I_q})]$$

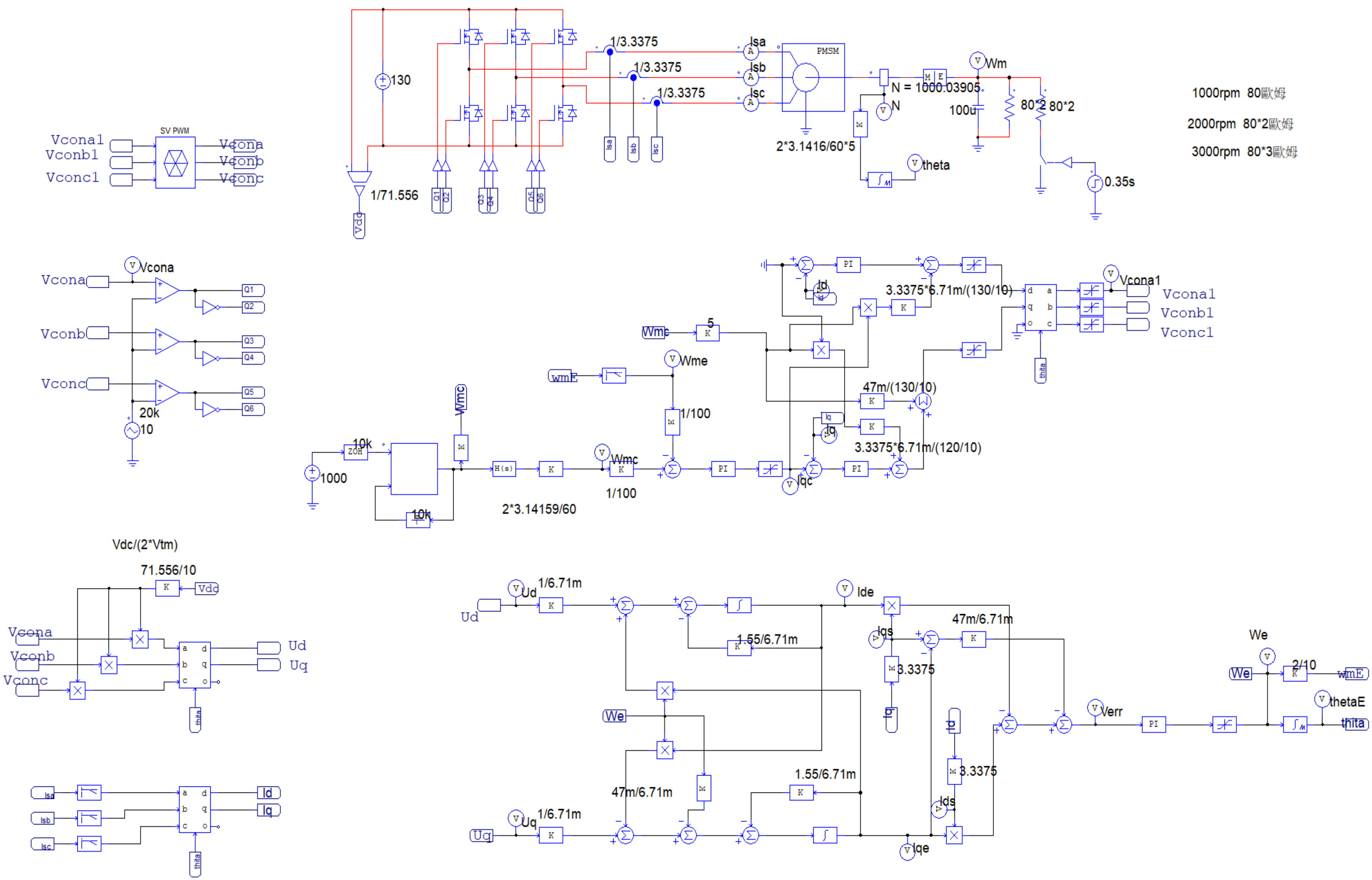
$$\widehat{\theta_e} = \int \widehat{\omega_e} d\tau$$

MRAS Realization

$$\widehat{\omega_e} = \left(\frac{K_i}{s} + K_p\right)\left[I_d\widehat{I_q} - \widehat{I_d}I_q - \frac{\varphi_f}{L_s}\left(I_q - \widehat{I_q}\right)\right]$$

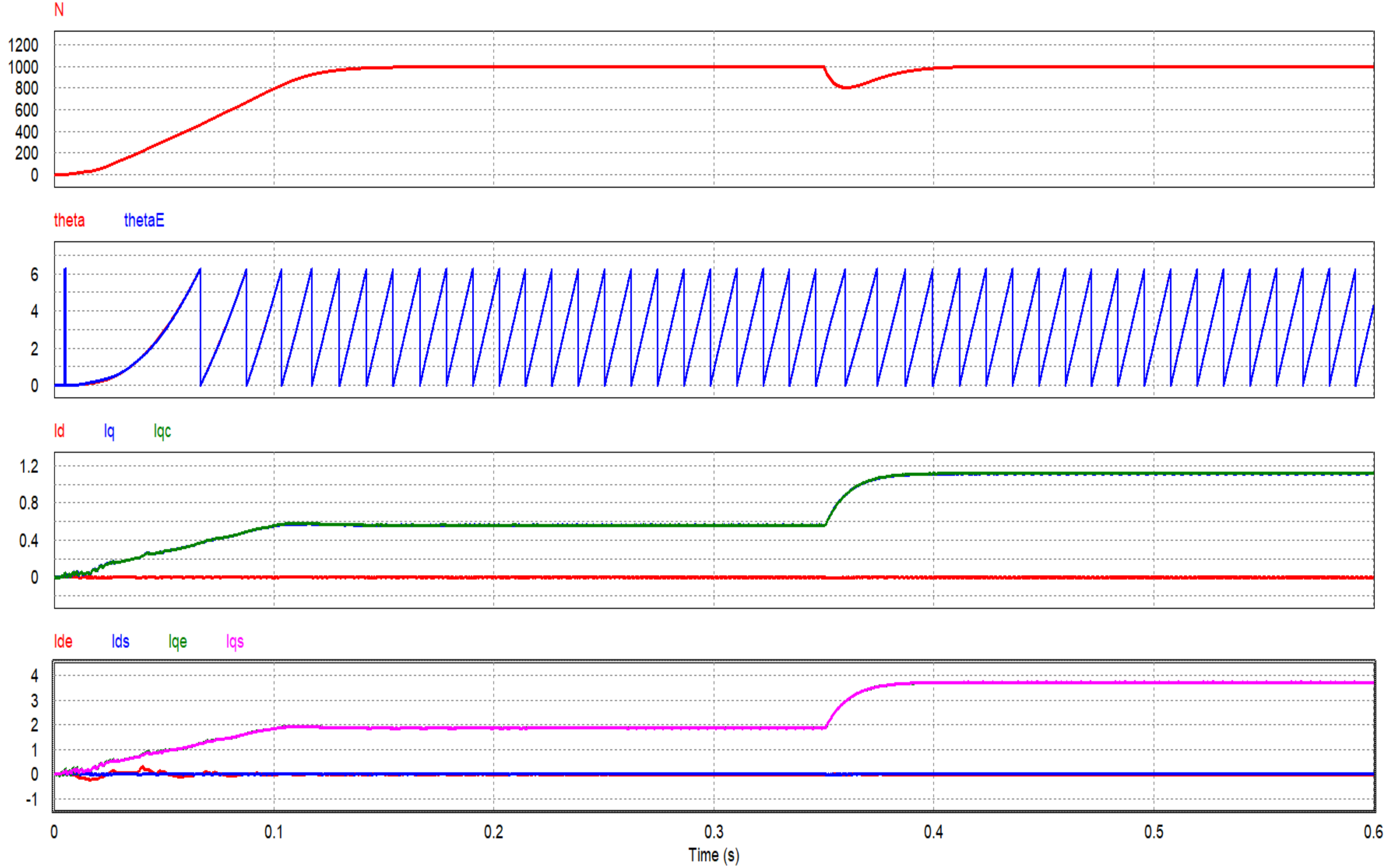


Simulation Circuit

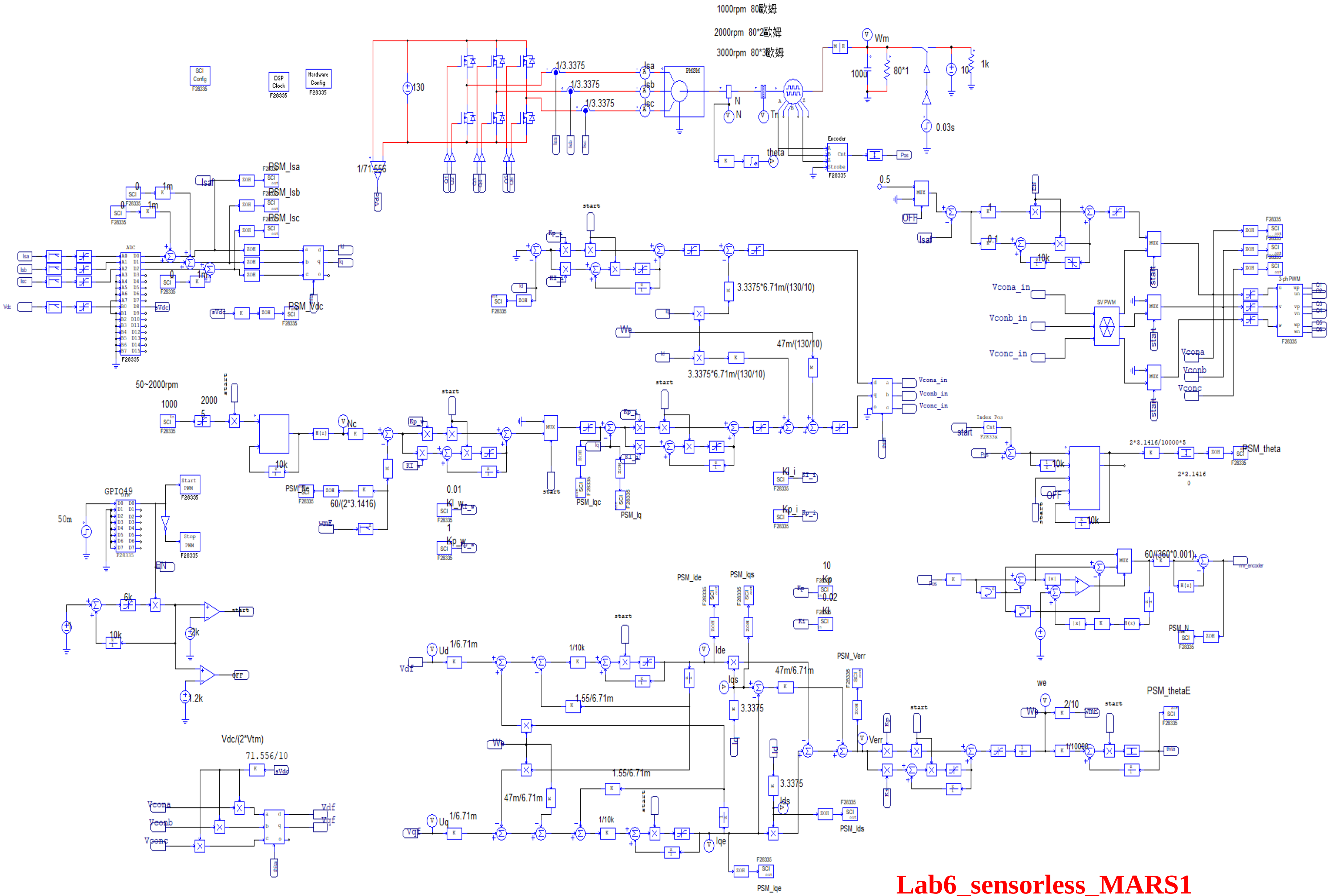


A_sensorless_MARS1

Simulation Result

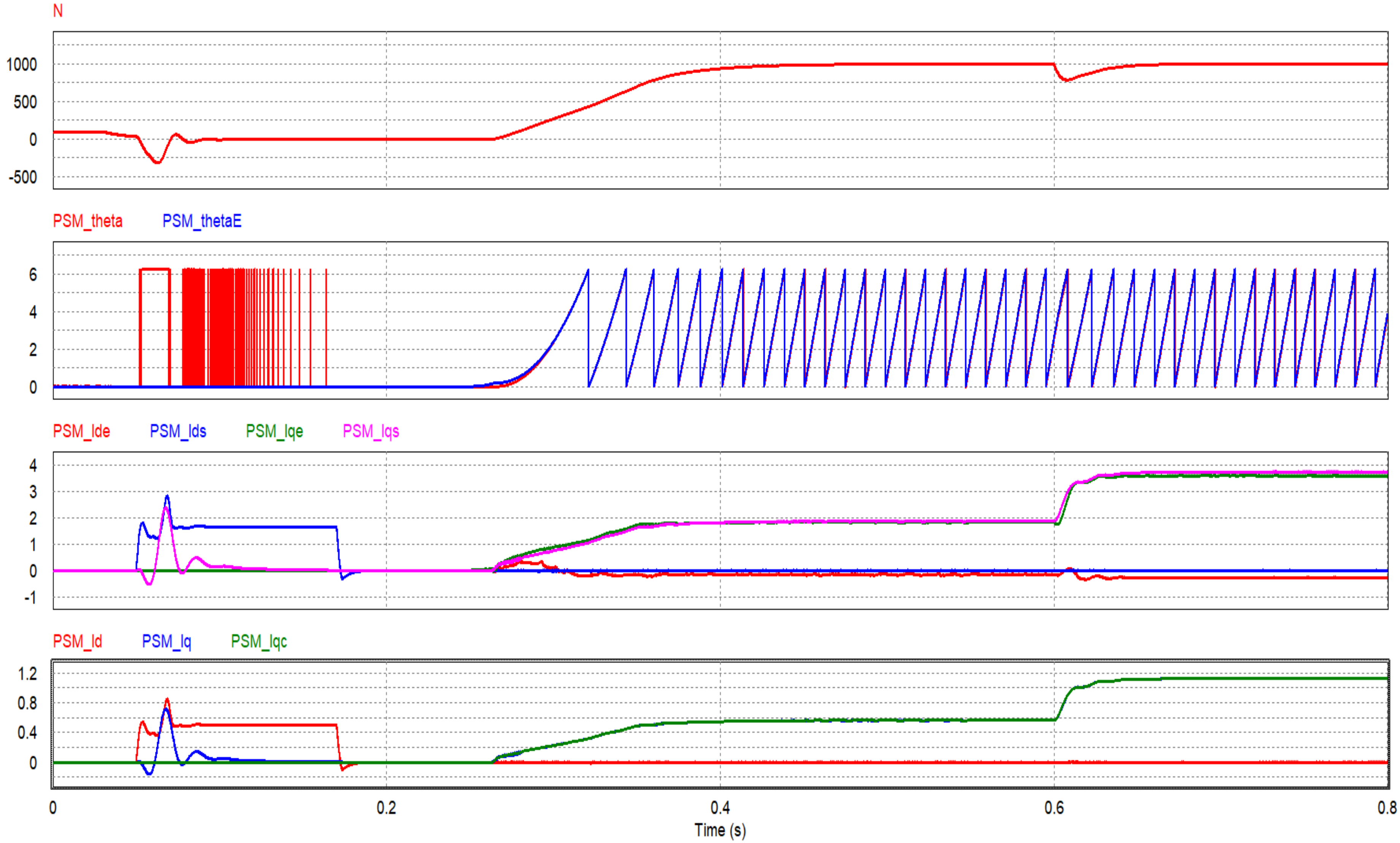


Control Circuit Realized with SimCoder



Lab6_sensorless_MARS1

Simulation Result



Thank you for your attention