模擬輔助設計用於馬達驅動系統研發及驗證方法

臺北科技大學 電機系
黃明熙

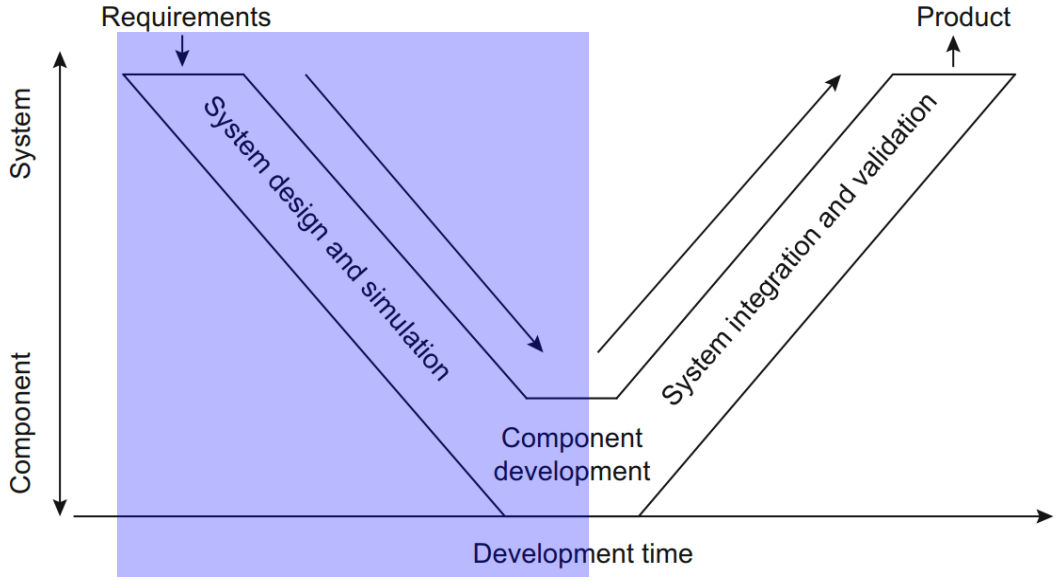
2024.06.25

大綱

- 模擬輔助設計簡介
- 馬達驅動系統基礎
- 模擬軟體用於馬達及其驅動器設計
- 結論
- Q and A

模擬輔助設計簡介

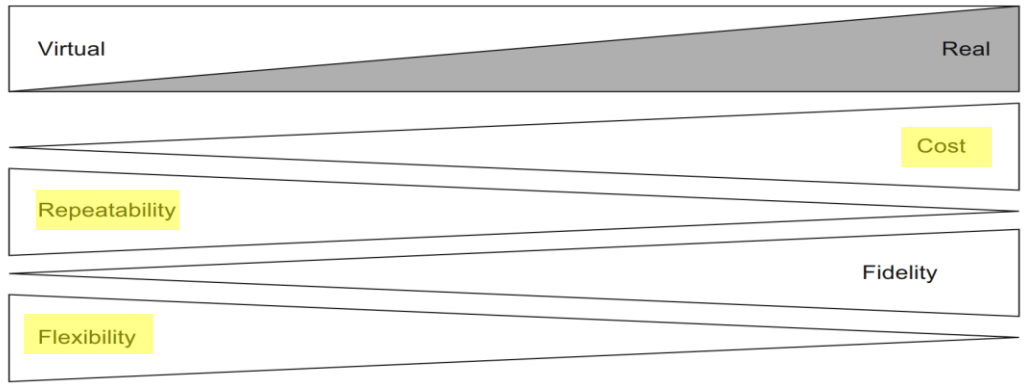
◘ V-model 研發流程



模擬(Simulation)與
驗證(Verification)

每一階段
皆須做模
擬與驗證

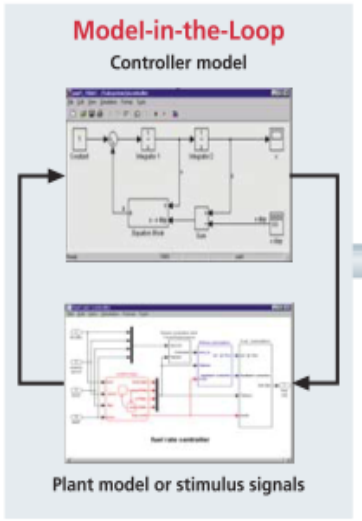
	xCU Test	Engine testbed	Transmission testbed	E-Motor tesbed	Battery tesbed	Powertrain testbed	Vehicle CD testbed	Road test
VALIDATION								Maneuvers
								Chassis
							Wheels	Wheels
					Battery	Battery	Battery	Battery
				E-Motor		E-Motor	E-Motor	E-Motor
			Transmission			Transmission	Transmission	Transmission
		IC engine				IC engine	IC enginer	IC engine
	xCU	ECU	TCU	xCU	BMS	xCU	xCU	xCU
SIMULATION	IC engine		IC engine	IC engine	IC engine			
	Transmission	Transmission		Transmission	Transmission			
	E-Motor	E-Motor	E-Motor		E-Motor			
	Battery	Battery	Battery	Battery				
	Wheels	Wheels	Wheels	Wheels	Wheels	Wheels		
	Chassis	Chassis	Chassis	Chassis	Chassis	Chassis	Chassis	
	Maneuvers	Maneuvers	Maneuvers	Maneuvers	Maneuvers	Maneuvers	Maneuvers	

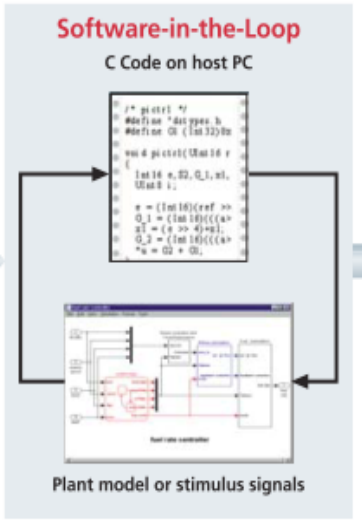


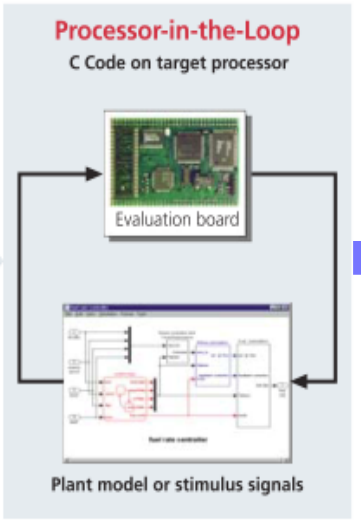
Source: Michael Paulweber and Klaus Lebert, Powertrain Instrumentation and Test Systems, Springer 2016

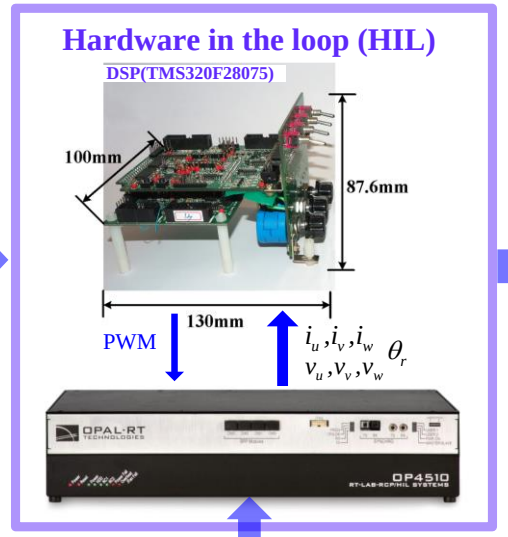
模擬輔助設計簡介

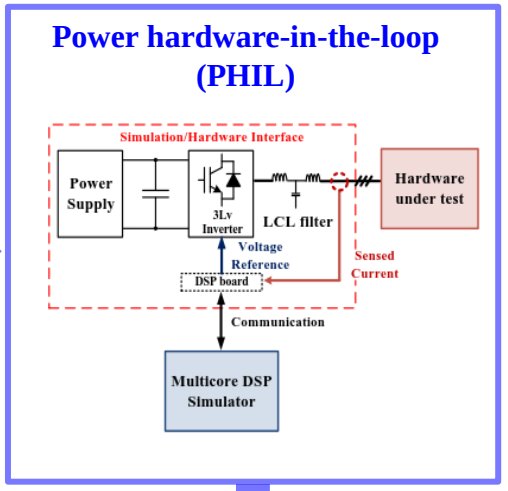
□產品開發模式 - 模擬導向設計







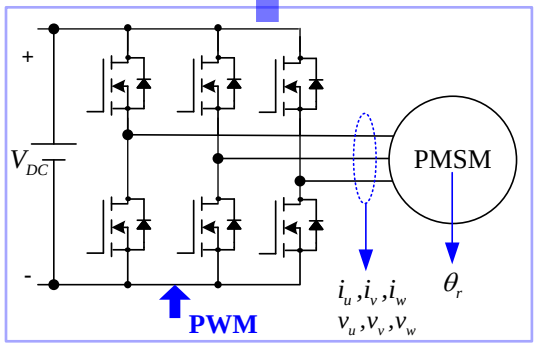




***Plant nonlinearity**
***Controller design**

***Integration and consistency (MISRA-C)**

***Portability for dedicated microprocessor**

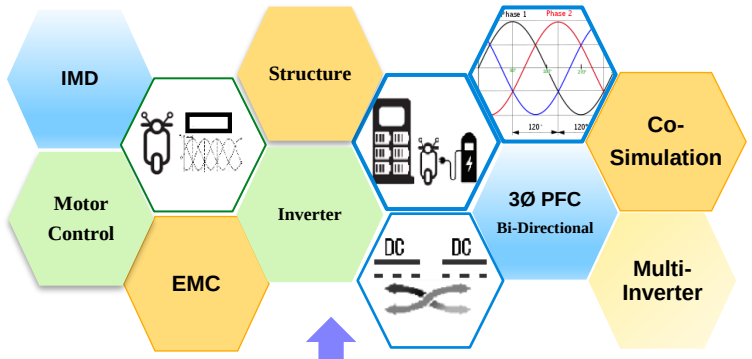


Real system test

＊MISRA:Motor Industry Software Reliability Association

模擬輔助設計簡介

◘ 虛擬設計與實務研究並行



如何確認模擬結果是正確的?

驗證方法及合適量測設備

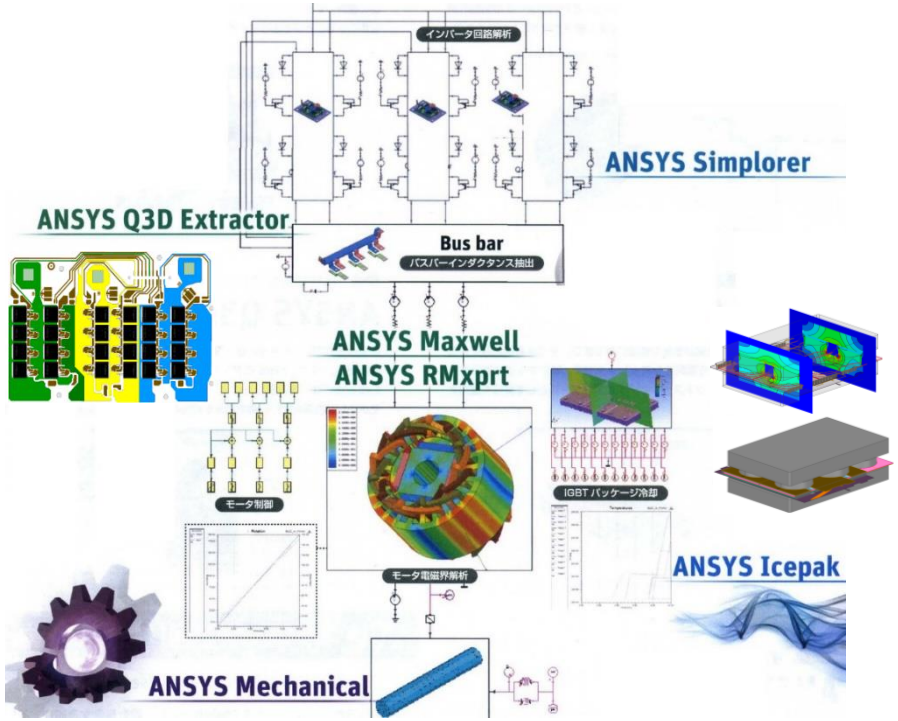
實務研究
Practical research

虛擬設計
Virtual design

Multi-physics and coupled field:
Electric, magnetic, thermal, and mechanical

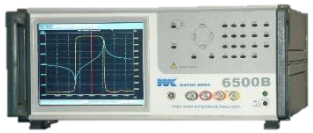
Ansys academic partner

Multi-physics and co-simulation



Verification equipment

WK6500B



Agilent N9020A

FRA5097

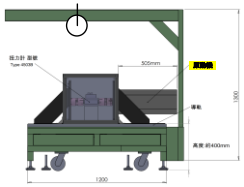
RTO 64

YOKOGAWA WT1800

YOKOGAWA PX8000

FLIR T540

M-G set



大綱

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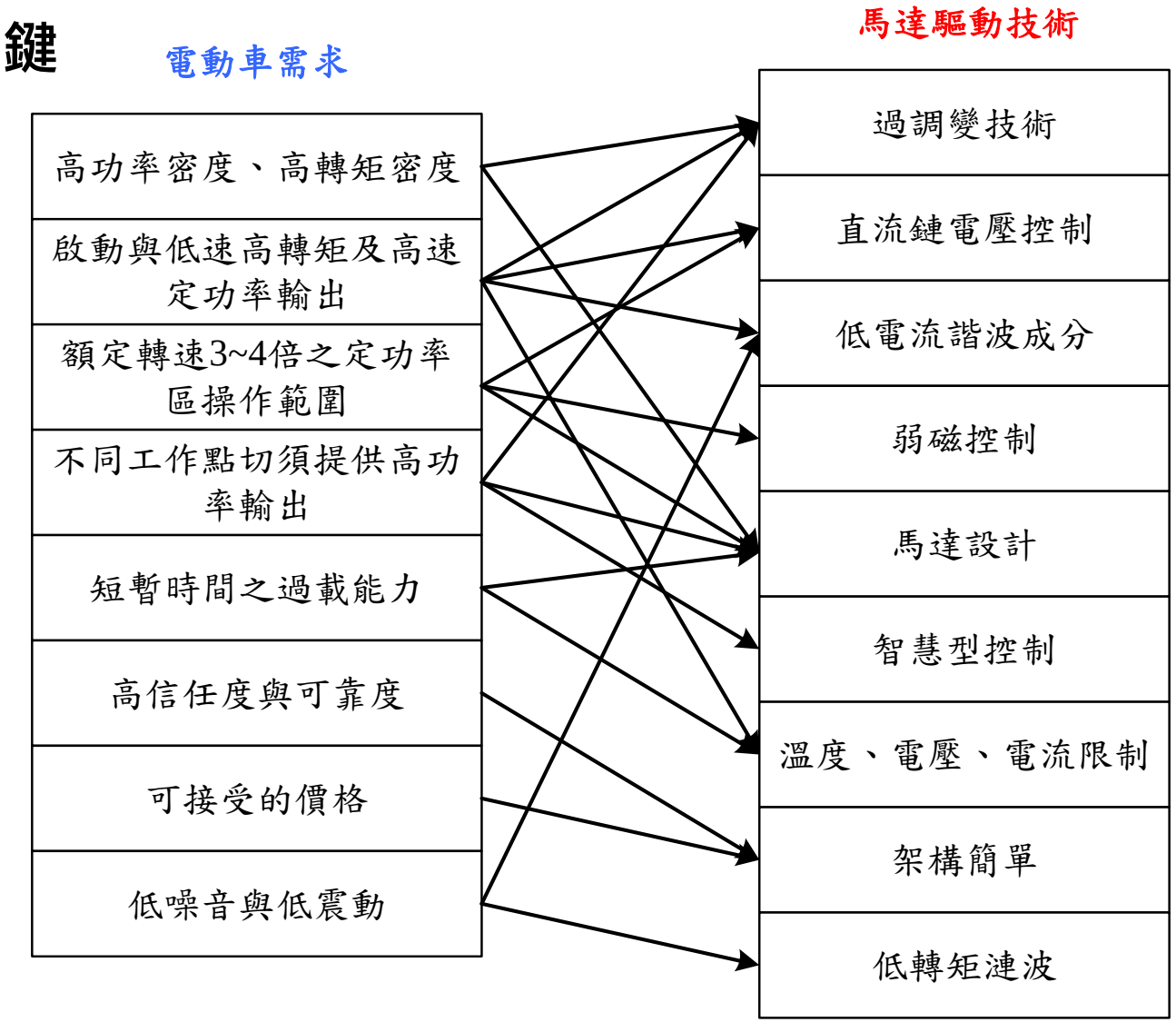
- **馬達驅動系統基礎**
- 模擬軟體用於馬達及其驅動器設計
- 結論
- Q and A

馬達驅動系統基礎

□ 系統需求與馬達及其驅動控制之關係

√ 馬達特性是滿足系統需求之關鍵

√ 驅動技術須配合馬達特性來滿足系統需求>性價比

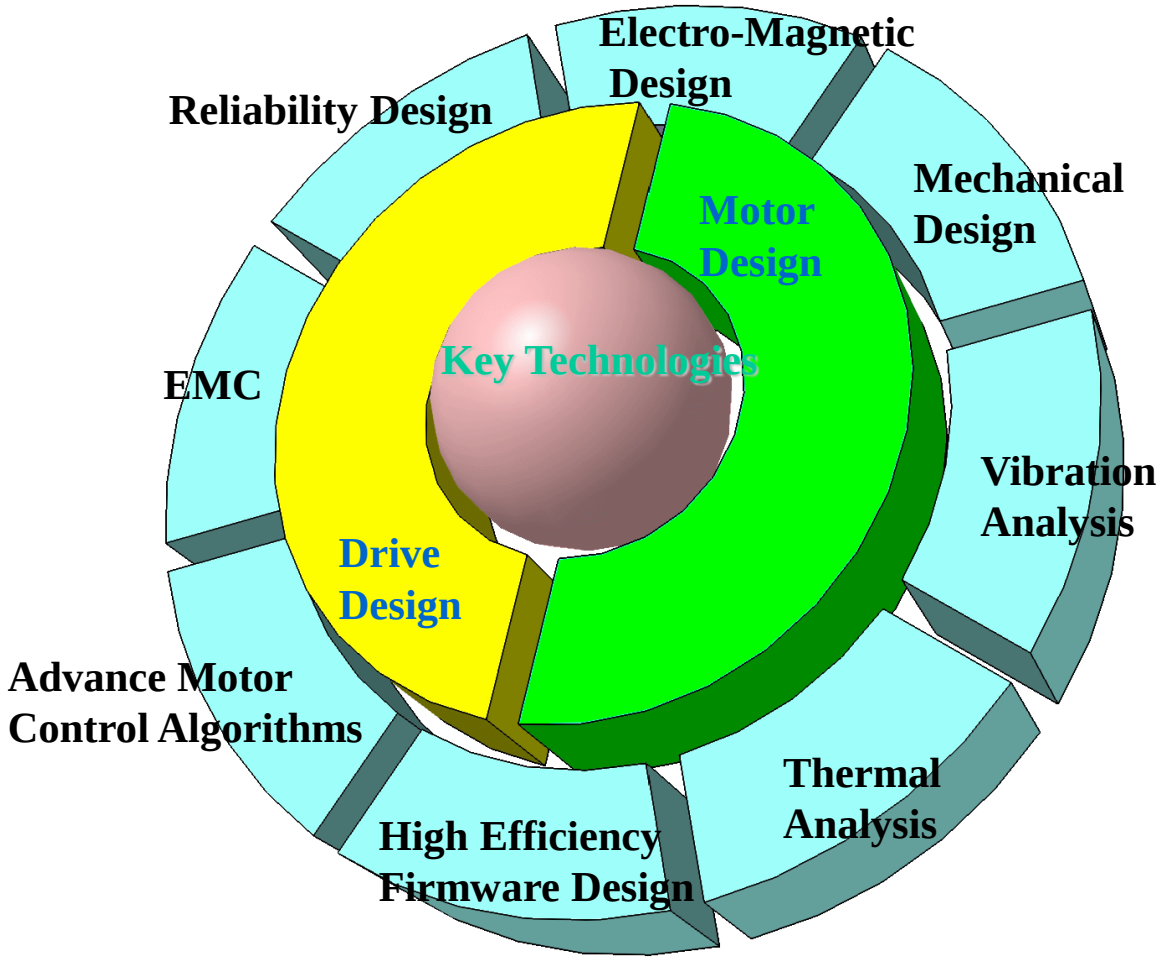


馬達驅動系統基礎

◘ 馬達及其驅動器之核心技術

✓ 電、磁、力、熱流及結構之跨領域技術 >> 不同物理量之相互影響

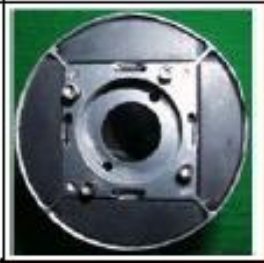
✓ 傳統設計方法已難以因應快速設計之需求



馬達驅動系統基礎

◘ 馬達分類及特性比較

永磁同步馬達　　感應馬達　　磁阻馬達

		Permanent Magnet Synchronous Motor			Induction Motor	Reluctance Motor	
		Rare-earth Magnet	Ferrite Magnet				
			Radial-type	Axial-type		SynRM	SRM
Stator Structure							
Rotor Structure							
Features for Industrial Use	Size	◎	△	○	×	△	△
	Efficiency	◎	○	○	×	△	○
	Cost	×	○	◎	○	◎	◎
	Noise	○	◎	◎	○	△	×
	Total	○	○	◎	×	△	△

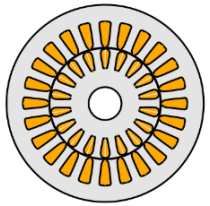
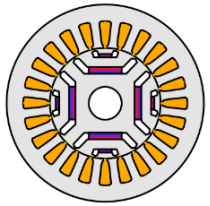
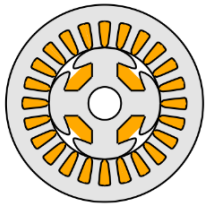
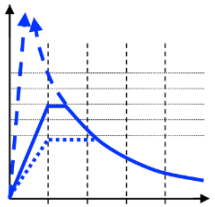
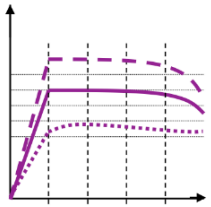
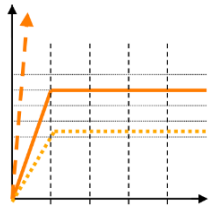
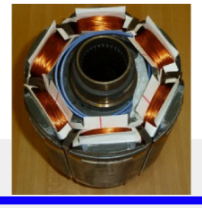
體積
效率
成本
噪音
總評

Source: Hitachi

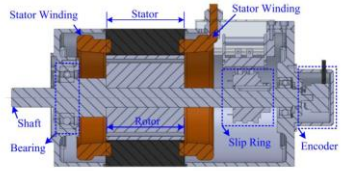
馬達驅動系統基礎

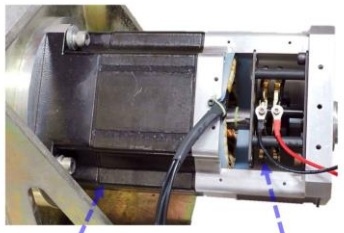
◘ 馬達分類及特性比較

電氣激磁交流同步馬達(Electric excited AC synchronous motor, EESM)

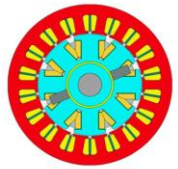
	Asynchronous Motor	Internal perm. Motor	SSM
Principle			
Large speed range with constant power	 NO	 YES	 YES
Magnet needed	No	Yes, 1.5 kg/100 kW Peak	NO
Disadvantage	Poor Power Curve	Magnets	Construction
Advantage	Construction	Good Power Curve	No Magnets, Good Power Curve
Rotor			

無稀土磁石





EESM 2D

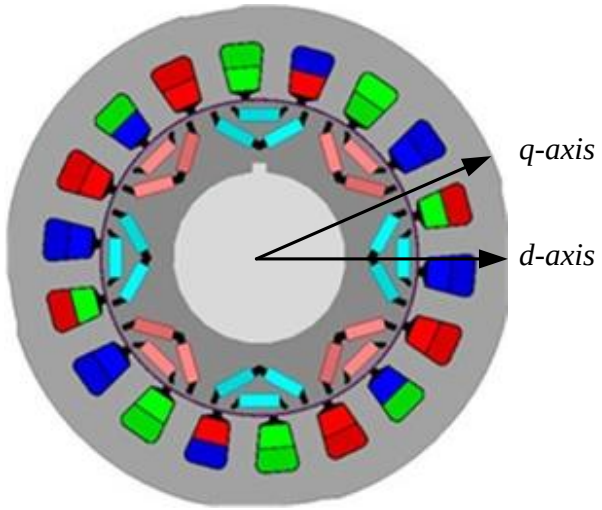


EESM rotor/stator

Illiano, E, “Design of a brushless separately excited synchronous motor,” www.brusa.biz

馬達驅動系統基礎

◘ 內置磁石永磁同步馬達及其主導方程式(理想條件)

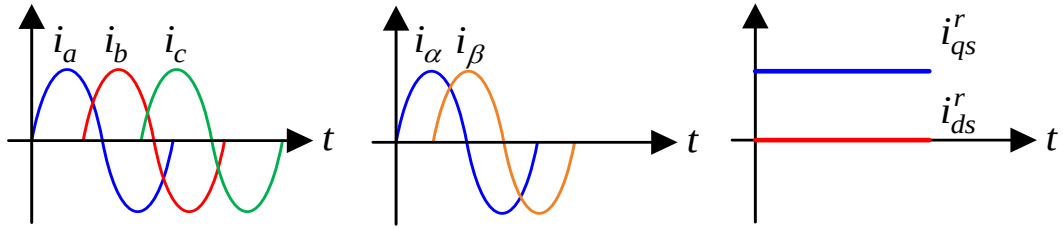


$$\begin{bmatrix} v_{qs}^r \\ v_{ds}^r \end{bmatrix} = \begin{bmatrix} r_s + pL_{qs} & \omega_r L_{ds} \\ -\omega_r L_{qs} & r_s + pL_{ds} \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_m \\ 0 \end{bmatrix}, \quad \begin{bmatrix} \lambda_{qs}^r \\ \lambda_{ds}^r \end{bmatrix} = \begin{bmatrix} L_{qs} & 0 \\ 0 & L_{ds} \end{bmatrix} \begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_m \end{bmatrix}$$

$$T_e = \frac{3}{2}\frac{P}{2}[\lambda_m i_{qs}^r + (L_{ds} - L_{qs}) i_{qs}^r i_{ds}^r] = \frac{3}{2}\frac{P}{2}\lambda_m i_{qs}^r + \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs}) i_{qs}^r i_{ds}^r$$

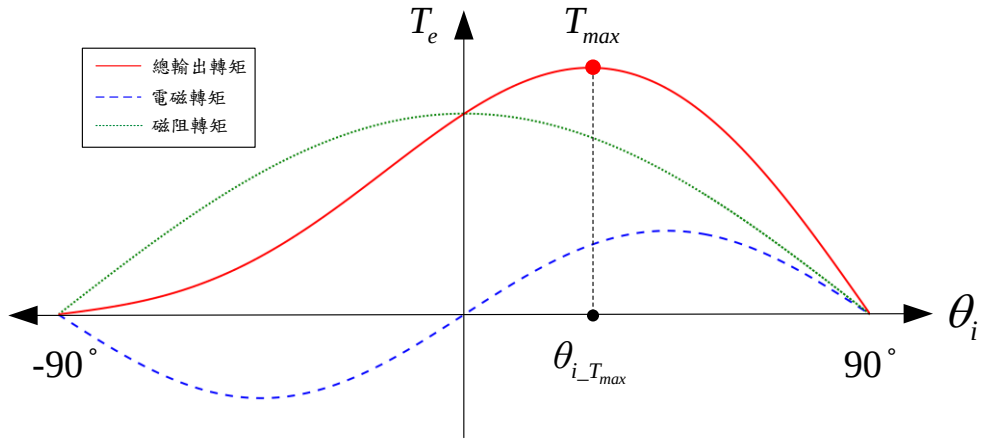
電磁轉矩　　磁阻轉矩

$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_m I_s \cos(\theta_i) + \frac{(L_{qs} - L_{ds})}{2} I_s^2 \sin(2\theta_i)\right]$$



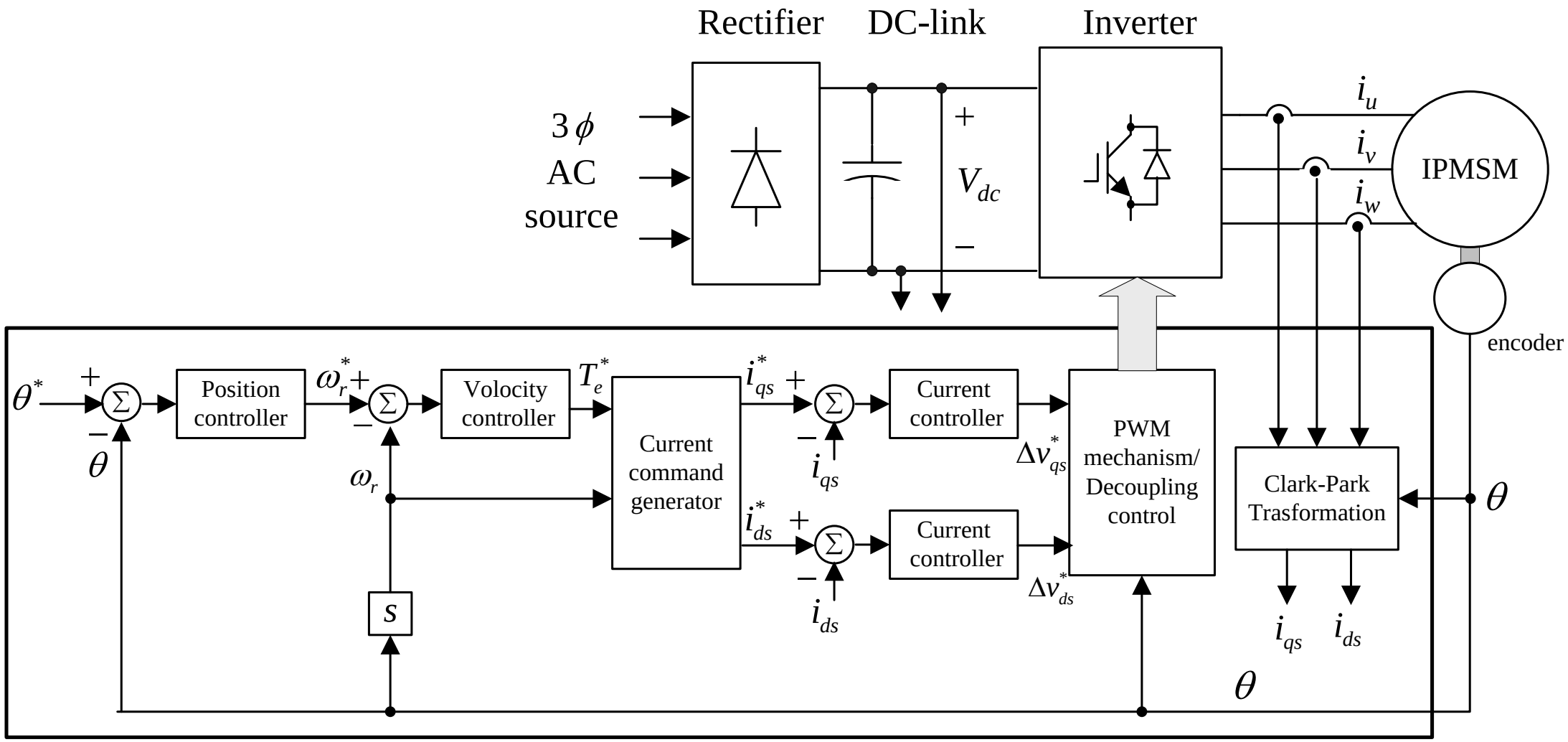
三相靜止框　　兩軸靜止框　　兩軸同步框

理想條件



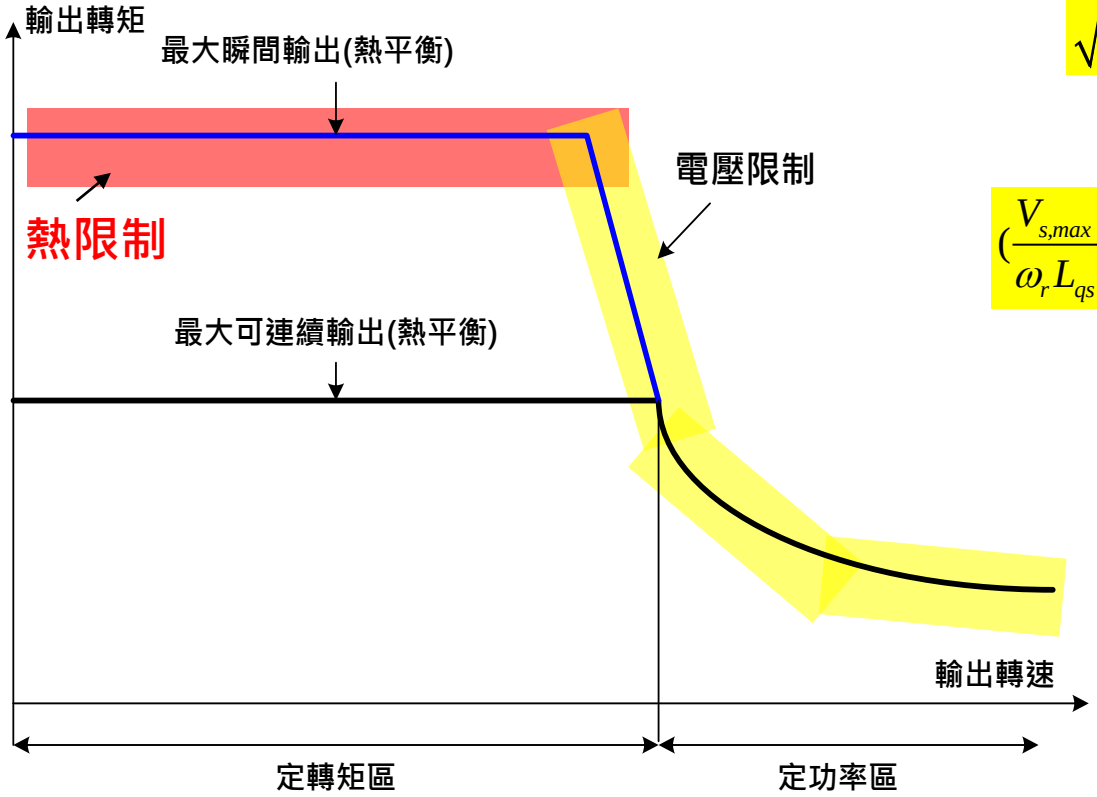
馬達驅動系統基礎

◘ 驅動器控制架構



馬達驅動系統基礎

◘ 馬達輸出特性-轉矩 vs. 速度

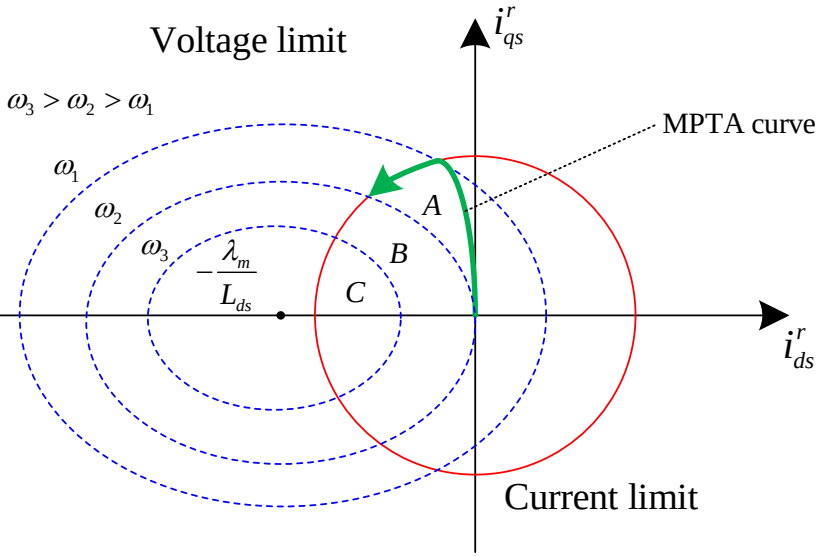


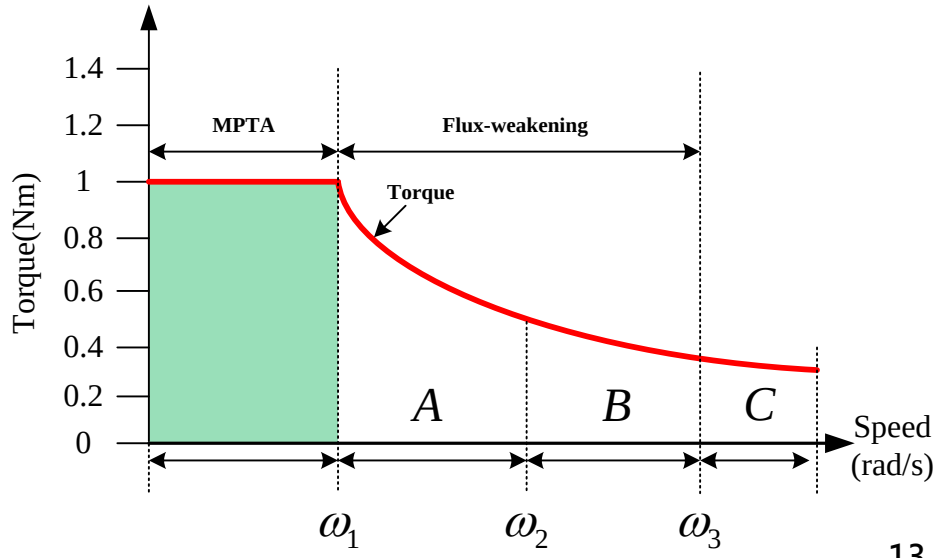
電壓及電流限制

$$\sqrt{(v_{ds}^r)^2+(v_{qs}^r)^2} \le V_{s,max}$$

$$\sqrt{(i_{ds}^r)^2+(i_{qs}^r)^2} \le I_{s,max}$$

$$\left(\frac{V_{s,max}}{\omega_r L_{qs}}\right)^2 \ge \left(\frac{L_{ds}}{L_{qs}}\right)^2\left(i_{ds}^r+\frac{\lambda_m}{L_{ds}}\right)^2+(i_{qs}^r)^2$$





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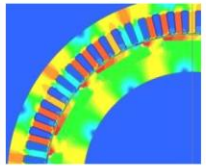
模擬軟體用於馬達及其驅動器設計

◘ 多物理量耦合分析(Multi-physics coupled fields analysis)-模擬協同設計

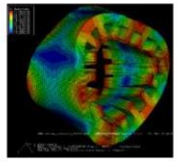
IGBT & WBG devices

HF laminated steel

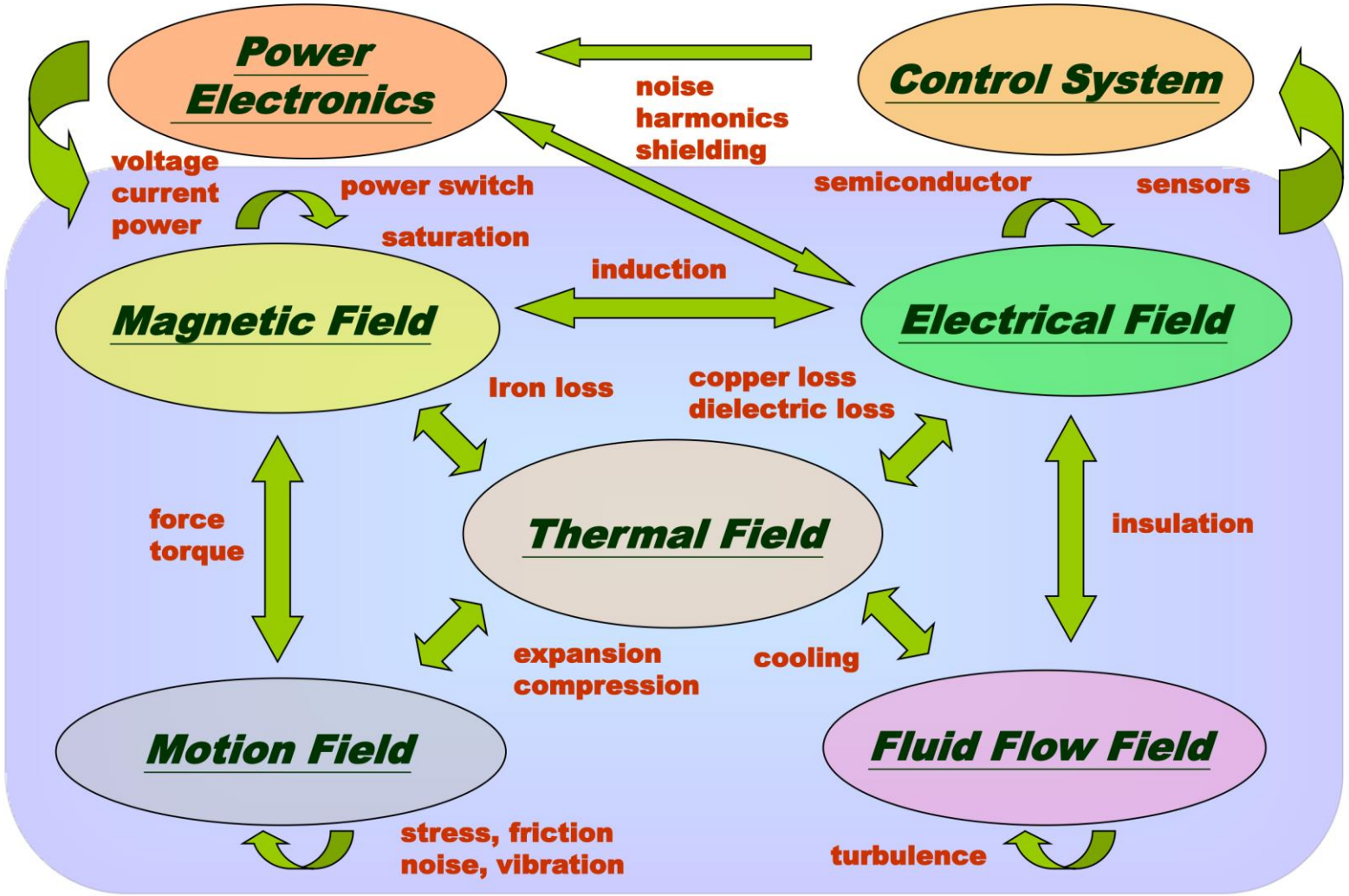
NdFeB magnet



Flux

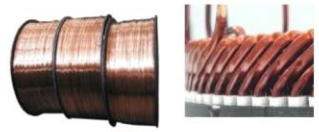


NVH

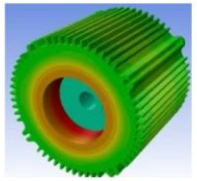


DSP

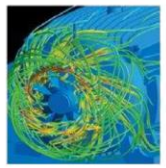
Resolver & Encoder



Magnet wire



Heat transfer

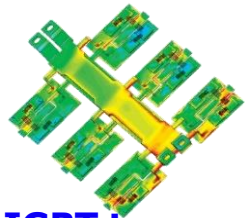


Flow

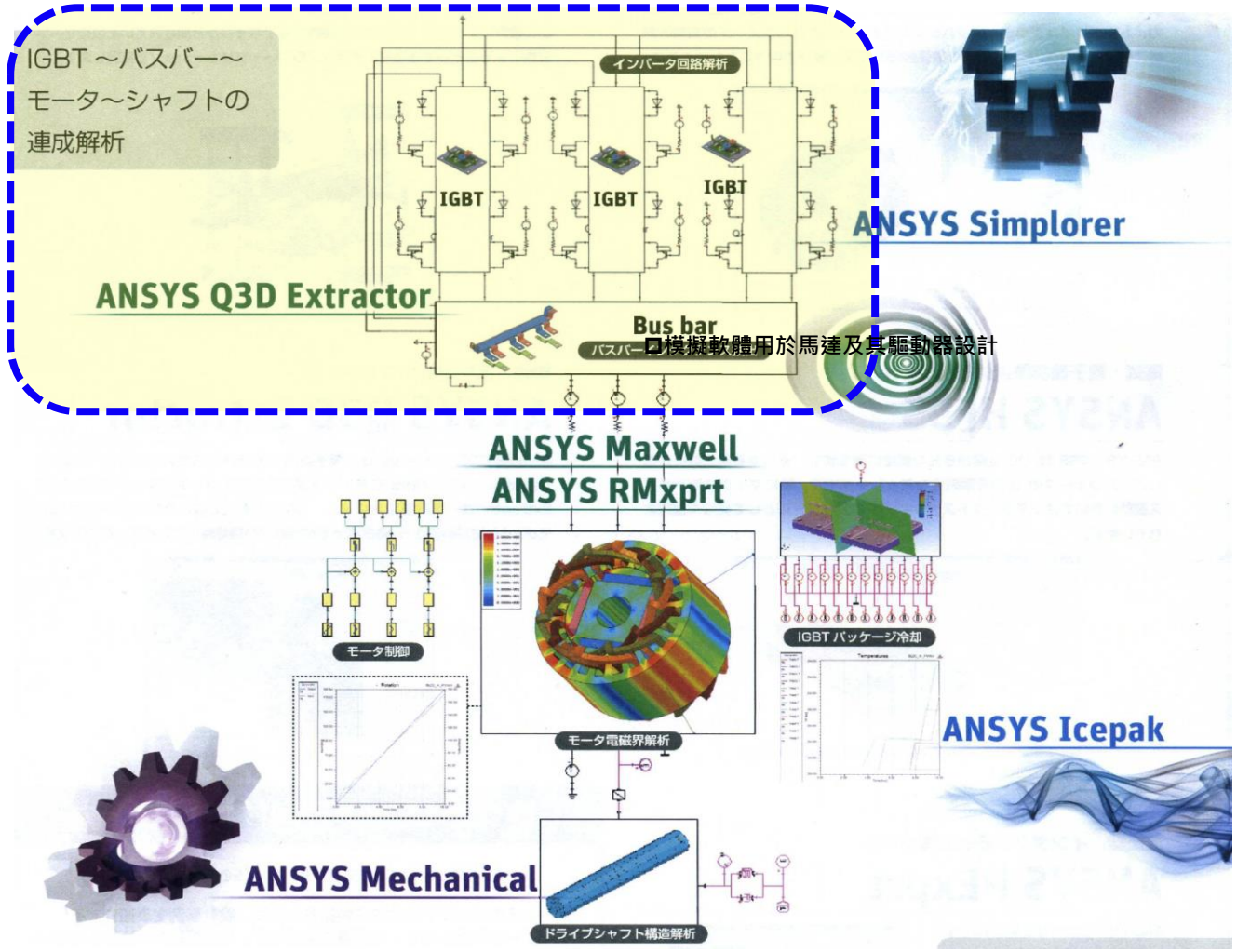
模擬軟體用於馬達及其驅動器設計

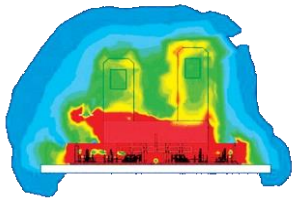
◘ 馬達及驅動器之模擬環境

- ✓ 多物理量(Multi-physics) : electric, magnetic, mechanic and thermal
- ✓ 耦合場分析(coupled field analysis)



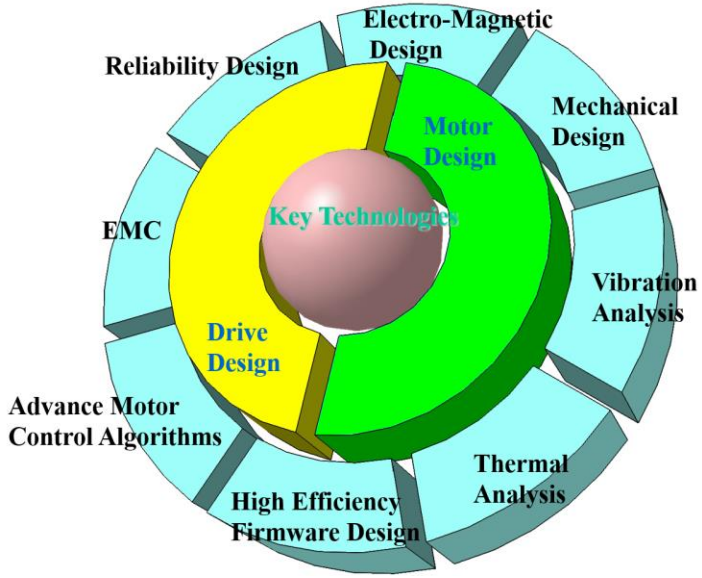
IGBT temp. distribution





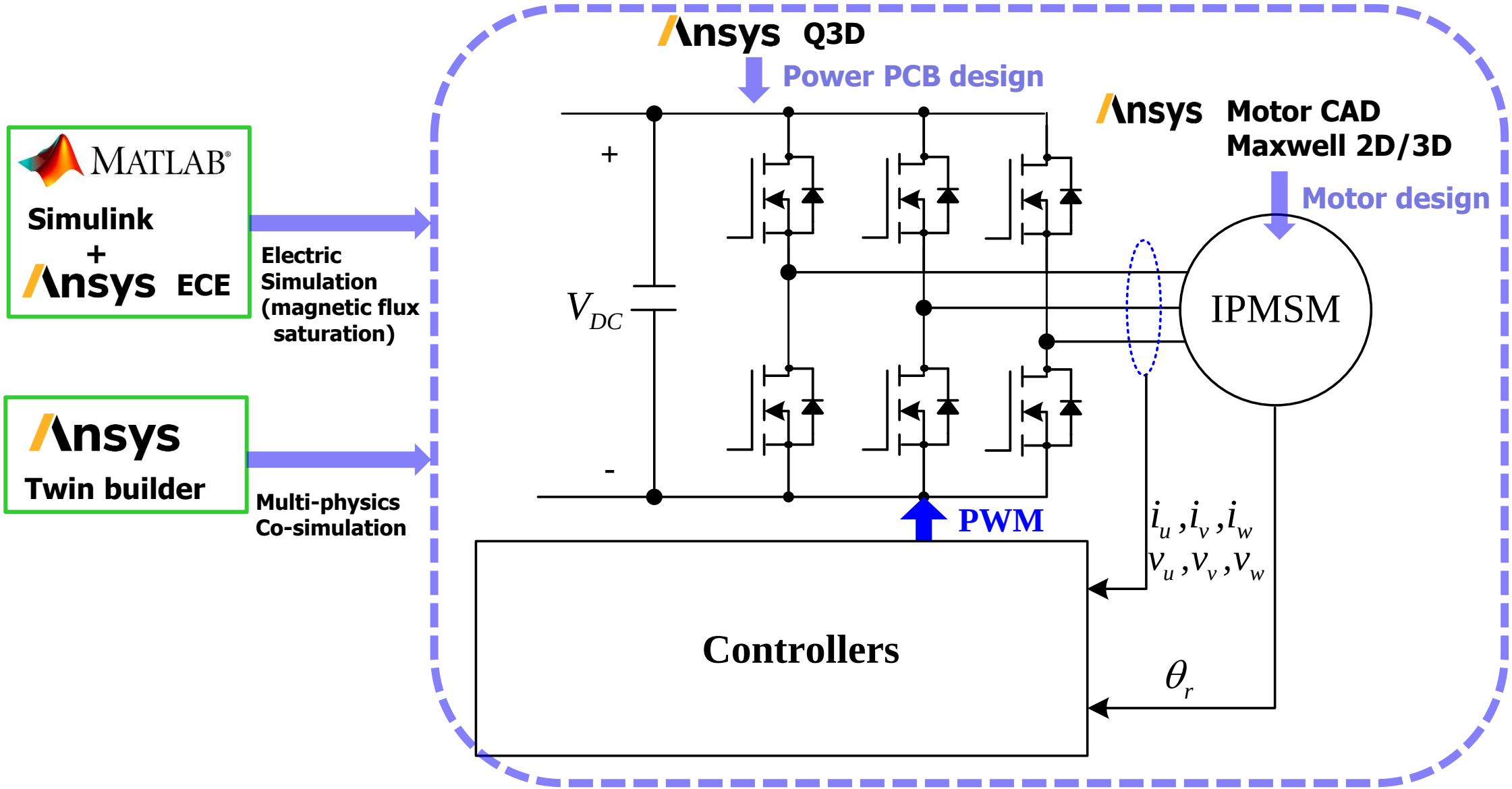
EMI/EMC

Source: Ansys



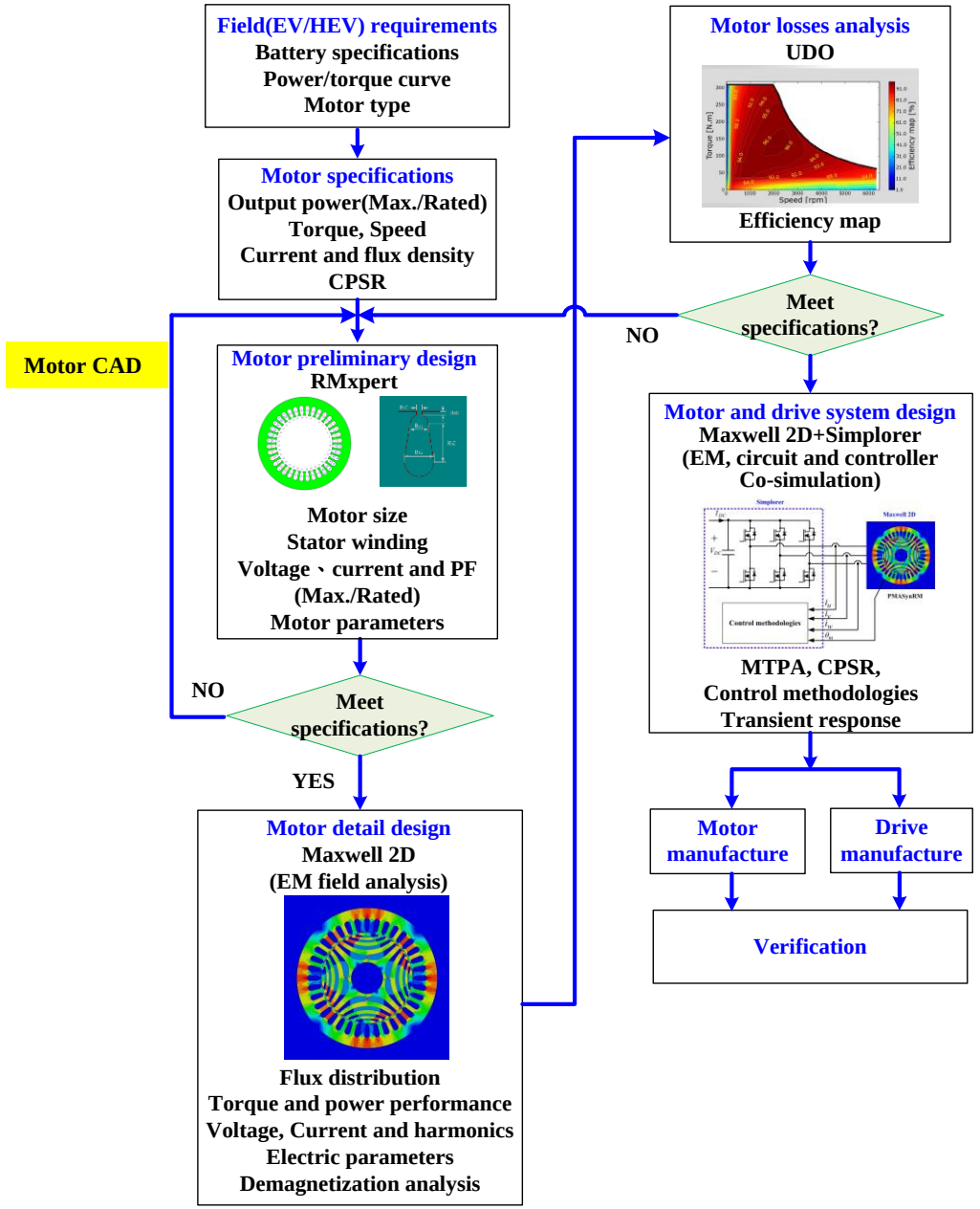
模擬軟體用於馬達及其驅動器設計

◘ 馬達及其驅動器之輔助設計軟體



模擬軟體用於馬達及其驅動器設計

◘ 馬達設計程序

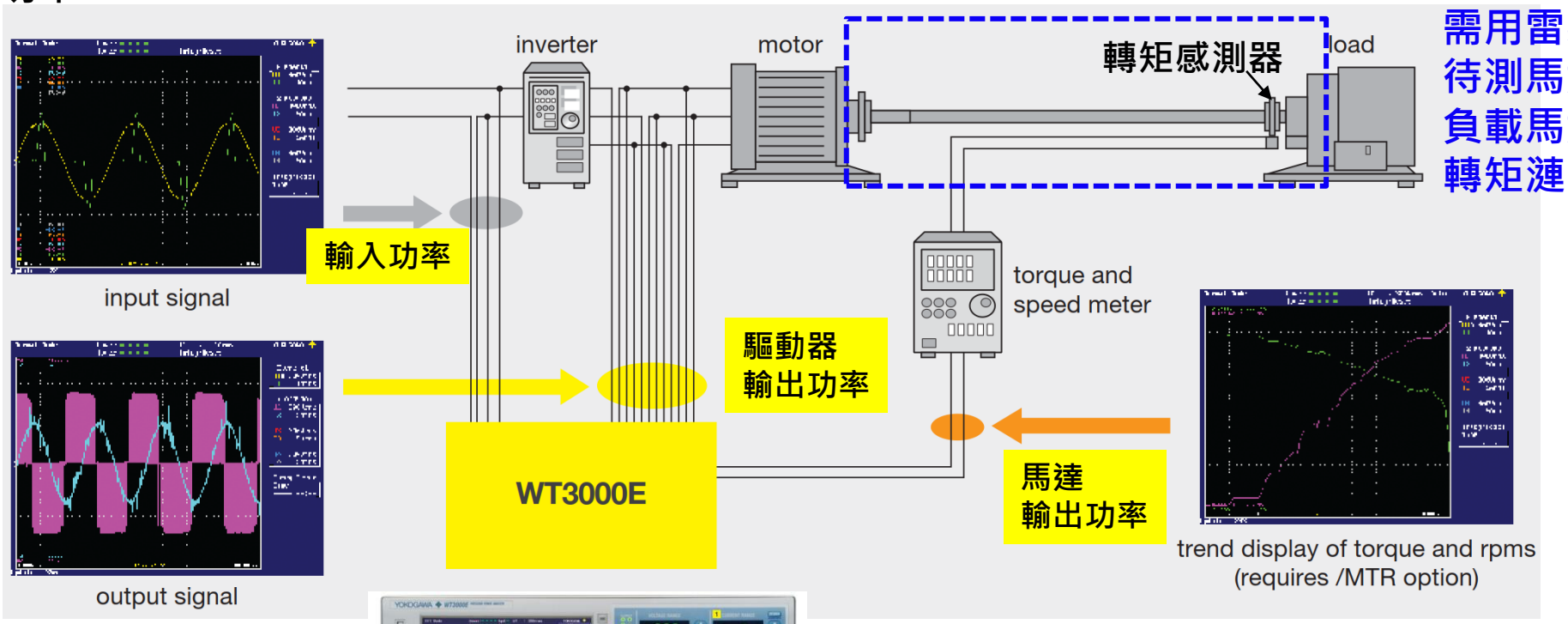


模擬軟體用於馬達及其驅動器設計

◘驅動系統輸出轉矩及效率量測

- ✓ 永磁同步馬達驅動系統一般是馬達跟驅動器一起銷售
- ✓ 永磁同步馬達驅動系統標示效率為整體效率
- ✓ 一般標示功率多是馬達輸出機械量，如轉矩、轉速及機械功率

驅動器效率＝驅動器輸出功率/輸入功率
馬達效率＝馬達輸出功率/驅動器輸出功率
馬達驅動系統效率＝馬達輸出功率/輸入功率



需用雷射對心儀協助讓
待測馬達、torque sensor及
負載馬達三者軸端在同心圓
轉矩漣波及損壞torque sensor

功率計

Source: Yokogawa

模擬軟體用於馬達及其驅動器設計

◘ 馬達及其控制之模擬

- ✓ 馬達數學等效模型>>**Matlab Simulink**

  需要馬達電氣參數，很難考慮較精準的磁飽和

- ✓ **ECE(Equivalent Circuit Extraction) >> Ansys Twin builder +Matlab Simulink**，由**Maxwell 2D/3D**產生，已加入磁飽和現象但早期版本沒考慮core loss

- ✓ **Maxwell 2D/3D >> Ansys Twin builder**

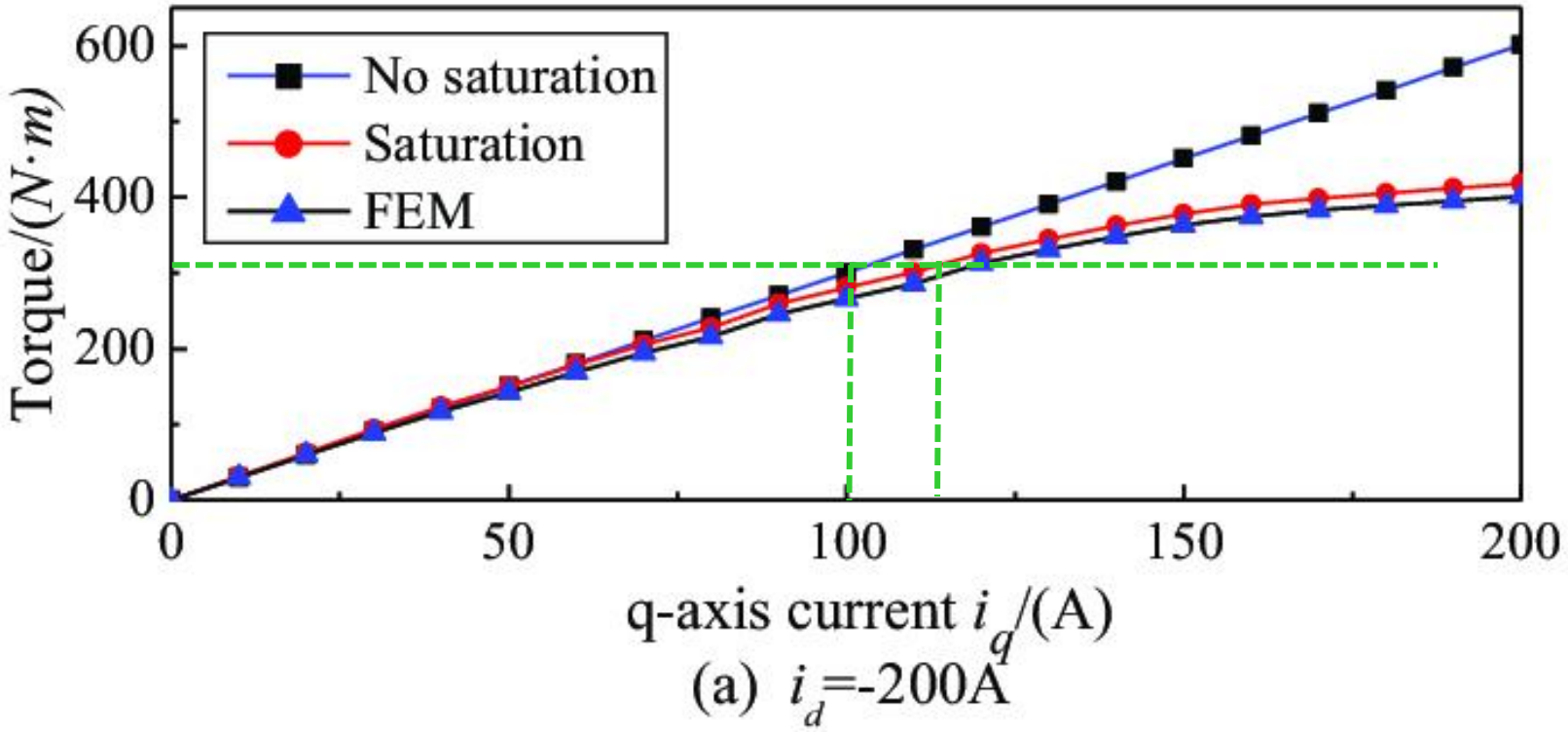
  加入磁飽和現象、銅損及鐵損

模擬軟體用於馬達及其驅動器設計

◘ 非理想條件永磁同步馬達輸出轉矩與電流的關係

非理想主要來自矽鋼片磁場飽和特性，此時主導方程式只能作為參考；以有限元素法為基礎之Maxwell 2D/3D模擬軟體可導入矽鋼片及磁石材料特性，可估算出較精準的輸出轉矩。

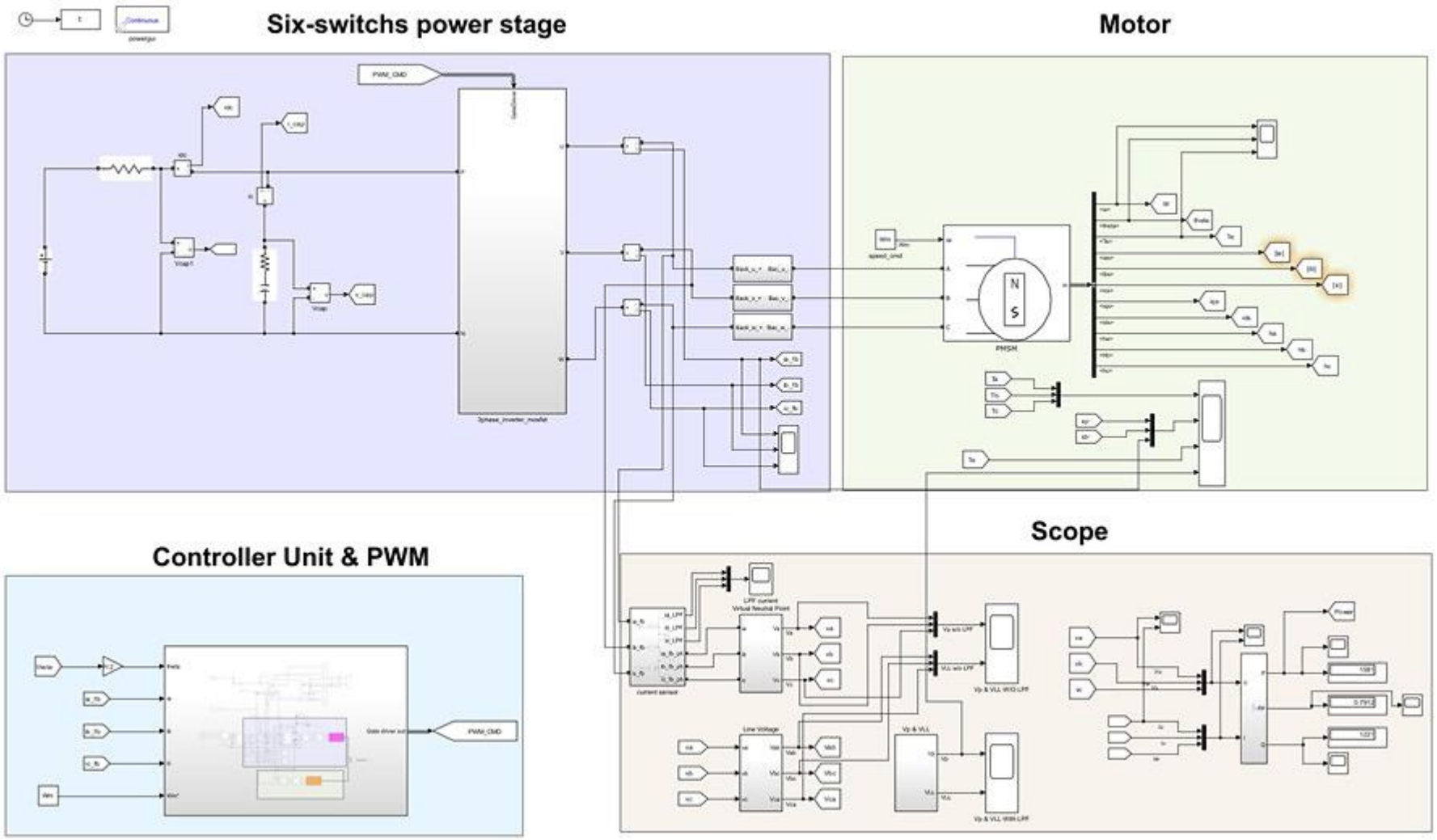
$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m i_{qs}^r + \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})i_{qs}^r i_{ds}^r$$



Ref: Modeling of electromagnetic torque considering saturation and magnetic field harmonics in permanent magnet synchronous motor for HEV

模擬軟體用於馬達及其驅動器設計

◘ 馬達及其控制之模擬 – Matlab /Simulink



模擬軟體用於馬達及其驅動器設計

◘ 馬達及其控制之模擬 – 馬達參數取得或量測

永磁同步馬達 電氣參數表					
項目	單位	數值	項目	單位	數值
額定相電壓	Vrms		相電阻	Ohm	
額定相電流	Arms		D 軸電感	H or mH	
額定轉速/ 最高轉速	rpm		Q 軸電感	H or mH	
額定轉矩	Nm		無載相反電動勢 @1000 rpm	Vrms	提供波形圖
額定功率	kW or W		無載相反電動勢諧波 @1000 rpm	Vrms or % of 基頻	提供圖
額定點效率	%		相反電動勢常數(Ke)	量測 Vrms/rpm, 公制單位 Vrms/(rad/sec) or Vpeak/(rad/sec)	
功率因數			轉矩常數(Kt)	Nm/Arms or Nm/Apeak	
轉子極數			位置感測器對位方式		提供圖
位置感測器 型式及解析度	Pulses/rev. or...				

主要項目之量測複雜度
與使用需求有關

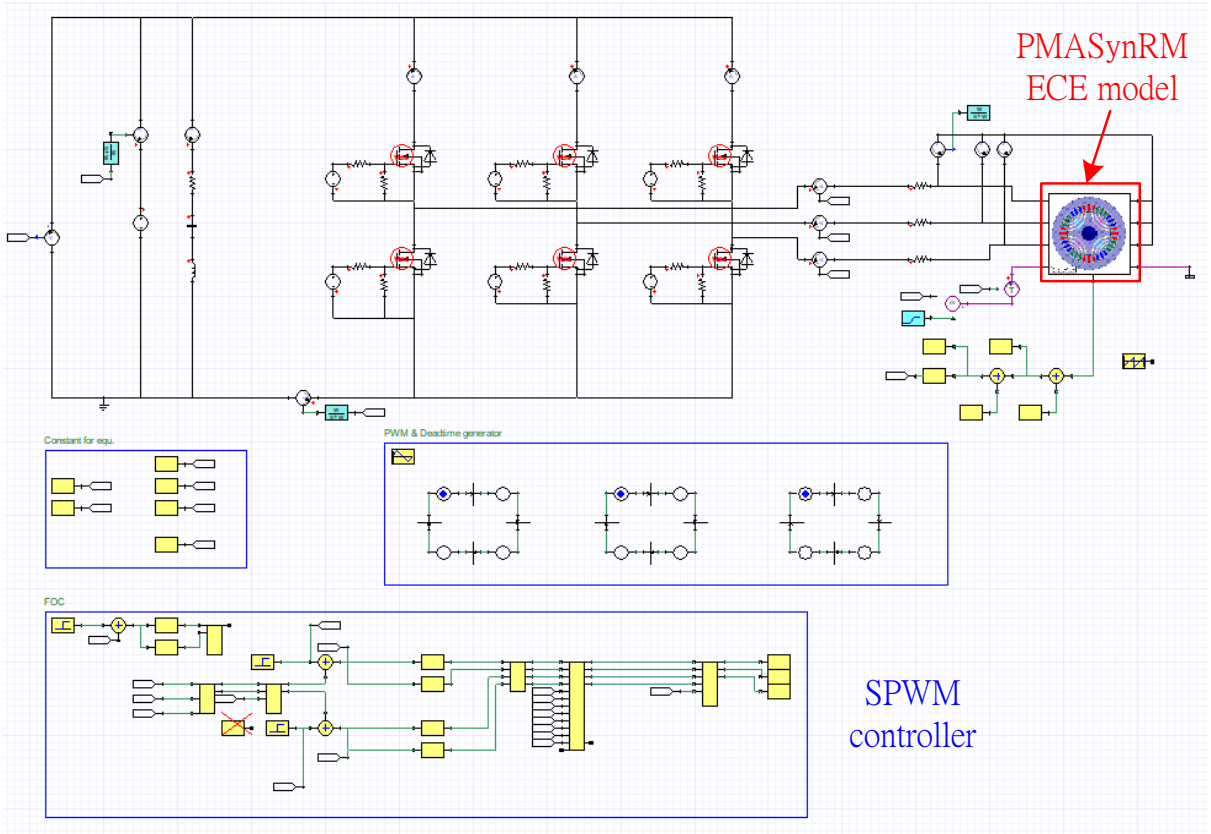
設計驗證、建立模擬環境及控制有關

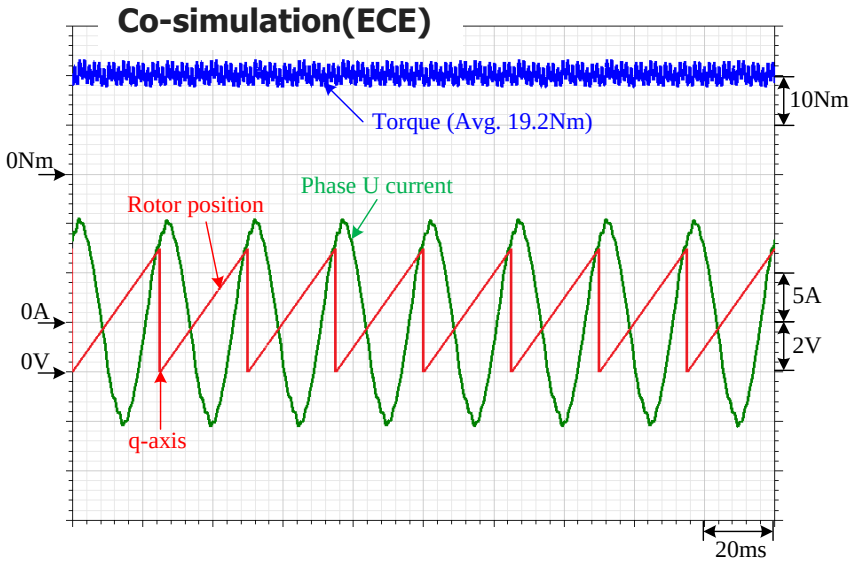
參考教學影帶:

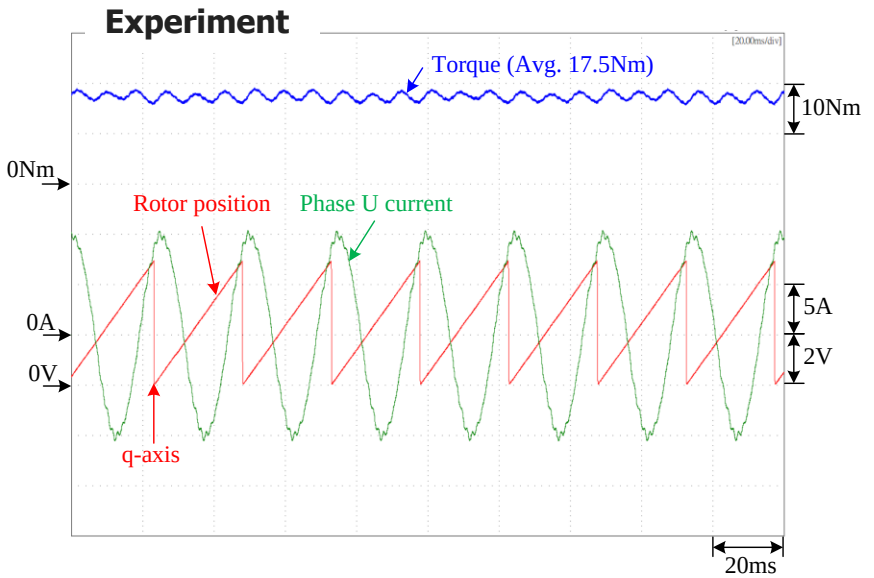
永磁同步馬達的等效電路模型
及電氣參數量測 2022.04.21

模擬軟體用於馬達及其驅動器設計

◘ 馬達及其控制之模擬 – Ansys Twin builder with ECE







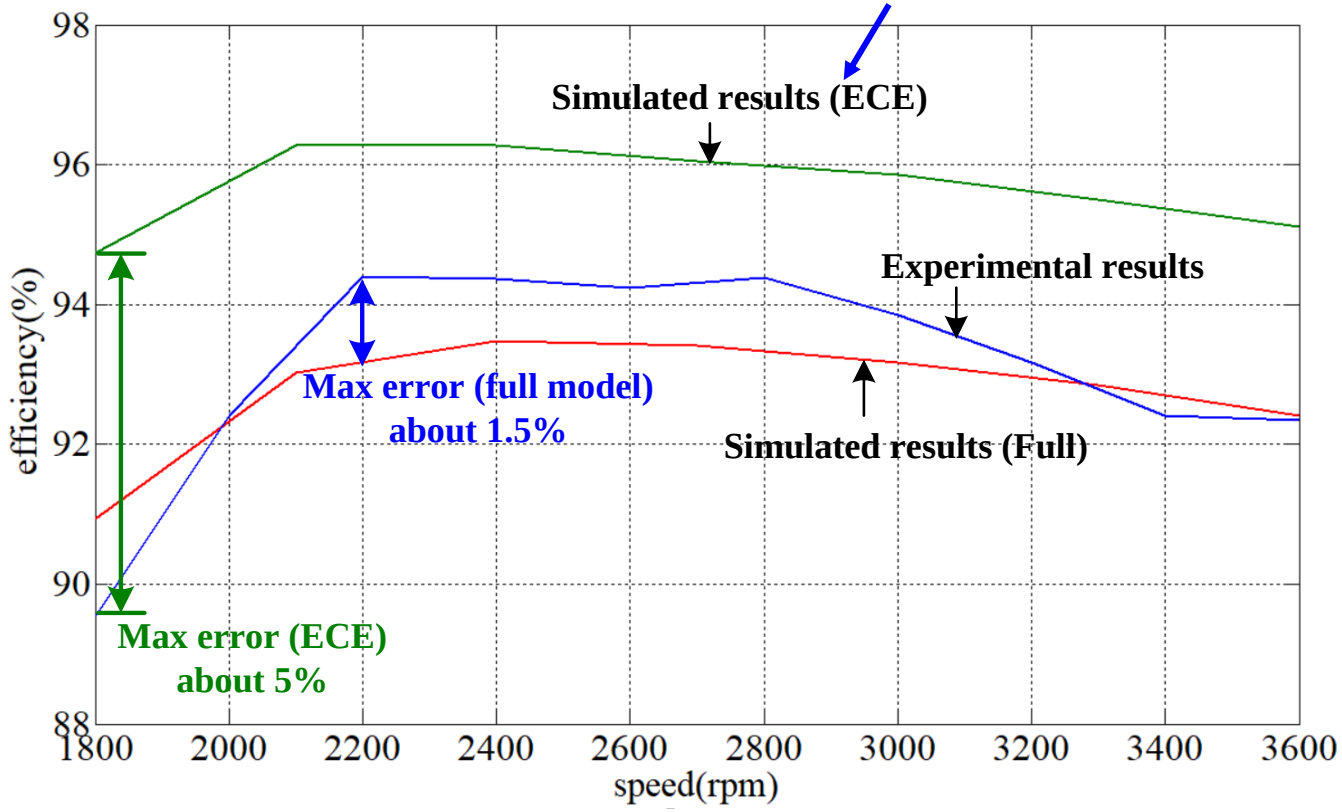
模擬軟體用於馬達及其驅動器設計

◘ 馬達及其控制模擬與結果比較

	Experimental result	Simulated result (ECE)	Simulated result (full model)
Torque(Nm)	15.20	15.52	15.38

@V_{DC}=180V, 2100rpm, θ_v=45°

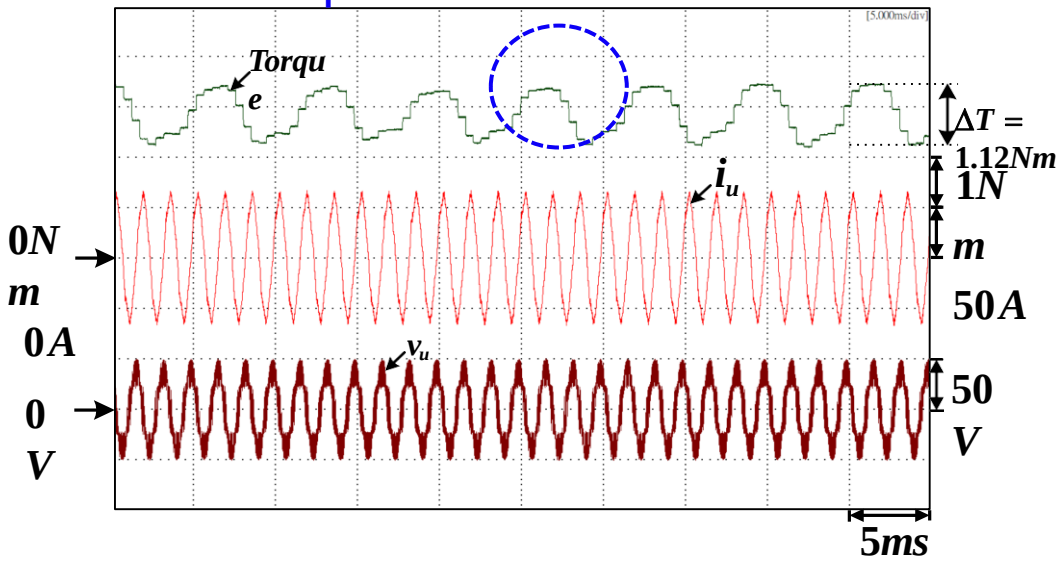
The ECE do not consider the iron loss which yield higher efficiency!

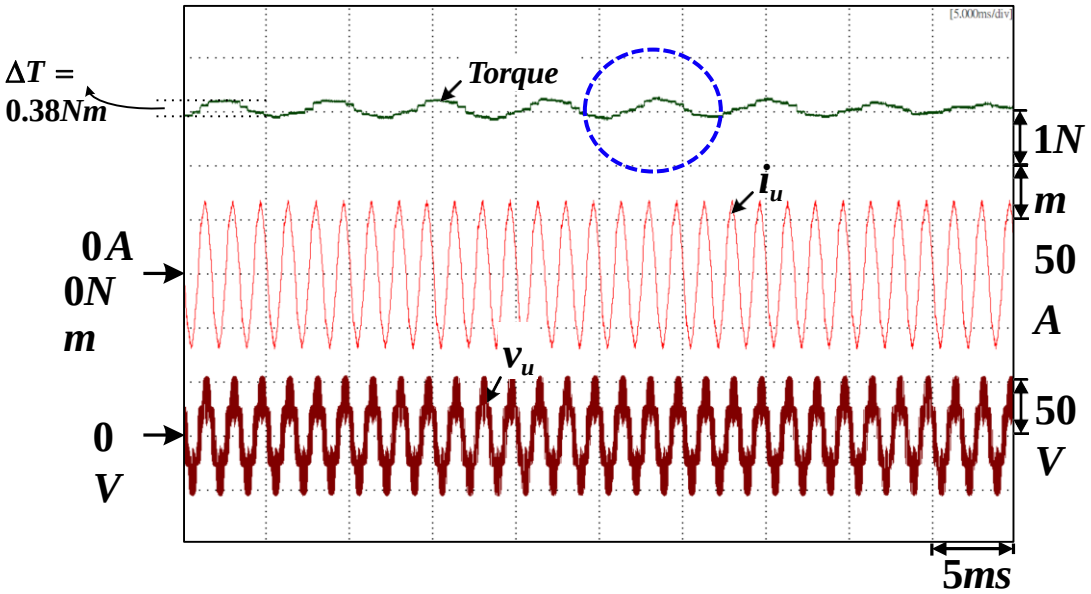


模擬軟體用於馬達及其驅動器設計

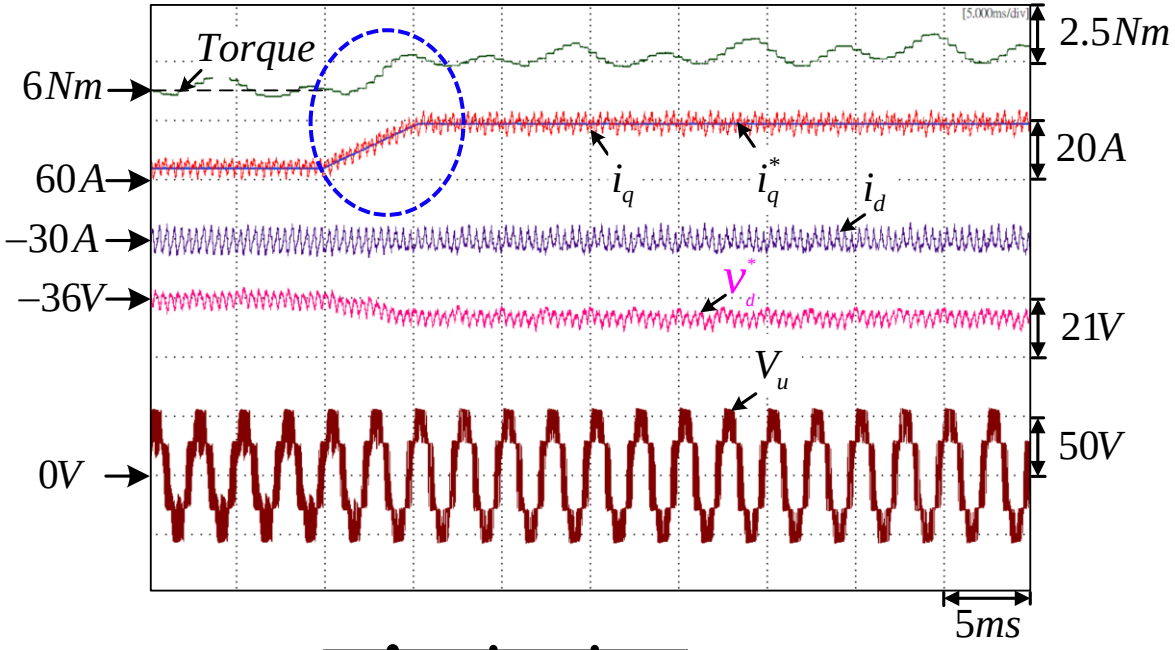
◘輸出轉矩漣波>>真的?

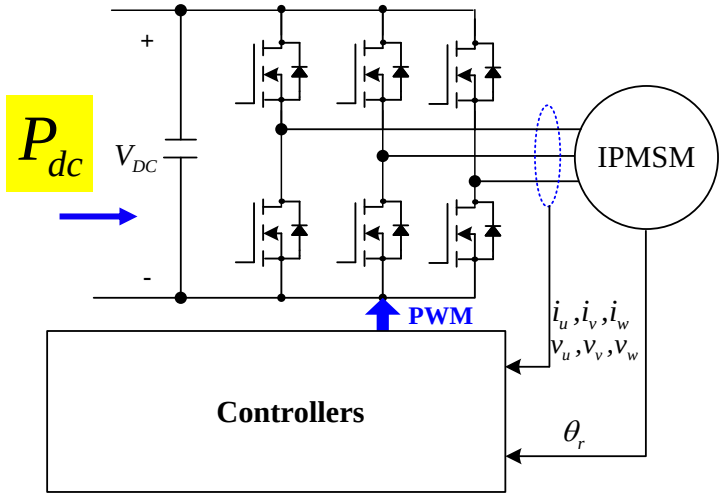
待測馬達、torque sensor及負載馬達三者軸不在同心圓上





Step torque command可能激發
Torque sensor輸出電氣訊號共振

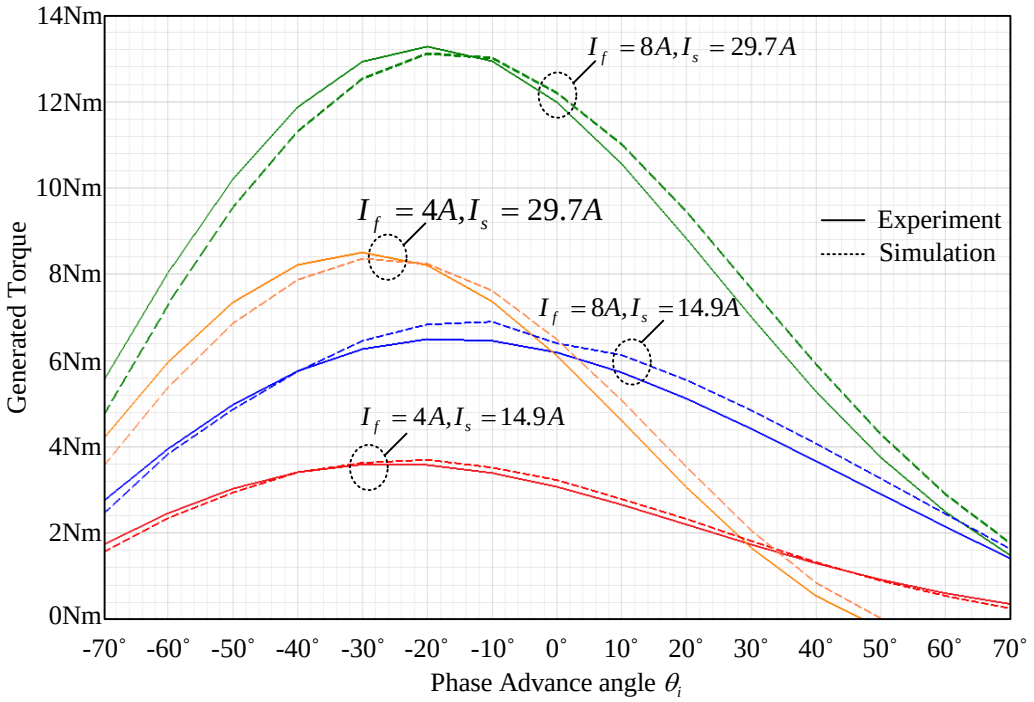




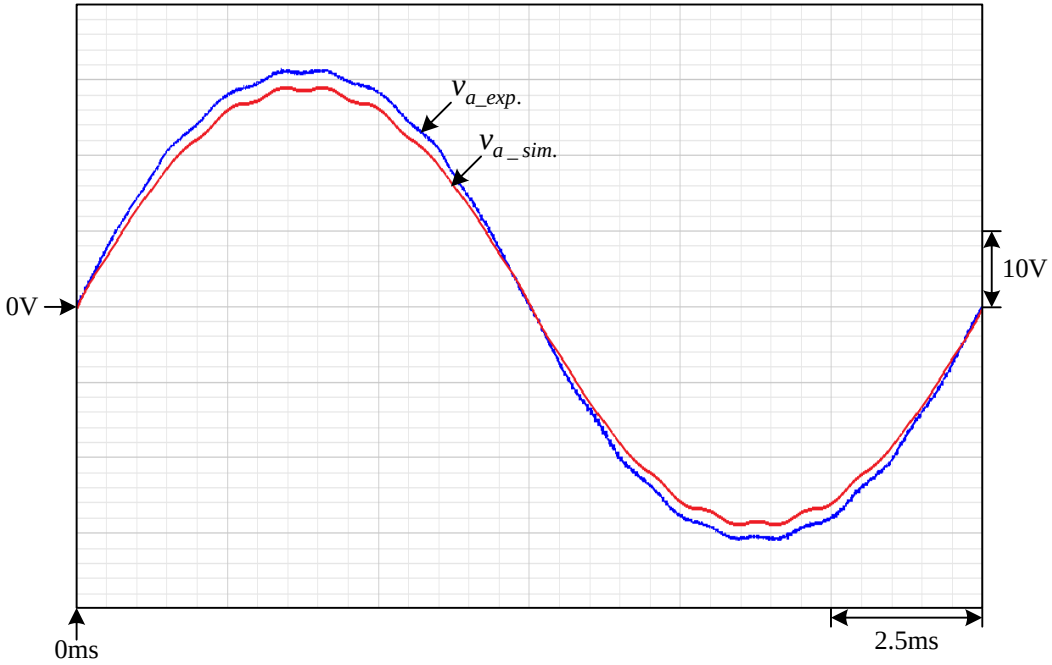
模擬軟體用於馬達及其驅動器設計

◘ 馬達之模擬與實測結果比對

➢ Average torque



➢ Back EMF@1000rpm I_f=8A



$$Error = \left| \frac{Sim. - Exp.}{Exp.} \right| \times 100\%$$

➢ Torque @3kw(3000rpm)

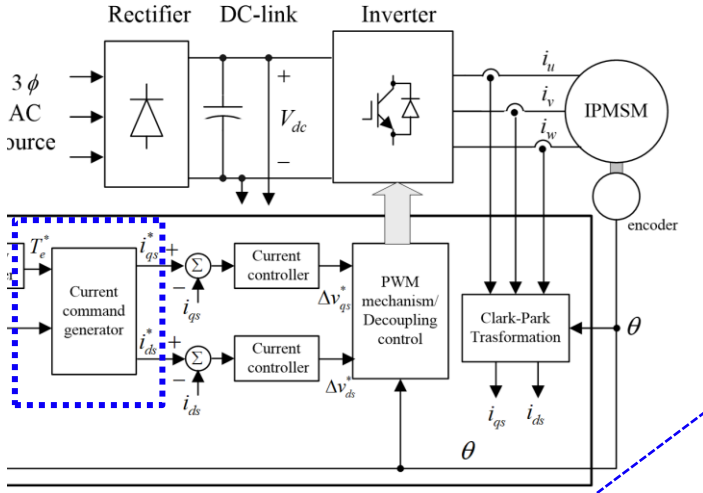
	I_f	I_s	θ_i	Torque	$V_{line,rms}$	η_{motor}
Sim.	8A	22.4A	-10°	9.84Nm	186V	91%
Exp.	8A	22.4A	-10°	9.76Nm	194V	91%
Error				0.8%	4.1%	

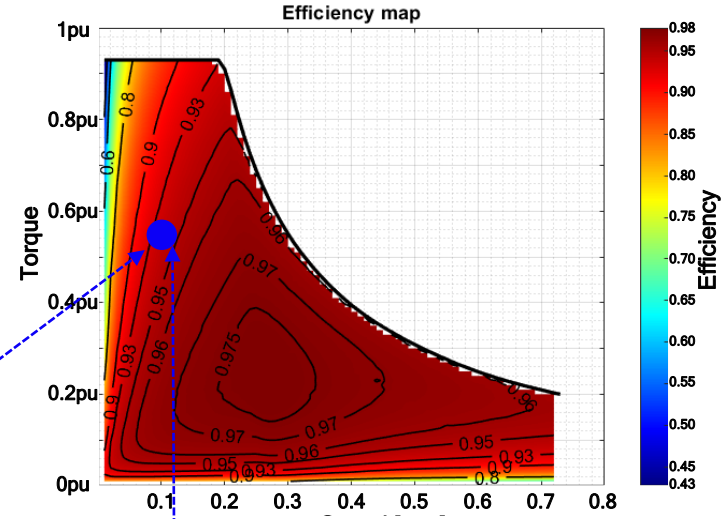
➢ FFT of Back EMF

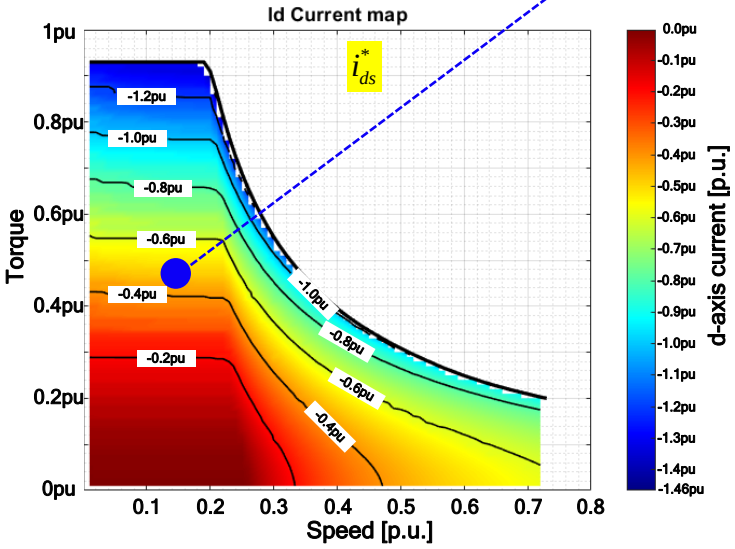
	1st	3rd	5th	7th	9th	11th	13th	THD
Sim.	20.9V	0.59V	0.04V	0V	0.01V	0.02V	0.08V	3.3%
Exp.	22.6V	0.87V	0.08V	0.02V	0.01V	0.01V	0.08V	4.0%
Error	7.5%	32.2%						

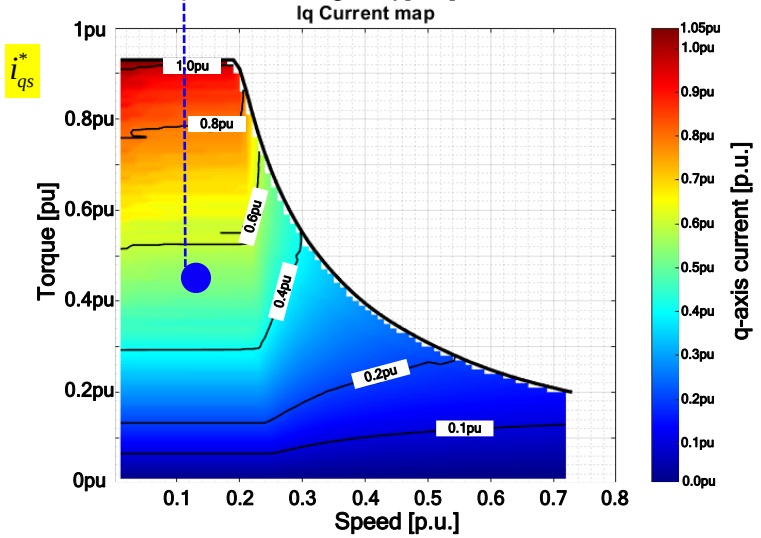
模擬軟體用於馬達及其驅動器設計

- 如何使用馬達模擬結果 >> 依據需求轉矩及目前轉速產生電流命令，惟須確認模擬結果之正確性







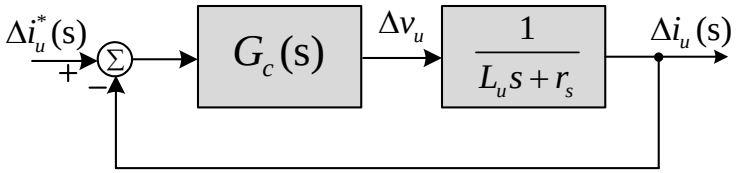


Test bed for traction motor

https://www.avl.com/en/testing-solutions/e-mobility-testing/e-motor-testing

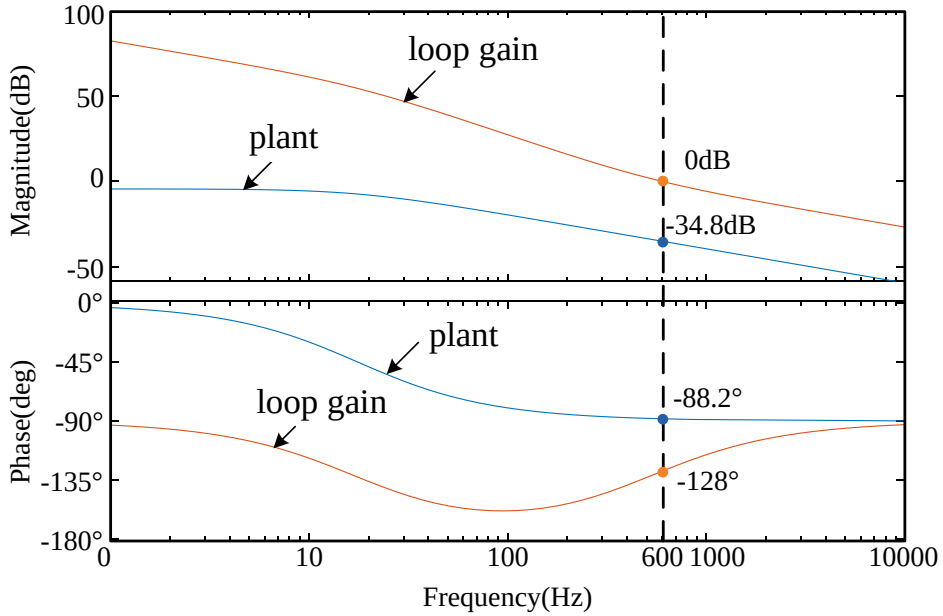
模擬軟體用於馬達及其驅動器設計

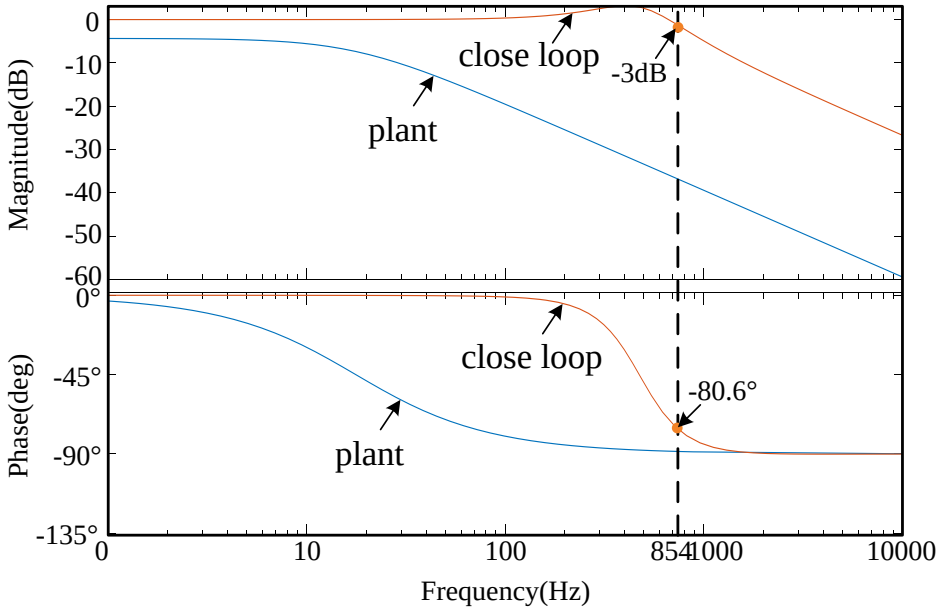
◘ 電流迴路設計與驗證



Controller specifications	
Crossover frequency	600Hz
Phase margin	52°

PMSM參數及規格	
參數	數值
L_d	14.26mH
L_q	14.80mH
L_s	14.53mH
R_s	1.74Ω
ke	31.5V_{rms}/1000rpm
額定轉速	2000rpm
額定轉矩	1.9Nm
額定電流	2.6A





參考教學影帶:

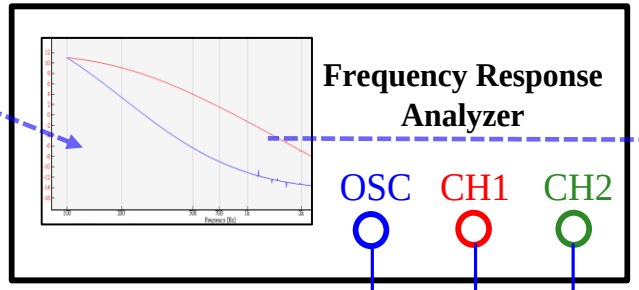
永磁同步馬達電流迴路設計/驗證及功率量測 2022.04.28

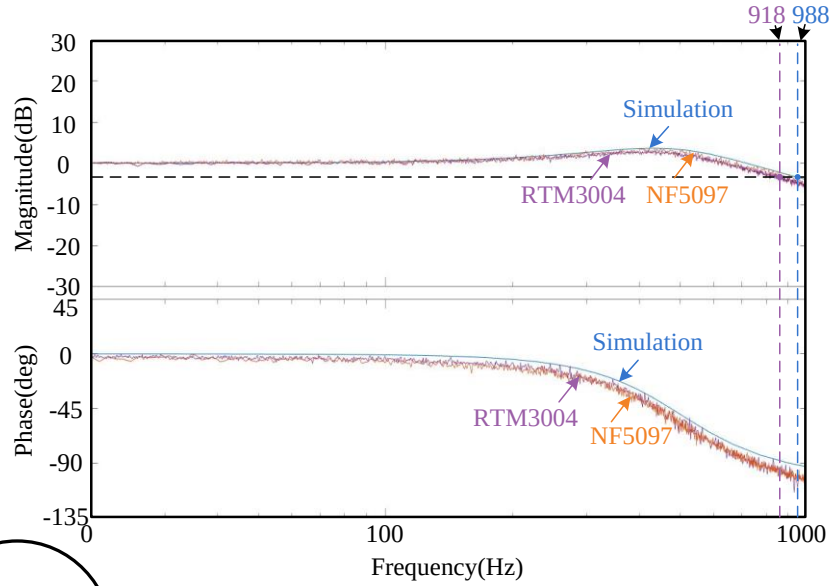
模擬軟體用於馬達及其驅動器設計

◘ 電流迴路驗證設置

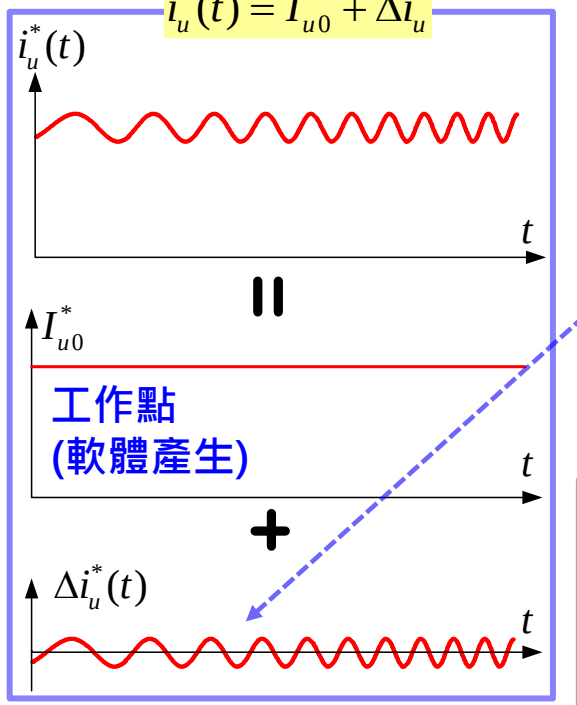
Bode plot

$$\frac{\Delta i_u(s)}{\Delta i_u^*(s)}$$

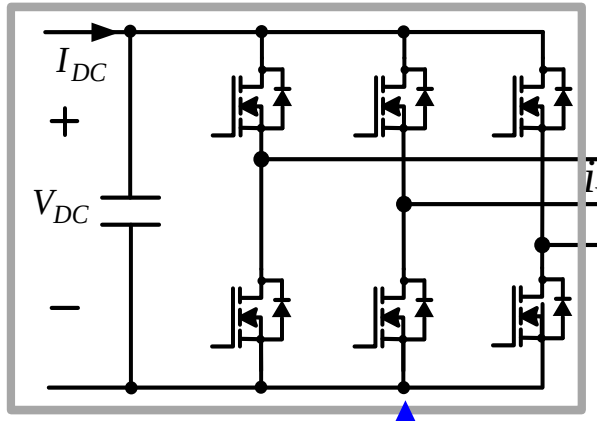


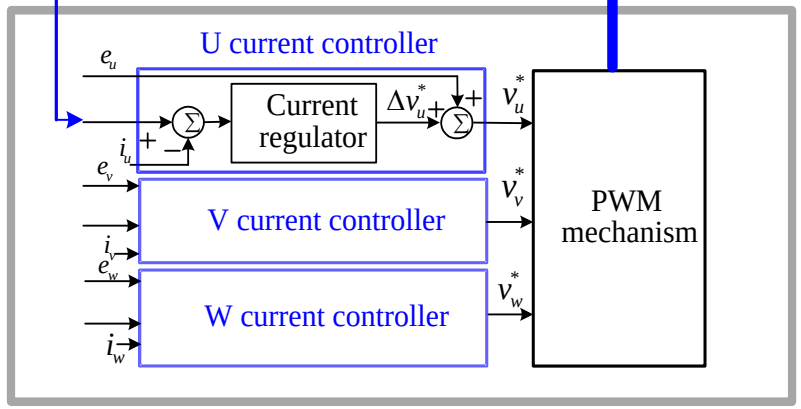


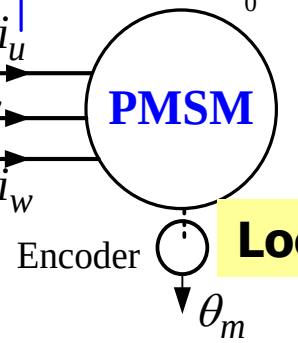
$$i_u^*(t) = I_{u0}^* + \Delta i_u^*$$



擾動命令







Lock rotor

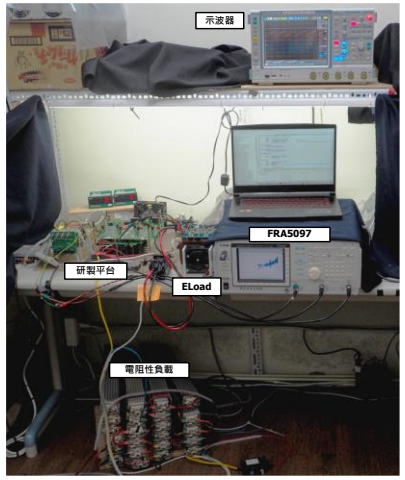
$$i_v^* = i_w^* = -\frac{I_{u0}^*}{2}$$

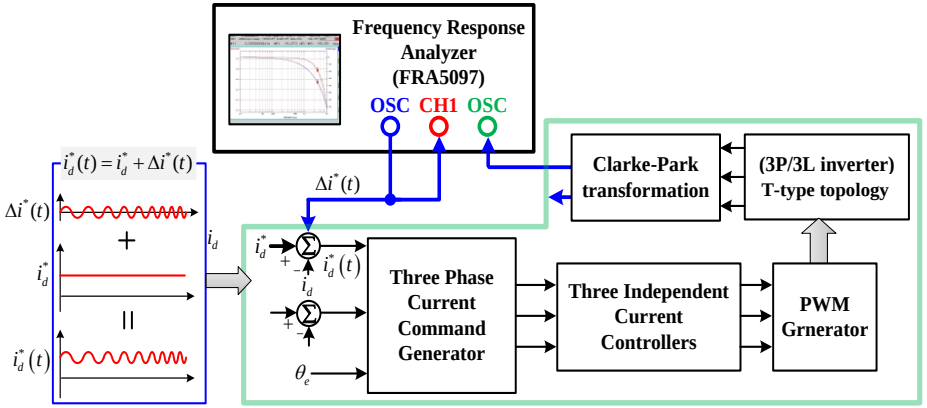
$$e_u = e_v = e_w = 0$$

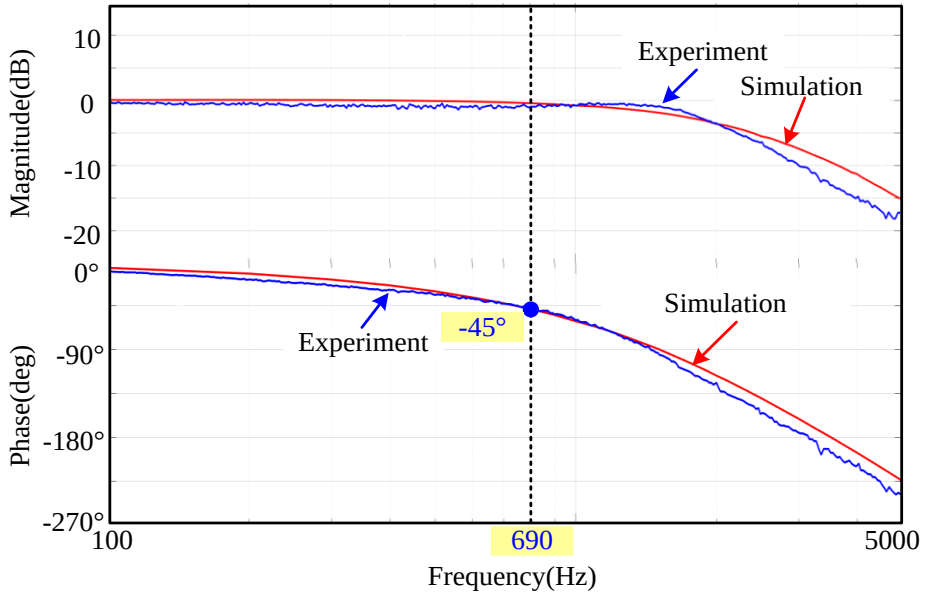
輸入訊號先放大，讀入MCU後再以軟體縮小，以降低AD converter有限解析度的影響!

模擬軟體用於馬達及其驅動器設計

三相交流-直流轉換器之電流迴路模擬vs.驗證結果



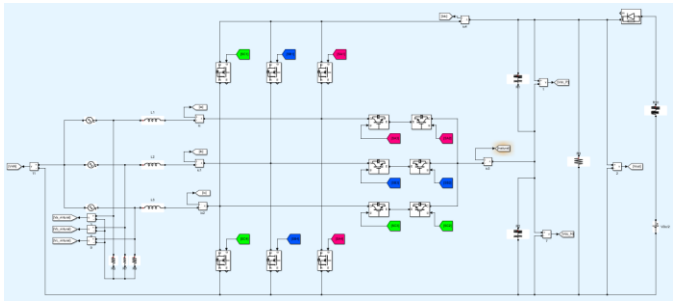




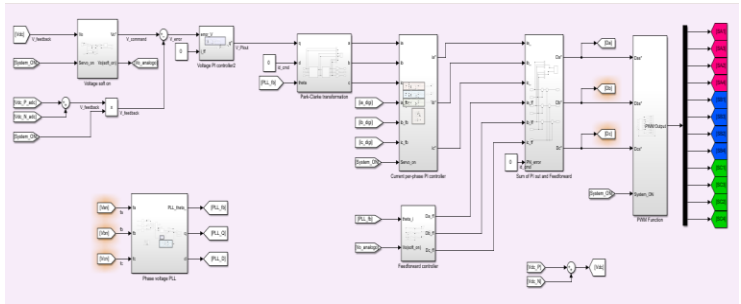
MATLAB & SIMULINK

Linearize Simulink Model at Model Operating Point

Virtual design



Power stage



Control stage

模擬軟體用於馬達及其驅動器設計

◘ 功率級設計重點及使用模擬軟體與驗證工具

- ✓ Q3D: extract the parasitic parameters
- ✓ Spice model: characteristics analysis of power switch
- ✓ Twin builder/circuit simulation S/W: operation of the power stage (stress/current sharing) and losses estimation for thermal design

Simulation Tools

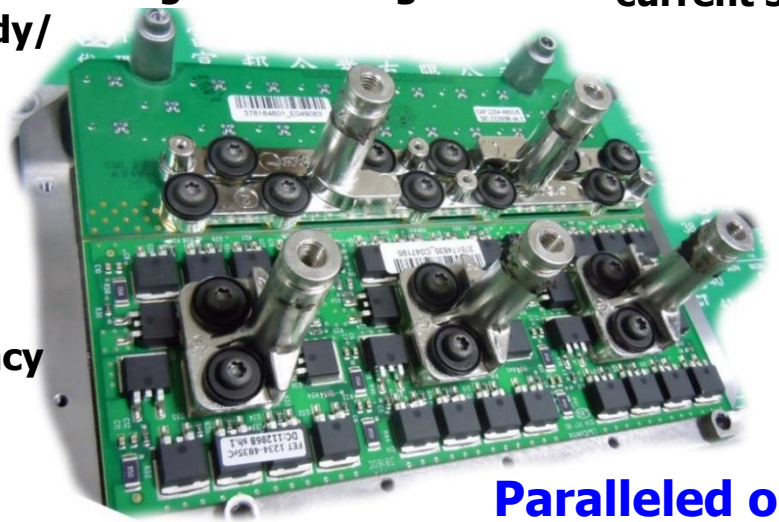
- ✓ Double pulse tester: verify the simulation results

Verification

Power switch
*stress analysis
*characteristics of steady/ transient state
*losses

Thermal design
*losses estimation
*cooling methodologies

Busbar design
*stray inductance
*current sharing among capacitors



Power connection bar
*current density distribution
*loss

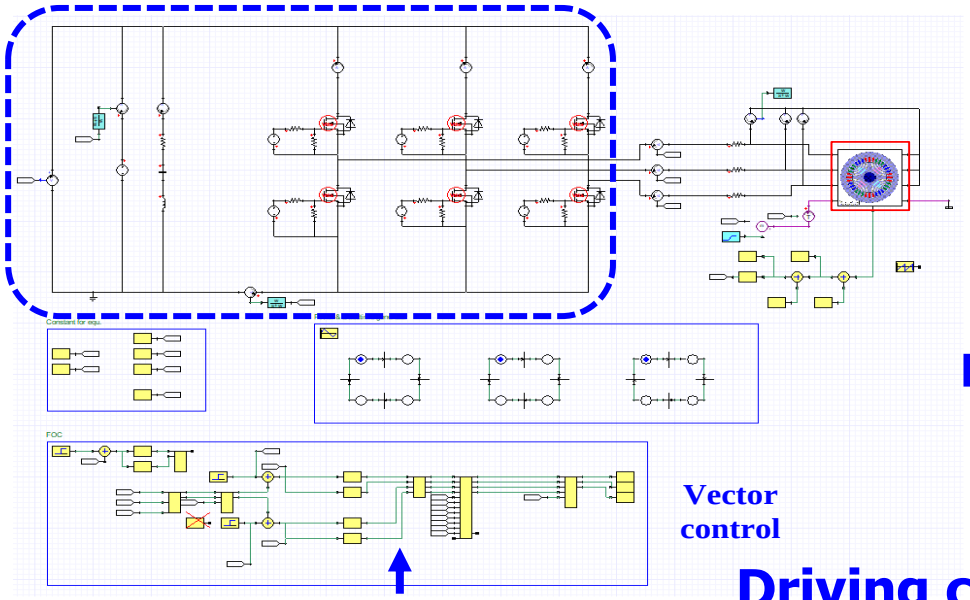
DC link capacitor
*impedance vs. frequency
*estimate losses

Paralleled operation of power switches
current sharing at steady and transient state

EMI/SI(Signal integrity)?

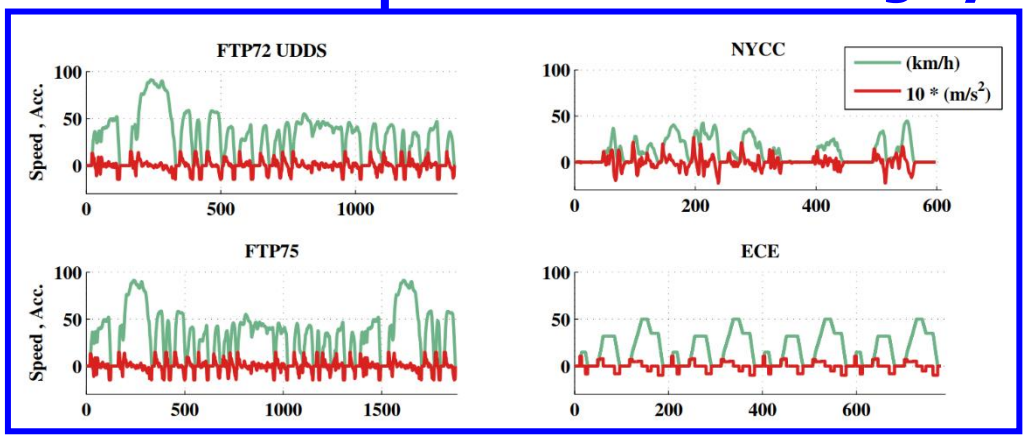
模擬軟體用於馬達及其驅動器設計

- 軟體協助功率級設計是希望在硬體製作前即可預估功率晶體損失，作為散熱設計之參考。
- 功率級之損失主要來自功率晶體之切換及傳導損失。

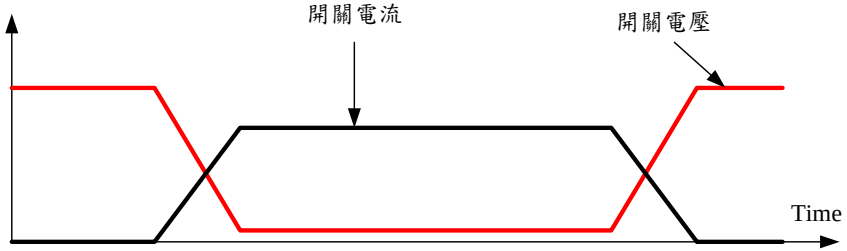


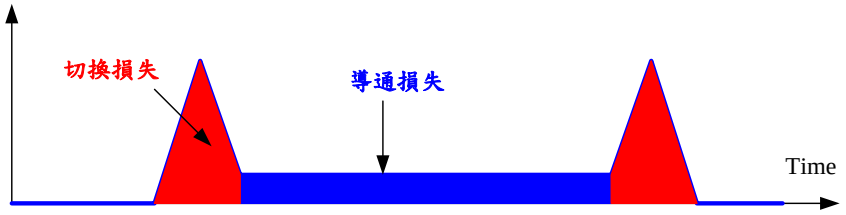
Estimate heat dissipation of power stage under required driving cycle and output power by Spice model and co-simulation

Driving cycle



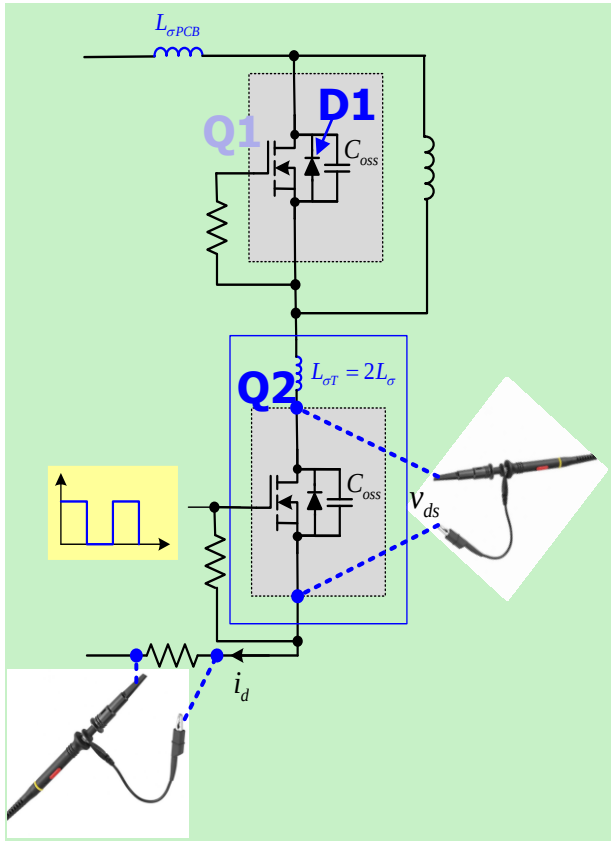
功率晶體損失

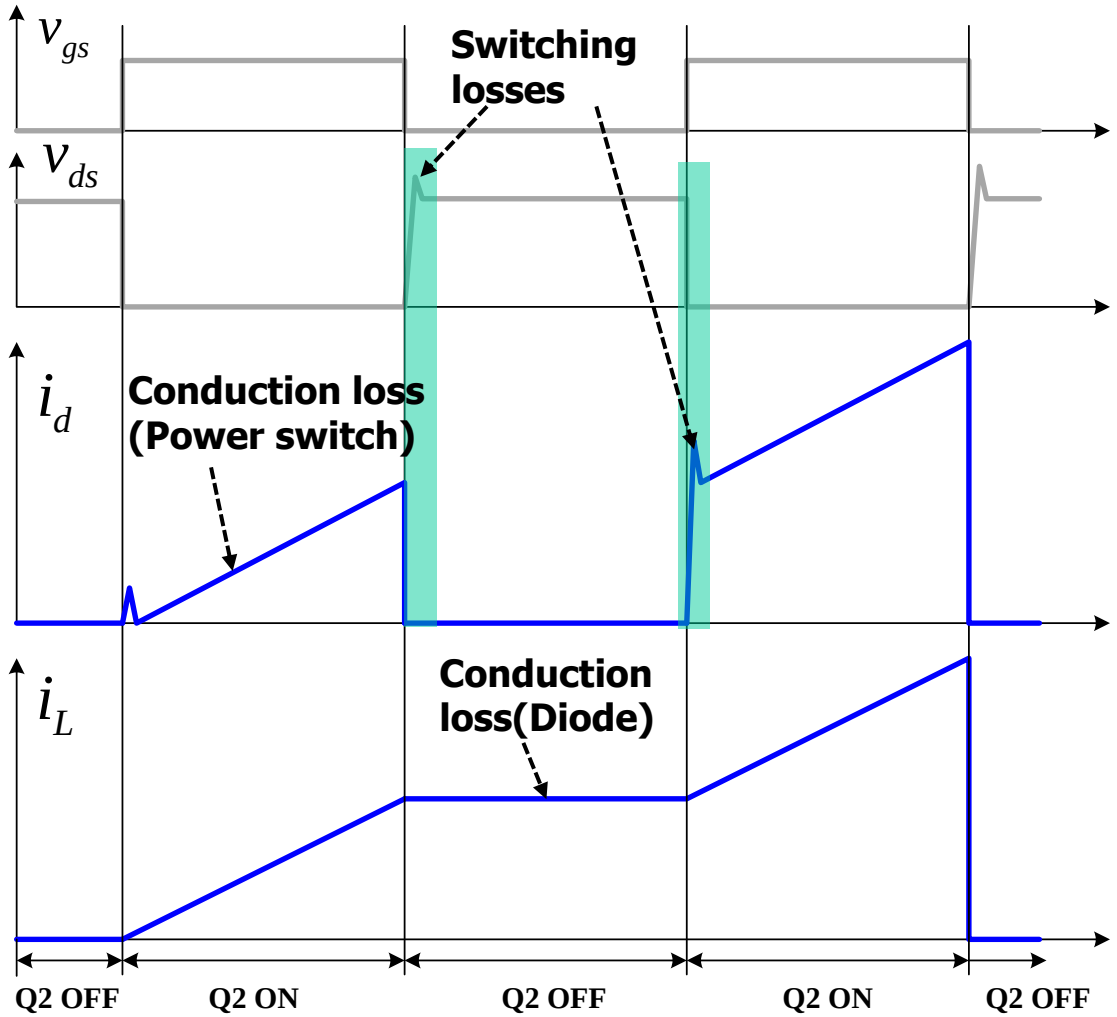




☐ Power switch loss

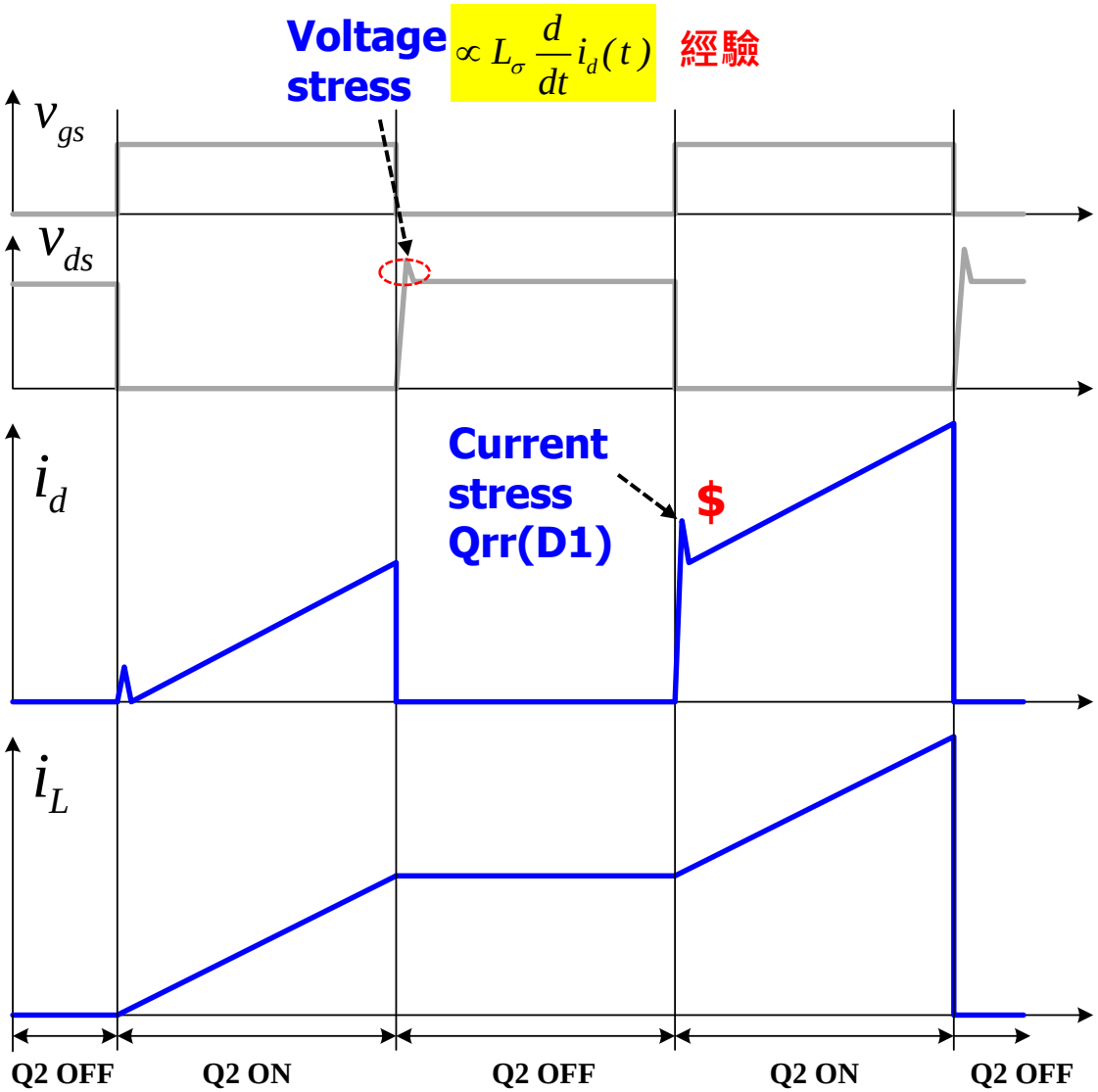
- ✓ 傳導損失(conduction loss) : 合適的功率開關選擇可有效降低傳導損失。
- ✓ 切換損失(switching loss): 合適的功率開關選擇(SiC diode)及降低PCB主要能量流動路徑之雜散電感 $L_\sigma = L_{\sigma PCB} + L_{\sigma T}$ ，可有效降低切換損失。



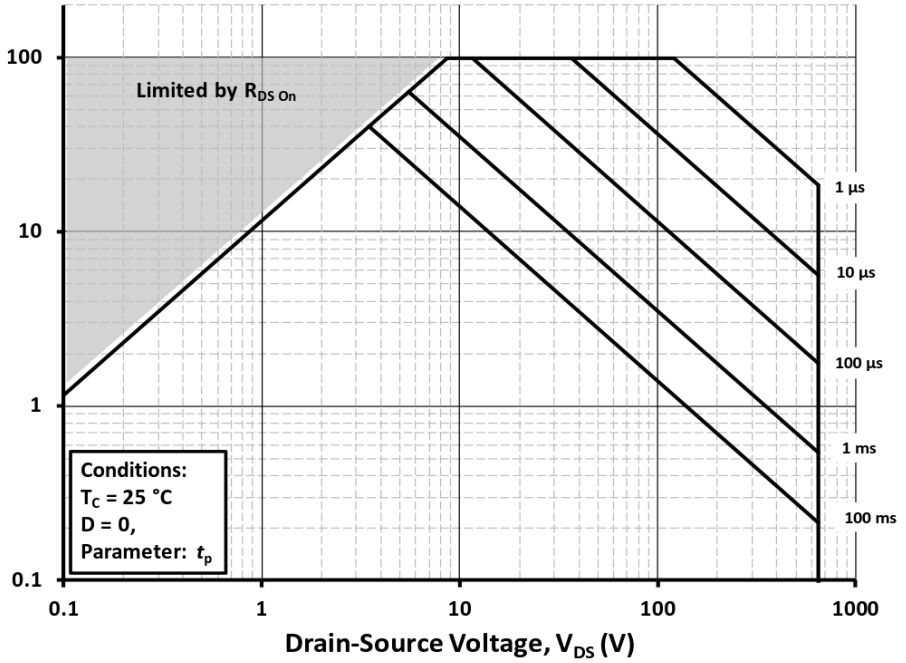


模擬軟體用於馬達及其驅動器設計

◘ PCB主要能量流動路徑之雜散電感對power switch之影響



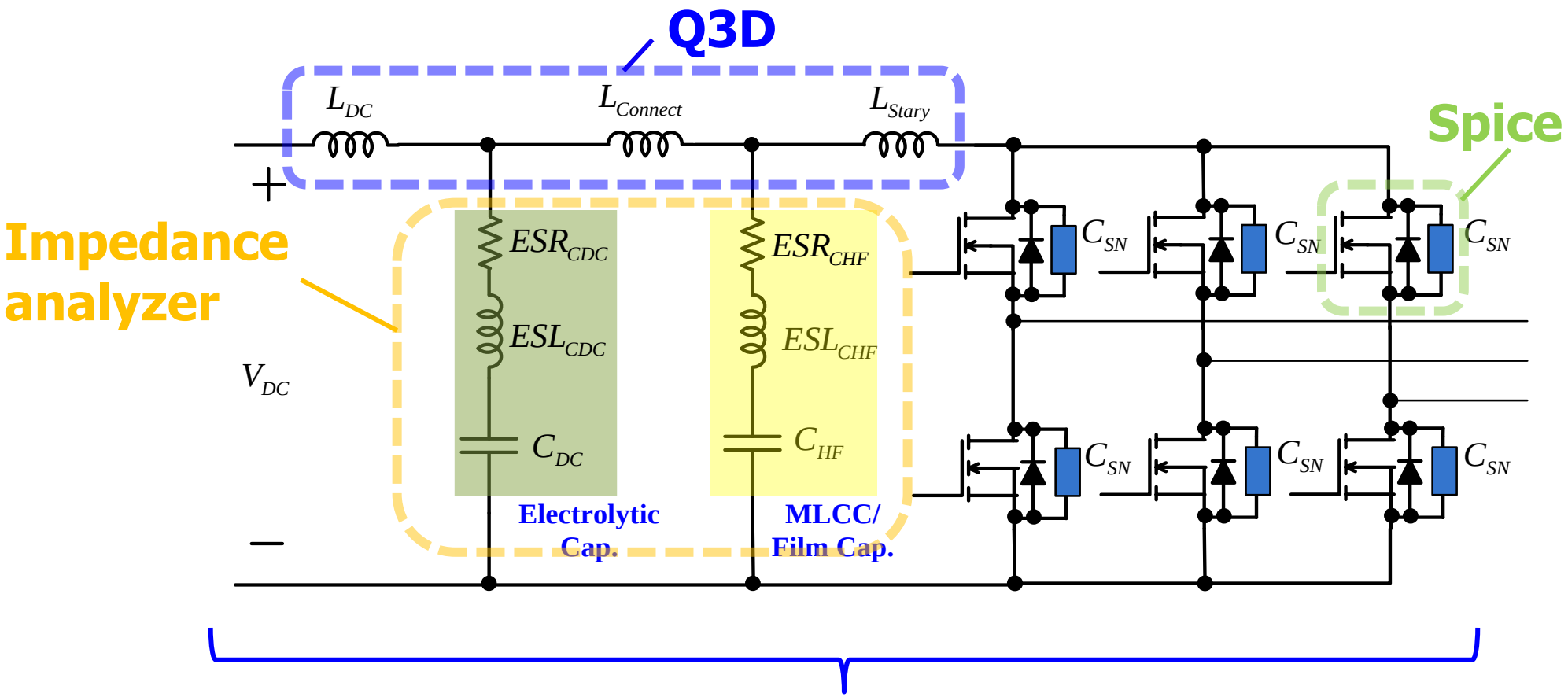
Effect of voltage and current stress



Source: C3M0060065L
Silicon Carbide Power MOSFET

模擬軟體用於馬達及其驅動器設計

功率級雜散電感模型(忽略功率晶體之雜散電感)

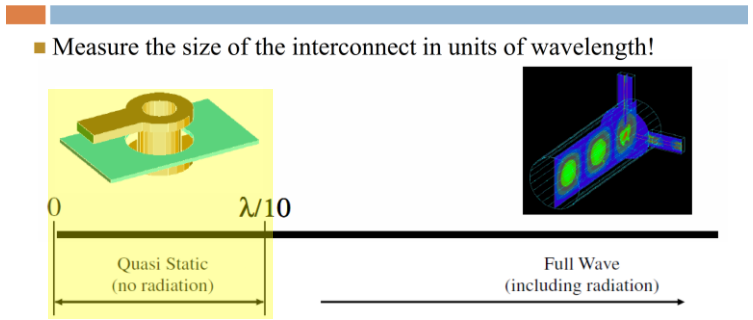


模擬軟體用於馬達及其驅動器設計

Q3D介紹

- ✓ Calculate the parasitic parameters of frequency-dependent resistance, inductance, capacitance and conductance (RLCG) for the quasi-static behavior of electronic products.
- ✓ Can import or create arbitrary 3-D electronic structures, such as connectors, vias, wire bonds, solder balls, signal traces, and power and ground planes.

Quasi-static or full-wave techniques



Wavelength for copper vs. frequency

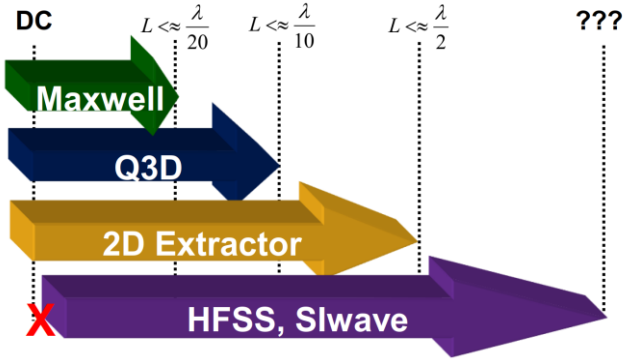
Frequency (Hz)	λ(m)	λ/10(m)
100k	1686.3	168.63
1M	168.6	16.86
10M	16.8	1.68
100M	1.7	0.17
500M	0.3	0.03

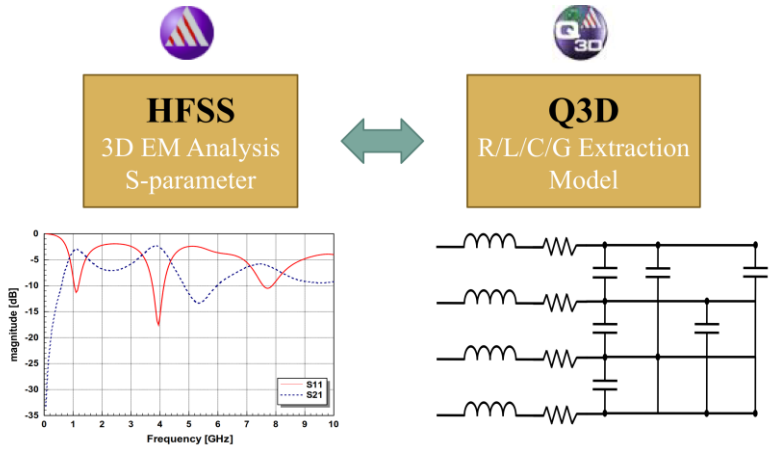
Power stage

$$\lambda = \frac{3\times10^8\, m/s}{\sqrt{\varepsilon_{eff}}\times f}$$

$$\varepsilon_{eff} = 3.165(\text{copper})$$

Simulation tools according to frequency

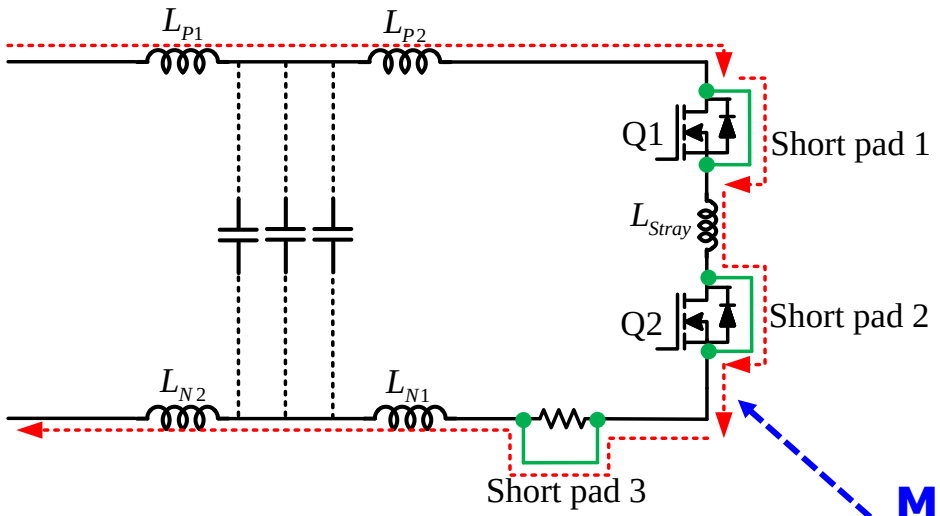


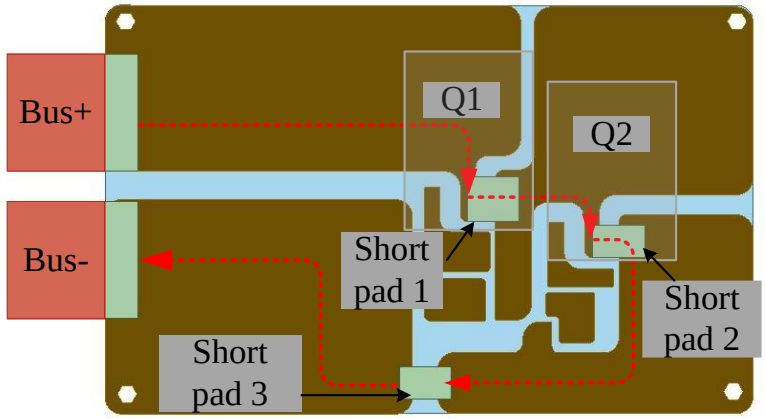


Source: Ansys

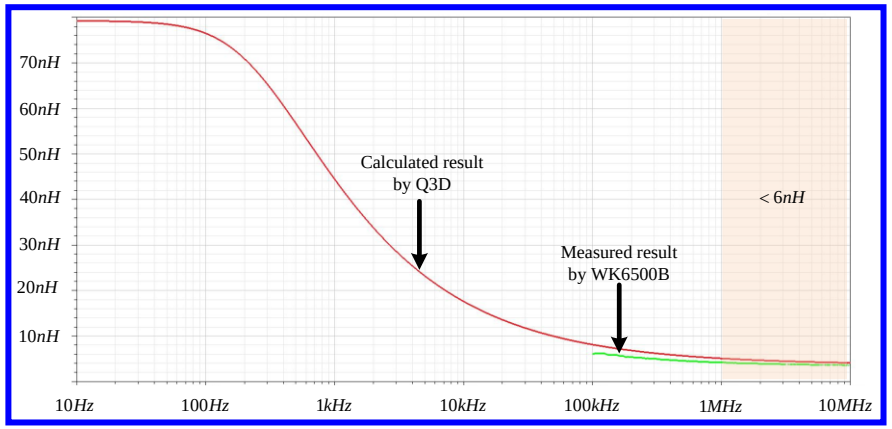
模擬軟體用於馬達及其驅動器設計

Q3D模擬雜散電感及量測結果

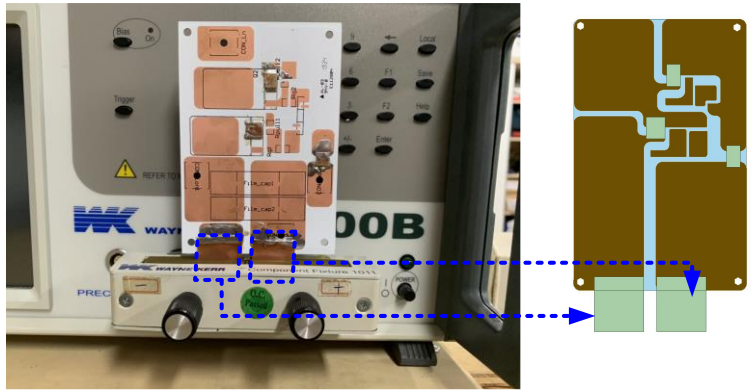




Minimize the stray inductance by Q3D to reduce turn-off voltage spike and turn off loss.



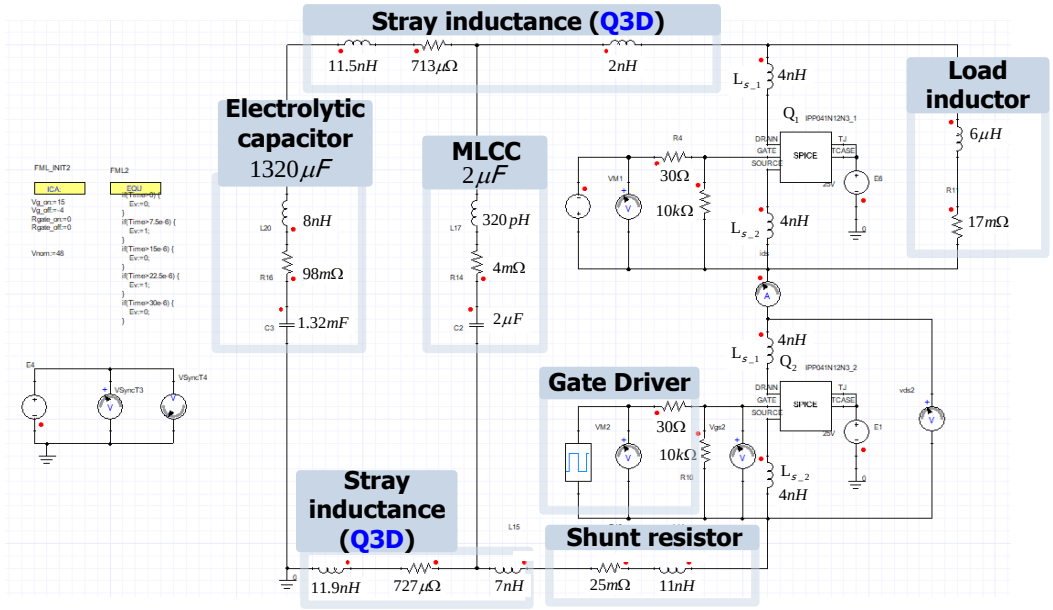
Impedance analyzer (WK 6500B)



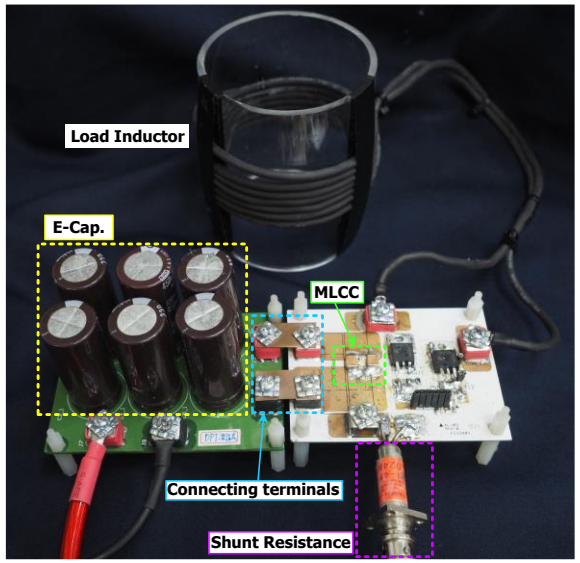
The stray inductance is dependent on frequency!

模擬軟體用於馬達及其驅動器設計

◘ 功率晶體切換損失(Turn off)模擬及量測結果



Double pulse test(DPT)

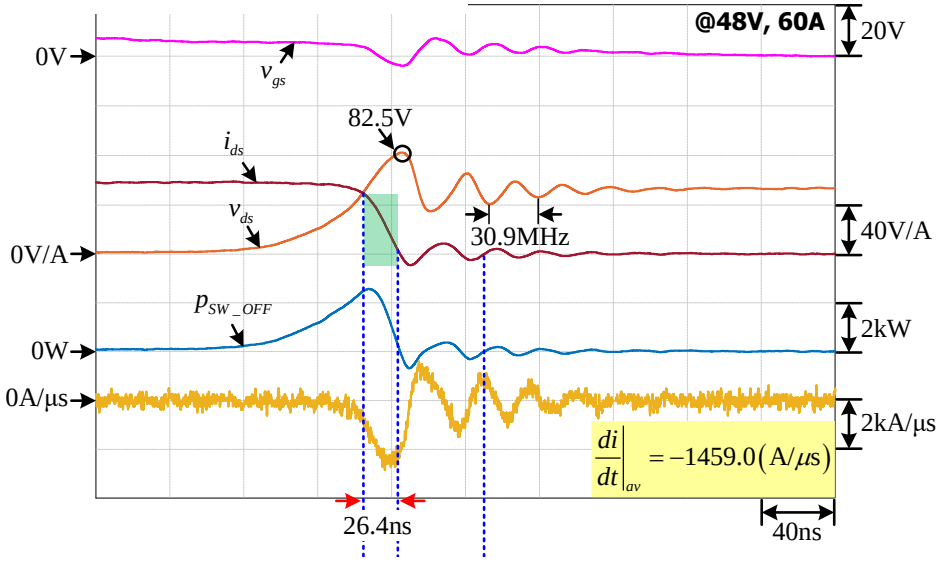


參考教學影帶:

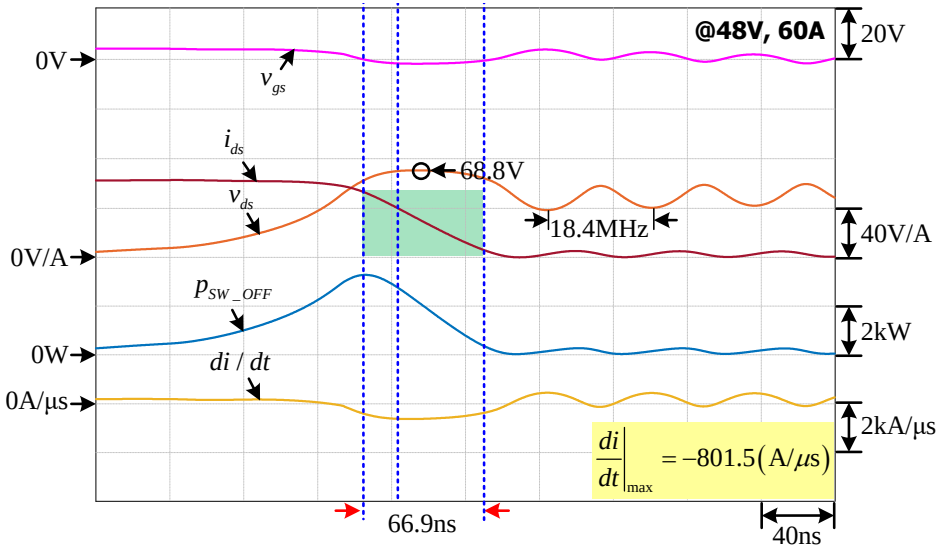
以Double Pulse Tester協助寬能隙半導體於電源轉換器功率級的設計及驗證
2023.12.07

ROHDE&SCHWARZ

Tested results

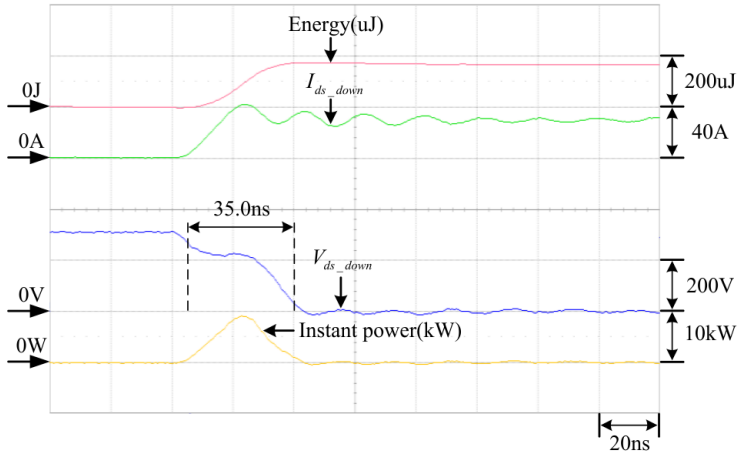
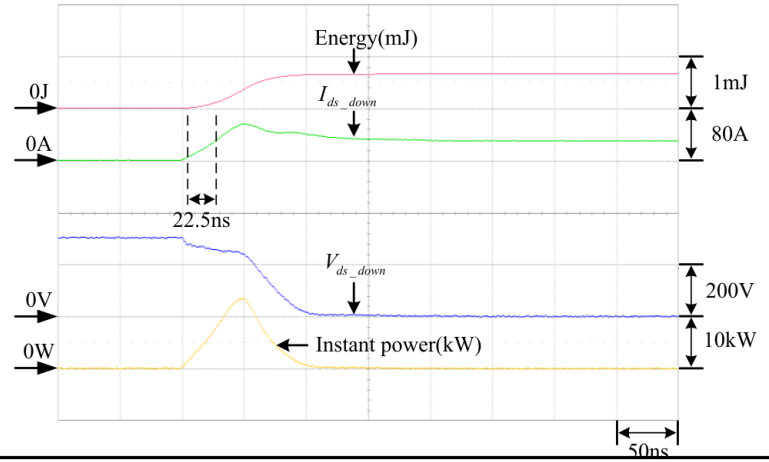
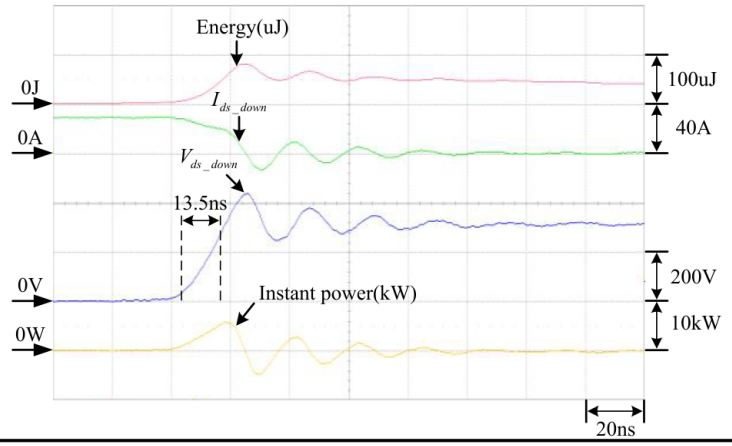
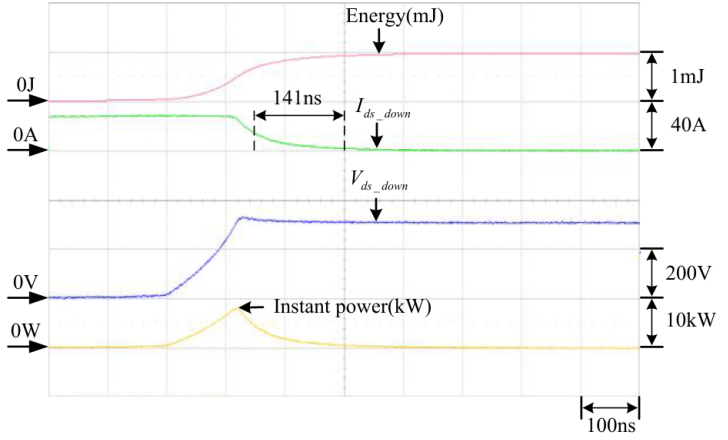


Simulated results



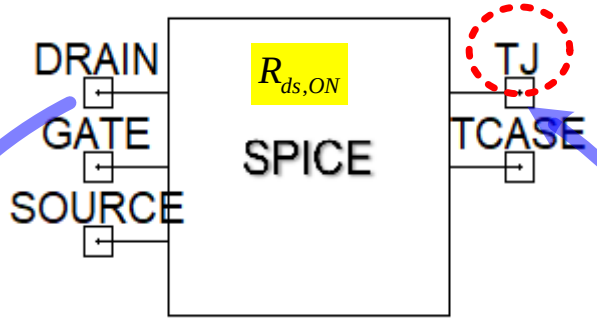
模擬軟體用於馬達及其驅動器設計

◘ DPT測試結果

	SiC MOSFET	IGBT
Turn on		
Turn off		

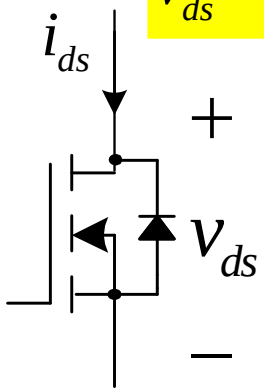
Switching loss of the SiC MOSFET and IGBT are 253.2μJ and 1597.0μJ, respectively.

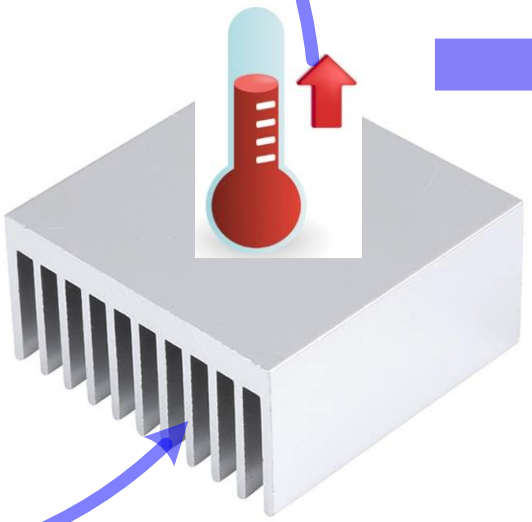
Electro thermo design



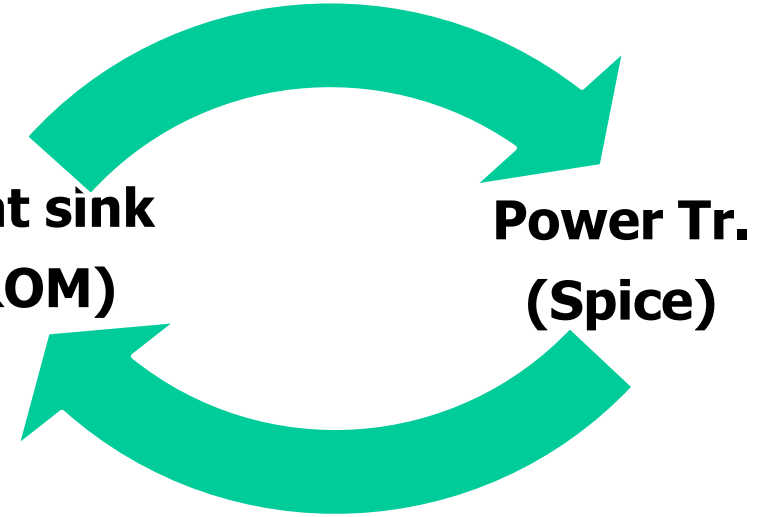
$$P_{cond} = \frac{1}{T}\int_0^{dT} v_{ds} i_{ds} dt$$

$$v_{ds} = i_{ds} R_{ds,ON}$$





Co-simulation



Icepak model

↓

ROM

結論

- 馬達及其驅動技術是電、磁、力、熱流及結構之跨領域整合技術，需考慮不同物理量之相互影響，傳統設計方法已難以因應快速設計之需求；

- 模擬輔助設計用於馬達驅動系統研發為目前重要趨勢，但在確認軟體模擬結果趨勢是否與實際相符前，有賴合適的驗證設備與方法協助建立經驗；

- AI對馬達及其驅動技術之影響及可協助那些項目，有待及早考量及導入。

Q and A