實作講義9 磁場導向控制

Handout 9 Field-Oriented Control, FOC

2022/11/29

上課準備

- 請至moodle下載教學用檔案。
- Please download the handouts from moodle.

Handout 9

大綱

HIL, hardware in loop

Code **FOC**

期末測試 Final Test

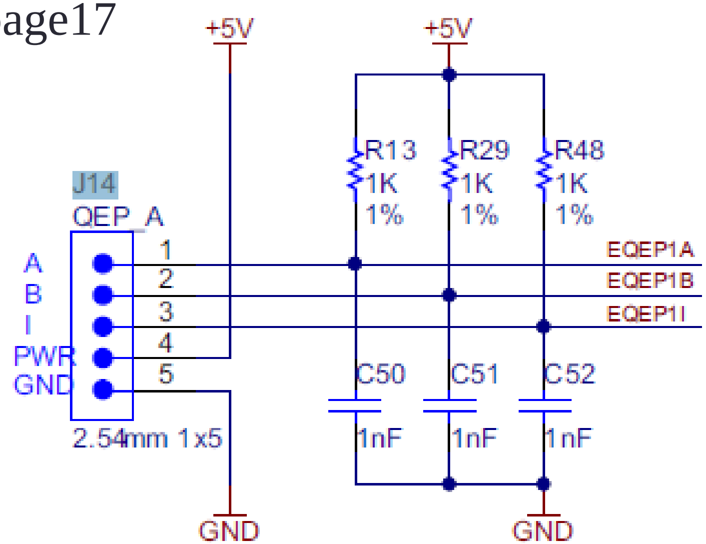
FOC CCS Test

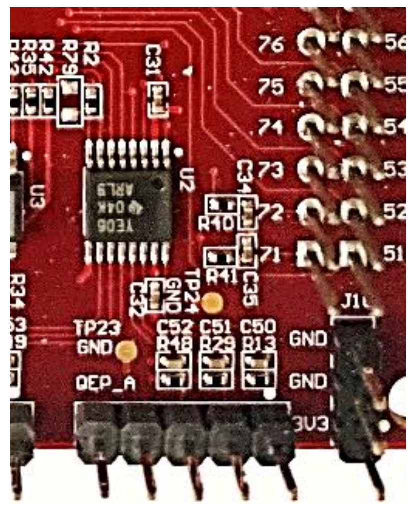
Handout 9 **Test Board**

LAUNCHXL-F28379D Overview (Rev. C)

input	output
ADCINA0_30	**EPwm1A_40**
ADCINA1_70	**EPwm1B_39**
ADCINA2_29	**EPwm2A_38**
eQEPA (J14)	**EPwm2B_37**
	EPwm3A_36
	EPwm3B_35

page17

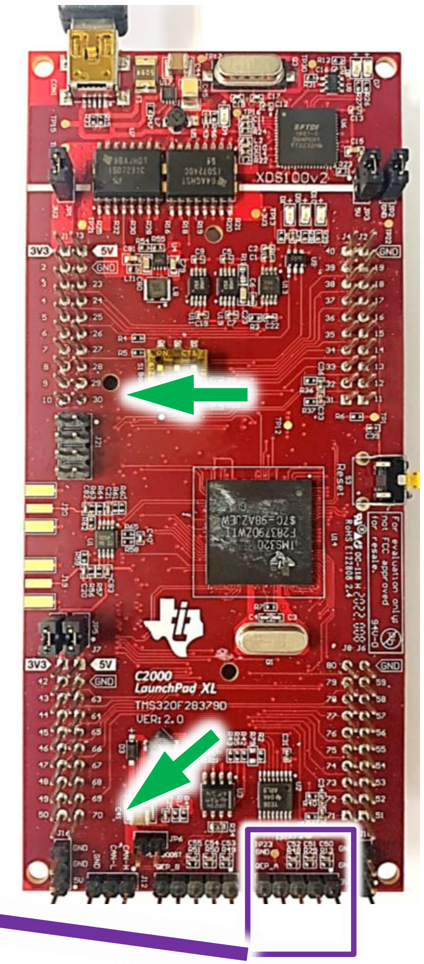




G P I B A

n 5

d V

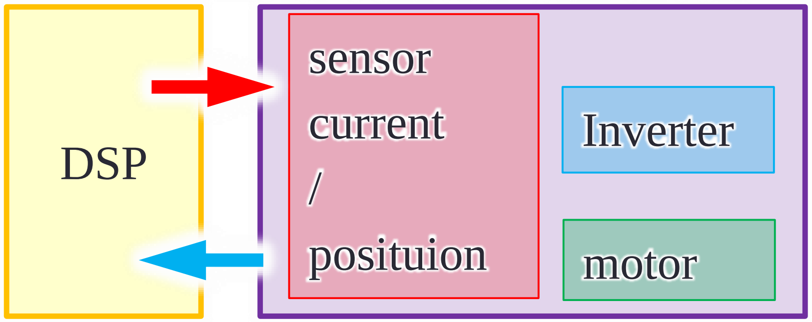


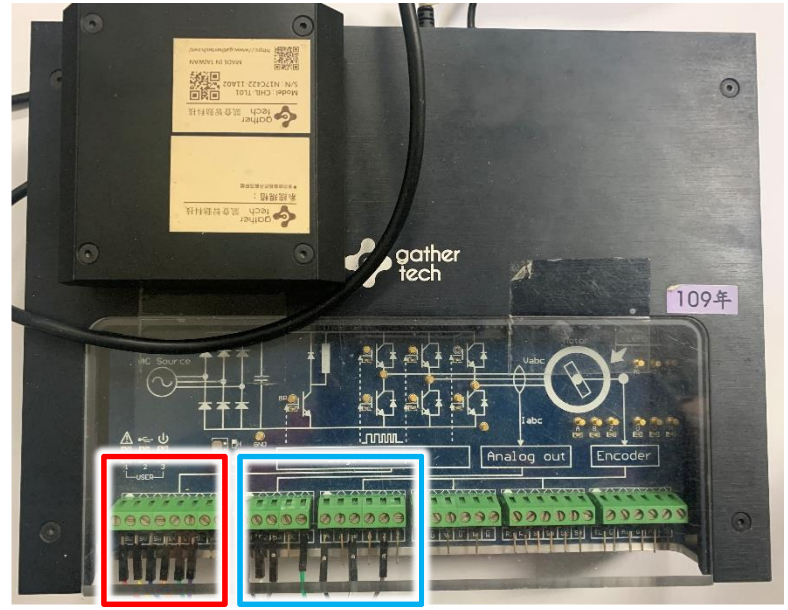
Enhanced Quadrature Encoder Pulse (eQEP)

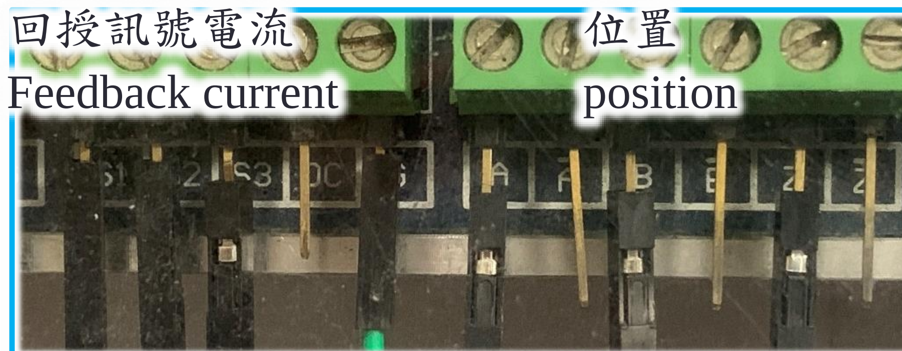
Handout 9 **HIL, hardware in loop**

馬達在線模擬儀器，

Simulate motor behavior with circuit.





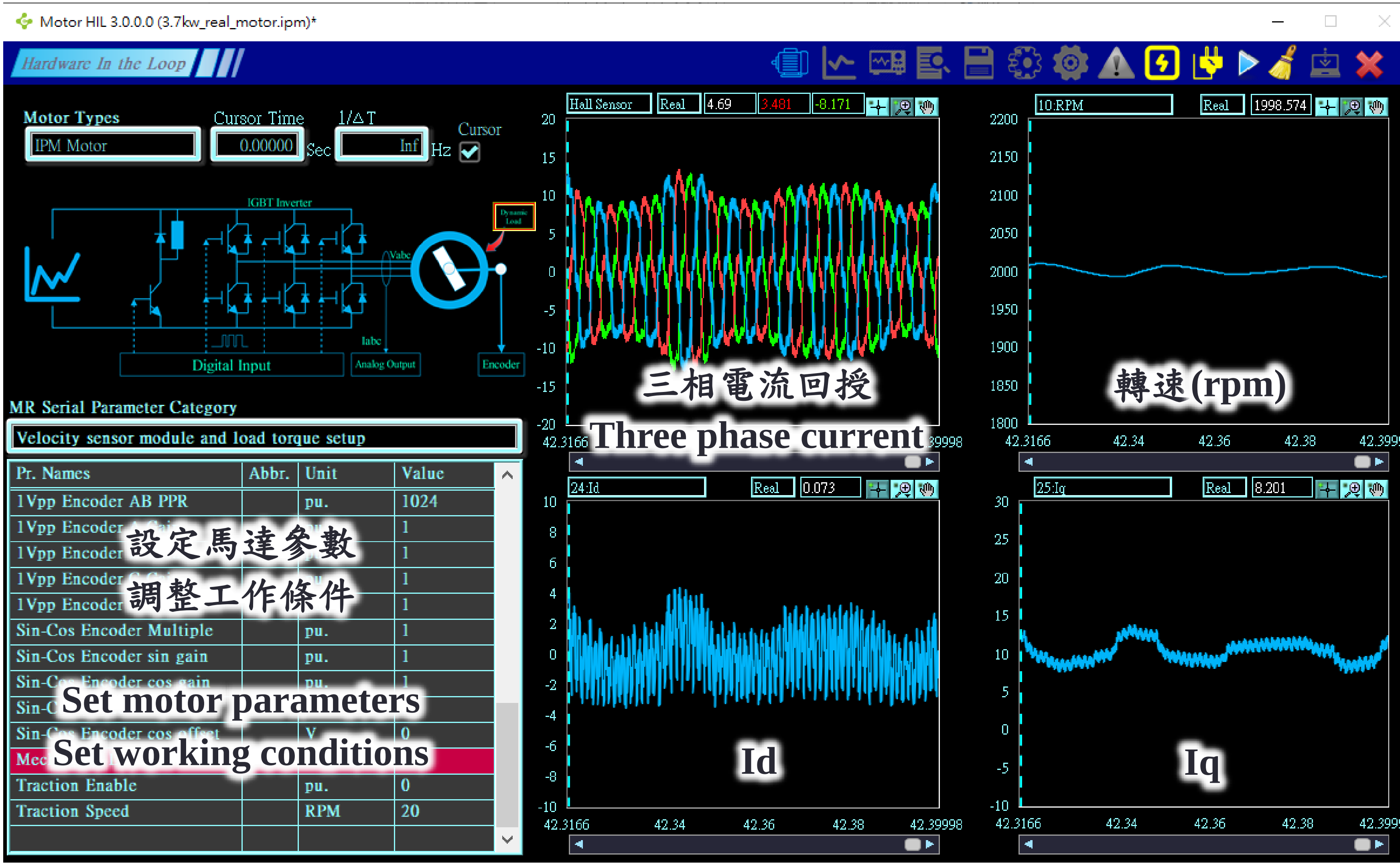


SU	SV	SW	SX	SY	SZ		G
U H 上	V H 上	W H 上	U L 下	V L 下	W L 下		gnd 地

S1	S2	S3		G
I A	I B	I C		G 地

A		B		Z		G
A		B		I Z		G 地

Handout 9 **HIL, hardware in loop**



Handout 9 **HIL, hardware in loop**

參數

Motor parameters setup

Pr. Names	Abbr.	Unit	Value
Motor OFF		pu.	0
Coordinate alignment	dq	Pi	0
Stator Winding Resistance	Rs	Ohm	0.1416
d-axis Inductance	Ld	mH	0.76
q-axis Inductance	Lq	mH	1.61
Back EMF Source		pu.	1
Back EMF constant (L-L)	Ke	V/kRPM	125.5
Rated Torque	Te	Nm	11.78
Rated Current	Irated	A	18.5
Poles	P	pu.	8
dq-axis Inductance Source		pu.	0
Inductance File Name	Path	N/A	
ECE Model File Name	Path	N/A	
Cogging Torque Enable		pu.	0
Cogging Torque File Name	Path	N/A	
Cross coupled inductance d	Lqd	mH	0
Cross coupled inductance q	Ldq	mH	0
Cross Inductance Source		pu.	0
Cross Inductance File Name	Path	N/A	
System Inertia	Jm	Kg·m^2	0.00633
System Damping	Bm	N*m/(rad/s)	0.002

MR Serial Parameter Category

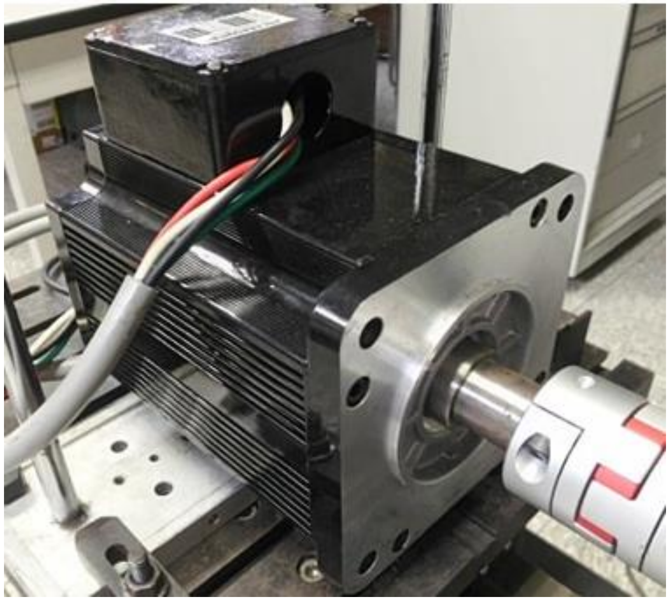
Input voltage and feedback signal scaling setup

Pr. Names	Abbr.	Unit	Value
AC Source Select		pu.	2
3-Ph AC Source (RMS)		V	155.6
3-Ph AC Source Frequency		Hz	60
DC Bus Shift		V	220
DC Bus Volt. AO Scaling		pu.	0
DC Bus Volt. AO Offset		V	0
DC Bus Volt. AO H Limit		V	3
DC Bus Volt. AO L Limit		V	0
U-Ph Current AO Scaling		pu.	0.03
V-Ph Current AO Scaling		pu.	0.03
W-Ph Current AO Scaling		pu.	0.03
U-Ph Current AO Offset		V	1.5
V-Ph Current AO Offset		V	1.5
W-Ph Current AO Offset		V	1.5
U-Ph Current AO H Limit		V	3
U-Ph Current AO L Limit		V	0
V-Ph Current AO H Limit		V	3
V-Ph Current AO L Limit		V	0
W-Ph Current AO H Limit		V	3
W-Ph Current AO L Limit		V	0
Current Sensing Mode		pu.	0
DI Active Level		pu.	0000000
Ignore short circuit		pu.	0
S1 AO Scaling		pu.	0
S1 AO Offset		V	0
S1 AO H Limit		V	10
S1 AO L Limit		V	-10

Velocity sensor module and load torque setup

Pr. Names	Abbr.	Unit	Value
Motor reset position enable		pu.	0
Motor reset position		degree	0
Speed Change Gears		pu.	1
Encoder shift angle		degree	0
Encoder Type		pu.	0
Encoder Pulse/Rev.		pu.	1024
Encoder Cable Loss		pu.	0
Encoder Cable Loss Duration		mSec	100
Encoder Inverse		pu.	000000
Resolver angle multiple		pu.	1
S13 Gain		pu.	0.5
S24 Gain		pu.	0.5
S13 shift angle		degree	0
S24 shift angle		degree	0
Hall sensor type		pu.	0
Hall sensor states		pu.	5,1,3,2,6,4
U Hall sensor shift angle		degree	0
V Hall sensor shift angle		degree	0
W Hall sensor shift angle		degree	0
PWM Encoder resolution		bit	10
PWM Encoder Carrier freq		Hz	1000
PWM Encoder max duty		%	95
PWM Encoder min duty		%	5
PWM Encoder Direction		pu.	0
1Vpp Encoder AB PPR		pu.	1024
1Vpp Encoder A Gain		pu.	1
1Vpp Encoder B Gain		pu.	1
1Vpp Encoder C Gain		pu.	1
1Vpp Encoder D Gain		pu.	1
Sin-Cos Encoder Multiple		pu.	1
Sin-Cos Encoder sin gain		pu.	1
Sin-Cos Encoder cos gain		pu.	1
Sin-Cos Encoder sin offset		V	0
Sin-Cos Encoder cos offset		V	0
Mechanical Load	TL	Nm	5
Traction Enable		pu.	0
Traction Speed		RPM	20

Handout 9 **HIL, hardware in loop**



Moment of inertia
J: 6.33e-3 kg·m^2

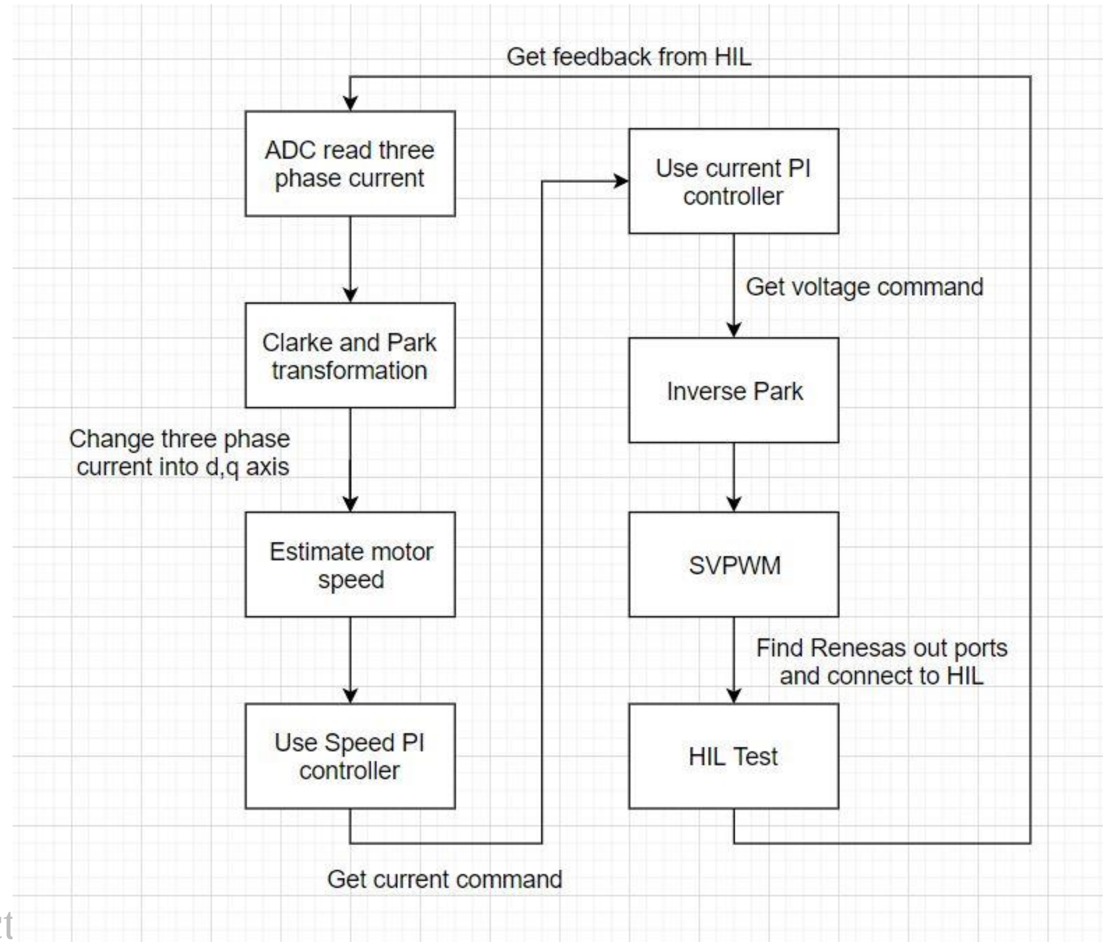
Specification	Value
Rated Torque T_{rated} (N.m)	11.78
Max. Torque T_{max} (N.m)	29.4
Rated Voltage V_{rated} (V_{pk})	220
Rated Current I_{rated} (A_{rms})	18
Max. Current I_{max} (A_{rms})	45
Rated Speed $N_{e,rated}$ (RPM)	3000
Rated Power P_{rated} (kW)	3.7
Pole	8
Torque Constant K_T	0.72
Voltage Constant K_e	0.7
Parameter	**Value**
D Axis Inductance L_d (mH)	0.76
Q Axis Inductance L_q (mH)	1.61
Resistance of Stator Windings R_s (mΩ)	175
Flux Linkage λ_m (mWb)	86.38

Handout 9 FOC

可能的程式流程圖　Possible program flow chart

The following explanation is not complete code, you need to make your own combination.

以下講解並非完整code，需要各位自己組合。



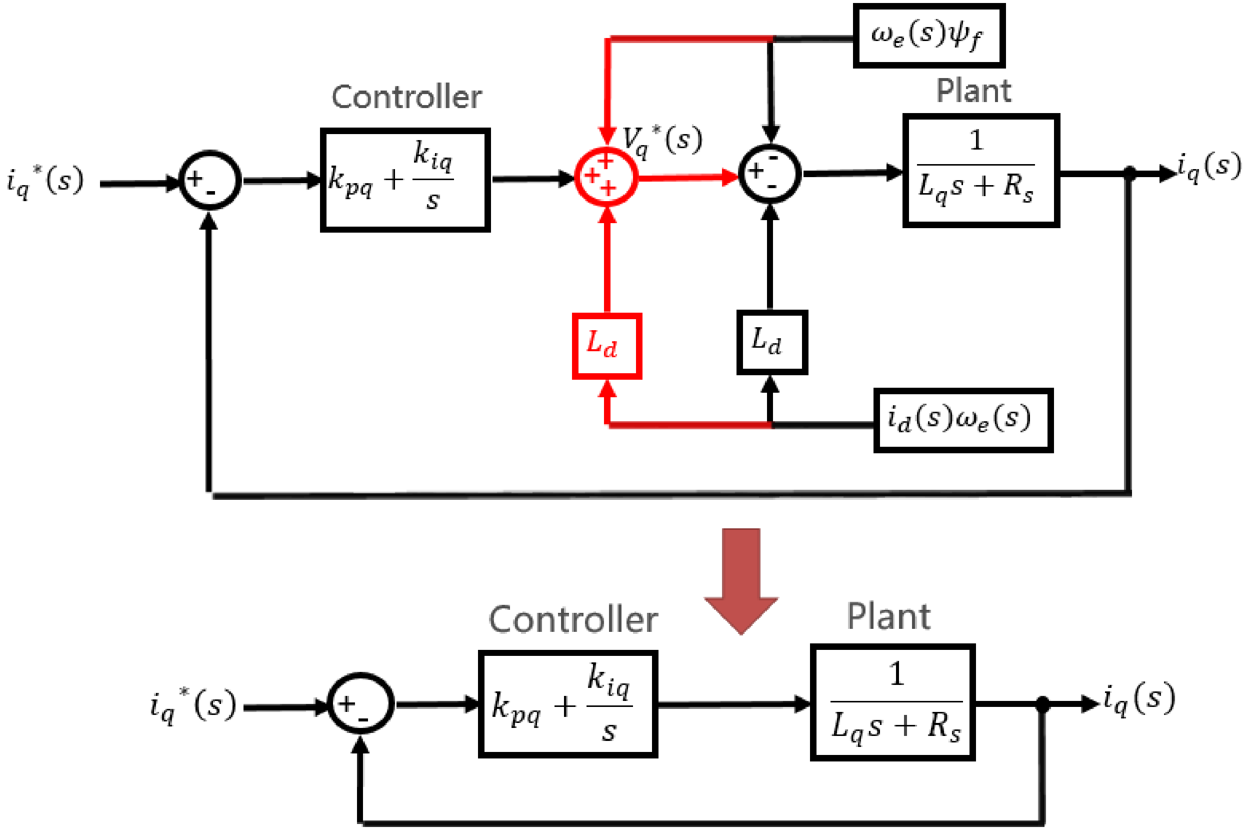
Handout 9 FOC

Controller in program

```
// Variable calculations
   TimeBase = 50000000.0 / 2 / SwitchingFreq; //  50M/2/10k=2.5k  Page115 for "/2"
   t_err = 1.0 / SwitchingFreq;
   encunit = 360.0 / encres;
   vdcrec = 1 / vdc;

   kp_w = 2.0 * 3.1415926 * fbw_w * J;
   ki_w = 2.0 * 3.1415926 * fbw_w * B;


   kp_d = 2.0 * 3.1415926 * fbw_i * Ld;
   ki_d = 2.0 * 3.1415926 * fbw_i * Rs;


   kp_q = 2.0 * 3.1415926 * fbw_i * Lq;
   ki_q = 2.0 * 3.1415926 * fbw_i * Rs;
```

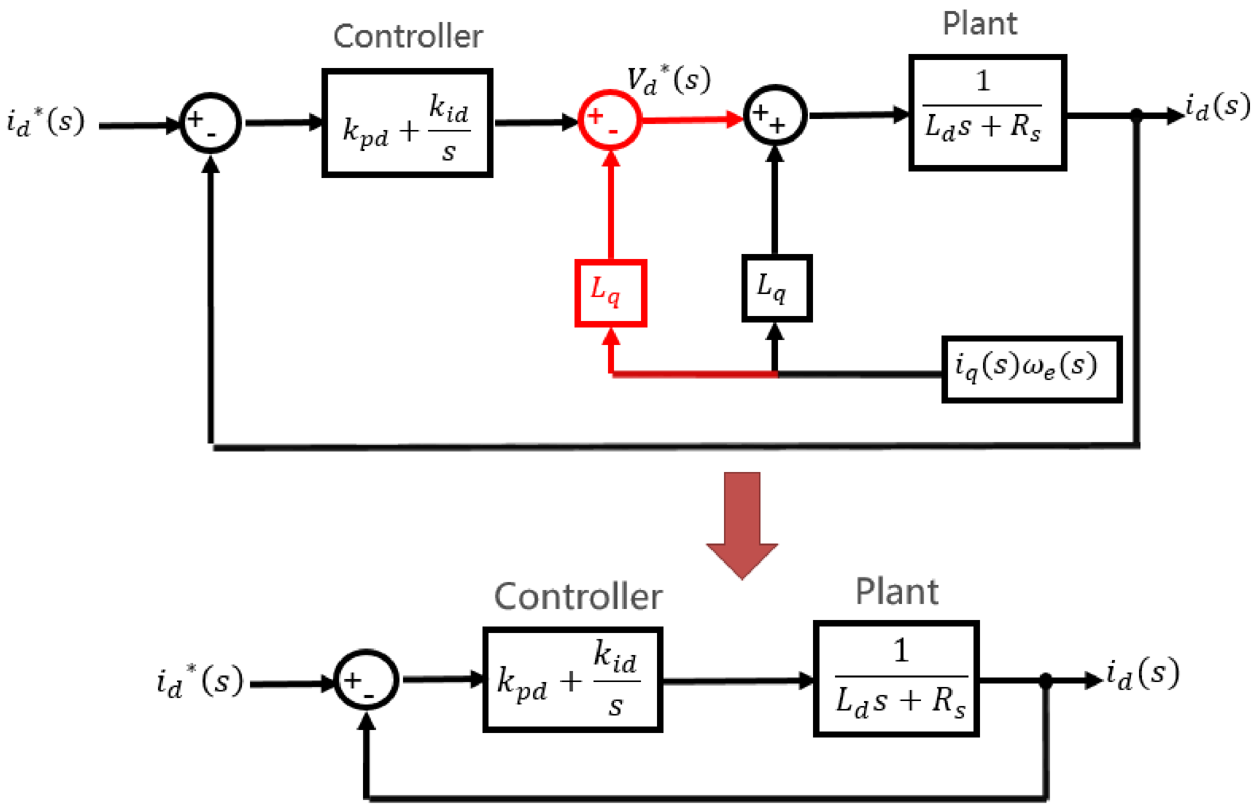
Handout 9 FOC

```
kp_q = 2.0 * 3.1415926 * fbw_i * Lq;
ki_q = 2.0 * 3.1415926 * fbw_i * Rs;
```



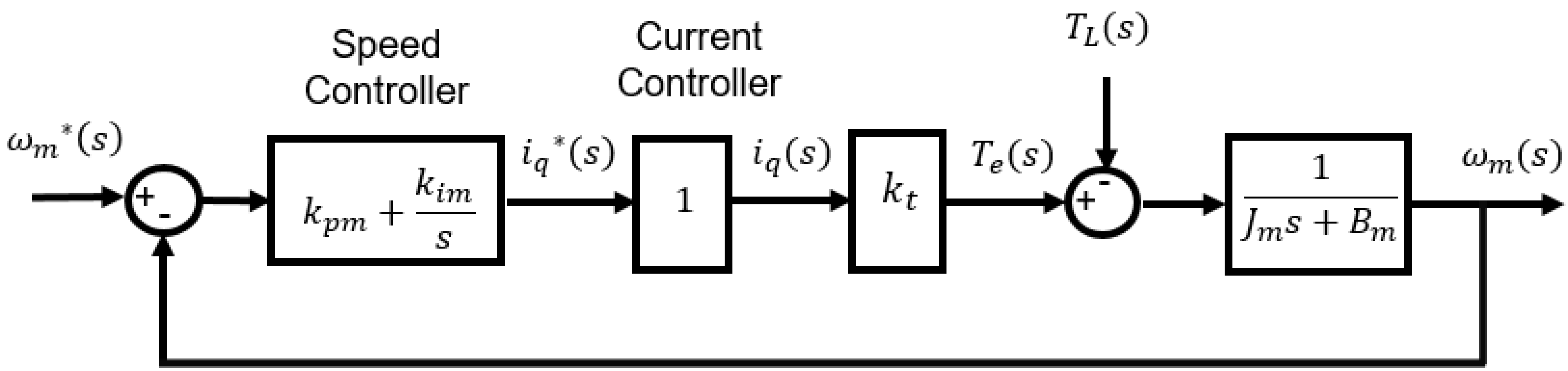
Handout 9 FOC

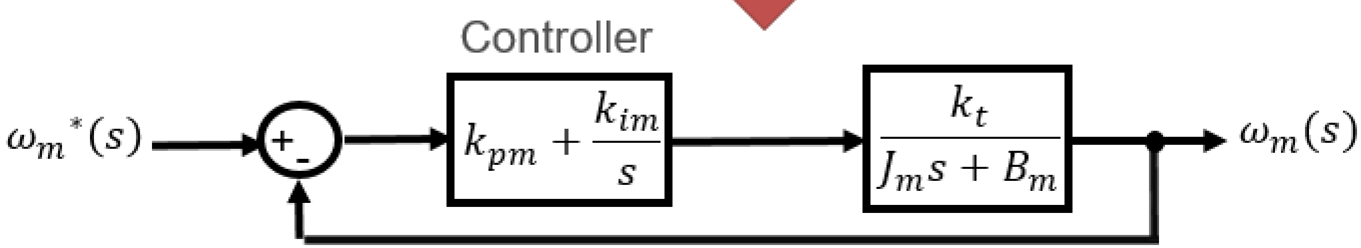
kp_d = 2.0 * 3.1415926 * fbw_i * Ld;
ki_d = 2.0 * 3.1415926 * fbw_i * Rs;



Handout 9 FOC

kp_w = 2.0 * 3.1415926 * fbw_w * J;
ki_w = 2.0 * 3.1415926 * fbw_w * B;





Handout 9 FOC

```
t_err = 1.0 / SwitchingFreq;
```

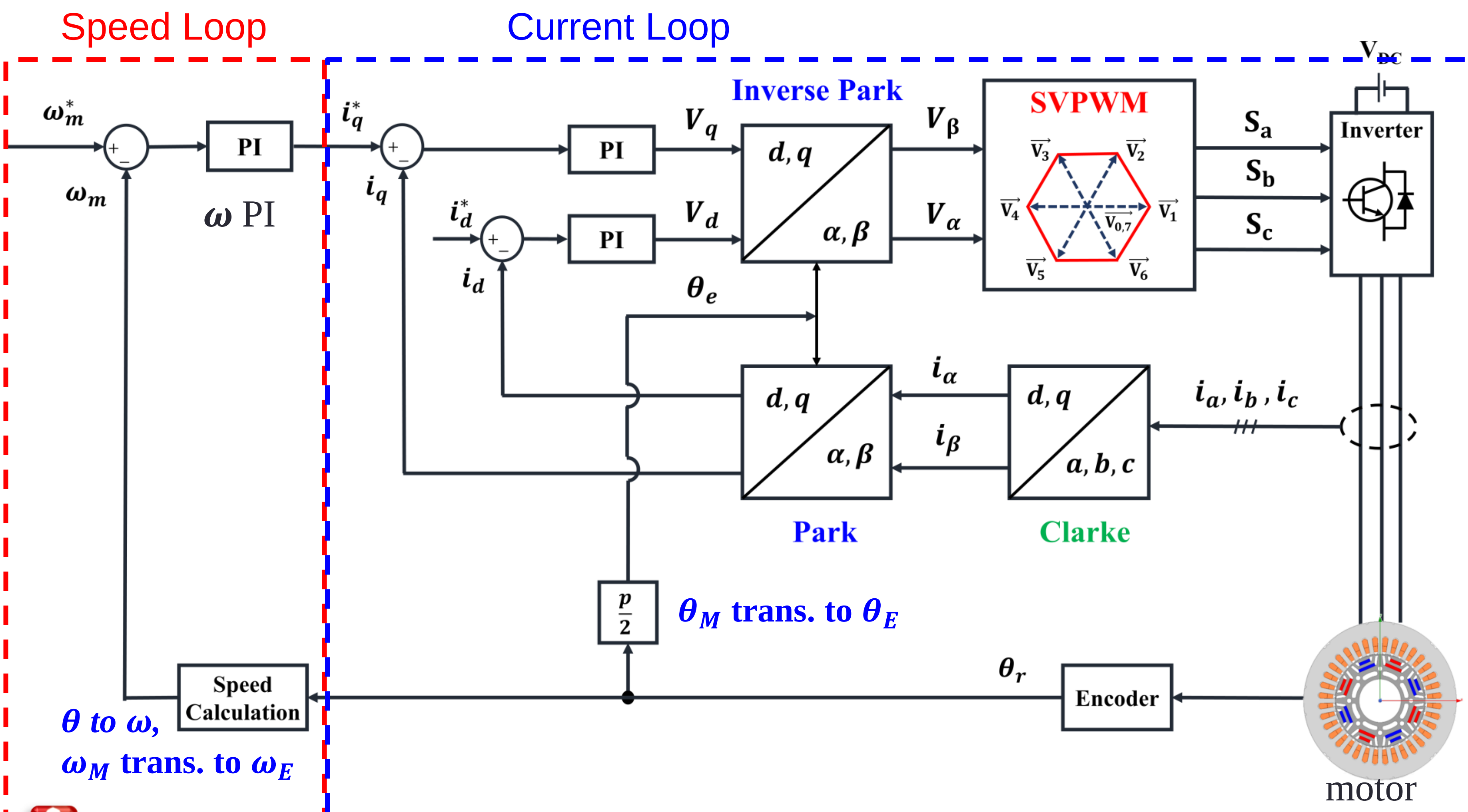
```
//Speed loop
s_w += (speed_comm - speed_fb) * t_err * Kt_rec;
iq_comm = kp_w * (speed_comm - speed_fb)
        + ki_w * s_w * 3.1415926 * 0.0333333;

if (iq_comm > i_max)
{
   iq_comm = i_max;
}
if (iq_comm < -i_max)
{
   iq_comm = -i_max;
}
```

Handout 9 FOC

```
//Current loop
s_d += (id_comm - id) * t_err;
s_q += (iq_comm - iq) * t_err;
vd = kp_d * (id_comm - id) + ki_d * s_d;
if (vd > (vdc * 0.577))
{
   vd = vdc * 0.577;
}
else if (vd < (-vdc * 0.577))
{
   vd = -vdc * 0.577;
}
vq = kp_q * (iq_comm - iq) + ki_q * s_q;
if (vq > (vdc * 0.577))
{
   vq = vdc * 0.577;
}
else if (vq < (-vdc * 0.577))
{
   vq = -vdc * 0.577;
}
```

Handout 9 FOC

Direct FOC block → id ≡ 0



Handout 9 FOC期末測試 Final Test

步驟一 Step1
確認座標轉換功能 Check PCT.

在微處理器中製作一時脈。亦可利用PWM中斷頻率(即切換頻率)。Make clock into program.
根據其速度製作出三角波的位置訊號。 Make virtual position signal.
配合弦波表製作模擬的三相電流波型。Make virtual three phase current signal.

將以上模擬訊號輸入座標轉換程式，確認是否能將三相弦波電流轉換α-β以及D-Q軸電流?
Check PCT. 3 phase to α-β and D-Q signal.

請解釋各種電流波形的相位角度關係。 Explain the relationship of their phase angle.

若轉換正確，
以eQEP程式讀取增量型編碼器的位置回授訊號取代模擬位置訊號， Read position with eQEP.
以ADC程式讀取電流計訊號取代模擬的電流訊號。 Read current with ADC.

Handout 9 FOC期末測試 Final Test

步驟二 (搭配HIL) Step2 work with JIL

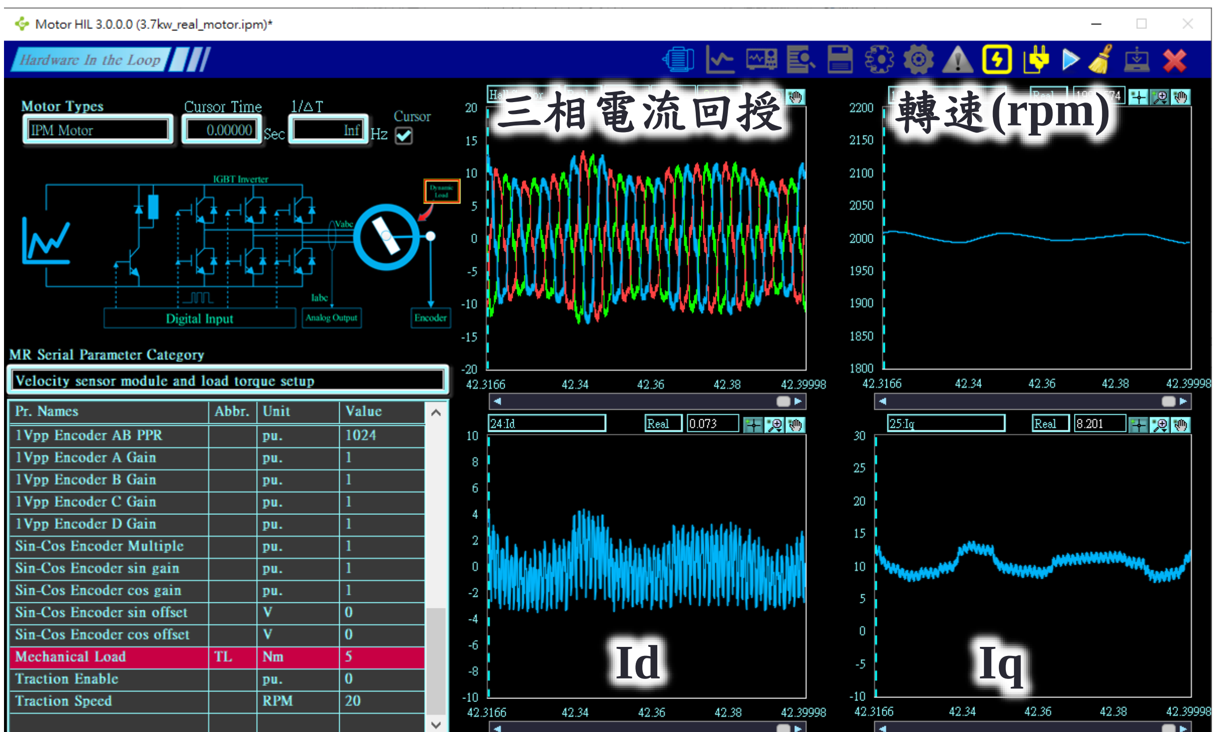
以外力緩慢帶轉馬達，確認轉速回授狀況，以及扇區判斷狀況。

Set traction speed in HIL, and check speed feedback of FOC program.

步驟三 Step3 Drive test

驅動控制虛擬馬達，並嘗試加載。記錄轉速轉矩和電流波形。

Drive motor, test with load, and record current and speed and torque.



Handout 9 FOC期末測試 Final Test

請完成FOC程式。並截圖記錄各波形的模擬情形。

並記得上MOODLE約時間，進行期末HIL實測。

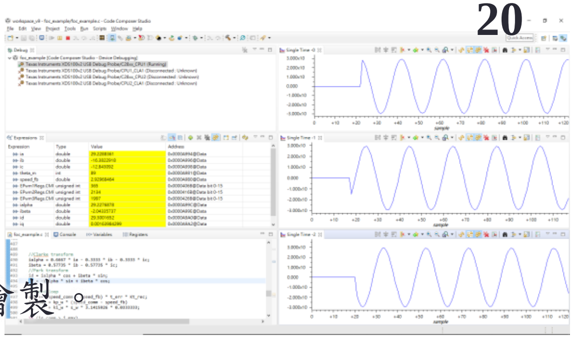
測試目標為實作測試時現場指定。可能範圍：速度20~3500 rpm，轉矩0.3~12 Nm。

Please complete the FOC program.
And take screenshot to record the simulation situation of each waveform.

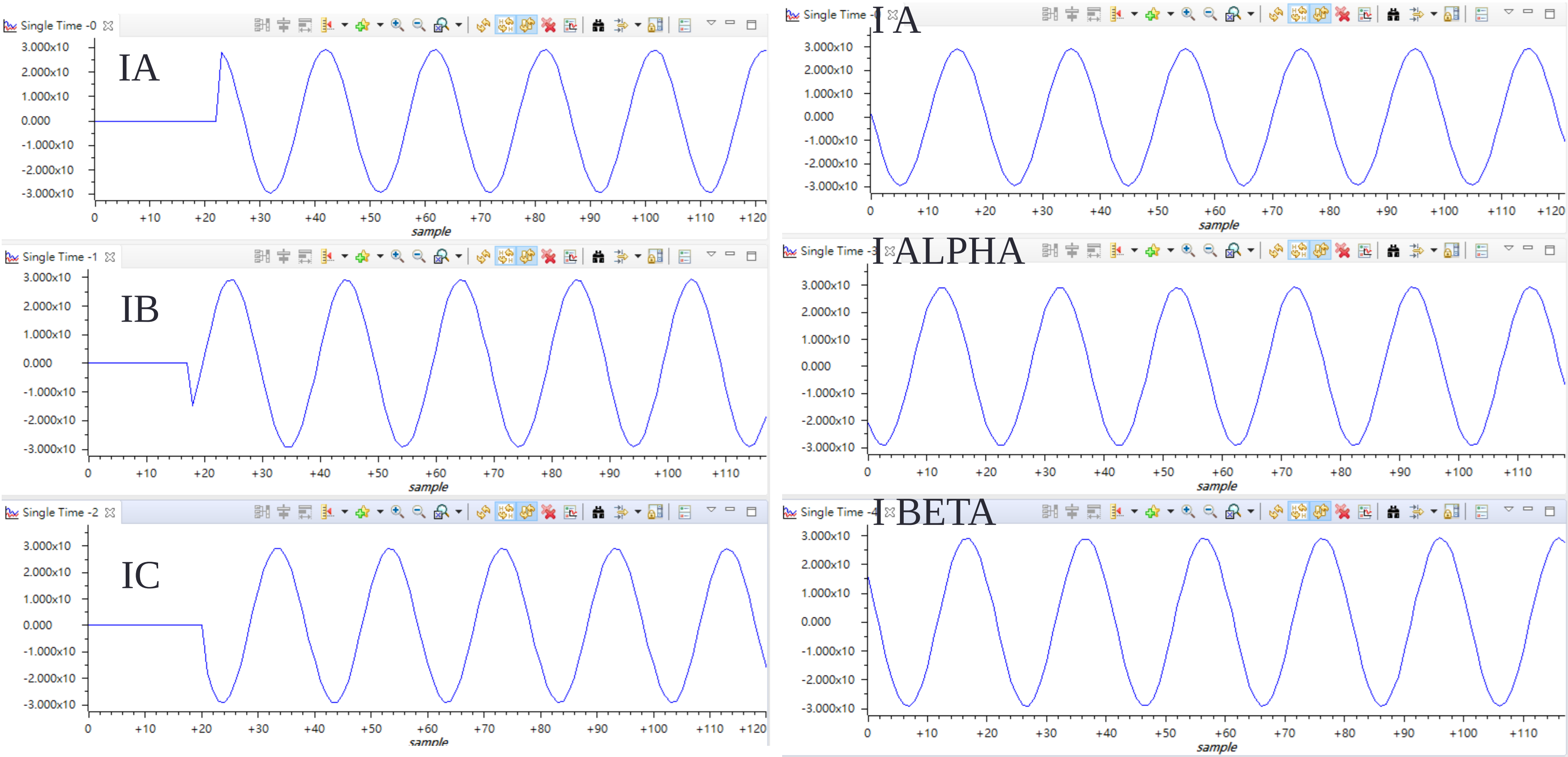
And use MOODLE to book test section for the final test with HIL .

Test condition will set at test. speed range is 20 to 3500 rpm, torque range is 0.3 to 12Nm.

Handout 9 FOC CCS Test

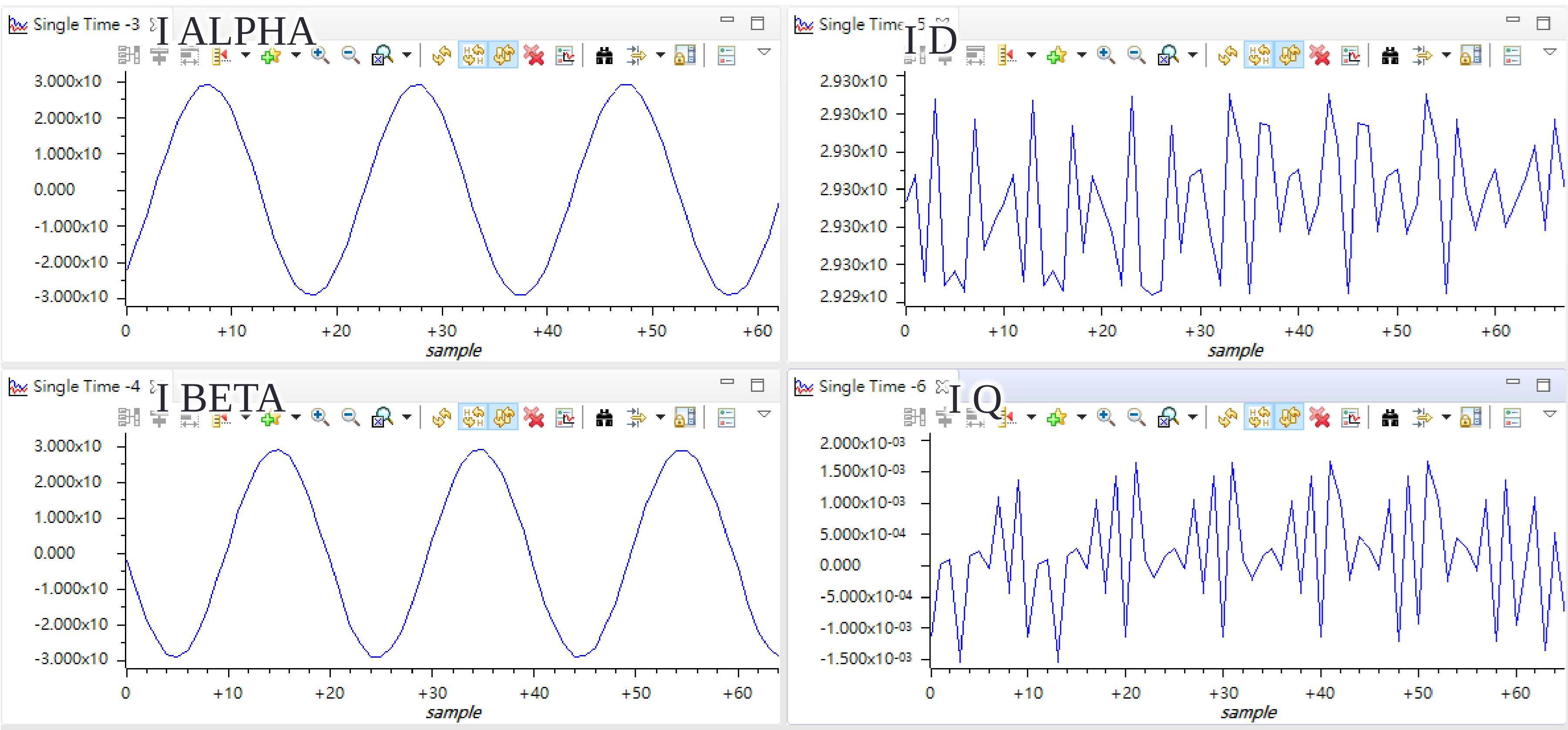


範例程式的執行圖:記得標記訊號名稱，也歡迎匯出用其他軟體繪製



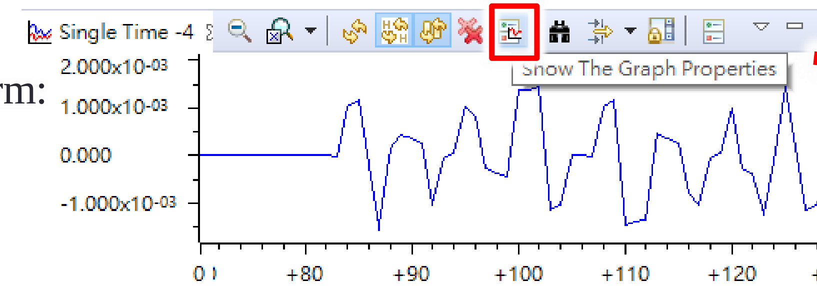
Handout 9 FOC CCS Test

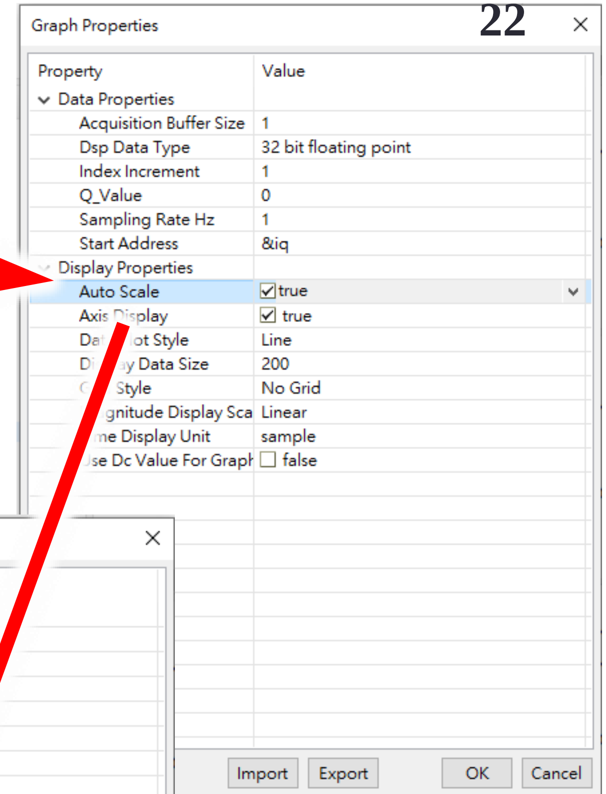
CCS test waveform:



Handout 9 FOC CCS Test

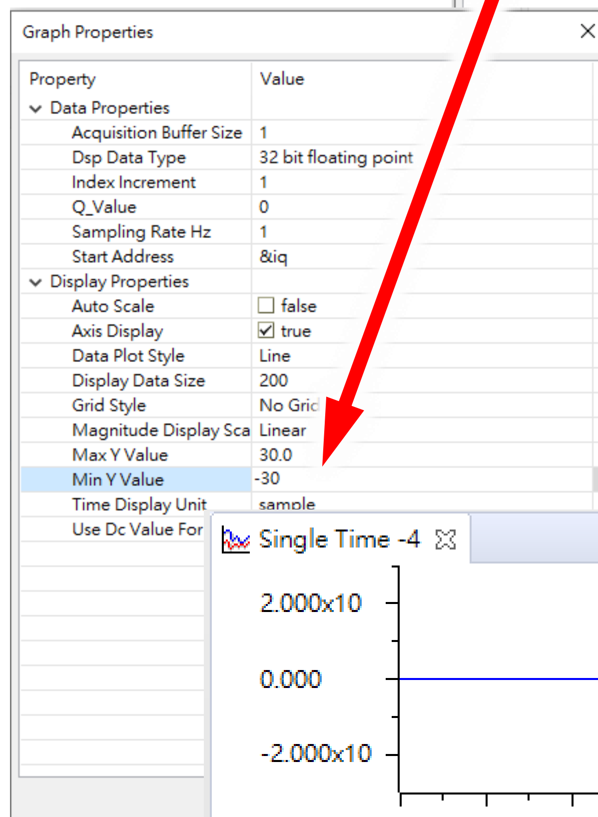
CCS test waveform:

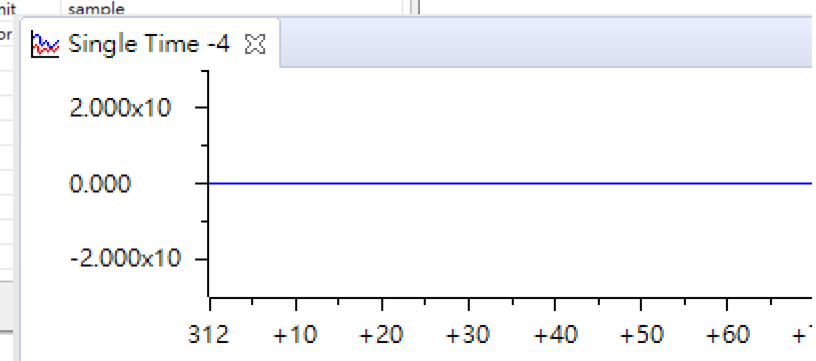




Auto Scale→ change to false and disable

Type in new legend.





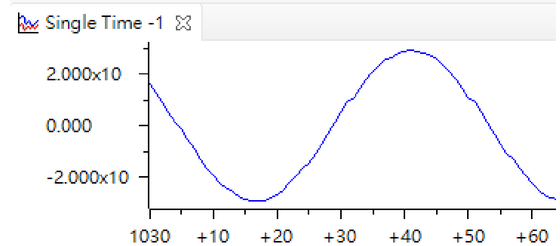
Handout 9 FOC CCS Test

CCS test waveform:

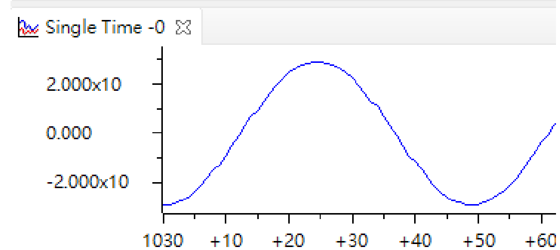
```
//////////////
TestTheta_eA = theta_e+90;
while (TestTheta_eA > 360)
{
    TestTheta_eA -= 360;
}
TestIa = (0.0001 * sine_table[TestTheta_eA] - 1.0) * 2000+2048;

TestTheta_eB = theta_e + 240+90;
while (TestTheta_eB > 360)
{
    TestTheta_eB -= 360;
}
TestIb = (0.0001 * sine_table[TestTheta_eB] - 1.0) * 2000+2048;
TestTheta_eC = theta_e + 120+90;
while (TestTheta_eC > 360)
{
    TestTheta_eC -= 360;
}
TestIc = (0.0001 * sine_table[TestTheta_eC] - 1.0) * 2000+2048;

///////////
```

Console | Expressions

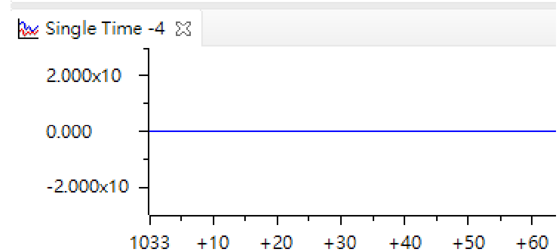
Expression	Value
ia	-26.7625713
ib	3.06279373
ic	23.703228
iq	0.00115203857
id	29.2952023
theta_m	321
speed_fb	1.19999886
EPwm1Regs.CMPA.	0
EPwm2Regs.CMPA.	2500
EPwm3Regs.CMPA.	1592



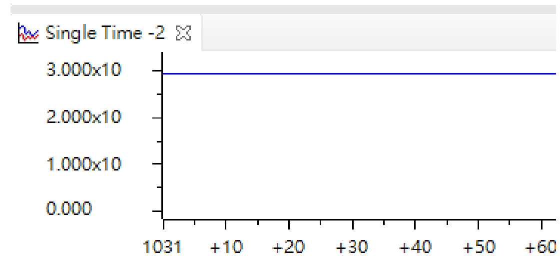
I A



I B



I Q



I D

Handout 9 FOC CCS Test

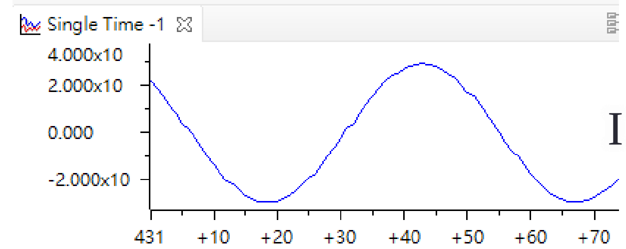
CCS test waveform:

```
TestTheta_eA = theta_e+0;
while (TestTheta_eA > 360)
{
    TestTheta_eA -= 360;
}
TestIa = (0.0001 * sine_table[TestTheta_eA] - 1.0) * 2000+2048;

TestTheta_eB = theta_e + 240+0;
while (TestTheta_eB > 360)
{
    TestTheta_eB -= 360;
}
TestIb = (0.0001 * sine_table[TestTheta_eB] - 1.0) * 2000+2048;
TestTheta_eC = theta_e + 120+0;
while (TestTheta_eC > 360)
{
    TestTheta_eC -= 360;
}
TestIc = (0.0001 * sine_table[TestTheta_eC] - 1.0) * 2000+2048;
```

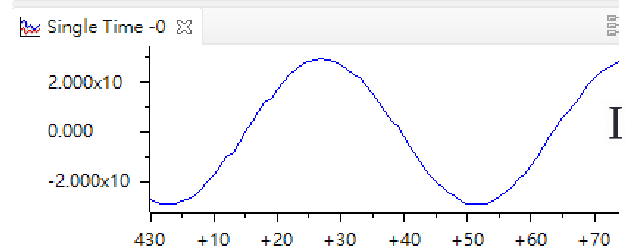
Try another phase shift, example 180 and so on.

Console | Expressions

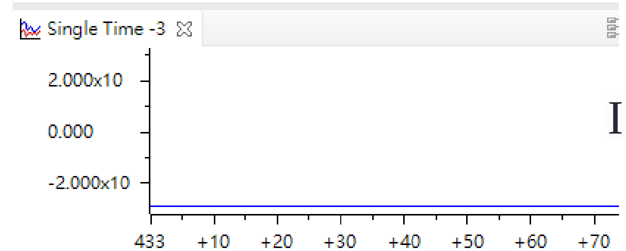
Expression	Value	Type
ia	-28.4266987	double
ib	8.07567978	double
ic	20.3544693	double
iq	-29.2984085	double
id	0.00191640854	double
theta_m	161	int
speed_fb	0.0	double
EPwm1Regs.CMPA.	0	unsign
EPwm2Regs.CMPA.	2500	unsign
EPwm3Regs.CMPA.	1212	unsign



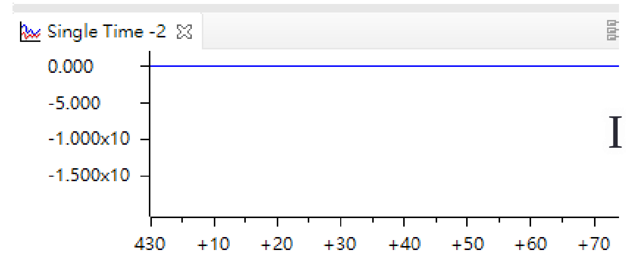
I A



I B



I Q

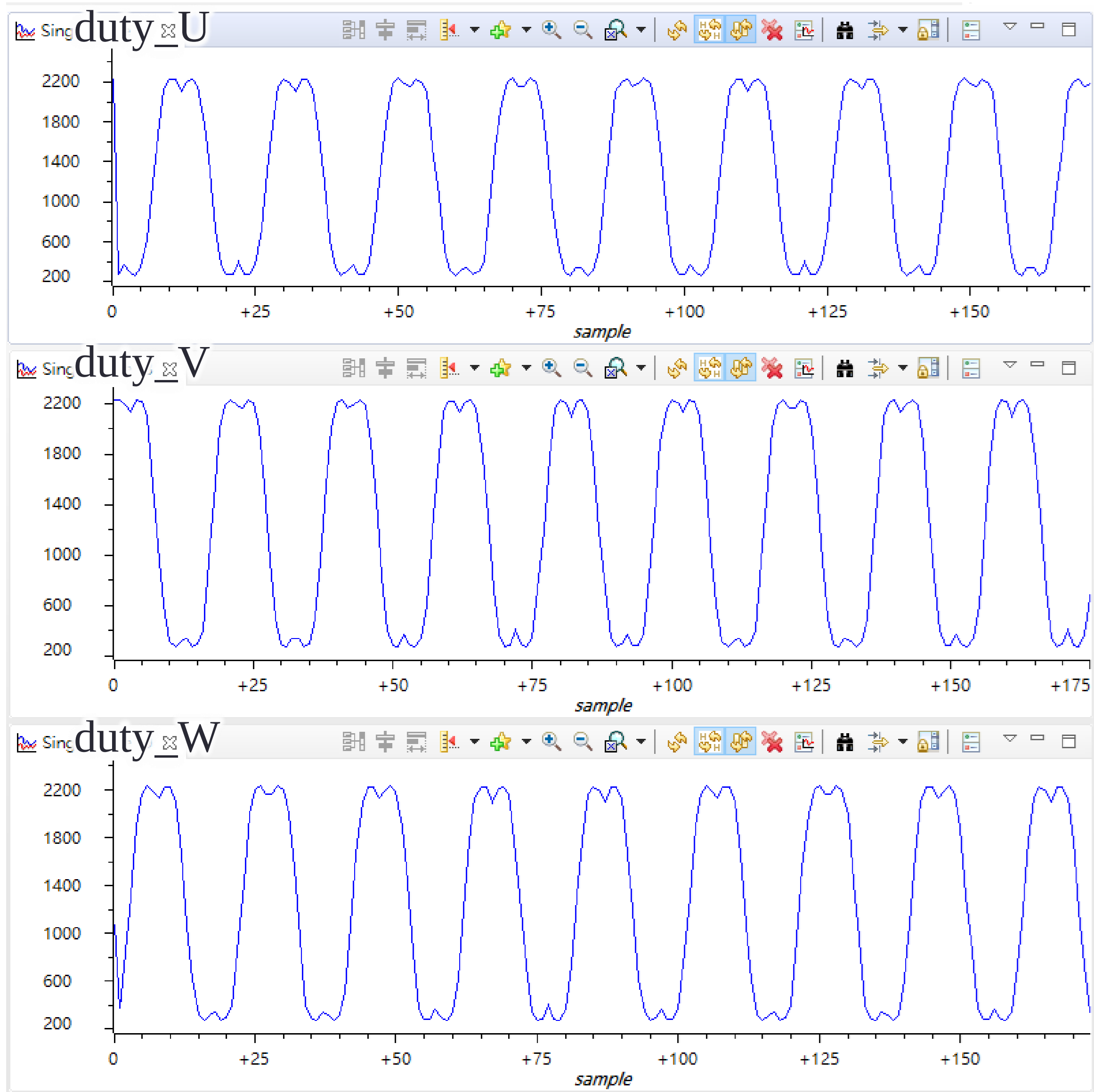


I D

Handout 9 FOC CCS Test

To avoid saturation, the test conditions can be reduced (after all, the original test current is 2000/2048, which may be too large)

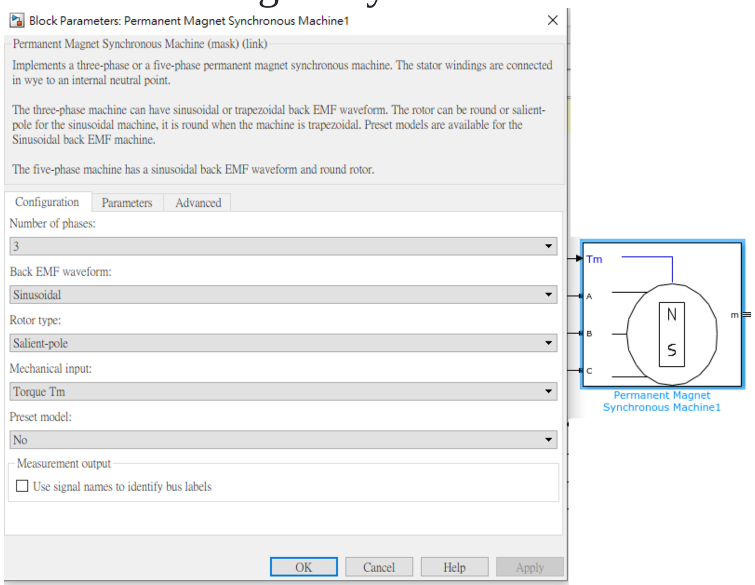
```
valpha = (vd*cos-vq*sin)*Xvalue;
vbeta = (vd*sin+vq*cos)*Xvalue;
```



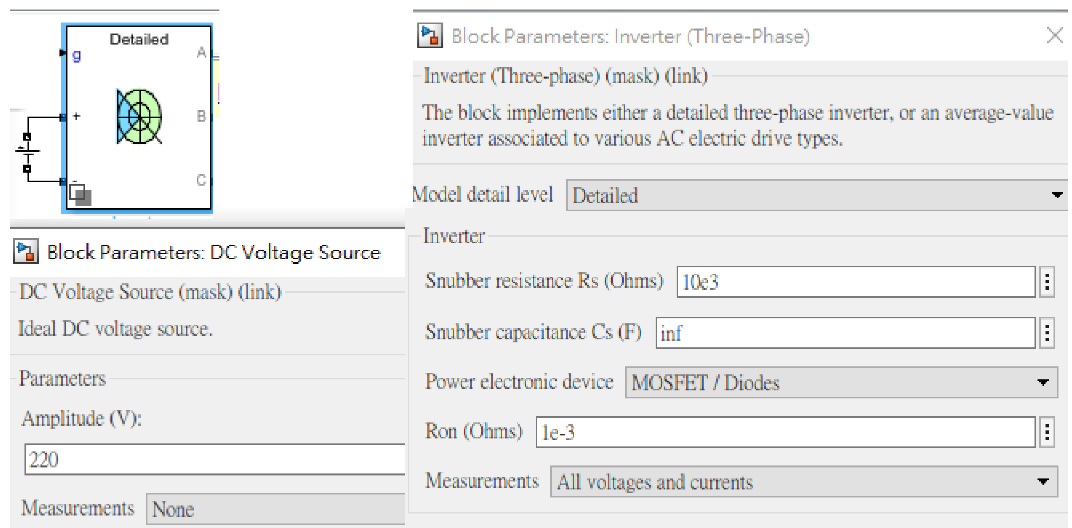
Handout 9 FOC in Simulink

To prepare for the next lesson, check that your Matlab Simulink has the simscape models installed.

Permanent Magnet Synchronous Machine



Inverter (three-phase)



(Inverter can be replaced by other discrete model.)