

交流永磁同步電動機的驅動、控制、應用及  
關鍵性技術開發

100年元月25日（二）PM 1:30-PM 2:30

國立臺灣科技大學電機系

劉添華

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大綱

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- V. 實測
- VI. 洗衣機應用
- VII. 結論

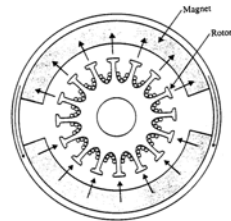
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## I. 簡介

電動機の種類:

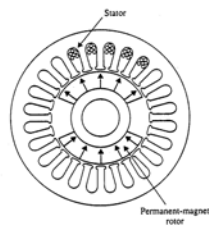
- 直流永磁電動機
- 交流永磁同步電動機
- 交流感應電動機
- 直流無刷電動機

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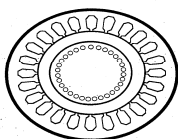


直流永磁

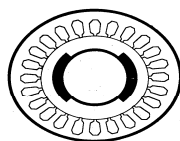
交流永磁同步



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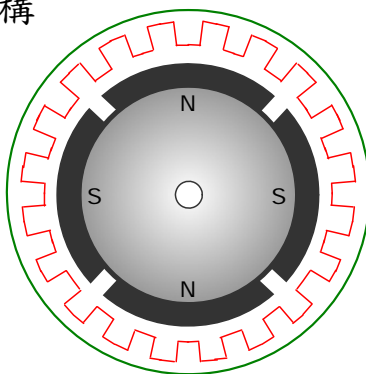
(A) 感應馬達的結構



(B) 無刷馬達的結構

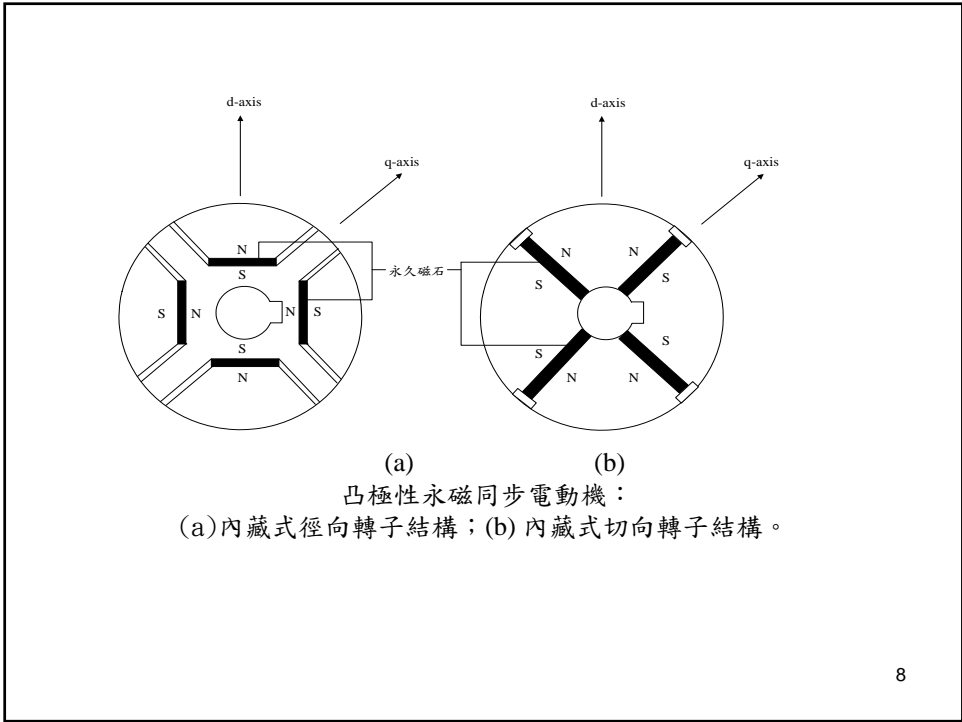
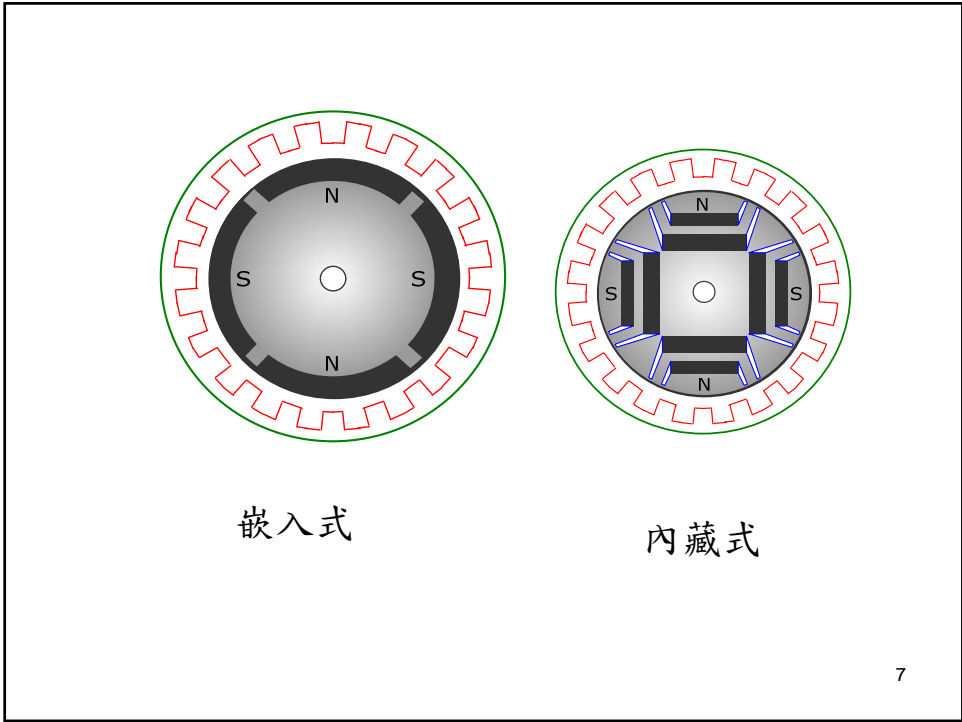
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### 永磁同步電動機的結構



• 表面附著式

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表面式、嵌入式與內藏式永磁同步電動機的比較表

結構	表面式	嵌入式	內藏式
轉子	轉子表面	轉子表面	轉子內部
d-q軸電感	相同	相同	不同
磁阻轉矩	無	無	有
等效激磁轉矩	有	有	有
電磁轉矩	小	小	大

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• 內藏式永磁同步電動機的優點

- 效率高
- 轉矩/電流比大
- d-q軸電感不同
- 可高速運轉

• 使用轉軸角度估測法則的優點

- 避免雜訊干擾
- 降低成本，節省空間

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## II. 數學模式

- 電壓方程式

$$v_d = r_s i_d + L_{ds} \frac{di_d}{dt} - \omega_e L_{qs} i_q \quad (1)$$

$$v_q = r_s i_q + L_{qs} \frac{di_q}{dt} + \omega_e L_{ds} i_d + \omega_e \lambda'_m \quad (2)$$

- 電磁轉矩方程式

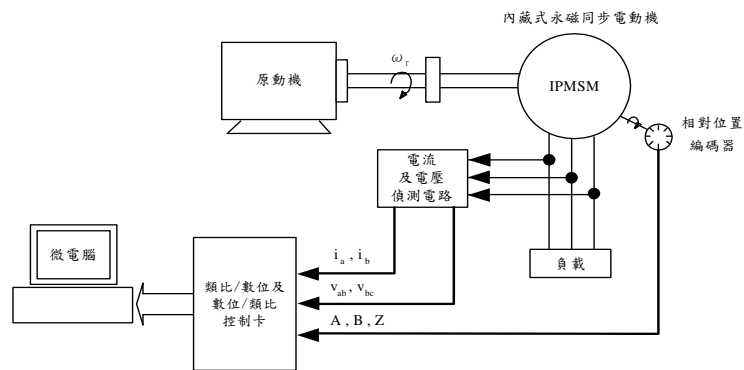
$$T_e = \frac{3}{2} \frac{Pole}{2} [(L_{ds} - L_{qs}) i_d i_q + \lambda'_m i_q] \quad (3)$$

- 轉速動態方程式

$$\frac{d\omega_r}{dt} = \frac{1}{J_m} (T_e - T_L - B_m \omega_r) \quad (4)$$

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## III. 參數鑑定



全數位化參數量測之系統方塊圖

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- 定子電阻的量測方法

$$R = \frac{V_{dc}}{I_{dc}} \quad (5)$$

$$r_s = \frac{1}{2}R \quad (6)$$

- 磁通鏈的量測方法

$$\dot{\lambda}_m = \frac{V_m}{\omega_e} = \frac{V_m}{\omega_r} \frac{2}{Pole} \quad (7)$$

$$v_{as} = V_m \cos\theta_e \quad (8)$$

$$v_{bs} = V_m \cos(\theta_e - \frac{2\pi}{3}) \quad (9)$$

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$$v_{cs} = V_m \cos(\theta_e + \frac{2\pi}{3}) \quad (10)$$

定子側電流為零，因此由(2)式可改寫為：

$$v_q = \omega_e \dot{\lambda}_m \quad (11)$$

將(8)-(10)式透過座標轉換可以得到：

$$\begin{bmatrix} v_q \\ v_d \\ v_o \end{bmatrix} = \begin{bmatrix} V_m \\ 0 \\ 0 \end{bmatrix} \quad (12)$$

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- 直/交軸電感的量測方法

將(1)及(2)式之電壓方程式重新整理如下：

$$\omega_e \dot{\lambda}_m = v_q + r_s i_q + L_{qs} \frac{d}{dt} i_q + \omega_e L_{ds} i_d \quad (13)$$

$$0 = v_d + r_s i_d + L_{ds} \frac{d}{dt} i_d - \omega_e L_{qs} i_q \quad (14)$$

$$L_{ds} = \frac{1}{\omega_e i_d} (\omega_e \dot{\lambda}_m - v_q - r_s i_q) \quad (15)$$

$$L_{qs} = \frac{1}{\omega_e i_q} (v_d - r_s i_d) \quad (16)$$

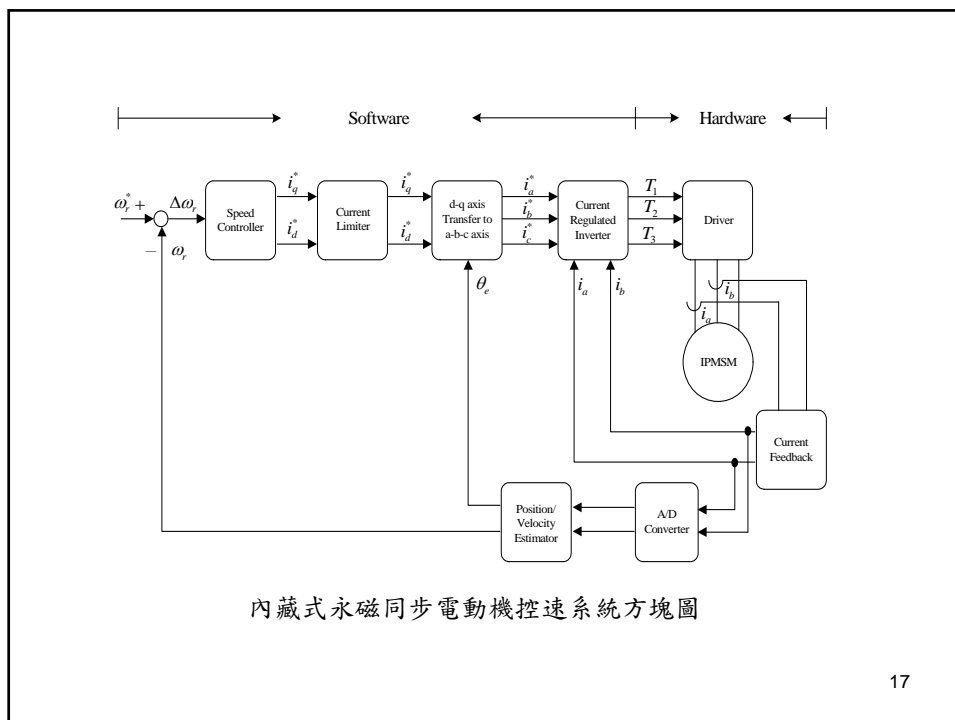
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內藏式永磁同步電動機參數表

參數	數值
極數	4
定子相電阻	1.9Ω
d軸電感	31 mH
q軸電感	15.1 mH
磁通鏈	0.227 V/(rad/sec)
電動機轉軸慣量	0.0005 kg·m <sup>2</sup>
電動機轉軸摩擦係數	0.03 N·m/(rad/sec)
原動機轉軸慣量	0.0222 kg·m <sup>2</sup>
原動機轉軸摩擦係數	0.0041 N·m/(rad/sec)

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#### IV. 轉軸角度估測法則

Sensorless 的優點:

- 省空間
- 省成本
- 提高可靠度
- 避免干擾

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### Sensorless 方法:

- 反電勢法
- 電流斜率法
- 高頻注入法

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當變頻器切換在 zero voltage vector 時  
忽略電阻時:  
當變頻器切換在 active mode 時

$$v_k = L \frac{di}{dt_{mode k}} + e$$

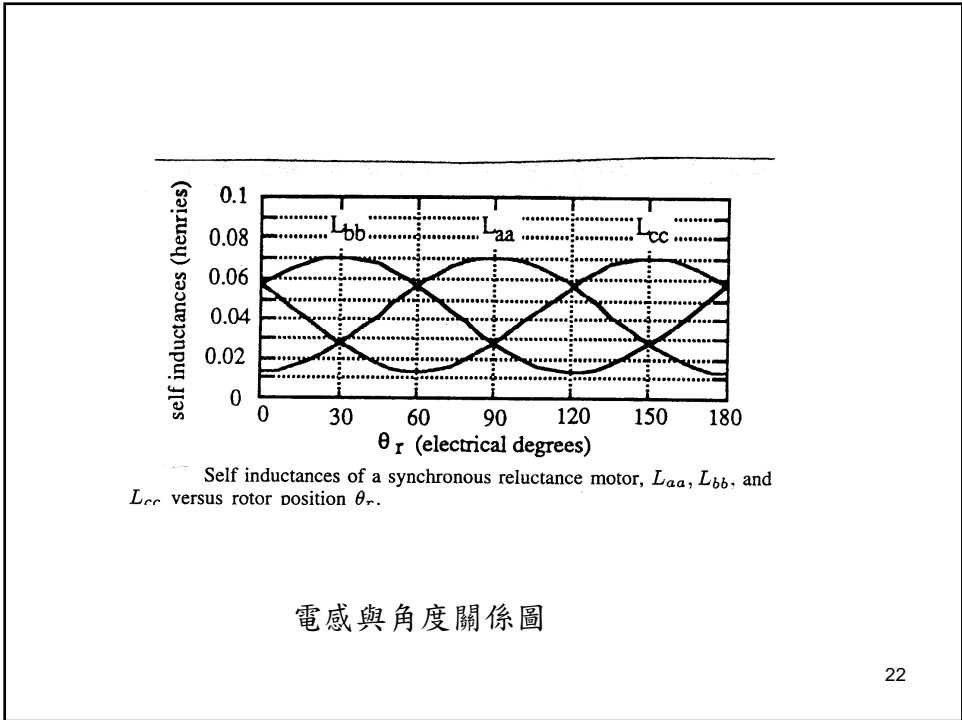
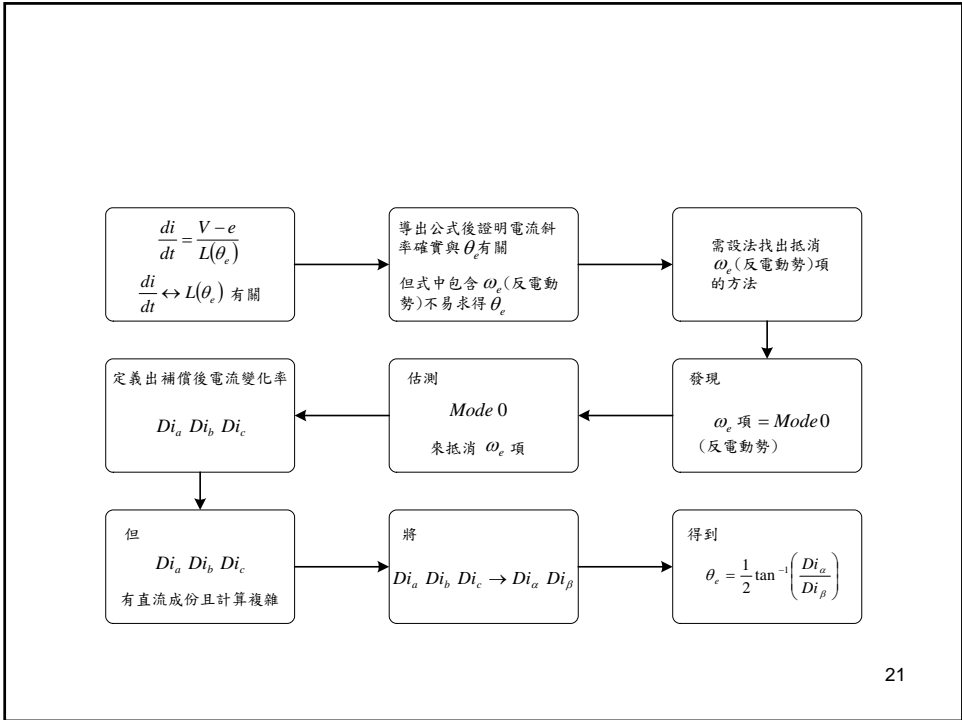
當變頻器切換在 zero voltage vector 時

$$v_k = L \frac{di}{dt_{mode 0}} + e$$

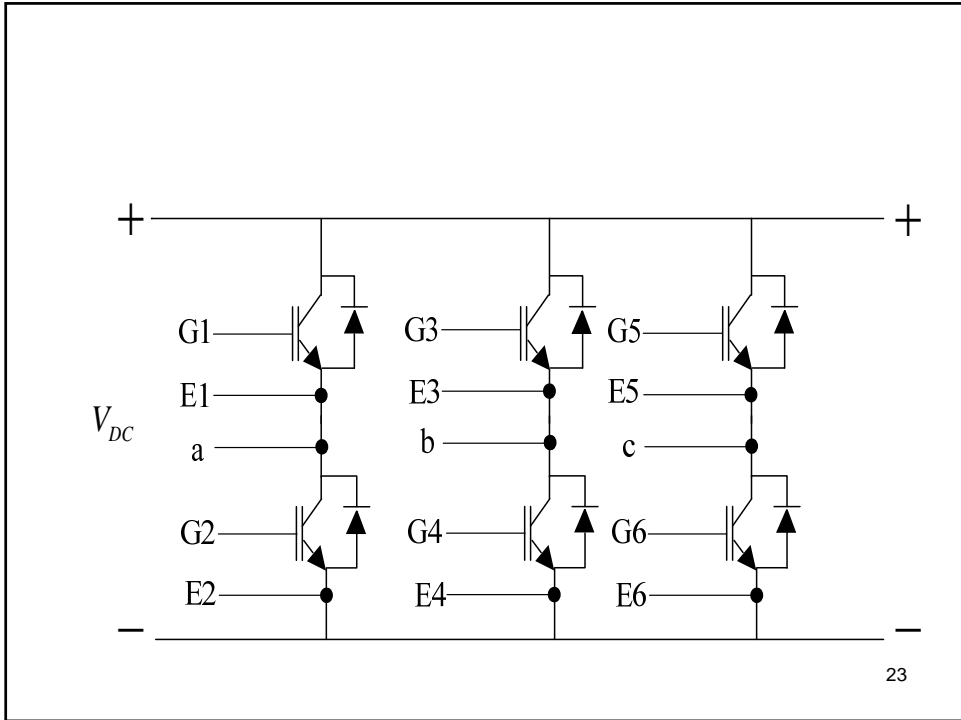
由 (\*\*) 得到

$$Di = \frac{di}{dt_{mode k}} - \frac{di}{dt_{mode 0}} = \frac{v_k}{L}$$

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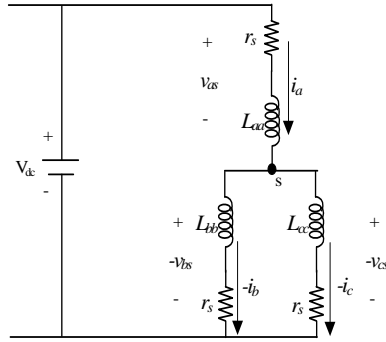
電感與角度關係圖



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	$S_1$	$S_2$	$S_3$	$V_{an}$	$V_{bn}$	$V_{cn}$	$V_{ab}$	$V_{bc}$	$V_{ca}$
$V_0(000)$	0	0	0	0	0	0	0	0	0
$V_1(100)$	1	0	0	$\frac{2}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$V_{DC}$	0	$-V_{DC}$
$V_2(110)$	1	1	0	$\frac{1}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$-\frac{2}{3}V_{DC}$	0	$V_{DC}$	$-V_{DC}$
$V_3(010)$	0	1	0	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$-V_{DC}$	$V_{DC}$	0
$V_4(011)$	0	1	1	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$-V_{DC}$	0	$V_{DC}$
$V_5(001)$	0	0	1	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	0	$-V_{DC}$	$V_{DC}$
$V_6(101)$	1	0	1	$\frac{1}{3}V_{DC}$	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$V_{DC}$	$-V_{DC}$	0
$V_7(111)$	1	1	1	0	0	0	0	0	0

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$$i_a = -(i_b + i_c) \quad (17)$$

$$V_{dc} = v_{as} - v_{bs} \quad (18)$$

$$v_{bs} = v_{cs} \quad (19)$$

變頻器切換狀態模式A+的等效電路

• 模式A+的三相電流變化率

$$\begin{aligned} \left. \frac{di_a}{dt} \right|_{\text{mode } A^+} &= \left[ 4V_{dc} \left( \frac{2}{3}L_{ls} + L_A + \cos(2\theta_e)L_B \right) \right. \\ &\quad + 2\omega_e L_B \left( -3\sin(2\theta_e)\dot{i}_a(3L_A + 2L_{ls}) \right. \\ &\quad \left. \left. + \sqrt{3}(i_b - i_c)(3L_B + \cos(2\theta_e)(3L_A + 2L_{ls})) + \lambda'_{ma} \right) \right] \\ &\quad / \left( (2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B)) \right) \end{aligned} \quad (20)$$

$$\begin{aligned} \left. \frac{di_b}{dt} \right|_{\text{mode } A^+} &= \left[ -2V_{dc} \left( \frac{2}{3}L_{ls} + L_A + (\cos(2\theta_e) - \sqrt{3}\sin(2\theta_e))L_B \right) \right. \\ &\quad + 2\omega_e L_B \left( -3\sqrt{3}(i_a - i_b)L_B \right. \\ &\quad \left. \left. + (\sqrt{3}\cos(2\theta_e)(i_a - i_b) - 3\sin(2\theta_e)\dot{i}_c)(3L_A + 2L_{ls}) + \lambda'_{mb} \right) \right] \\ &\quad / \left( (2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B)) \right) \end{aligned} \quad (21)$$

$$\begin{aligned} \left. \frac{di_c}{dt} \right|_{\text{mode } A^+} &= \left[ -2V_{dc} \left( \frac{2}{3}L_{ls} + L_A + (\cos(2\theta_e) + \sqrt{3}\sin(2\theta_e))L_B \right) \right. \\ &\quad + 2\omega_e L_B \left( -3\sin(2\theta_e)\dot{i}_b(3L_A + 2L_{ls}) \right. \\ &\quad \left. \left. + \sqrt{3}(3(i_a - i_b)L_B - \cos(2\theta_e)(i_a - i_c)(3L_A + 2L_{ls})) + \lambda'_{mc} \right) \right] \\ &\quad / \left( (2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B)) \right) \end{aligned} \quad (22)$$

• 模式0的三相電流變化率

$$\left. \frac{di_a}{dt} \right|_{\text{mode } 0} = \left[ 2\omega_e L_B (-3\sin(2\theta_e) i_a (3L_A + 2L_{ls}) + \sqrt{3}(i_b - i_c) (3L_B + \cos(2\theta_e)(3L_A + 2L_{ls})) + \lambda'_{ma}) \right] / ((2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))) \quad (23)$$

$$\left. \frac{di_b}{dt} \right|_{\text{mode } 0} = \left[ 2\omega_e L_B (-3\sqrt{3}(i_a - i_b)L_B + (\sqrt{3}\cos(2\theta_e)(i_a - i_b) - 3\sin(2\theta_e) i_c)(3L_A + 2L_{ls}) + \lambda'_{mb}) \right] / ((2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))) \quad (24)$$

$$\left. \frac{di_c}{dt} \right|_{\text{mode } 0} = \left[ 2\omega_e L_B (-3\sin(2\theta_e) i_b (3L_A + 2L_{ls}) + \sqrt{3}(3(i_a - i_b)L_B - \cos(2\theta_e)(i_a - i_c)(3L_A + 2L_{ls})) + \lambda'_{mc}) \right] / ((2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))) \quad (25)$$

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• 補償後電流變化率

$$Di_a \Big|_{\text{mode } A^+} = \left. \frac{di_a}{dt} \right|_{\text{mode } A^+} - \left. \frac{di_a}{dt} \right|_{\text{mode } 0} = \frac{4V_{dc} \left( \frac{2}{3} L_{ls} + L_A + \cos(2\theta_e) L_B \right)}{(2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))} \quad (26)$$

$$Di_b \Big|_{\text{mode } B^+} = \left. \frac{di_b}{dt} \right|_{\text{mode } B^+} - \left. \frac{di_b}{dt} \right|_{\text{mode } 0} = \frac{2V_{dc} \left( 2\left(\frac{2}{3} L_{ls} + L_A\right) - (\cos(2\theta_e) + \sqrt{3}\sin(2\theta_e)) L_B \right)}{(2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))} \quad (27)$$

$$Di_c \Big|_{\text{mode } C^+} = \left. \frac{di_c}{dt} \right|_{\text{mode } C^+} - \left. \frac{di_c}{dt} \right|_{\text{mode } 0} = \frac{2V_{dc} \left( 2\left(\frac{2}{3} L_{ls} + L_A\right) + (-\cos(2\theta_e) + \sqrt{3}\sin(2\theta_e)) L_B \right)}{(2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))} \quad (28)$$

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座標轉換矩陣關係如

下：

$$\begin{bmatrix} Di_\beta \\ Di_\alpha \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Di_a \\ Di_b \\ Di_c \end{bmatrix} \quad (29)$$

$$Di_\alpha = \frac{6V_{dc}L_B \sin(2\theta_e)}{(2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))} \quad (30)$$

$$Di_\beta = \frac{6V_{dc}L_B \cos(2\theta_e)}{(2L_{ls} + 3(L_A - L_B))(2L_{ls} + 3(L_A + L_B))} \quad (31)$$

$$\theta_e = \frac{1}{2} \tan^{-1} \left( \frac{Di_\alpha}{Di_\beta} \right) \quad (32)$$

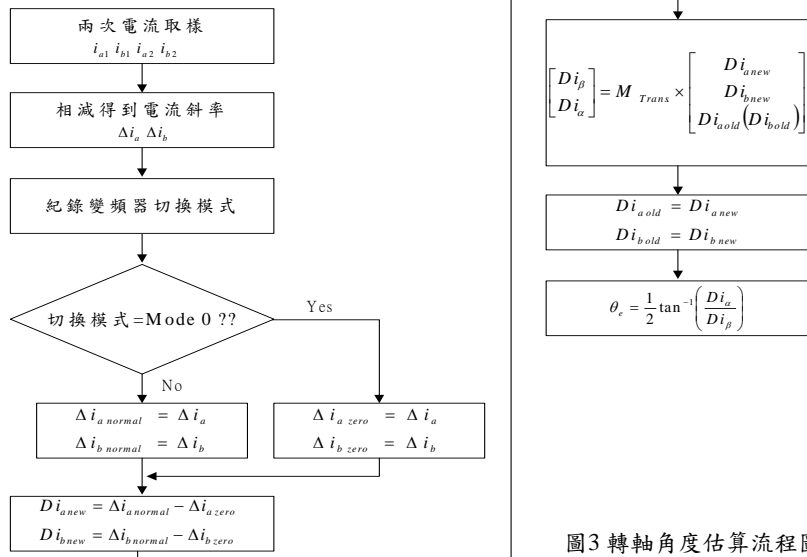
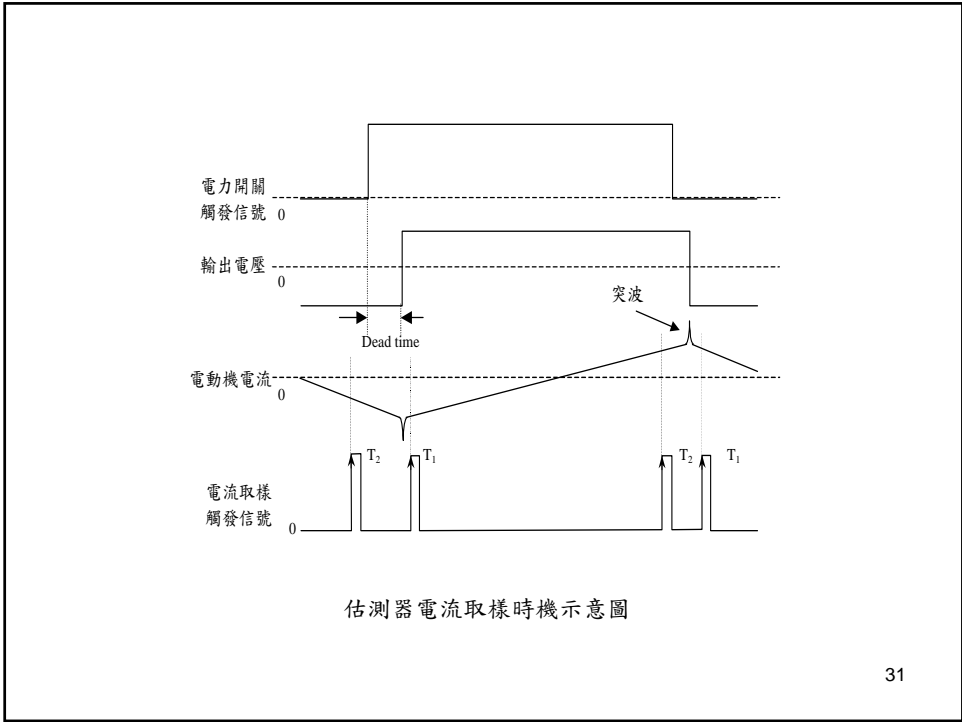
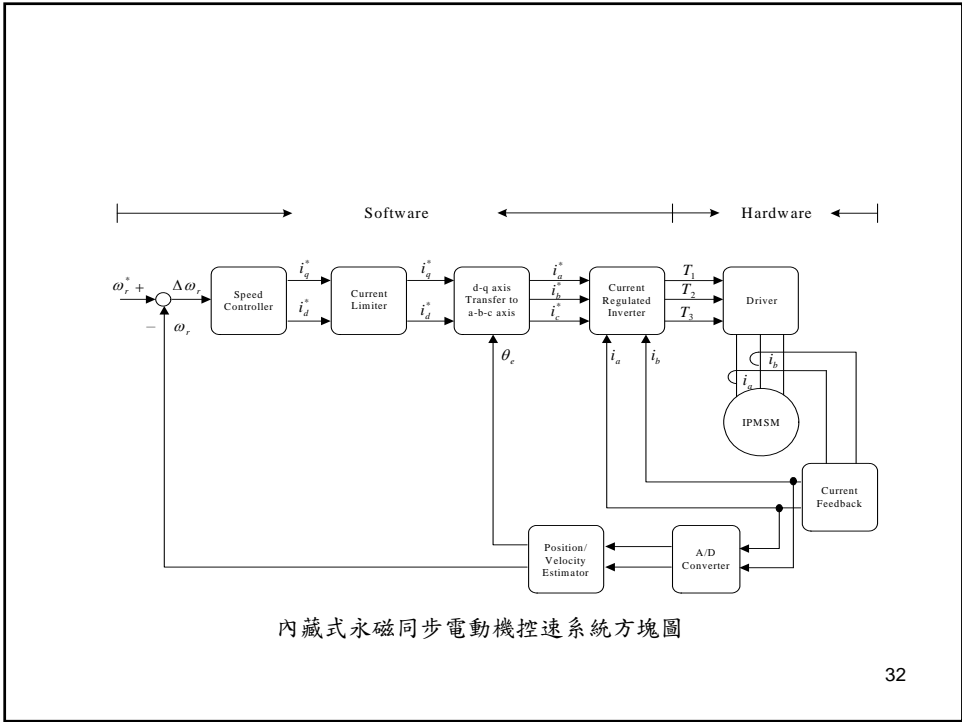


圖3 轉軸角度估算流程圖



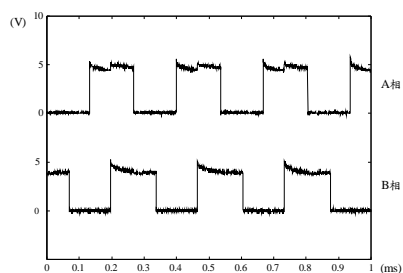
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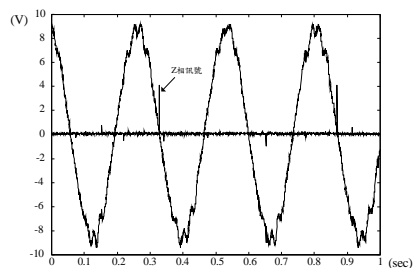
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## V. 實測結果

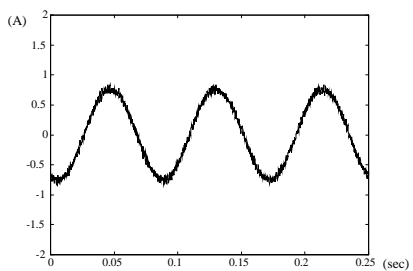


編碼器A相及B相訊號實測波形

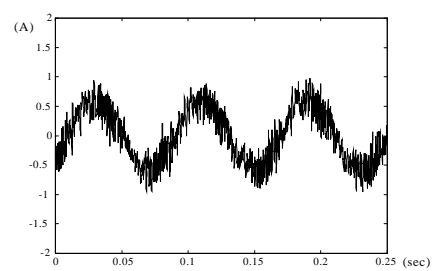


編碼器Z相訊號與電動機反電動勢實測波形

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(a)

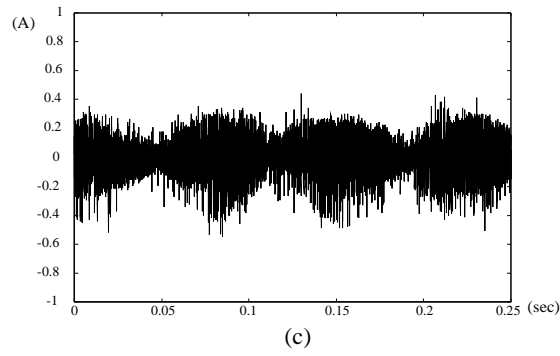


(b)

未加載，電動機穩態時a相電流波形：

(a) 命令；(b) 實際；(c) 誤差

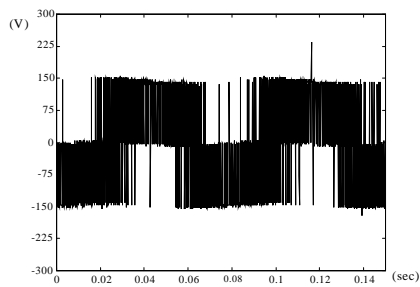
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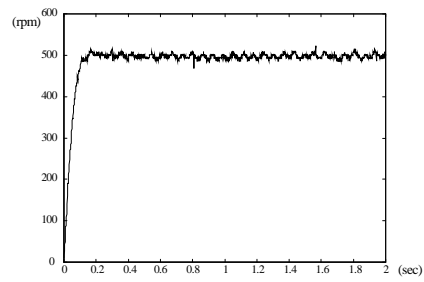
未加載，電動機穩態時a相電流波形：

(a) 命令；(b) 實際；(c) 誤差

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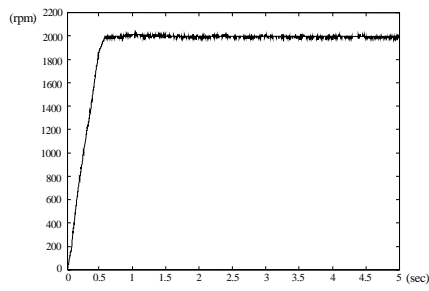


電動機線電壓  $V_{ab}$  實測波形

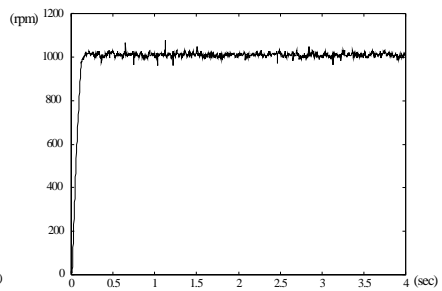


電動機轉速500轉/分，暫態響應波形

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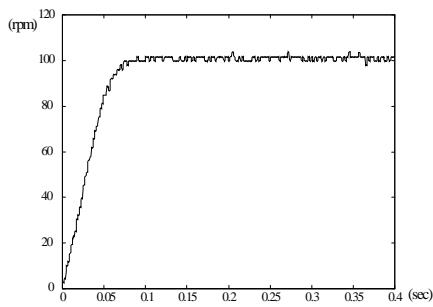


電動機轉速2000轉/分，暫態響應波形

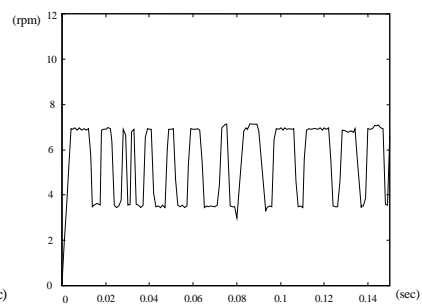


電動機轉速1000轉/分，暫態響應波形

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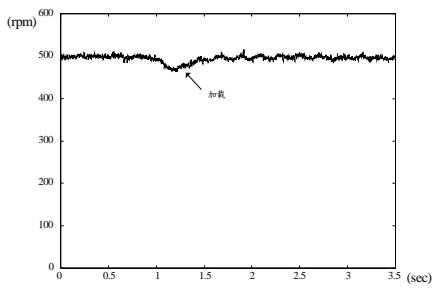


電動機轉速100轉/分，暫態響應波形

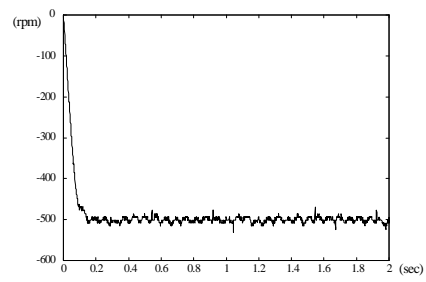


電動機轉速5轉/分，暫態響應波形

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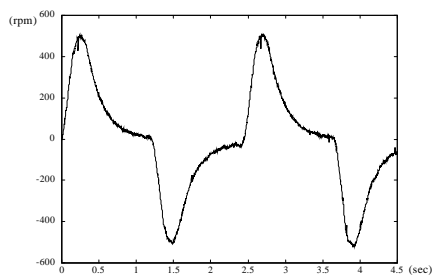


電動機轉速500轉/分，穩態下加載1  
牛頓-米之波形

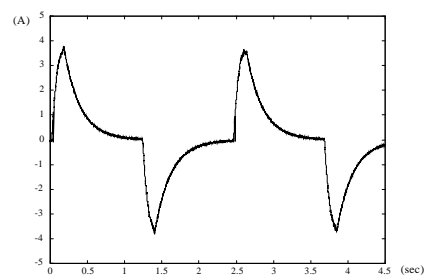


電動機轉速500轉/分，反轉之暫態響應  
波形

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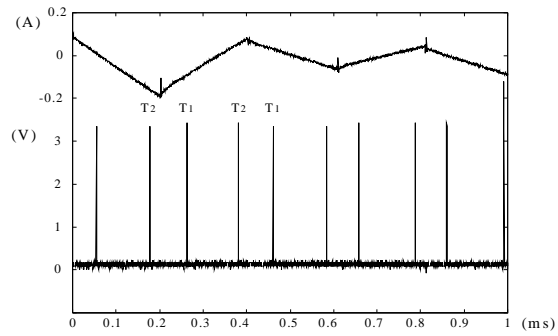


電動機於-500轉/分~500轉/分間運轉  
之轉速暫態響應實測波形

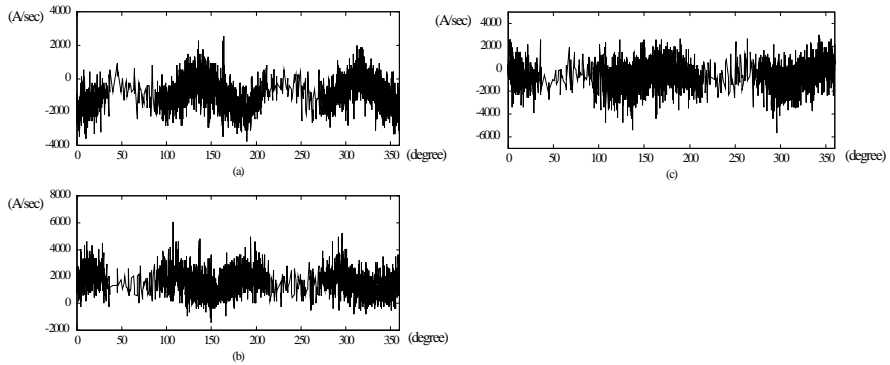


電動機於-500轉/分~500轉/分間運轉  
之q軸電流響應實測波形

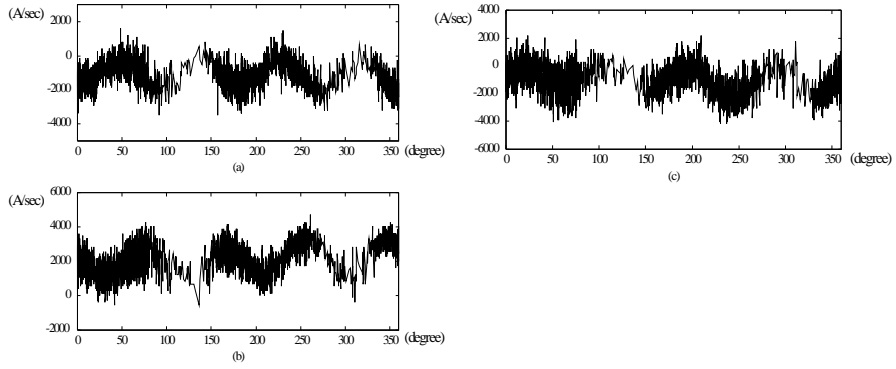
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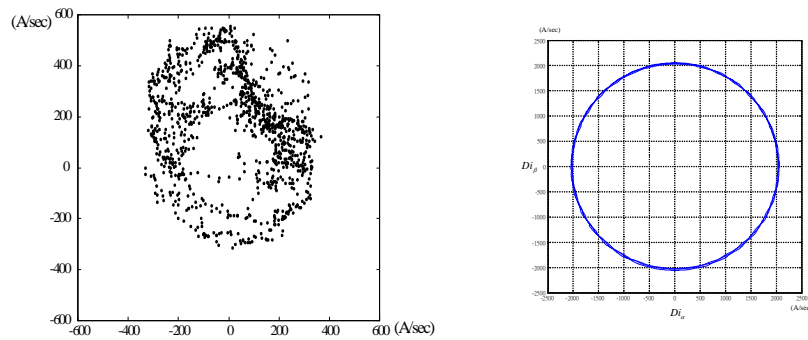
電流取樣時機及電流變化實測波形



無轉速補償時，模式A+ 的相電流變化率實測波形：(a) a相 (b) b相 (c) c相

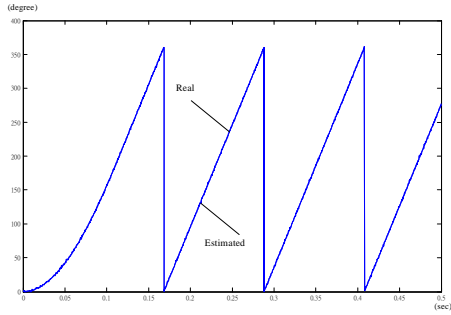


有轉速補償時，模式A+ 的相電流變化率實測波形：(a) a相 (b) b相 (c) c相

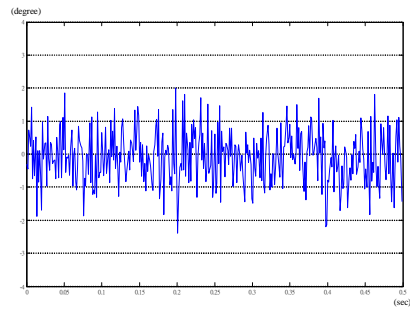


未加轉速補償時，電流變化率實測波形

加轉速補償時，電流變化率實測波形

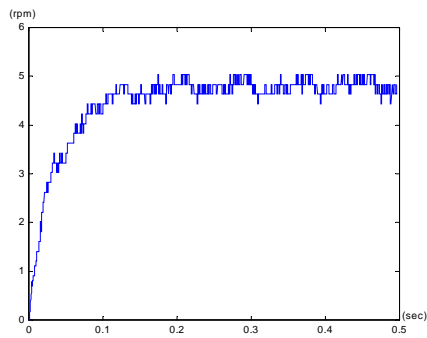


電動機轉速500轉/分，轉軸角度的實際值與估測值之比較波形



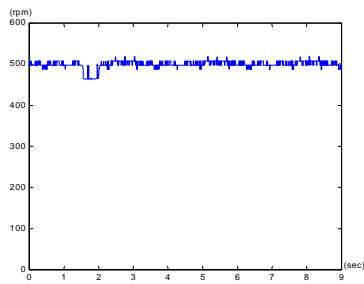
電動機轉速500轉/分，角度估測之誤差波形

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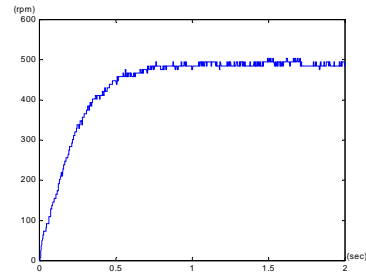


電動機轉速5轉/分實測波形

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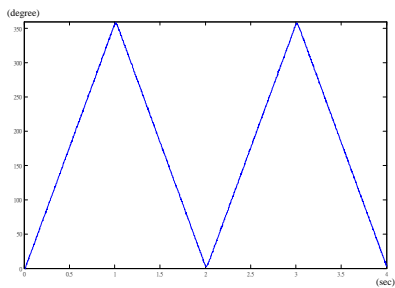


電動機轉速500轉/分加載1 Nt-m.

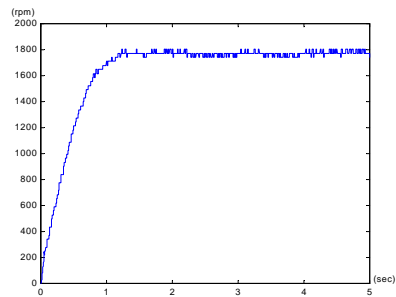


電動機轉速500轉/分實測波形

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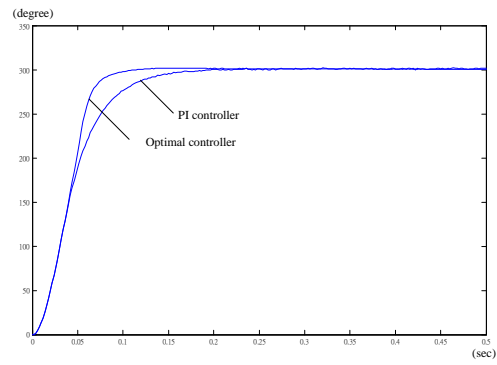
電動機實測波形



電動機轉速1800轉/分，速度實測波形

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電動機實測波形

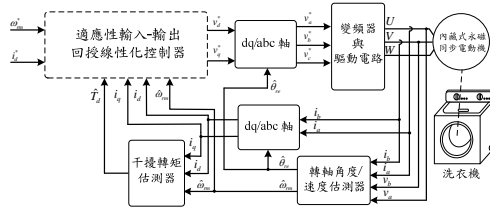
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## VI. 洗衣機實際應用

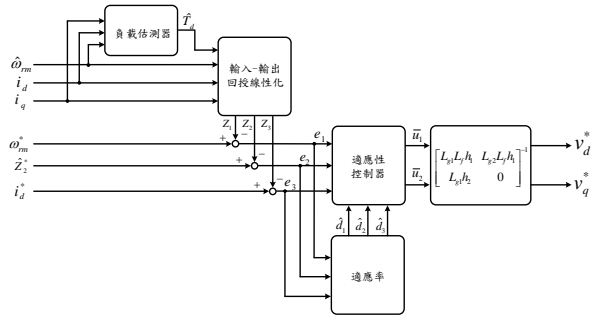
- 轉軸估測法則
- 控制器設計
- 實際應用

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### 控制器設計



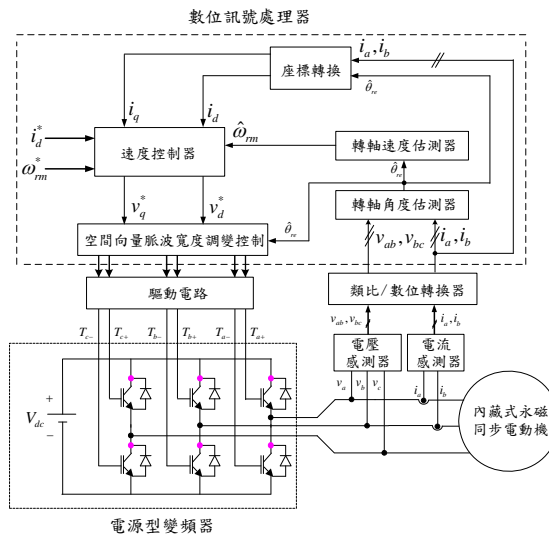
### 非線性控制設計示意圖



### 非線性控制器方塊圖

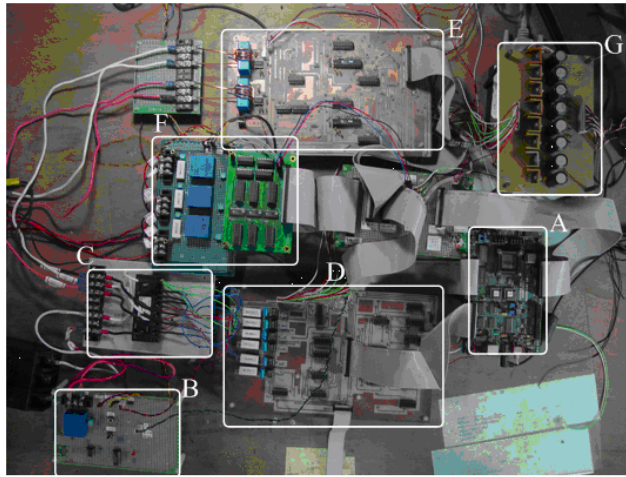
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### 系統研製



### 內藏式永磁同步電動機閉迴路驅動系統

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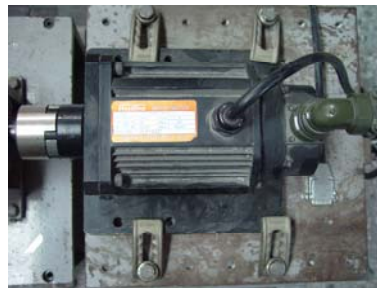


無轉軸偵測元件之內藏式同步電動機驅動系統實體圖

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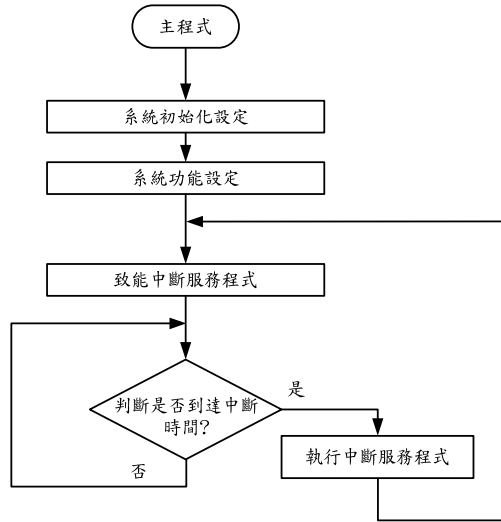
美泰克MAH5500滾筒式洗衣機實體圖



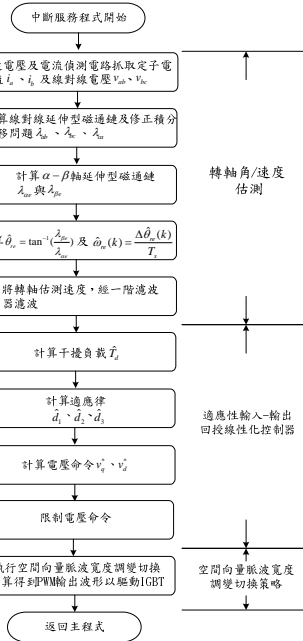
洗衣機用內藏式永磁同步電動機實體圖

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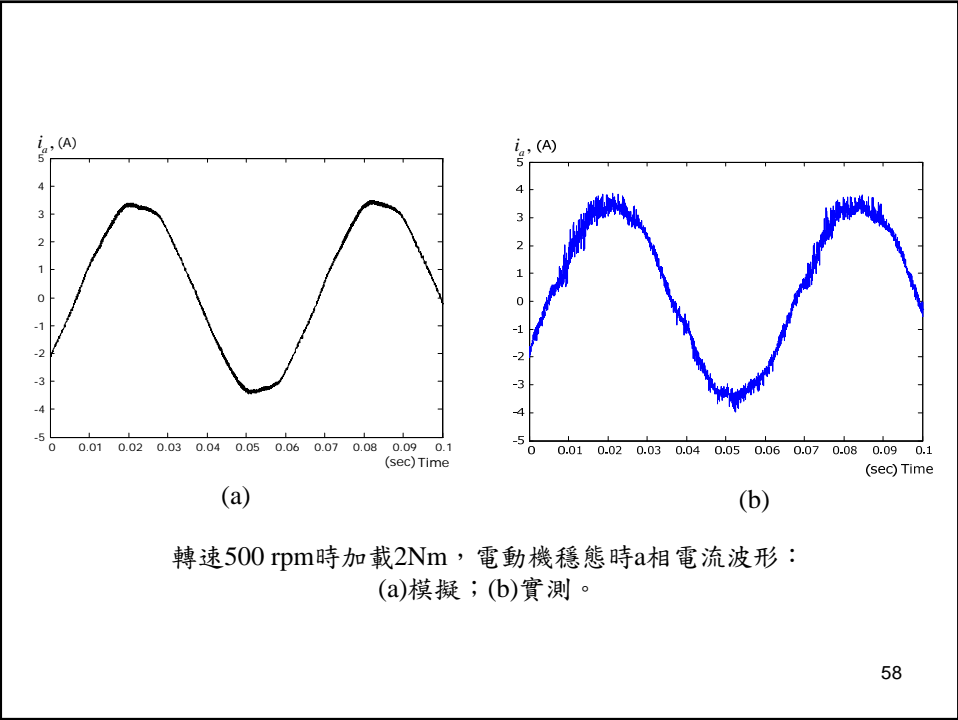
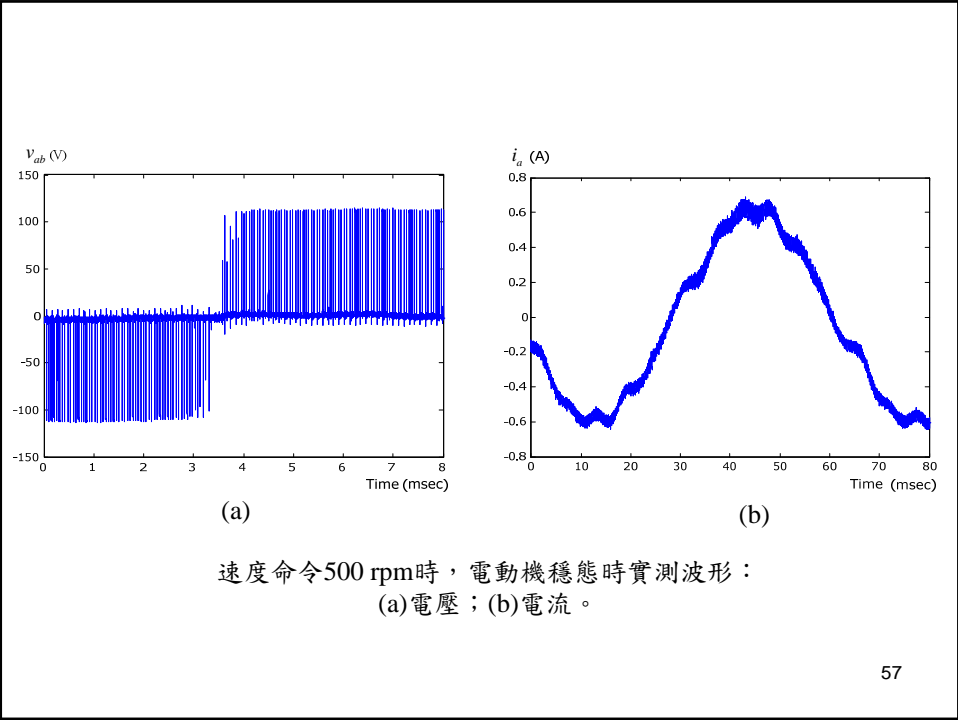
# DSP軟體流程

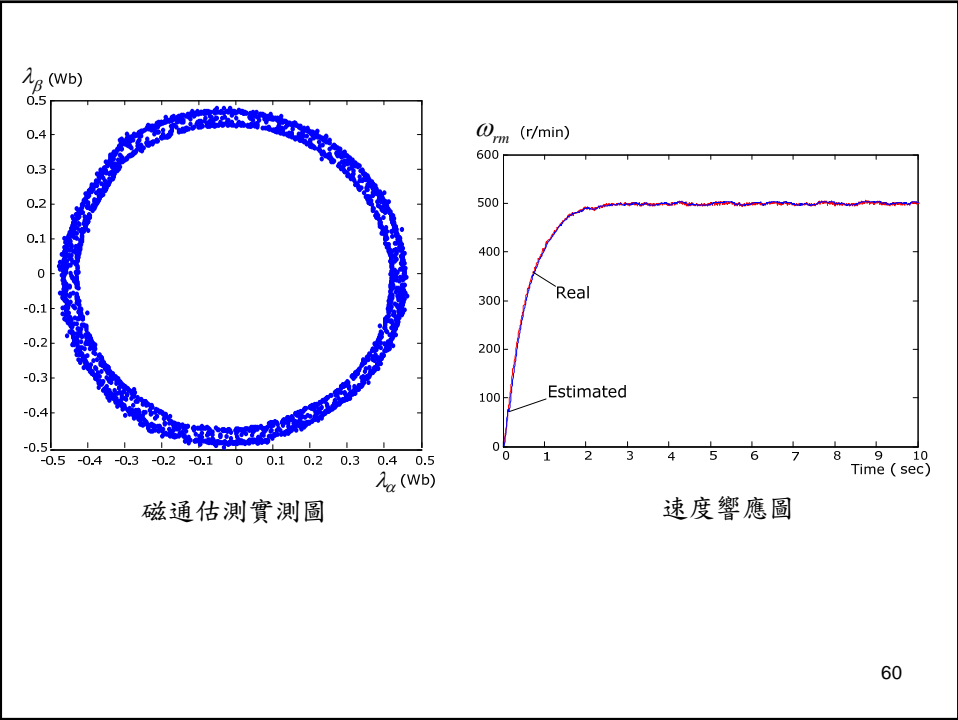
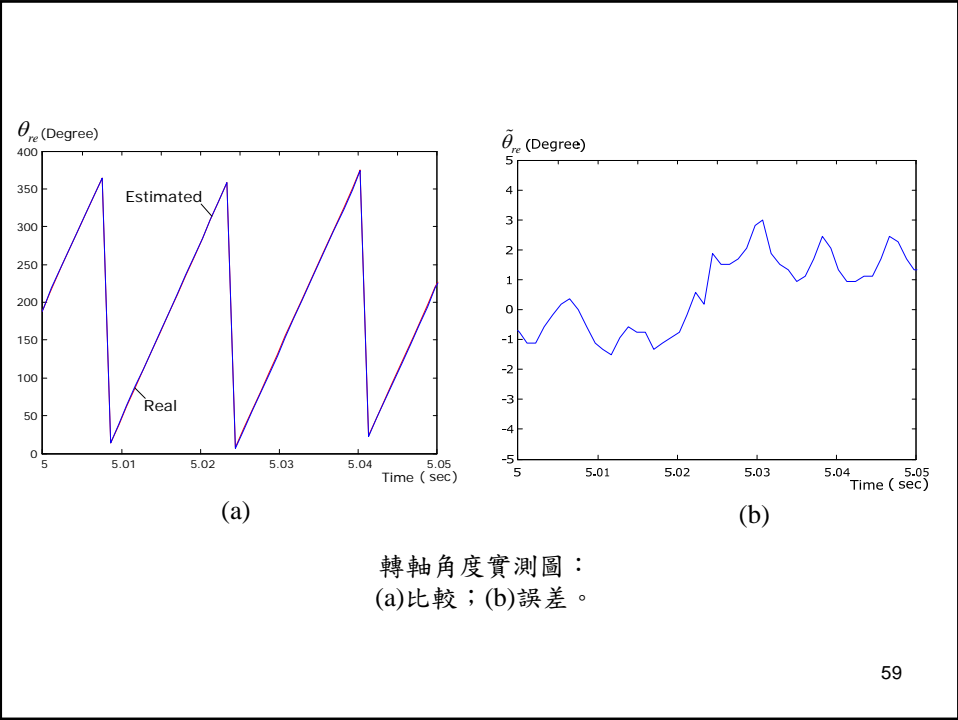


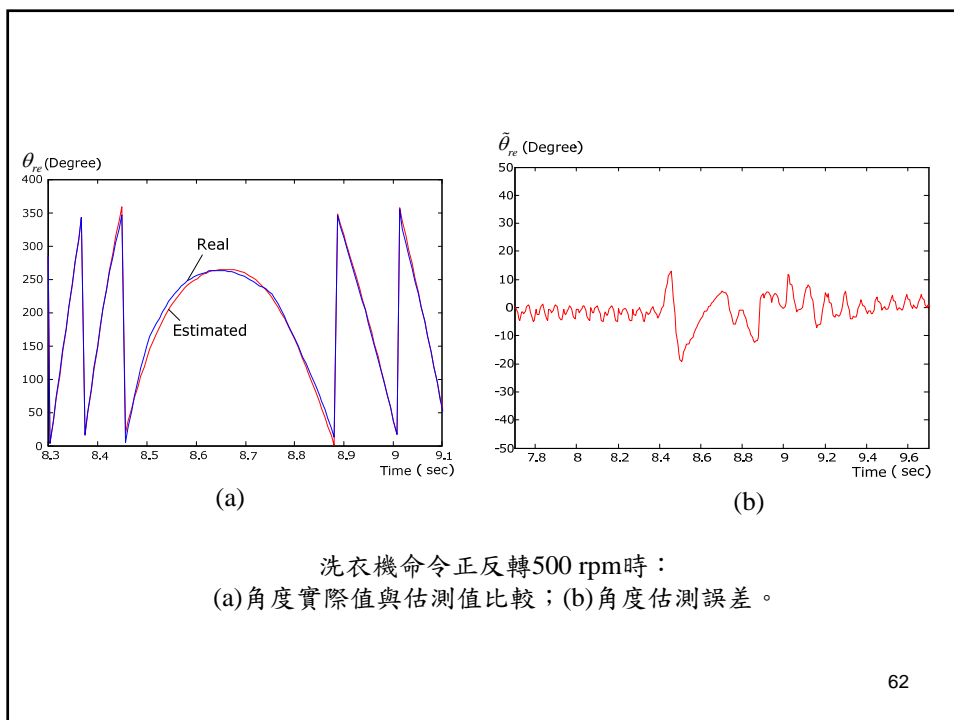
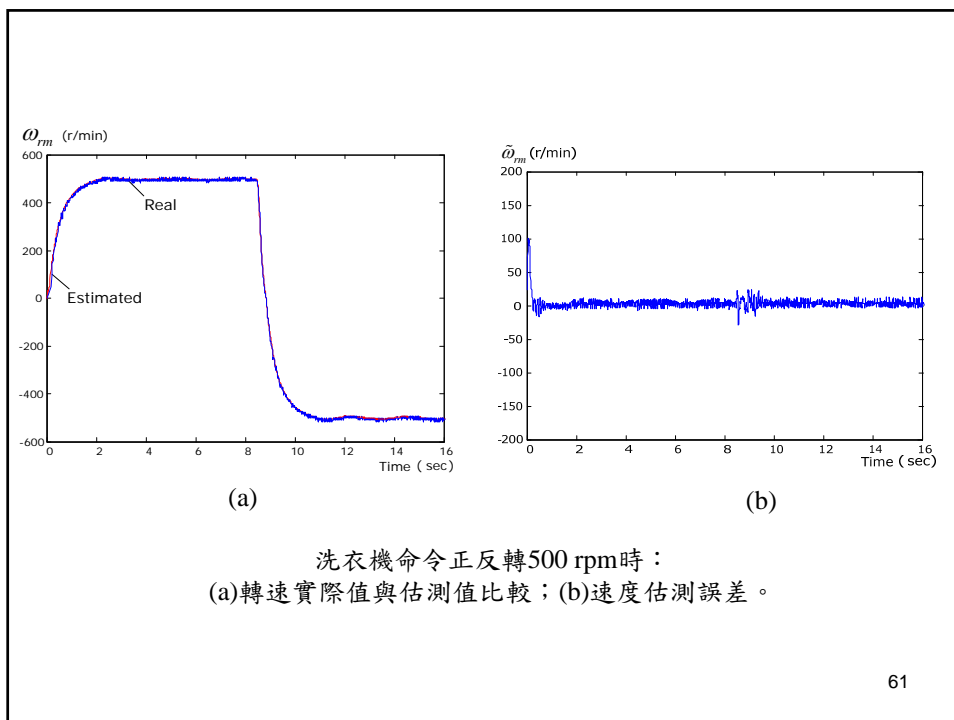
主程式流程圖

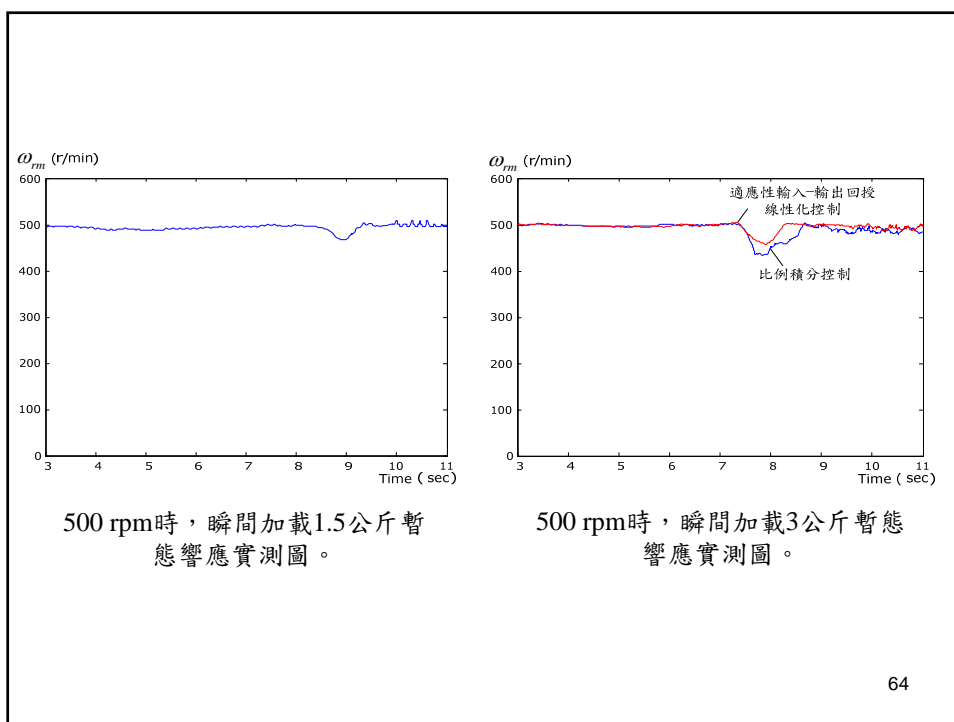
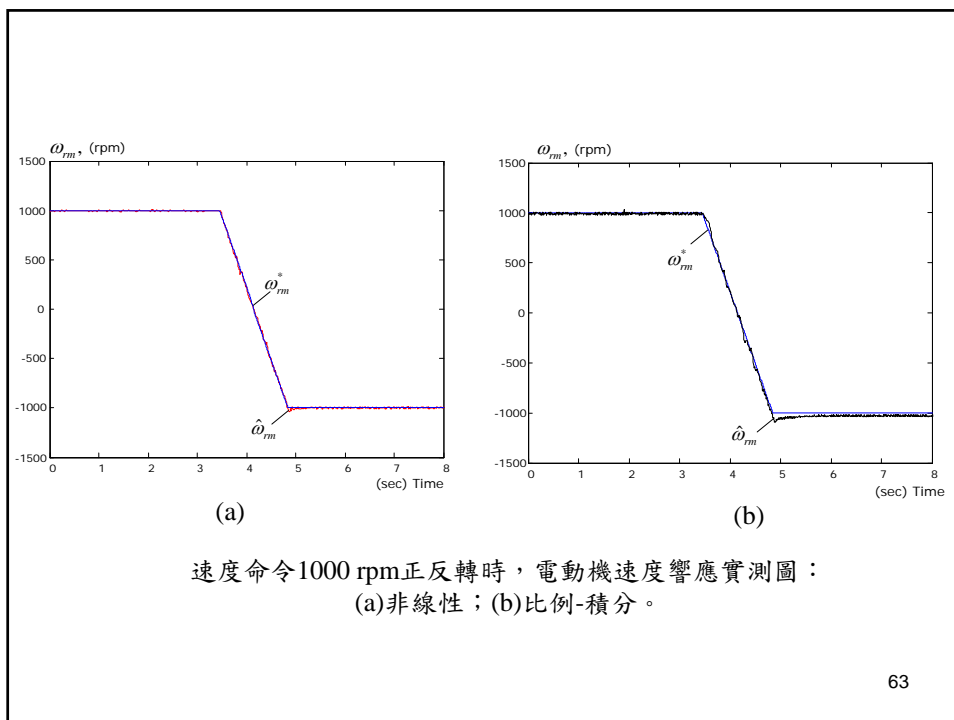


中斷服務程式流程圖

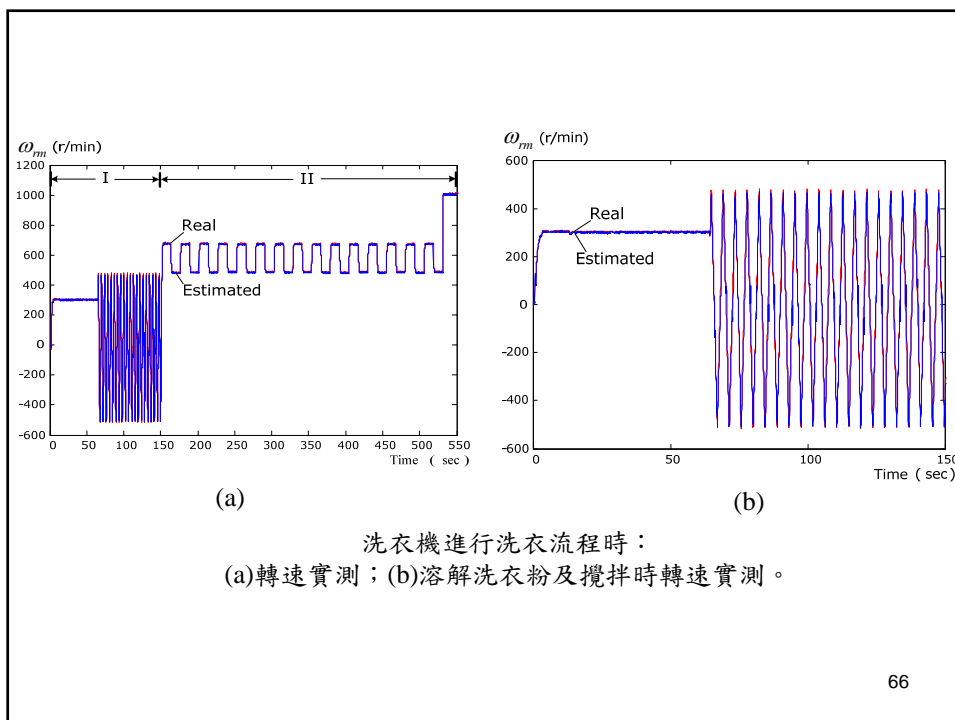
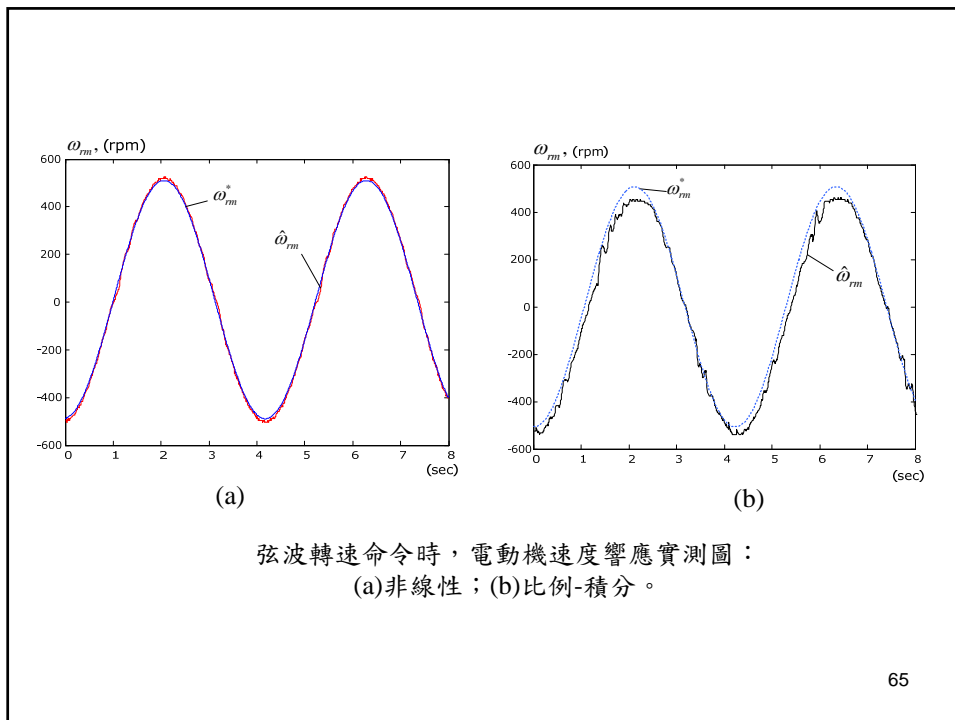


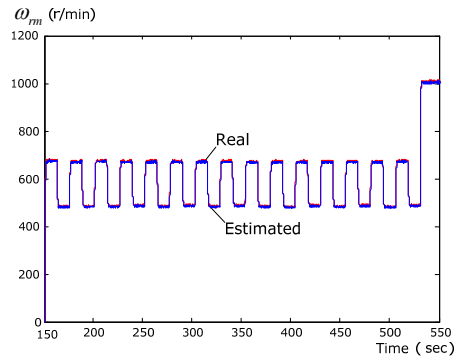












洗衣機進行洗衣流程時：攪拌再脫水時轉速實測

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## VII. 結論與討論

- 發展新型無轉軸角/速度估測方法，並以DSP實現。
- 發展非線性控制器，並以DSP實現。
- 應用於洗衣機驅動系統並具有良好的效果。

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