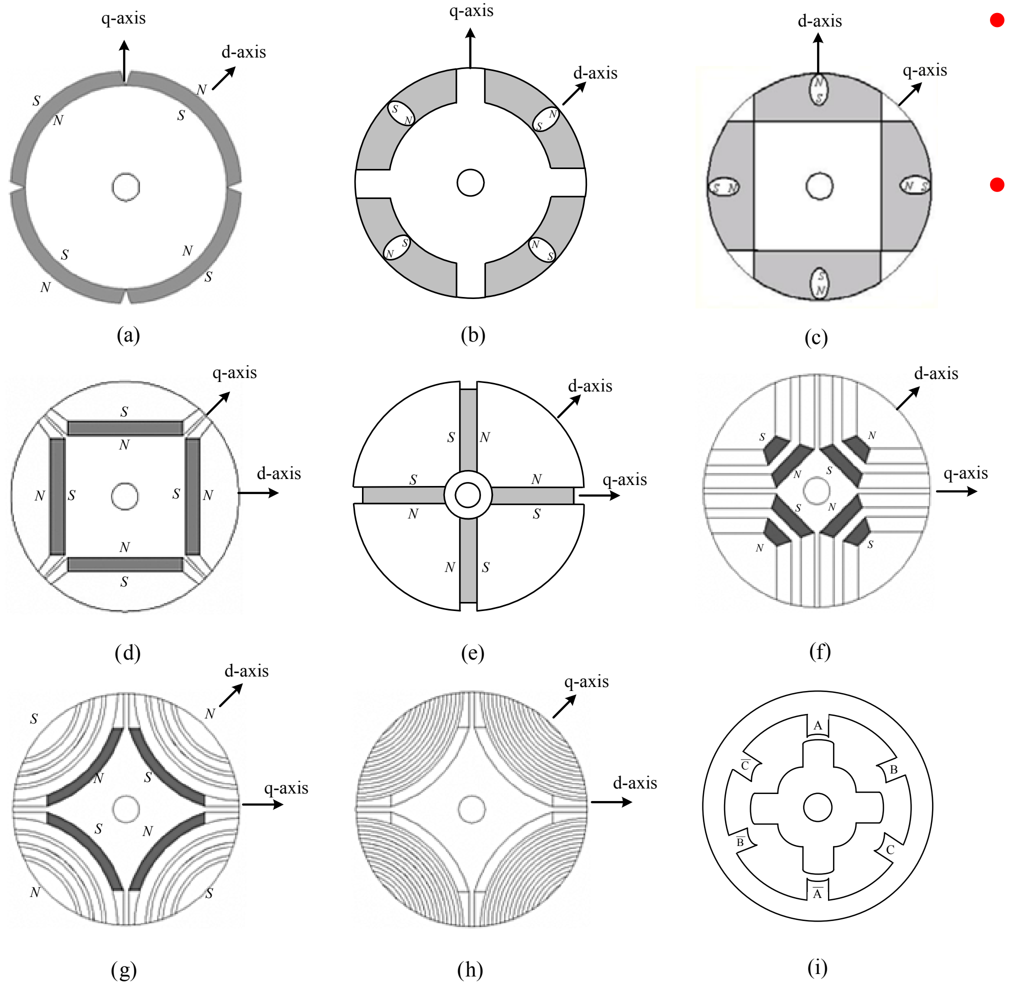
Introduction to permanent-magnet synchronous motor drive and brushless DC motor drive

- Motor types and section (SPMSM, IPMSM, SynRM?).
- Governing equations.
- Key parameters and variables measurements.'
- Inverter-fed PMSM drives:
  - (Sinewave PMSM + sinewave inverter): Complicated control scheme.
  - (Square-wave PMSM + square-wave inverter).
  - Hybrid: e.g., (Square-wave PMSM + sine-wave inverter).
- Control schemes and realized environments?
- Filter between inverter and motor.
- AC/DC front-end converter.

Motor types and selection

Some typical rotor structures of synchronous motors (SMs):
(a), (b), (c) SPMSM; (d), (e), (f) IPMSM; (g) PMASynRM; (h) SynRM; (i) SRM.

PMSM >> PMSM + RM >> SynRM



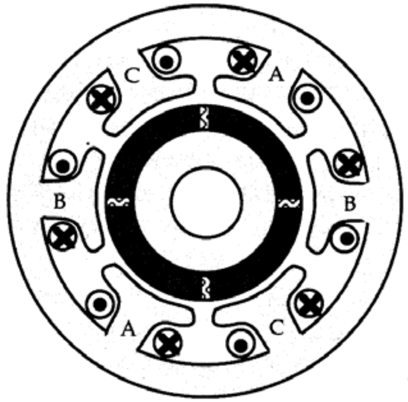
- PMASynRM: Permanent magnet assisted SynRM
- SynRM: Synchronous reluctance motor

Some typical stator structures

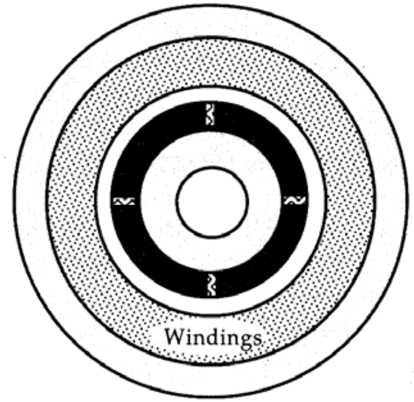
(a) 如圖(a)，為salient pole，係集中式電樞繞組(Concentrated winding)之定子結構：具有短的end turns，相與相間之 coupling較小，每一相之線圈不同時，與所有轉子磁鐵作用時，導致性能之降低。

(b) 如圖(b)，沒有slot (Slot-less)，故沒有齒隙轉矩(Cogging torque)，但線圈與後鐵間之熱導低，不利負荷之增加。又因沒有靜子齒，使得氣隙增長成轉子表面至後鐵，為維持適當大之 PC值，磁鐵之長度須增長。

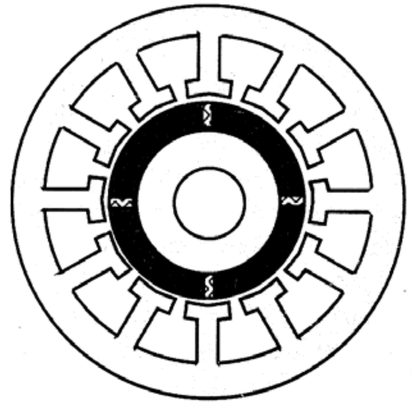
(c) 如圖(c)，為槽式用以容置分佈式繞組(Distributed winding) ，具有shoes在氣隙處，可減少氣隙磁導隨位置之變化，而減少Cogging torque。



(a)



(b)


(c)

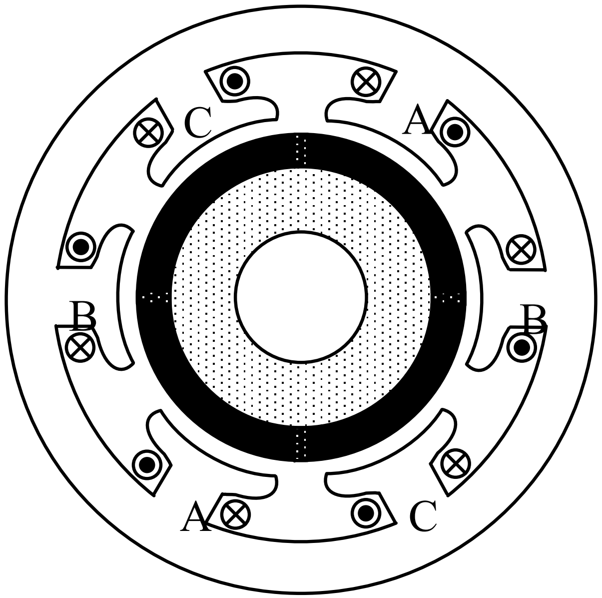
Difference between square-wave and sine-wave BDCMs

- **Square-wave BDCM:**
  - -- Rectangular distribution of air-gap magnet flux;
  - -- Rectangular winding current waveforms;
  - -- Concentrated stator armature winding.

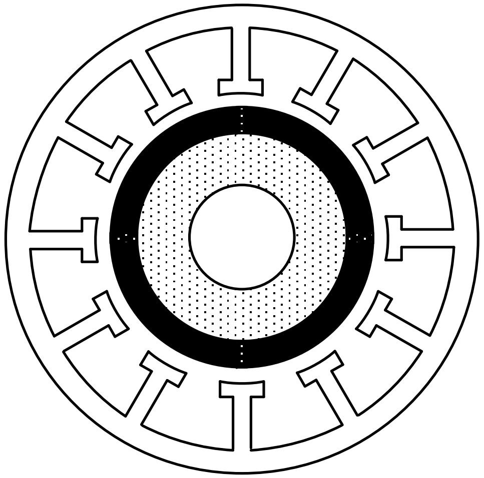
- **Sine-wave BDCM:**
  - -- Sinusoidal or quasi-sinusoidal distribution of air-gap magnet flux;
  - -- Sinusoidal or quasi-sinusoidal winding current waveforms;
  - -- Quasi-sinusoidal stator armature conductors, i.e., short-pitched and distributed stator armature conductors.

- ***If the stator winding current is not pure sine wave, and if the stator winding distribution is not purely sinusoidal, the time harmonics of the current can interact the space-harmonics of the conductor distribution to produce large torque ripple with only a slight increase of average torque.***

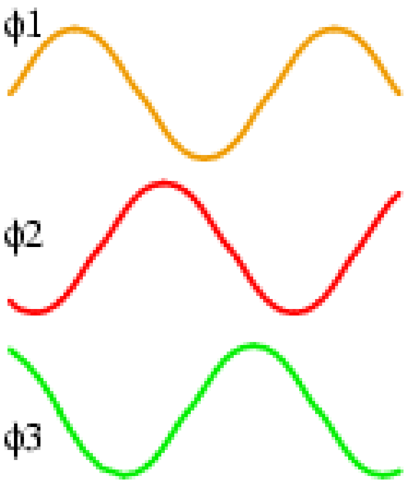
Concentrated armature winding (Square-wave motor)

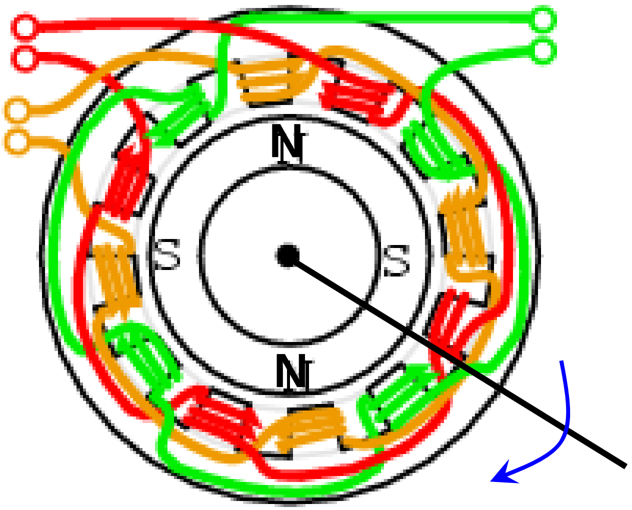


Distributed armature winding (Sine-wave motor)



Three-phase armature currents





Classification of BDCMs

- **Speed servo drive (square-wave BDCM): not suited for lower operation speeds**

  (a) Normally: concentrated armature windings.
  (b) Usually called BDCM.

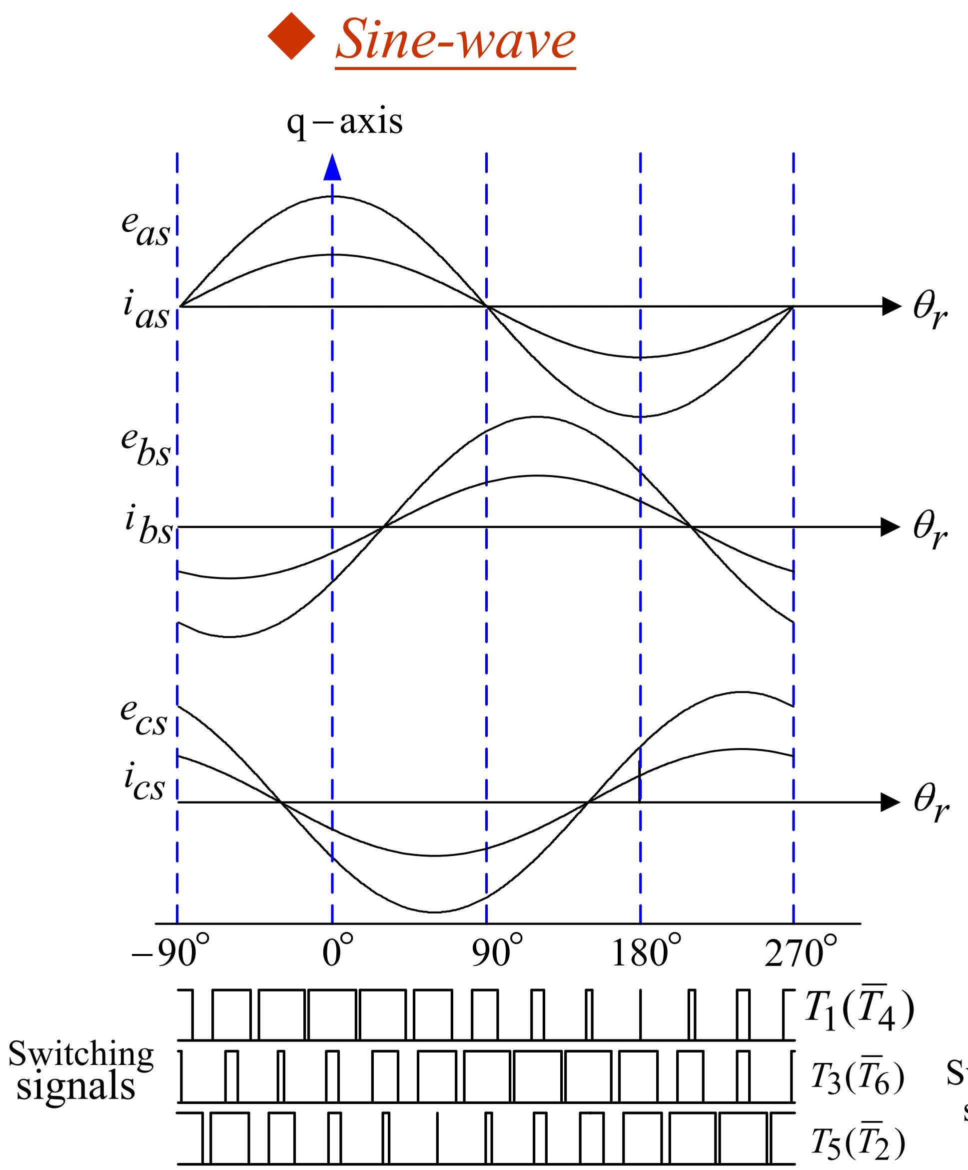
  - Using photo sensor
  - Using Hall sensor

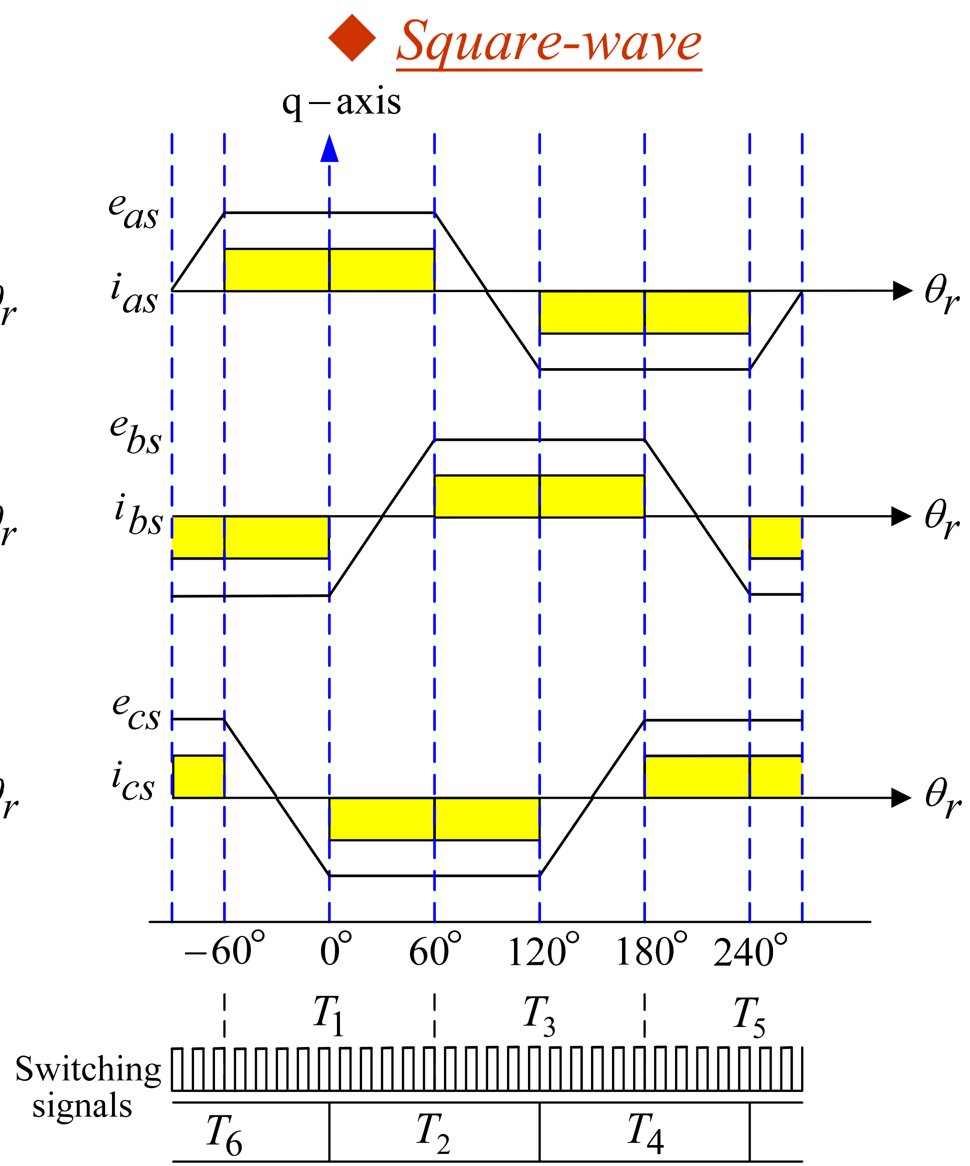
- **Position servo drive: sine-wave BDCM**

  (a) Normally: distributed armature windings.
  (b) Usually called PMSM.

- Sine-wave motor driven by square-wave inverter: theoretical torque ripple at low speed >= 13%.

BDCM PWM switching signal waveforms

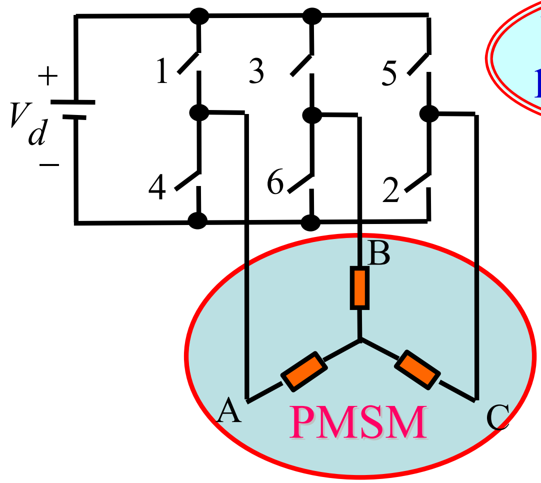




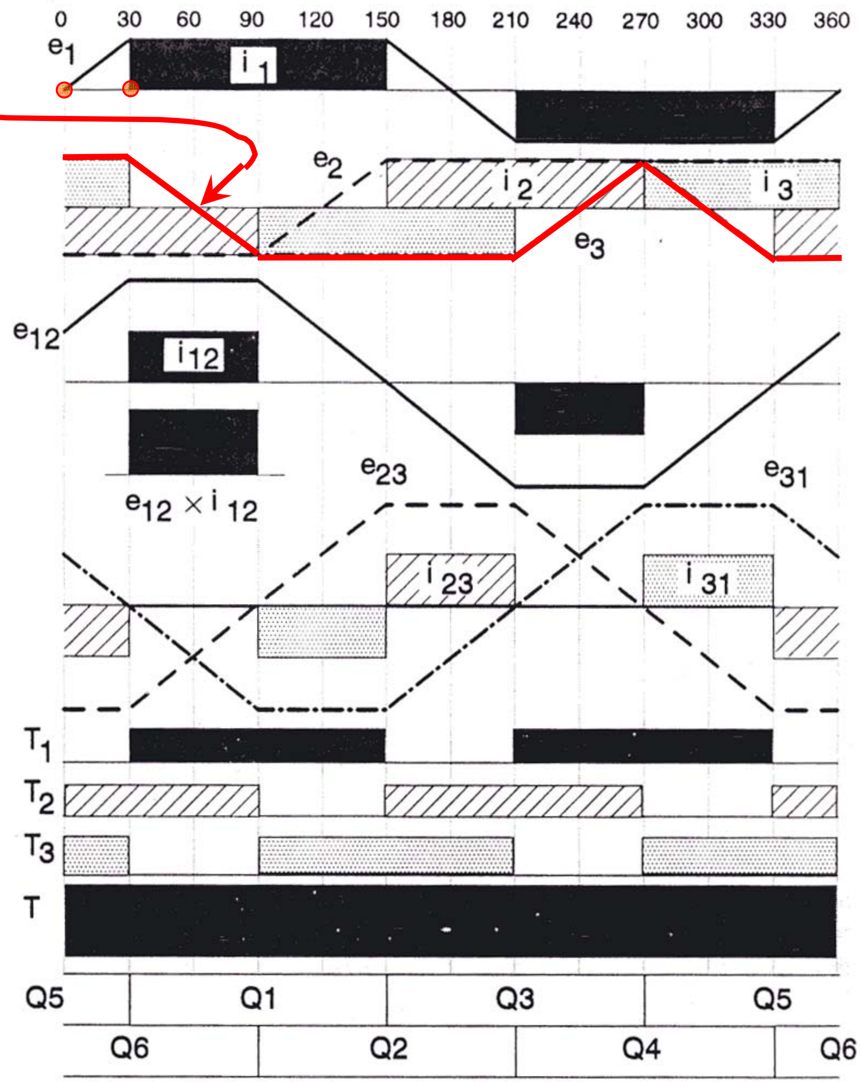
Three-phase square-wave BDCM

$$P_m = \sum e_k i_k = T_e \omega_r$$

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



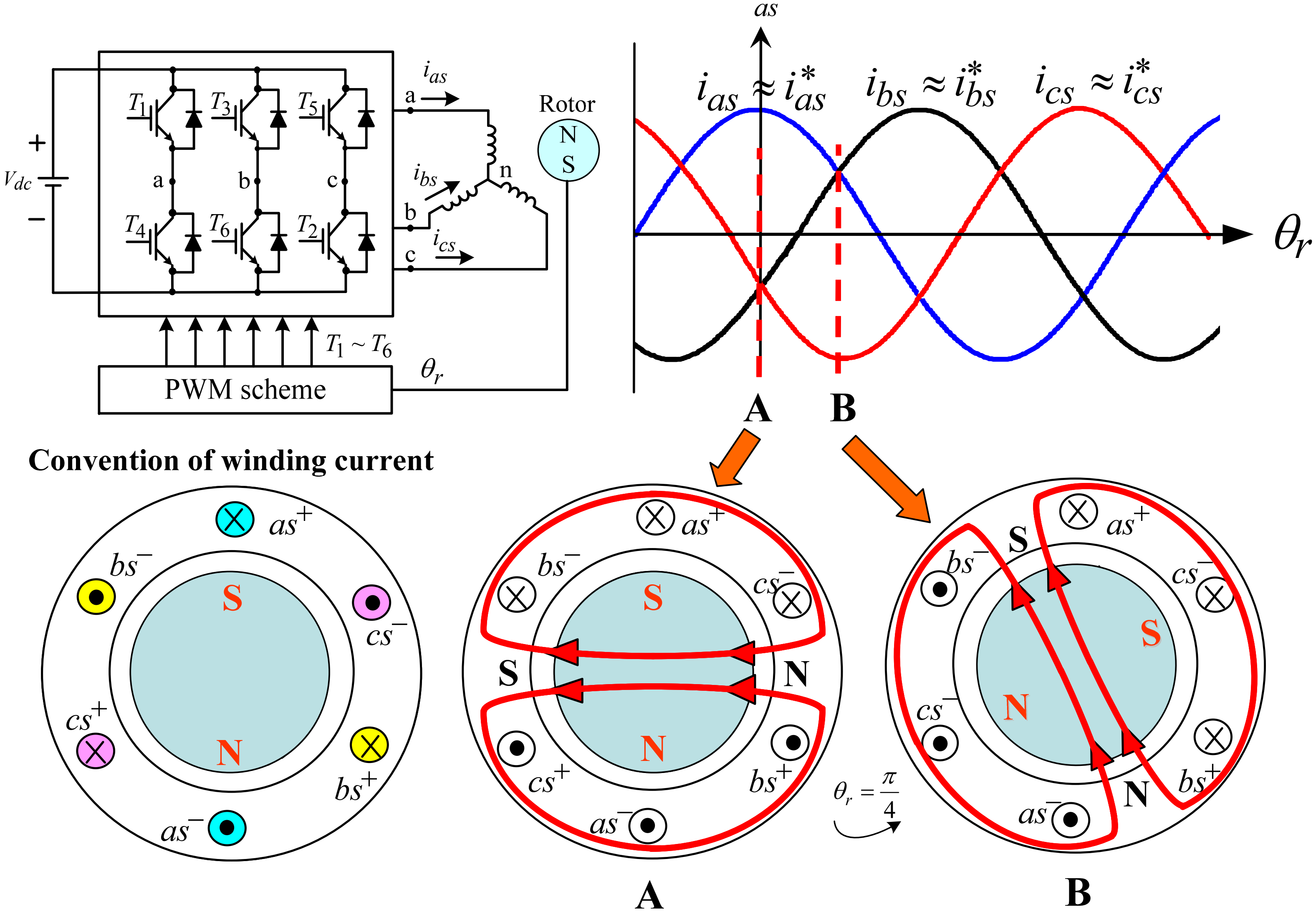
Non-conducting phase back-EMF



- Ideal waveforms of a Y-connected BDCM with 120^o flat-top back EMF.
- Non-ideal winding current and voltage waveforms and commutation ⇨ yielding torque ripple.

Sine-wave BDCM Operation principle and commutation instant tuning

☒ **Brushless DC Motors (BDCMs):** PMSM with winding commutation according to the sensed rotor position.



- Special application cases:

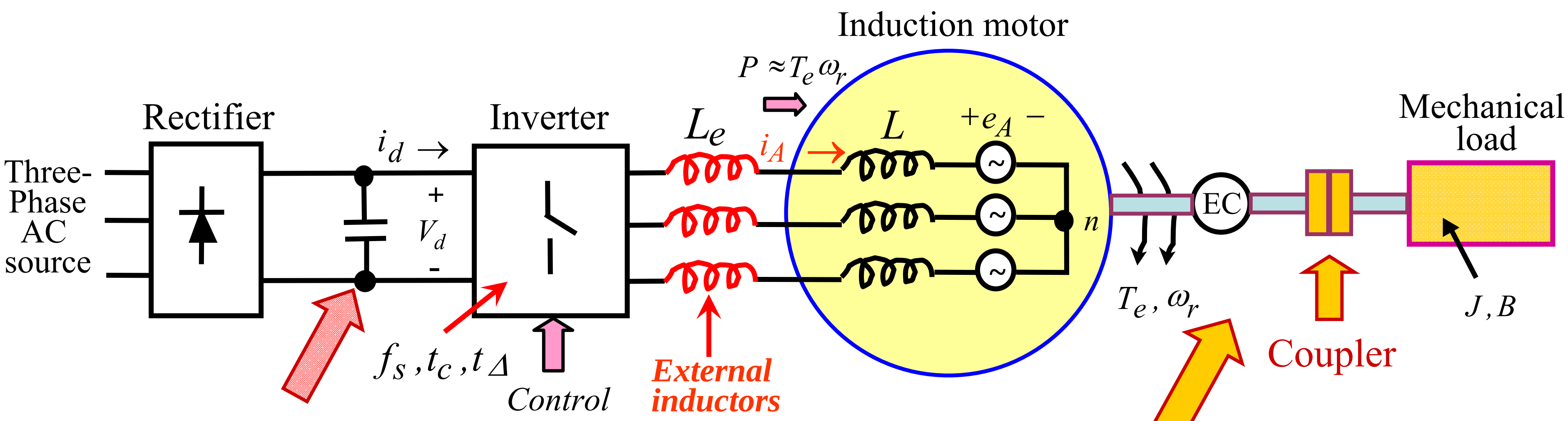
The SPMSMs are also found in high-speed applications. However, some key affairs should be treated:

(1) The permanent-magnet volume and thus the back-EMF at the maximum speed must be properly determined.

(2) Inverter DC-link voltage must be properly set.

(3) The demagnetization risk in real operation must be cared, especially for the position sensorless controlled PMSM drive.

Effects of non-ideal current waveforms



$$\frac{di_A}{dt} \propto \frac{V_d - e_A}{L}$$

- Voltage boosting.
- Field-weakening.

$$i_A \approx \frac{v_{A1} - e_{A1}}{Z_{A1}} + \sum_{h=2}^{\infty} \frac{v_{Ah}}{Z_{Ah}} \equiv i_{A1} + i_{Ah}$$

- ☒ Cause ripple torque and extra armature copper losses.
- ☒ The ripple current $\delta i_A \propto 1/(Lf_s)$
  $f_s \uparrow \Rightarrow$ switching losses $\uparrow$
- ☒ The external filter between inverter and motor is needed for the case with high fundamental frequency and low switching frequency.

$$\boxed{T_e = T_L + B\omega_r + J(d\omega_r/dt)}$$

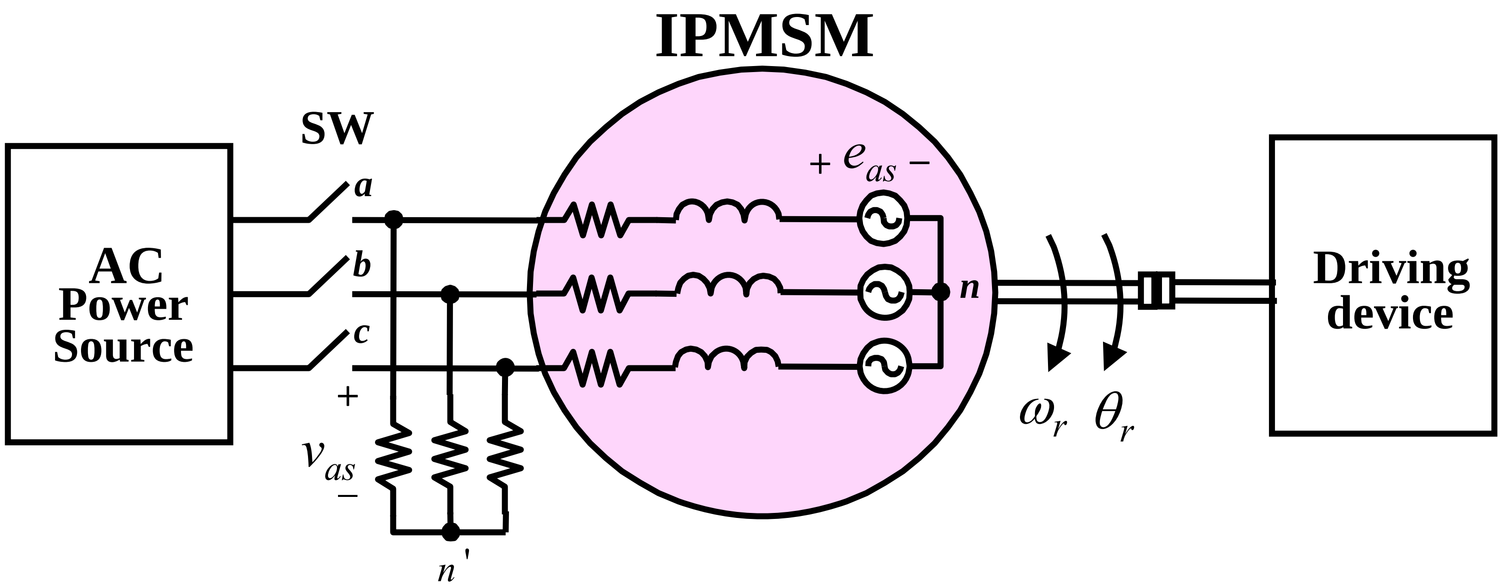
$$T_e = T_{av} + T_{eh} = T_L + B\omega_r + J(d\omega_r/dt) \Rightarrow$$

$$\omega_r = \omega_{av} + \omega_{rh}$$

- $(J/B)\uparrow \Rightarrow \omega_{rh} \downarrow$ >> Mechatronic affairs.
- The coupler between motor and load, the mechanical time constant, the ripple torque spectrum must be properly considered for the given mechanical load specifications.

永磁同步馬達之參數估測
(Parameter estimation of PMSM)

■ Experimental mechanism for making parameter estimation



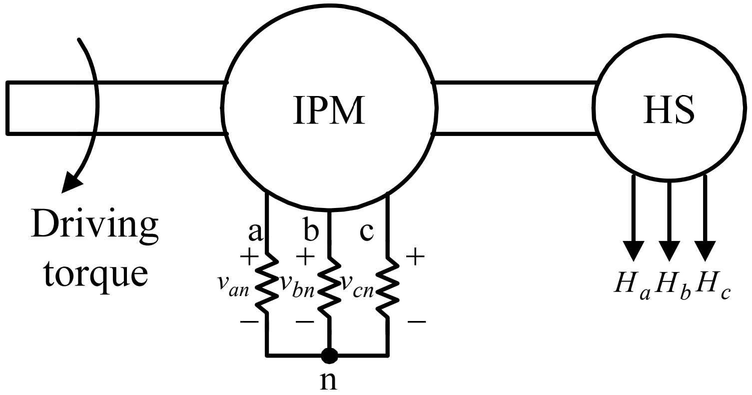
- Equivalent circuit parameter estimation: rotor is locked at a particular position and the winding is excited with a variable-frequency and variable-current AC source.
- Slip test: the rotor is driven at a speed slightly different from synchronous speed.
- The voltage, current and power are recorded.
- Back-EMF: measure motor open-circuit terminal voltages at different driven speeds.

換相時刻調整

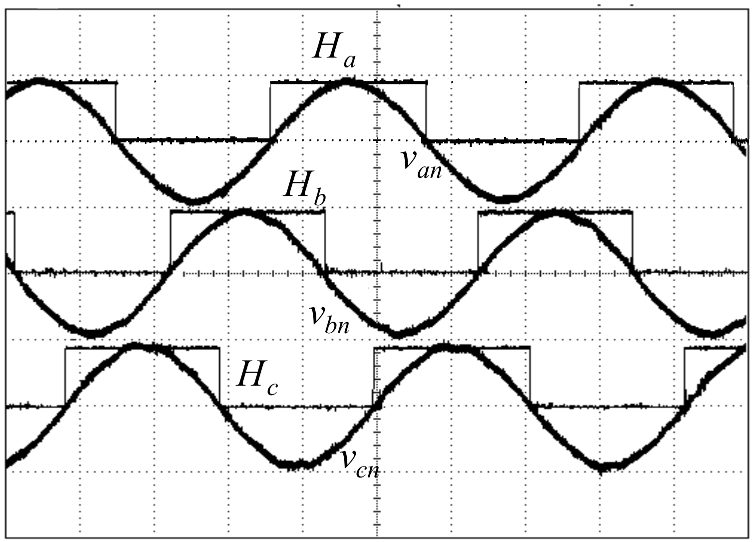
■ 相位校準及霍爾感測信號

- 機械對位調整
- 電氣對位調整

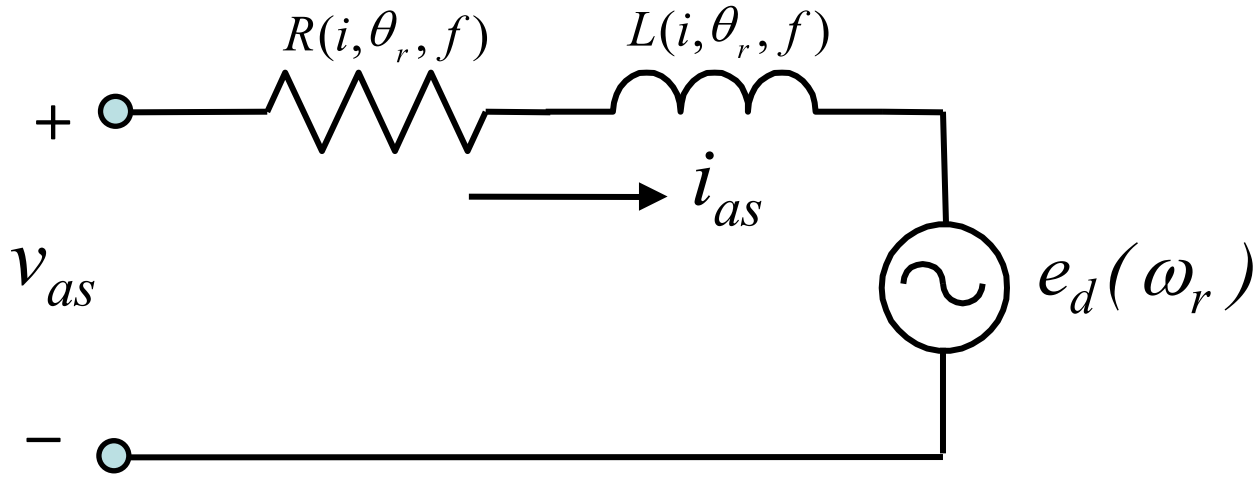
霍爾位置感測信號相位調校之機構



調整後量測所得之感測馬達之開路端電壓



Per-phase equivalent circuit model



- Back EMF constant estimation: $e_d = k_t\omega_r$
- Flux linkage amplitude estimation: λ'_m
- (a) Considering the correct measurement;
  (b) observing the wave shape of the back EMF.

☒ Winding inductances

$$L_{asas} = L_{ls} + L_A + L_B \cos 2\theta_r$$

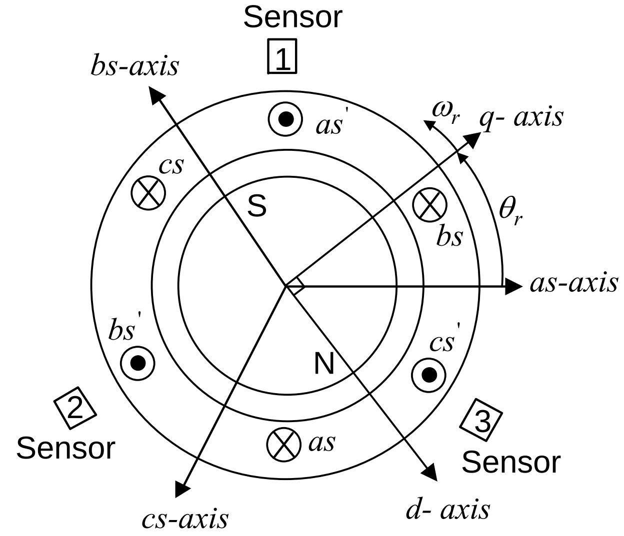
$$L_{bsbs} = L_{ls} + L_A + L_B \cos 2(\theta_r - \frac{2\pi}{3})$$

$$L_{cscs} = L_{ls} + L_A + L_B \cos 2(\theta_r + \frac{2\pi}{3})$$

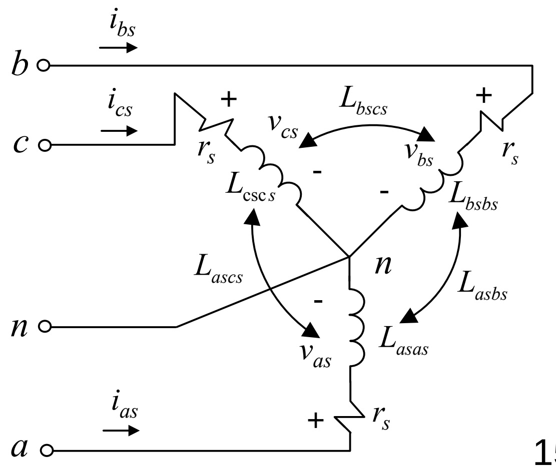
$$L_{asbs} = L_{bsas} = -\frac{1}{2} L_A + L_B \cos 2(\theta_r - \frac{\pi}{3})$$

$$L_{ascs} = L_{csas} = -\frac{1}{2} L_A + L_B \cos 2(\theta_r + \frac{\pi}{3})$$

$$L_{bscs} = L_{csbs} = -\frac{1}{2} L_A + L_B \cos 2(\theta_r + \pi)$$

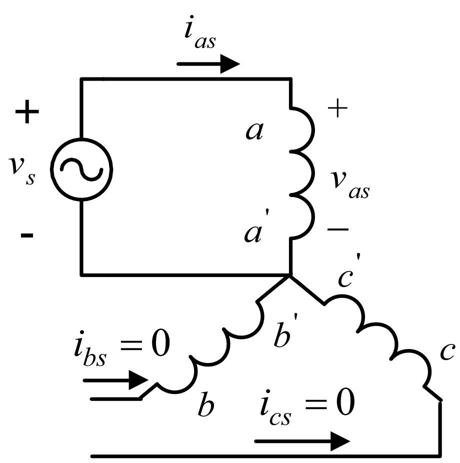


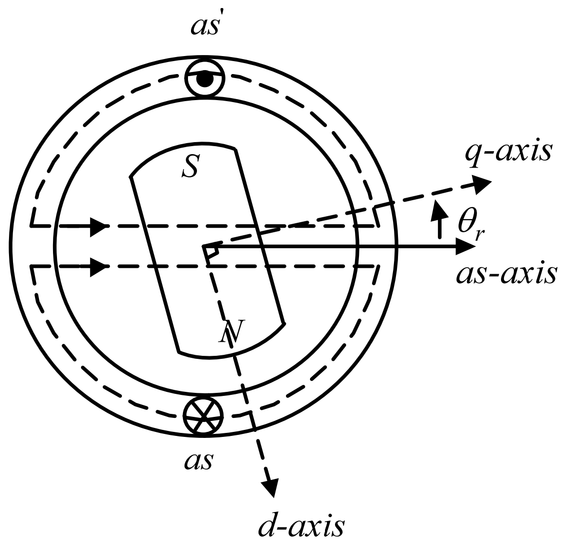
(a)



(b)

■ Y-connected with non-isolated neutral





$$\boxtimes\quad v_s = v_{as} = r_s i_{as} + \frac{d}{dt}\left[\left(L_{ls} + L_A + L_B\cos 2\theta_r\right) i_{as}\right] = r_s i_{as} + \frac{d}{dt}\left[L_{asas}(\theta_r) i_{as}\right]$$

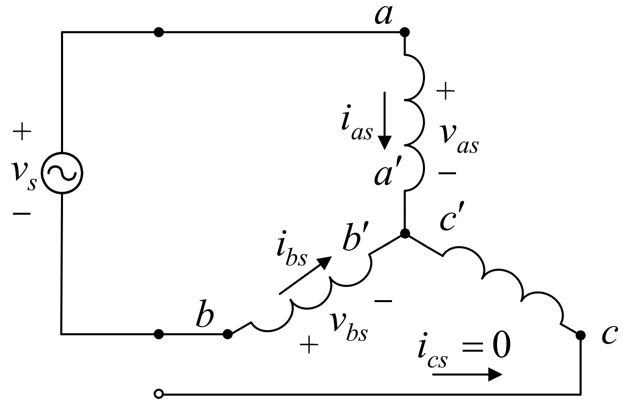
$$L_{asas,\max} = L_{asas}(\theta_r = 0) = L_{ls} + L_A + L_B$$

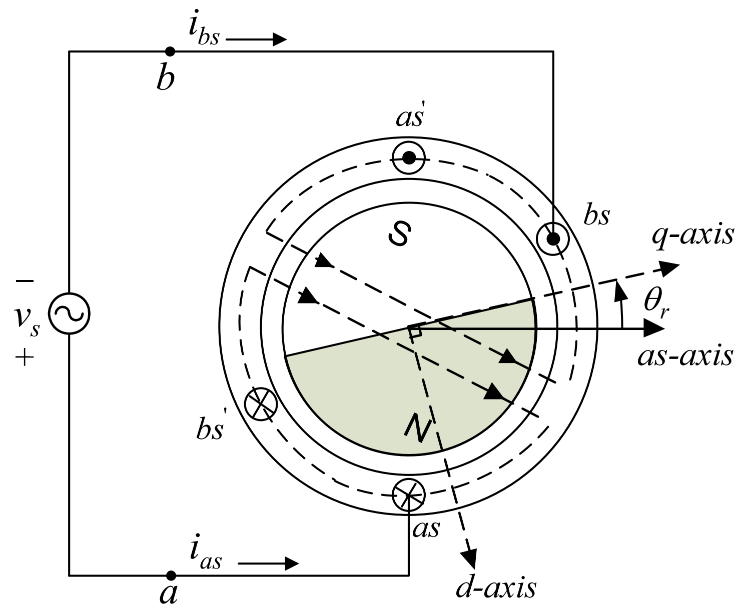
$$L_{asas,\min} = L_{asas}(\theta_r = 0.5\pi) = L_{ls} + L_A - L_B$$

$$L_q \approx \frac{3}{2} L_{asas,\max}, \quad L_d \approx \frac{3}{2} L_{asas,\min}$$

$$L_q \overset{\Delta}{=} L_{ls} + \frac{3}{2}(L_A + L_B), \quad L_d = L_{ls} + \frac{3}{2}(L_A - L_B)$$

■ Y-connected with non-isolated neutral





$\boxed{v_s = v_{as} - v_{bs}}$ $\boxed{i_{bs} = -i_{as}}$ $\boxed{i_{cs} = 0}$ $\boxed{\omega_r = 0}$

$$v_s \triangleq R_{ab} i_{as} + \frac{d}{dt}\{L_{ab}(\theta_r) i_{as}\}$$

$$R_{ab} = 2R_s$$

$$L_{ab}(\theta_r) = 2L_{ls} + 3L_A - 3L_B \cos(2\theta_r - 2\pi/3)$$

$$R_s = \frac{1}{2} R_{ab}$$

$$L_q = \frac{1}{2} L_{asbs,\max}$$

$$L_d = \frac{1}{2} L_{asbs,\min}$$

Estimation of Key Motor Parameters: Example

PM Flux Linkage λ'^{r}_{m} and Back EMF Constant k_e .

- Three Y-connected resistors with reasonably high resistance ($100\text{k}\Omega$) are connected at the stator terminals to measure the motor phase back-EMF at no-load.

- Let the PMSM be driven at a constant speed with terminal open-circuited.

$$i_{as} = i_{bs} = i_{cs} = 0$$

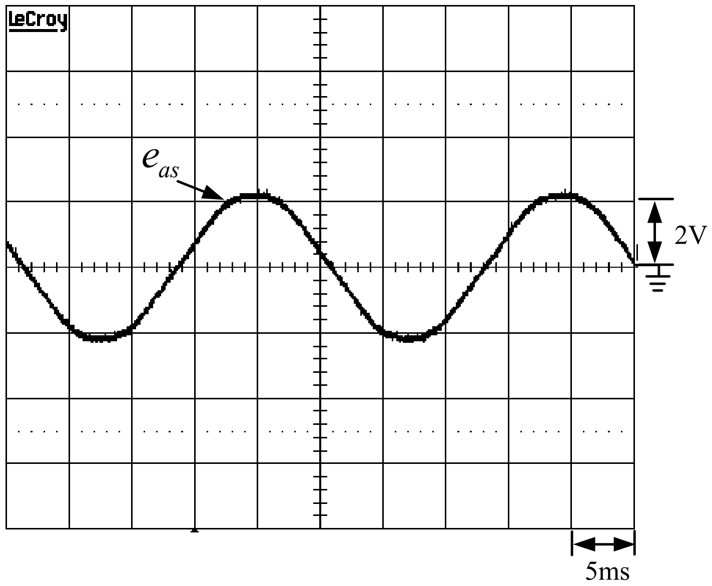
$$\Rightarrow \quad v_{as} = \omega_r \lambda'^{r}_{m} \cos\theta_r \triangleq \hat{E}_d \cos\theta_r \triangleq e_{as}$$

$$\Rightarrow \quad \lambda'^{r}_{m} = \frac{\hat{E}_d}{\omega_r}, \qquad E_d = k_e \omega_r$$

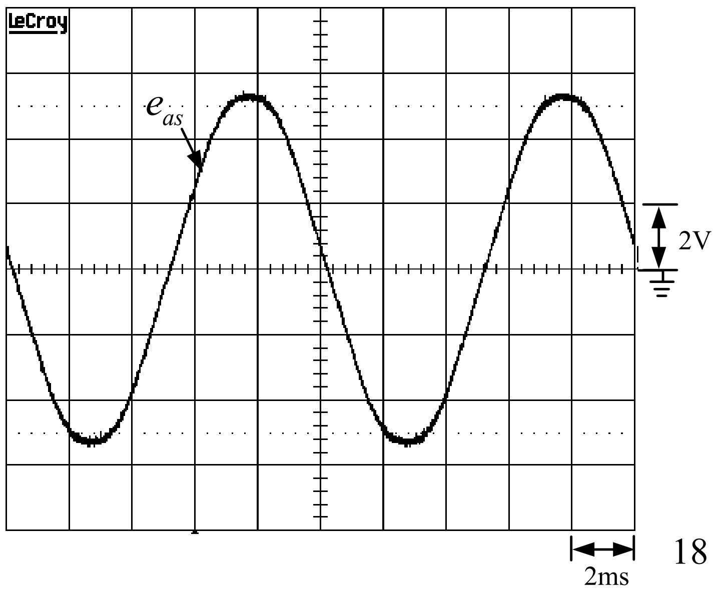
Estimated parameters:

$$\lambda'^{r}_{m} = 0.00858\,\text{Web}, \quad k_e = 3.81\,\text{V}_{\text{rms}}/\text{krpm}$$

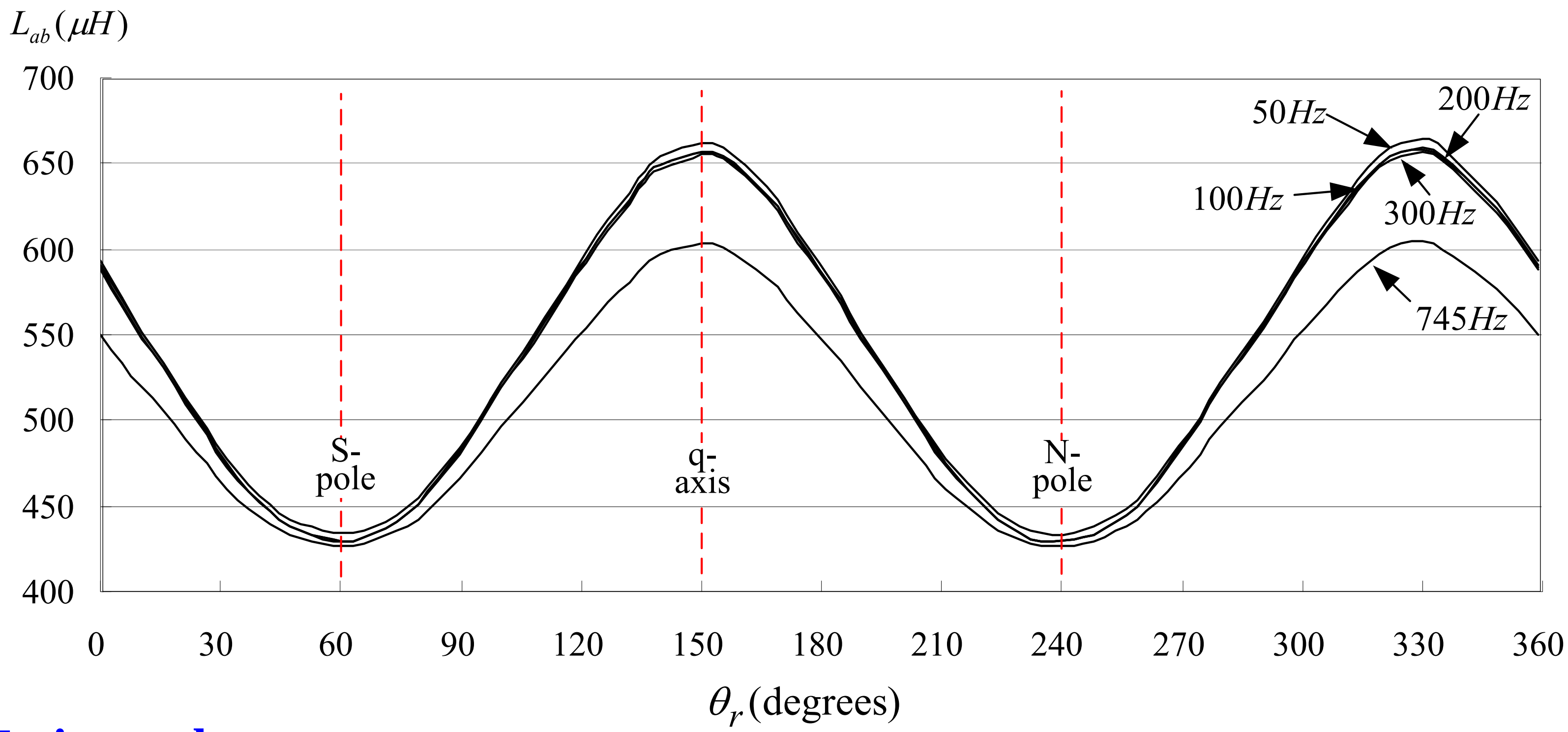
400rpm



1000rpm



- For simplicity, the parameters R_{ab} and $L_{ab}(\theta_r)$ are measured using off-the-shelf LCR meter (3532-50 LCR HiTester, HIOKI)



Estimated parameters ($f = 200\text{Hz}$):

$$\overline{R}_s = 0.60625\Omega$$

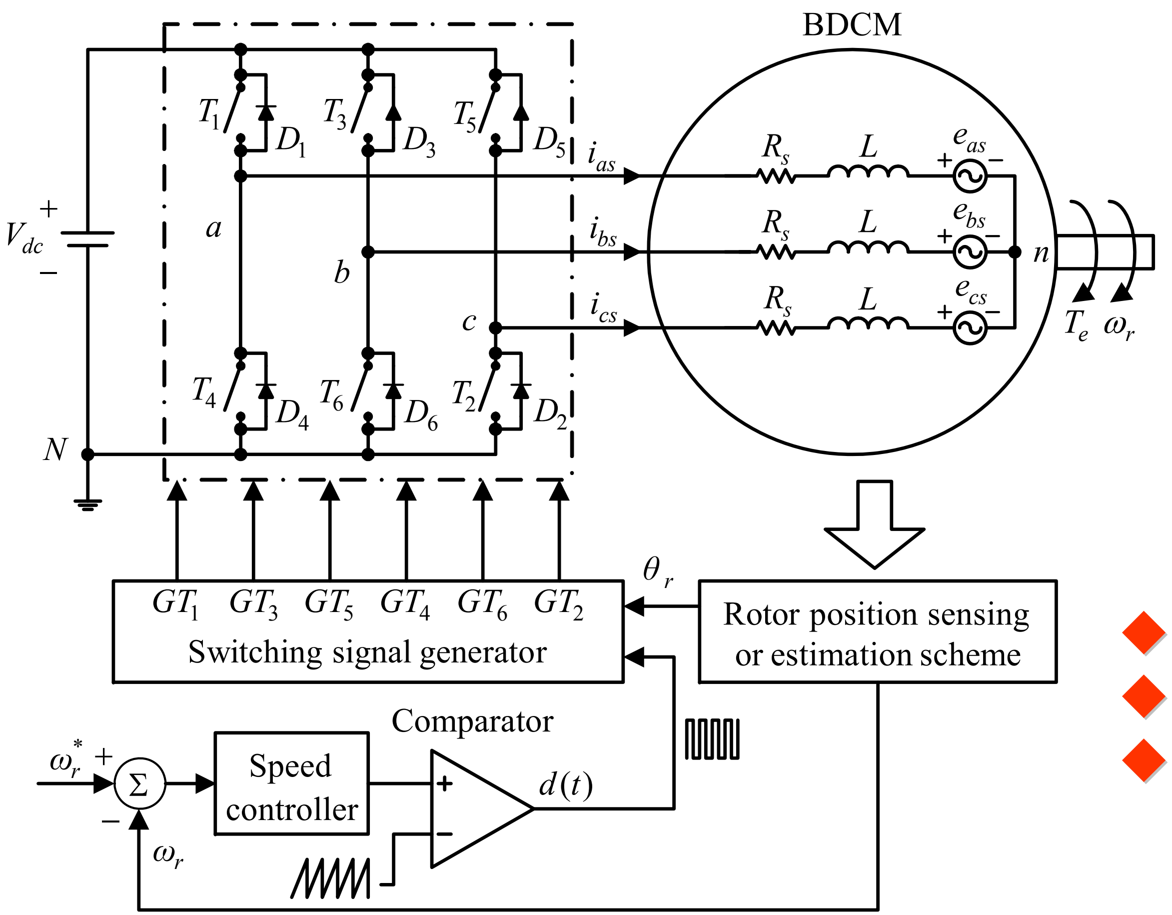
$$L_q = 1/2(L_{ab,\max}) = 328.415\mu\text{H}$$

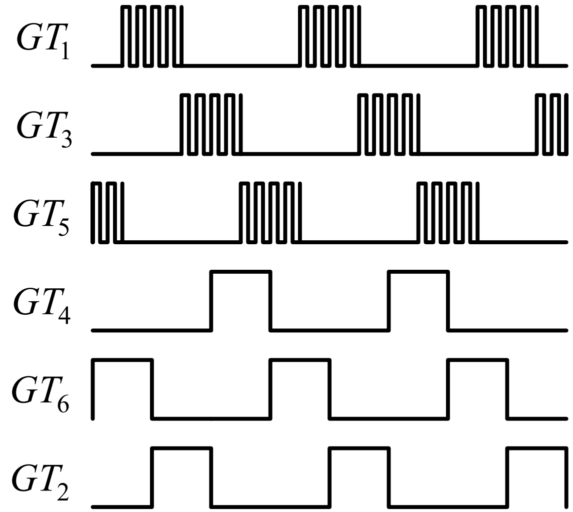
$$L_d = 1/2(L_{ab,\min}) = 214.635\mu\text{H}$$

- The parameters measured using LCR meter will not be accurate owing to its small-signal level excitation.
- The effects of inaccuracy and variations of motor parameters on the motor driving control performance will be handled by the proposed robust control approaches.

Possible control schemes for BDCMs

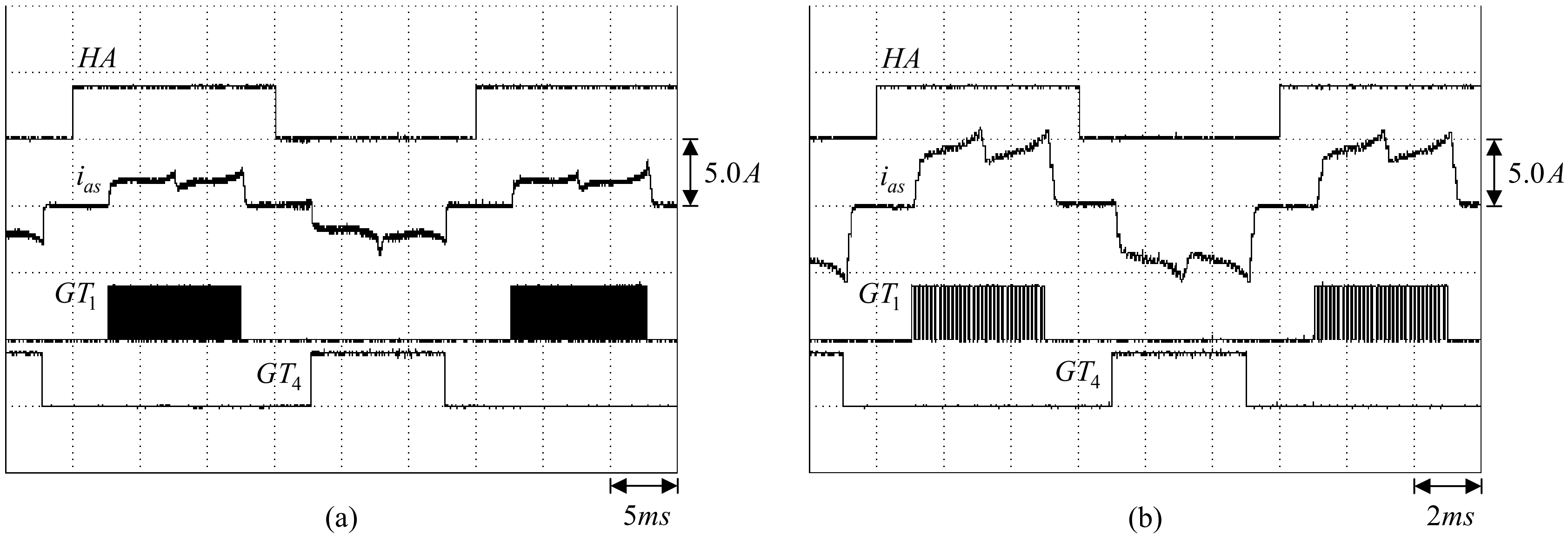
- Square-wave BDCM drive using direct duty ratio control (without current-mode control)





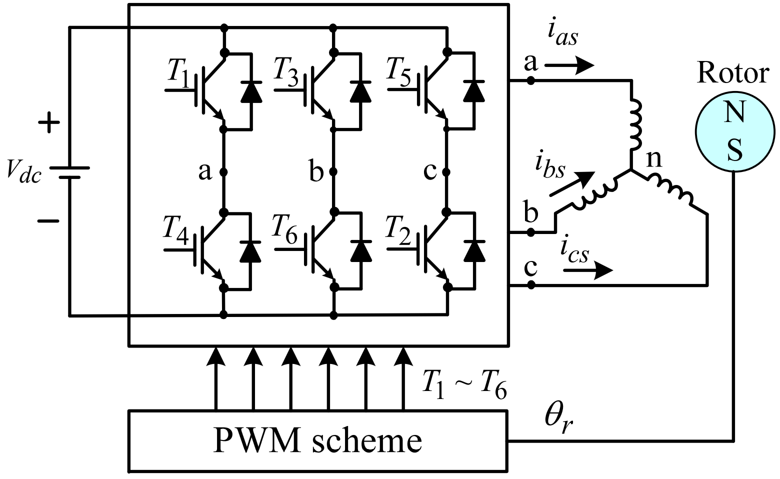
- Without current control loops.
- Simple implementation.
- Lower driving performance.

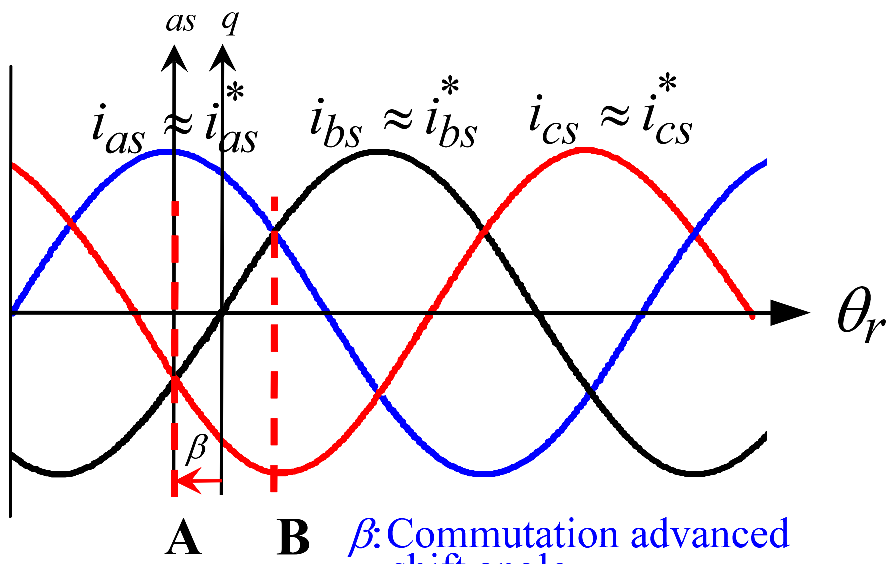
Measured results



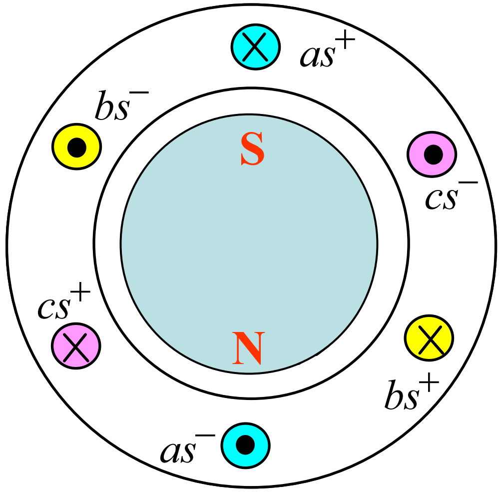
Measured waveforms of Hall sensor signal HA, motor line current i_{as}, the switching signals GT_1 and GT_4 of square-wave type BDCM drive with 120° conduction: (a) 1000 rpm, $R_L = 32.7\Omega$; (b) 2500 rpm, $R_L = 32.7\Omega$.

Sine-wave BDCM Operation principle and commutation instant tuning

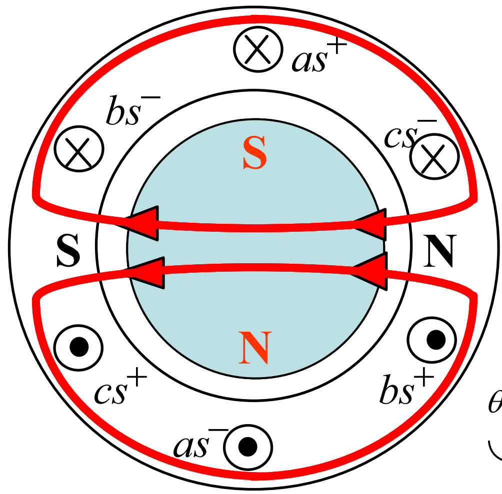




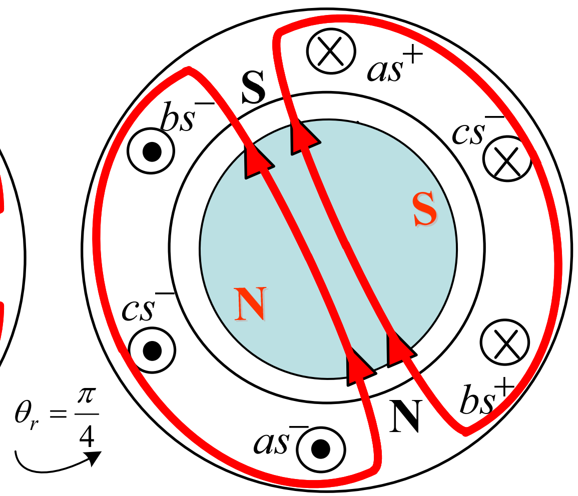
β: Commutation advanced shift angle



Convention of winding current

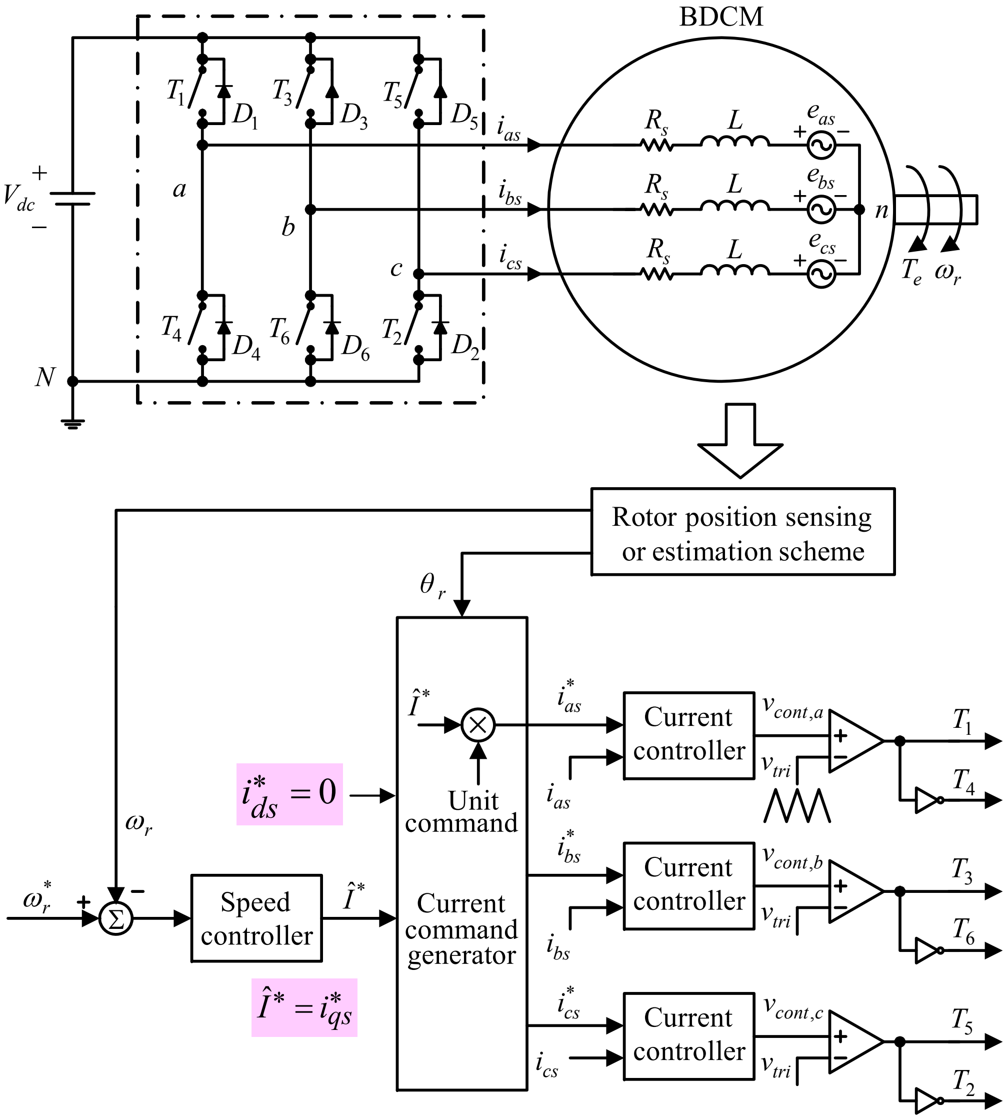


A



B

BDCM drive using sine-wave current-mode control (abc-domain)



Measured results

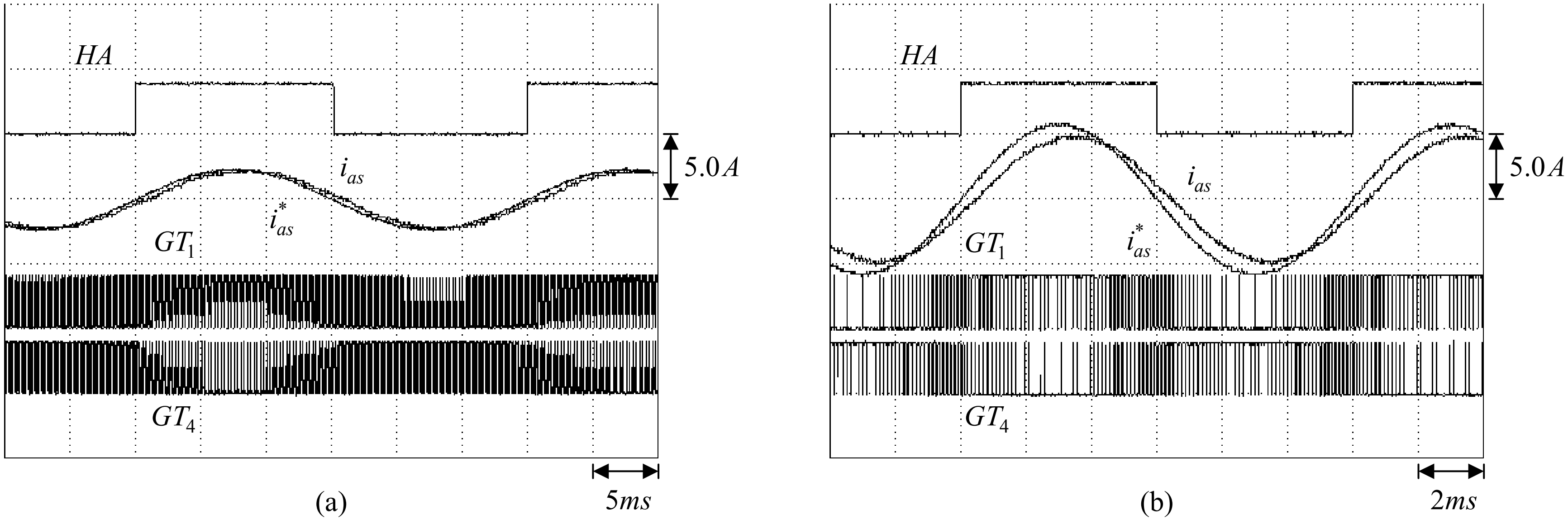


Fig. 2.16. Measured waveforms of Hall sensor signal HA, motor line current i_{as} and command i_{as}^*, the switching signals GT_1 and GT_4 of sine-wave type BDCM drive with current-controlled PWM switching control: (a) 1000 rpm, $R_L = 32.7\Omega$, (b) 2500 rpm, $R_L = 32.7\Omega$.

BDCM drive using robust sine-wave current-mode control with d-axis excitation control (dq-domain)

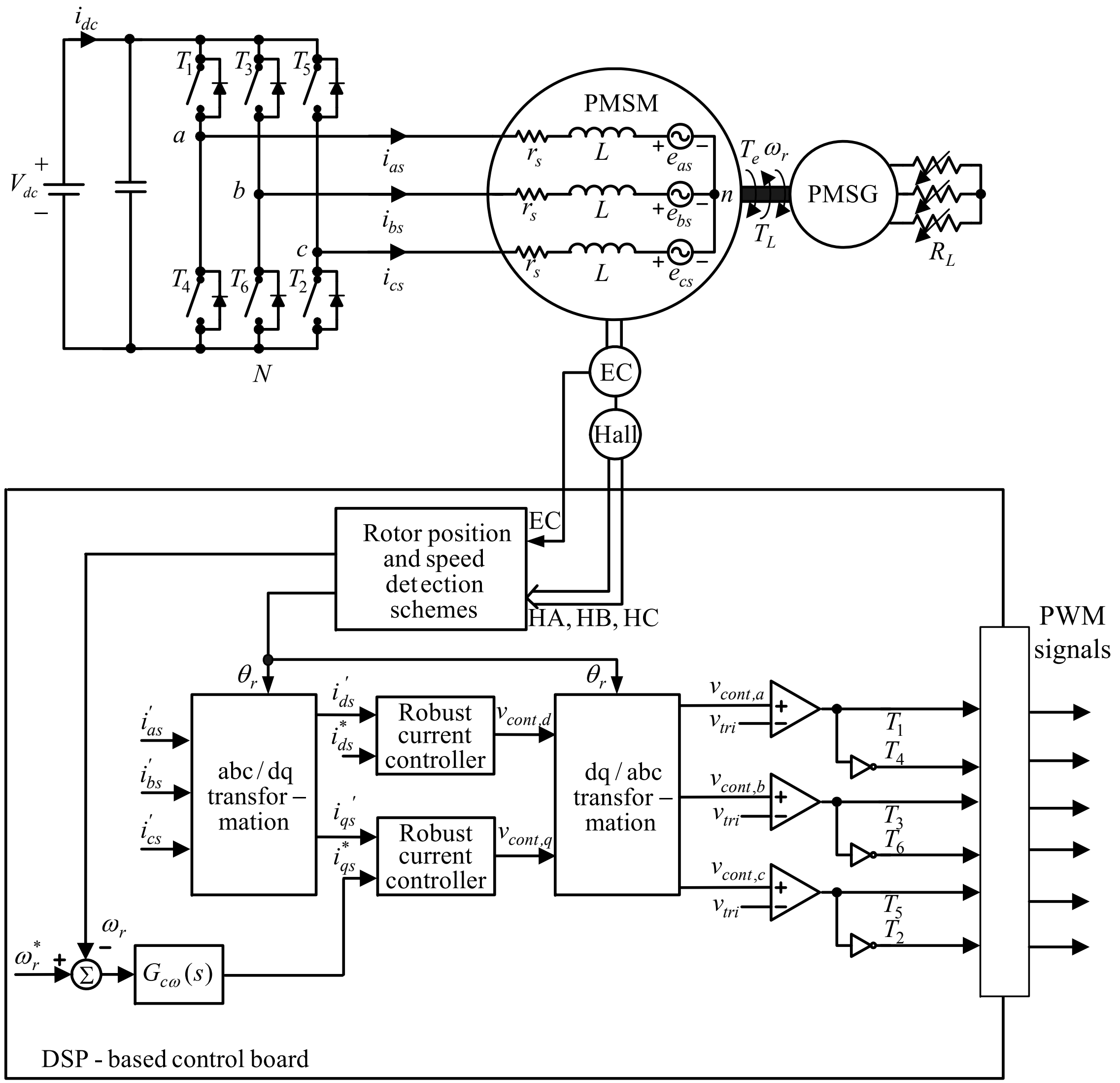
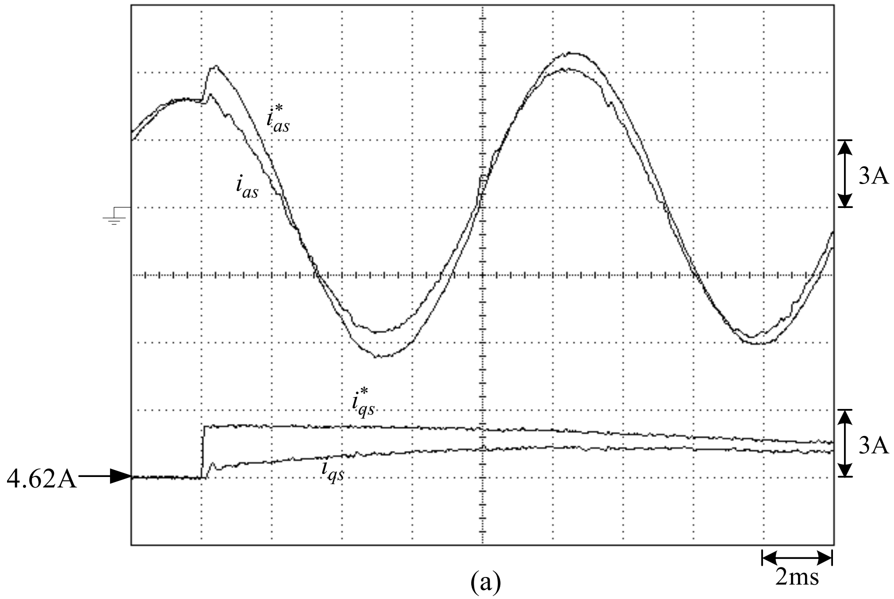


Fig. 4.3. Configuration of the CCPWM scheme in dq-domain.

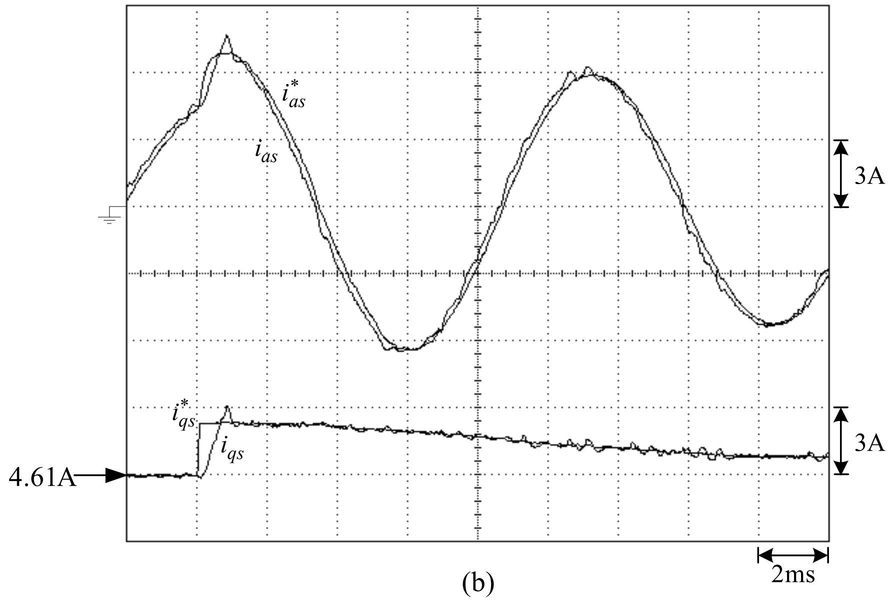
Measured results

PI control only

PI and robust controls



(a)



(b)

Fig. 4.12. Measured winding currents and commands due to a step speed command change ($R_L = 21.6\Omega$, $\omega_r = 2700\text{rpm} \rightarrow 3000\text{rpm}$) in dq-domain:(a) PI controller (W= 0); (b) robust controller (W= 0.9).

Measured results

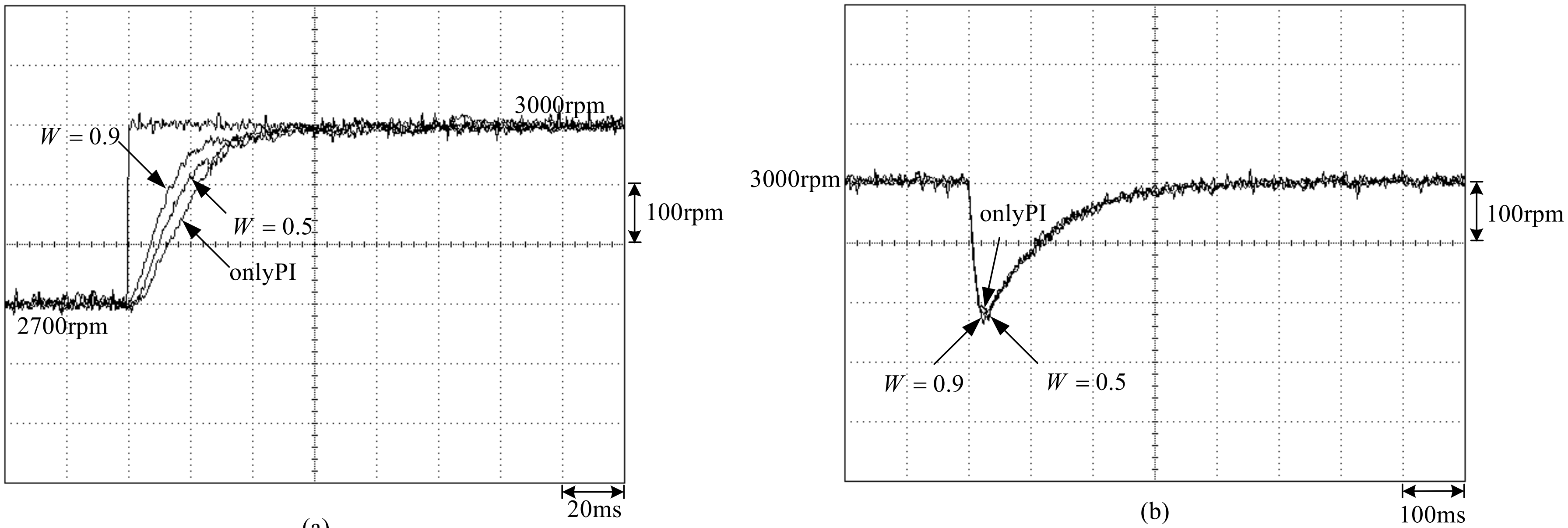


Fig. 4.13. Measured speed tracking and regulation responses in dq-domain by the PI controller and robust controller with different values of W: (a)$R_L = 21.6\Omega$, ω_r= 2700rpm→3000rpm; (b) ω_r= 3000rpm, $R_L = 43.9\Omega \rightarrow R_L = 21.6\Omega$.

Reference frame transformation

- abc to dq

$$\begin{bmatrix} f_{qs}^r \\ f_{ds}^r \\ f_{os}^r \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r + \frac{2\pi}{3}) \\ \sin\theta_r & \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix}$$

θ_r = rotor absolute angular position

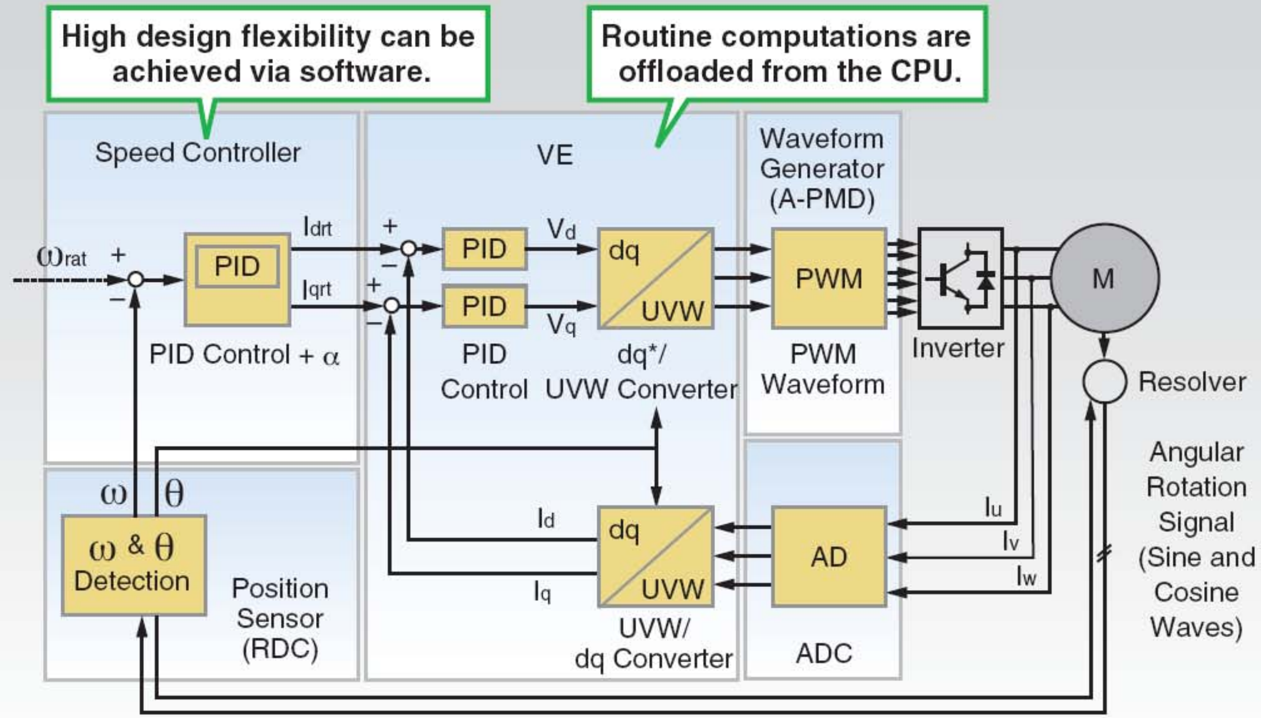
- dq to abc

$$\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r - \frac{2\pi}{3}) & 1 \\ \cos(\theta_r + \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} f_{qs}^r \\ f_{ds}^r \\ f_{0s}^r \end{bmatrix}$$

- **The sine-wave winding current can also be roughly obtained by applying SPWM voltage mode excitation:**
  - Without current control loops.
  - Simple implementation (however, how to realize SPWM schemes?).
  - Lower current and thus torque dynamic performances.
  - The driving performance can be improved via commutation instant shift

  (Example IPMs: Toshiba: **TB6551** sine-wave controller, **TB6581H** 3-Phase full-wave sine-wave PWM brushless motor rriver **= TB6551 +** TPD4103AK high-voltage driver.

Some example commercialized sine BDCM drives



Vector Controller Organization

PID: Proportional-Integral-Derivative

dq/UVW: Conversion from the dq axis to the UVW phase

α: Supplementary control added to PID control

ω_{rat}: Motor's angular speed target

I_{drt}, I_{qrt}: Motor current target in the dq axis

I_u, I_v, I_w: Motor current in the U, V and W phases of a three-phase alternating current

PWM: Pulse width modulation

UVW/dq: Conversion from the UVW phase to the dq axis

ω: Motor's angular speed

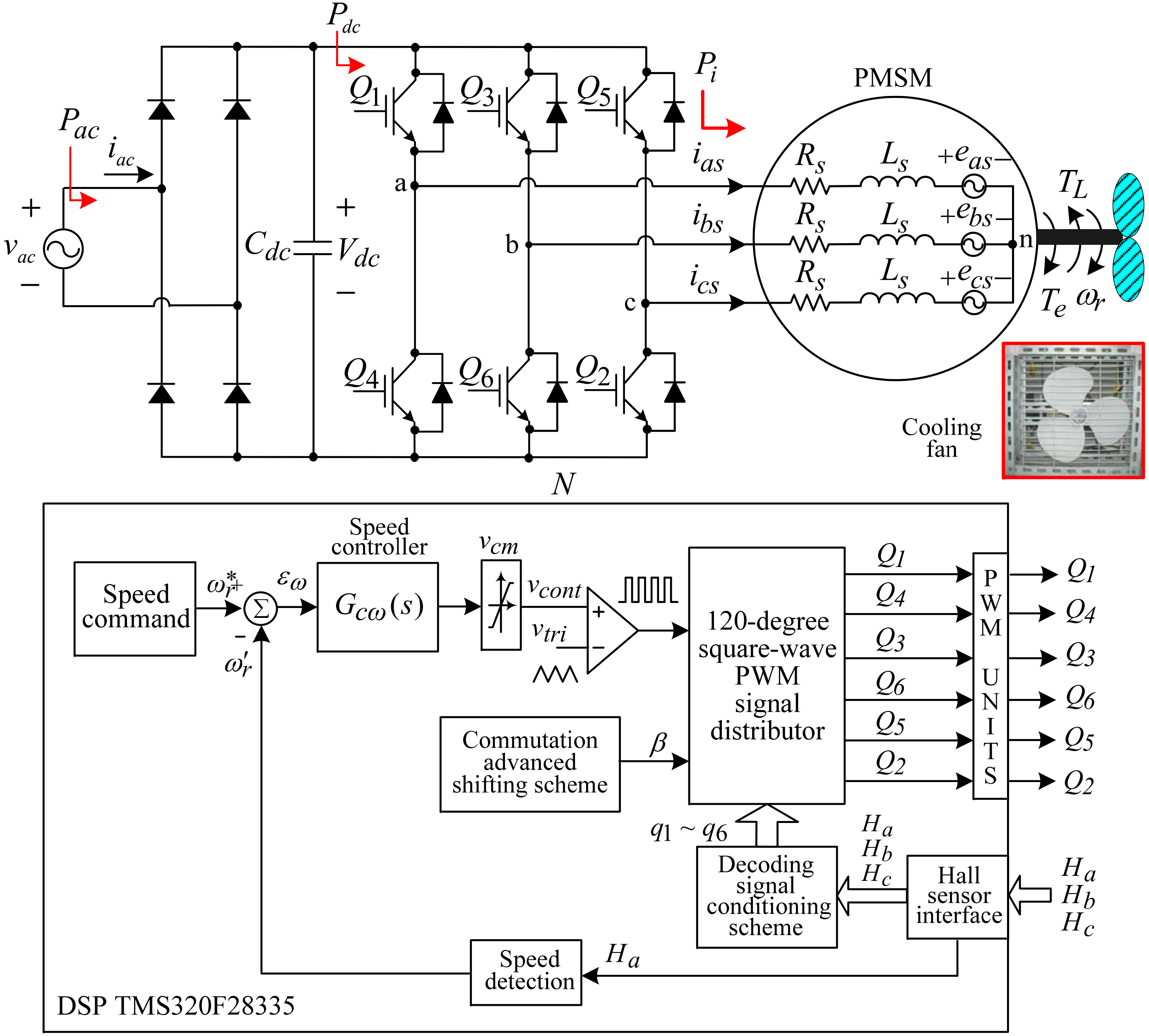
I_d, I_q: Motor current in the dq axis

V_d, V_q: Motor voltage in the dq axis

* Coordinate system where the magnetic pole direction of a motor's rotor is the d axis and the direction orthogonal to it is in the q axis

B. Standard Square-wave PMSM Driven Cooling Fan

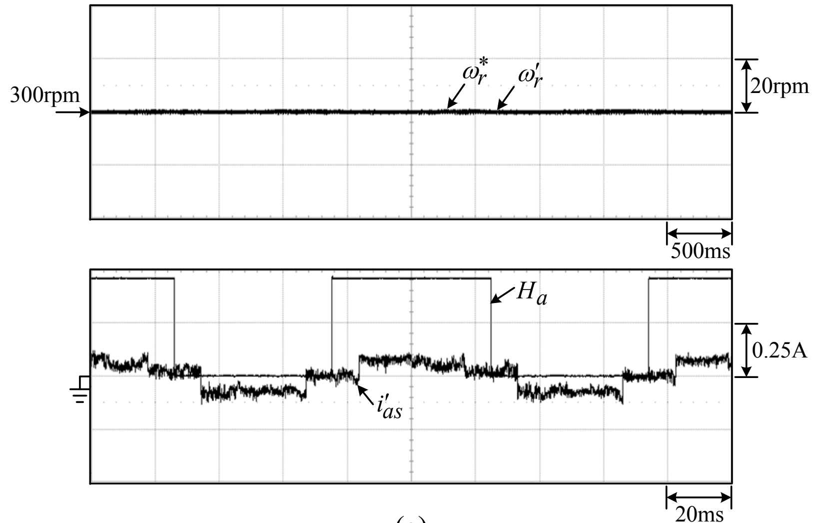
- System Configuration and Commutation Signal Generation



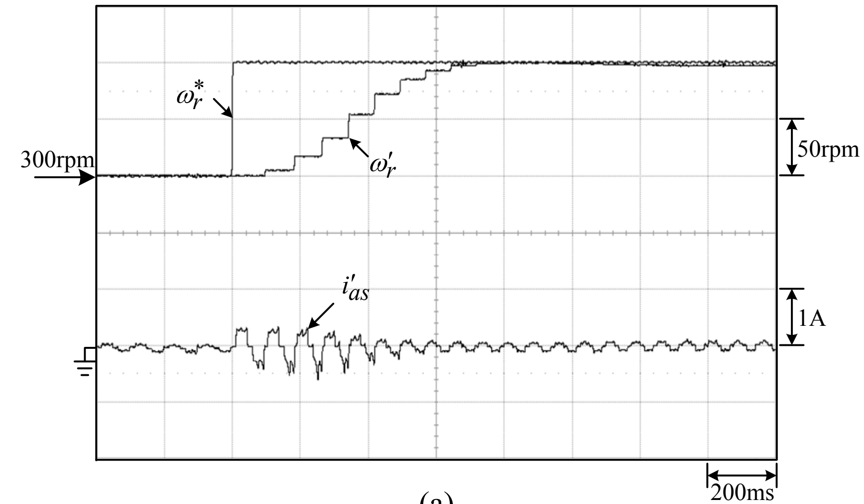
● Operating Performance

Standard Square-wave

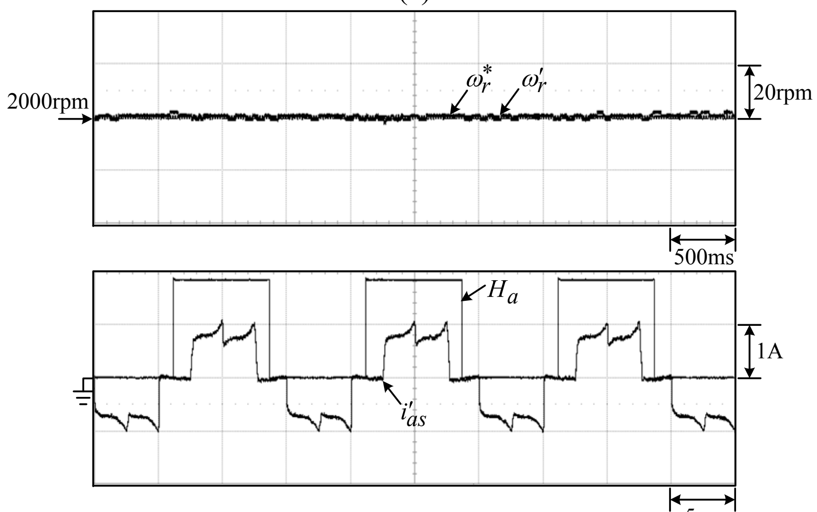
- Low speed: $G_{c\omega}(s) = K_p + \dfrac{K_I}{s} = 2 + \dfrac{2}{s}, \quad \omega_r^* \le 400\text{rpm}$
- High speed: $G_{c\omega}(s) = K_p + \dfrac{K_I}{s} = 2 + \dfrac{6}{s}, \quad 400\text{rpm} < \omega_r^* \le 2000\text{rpm}$



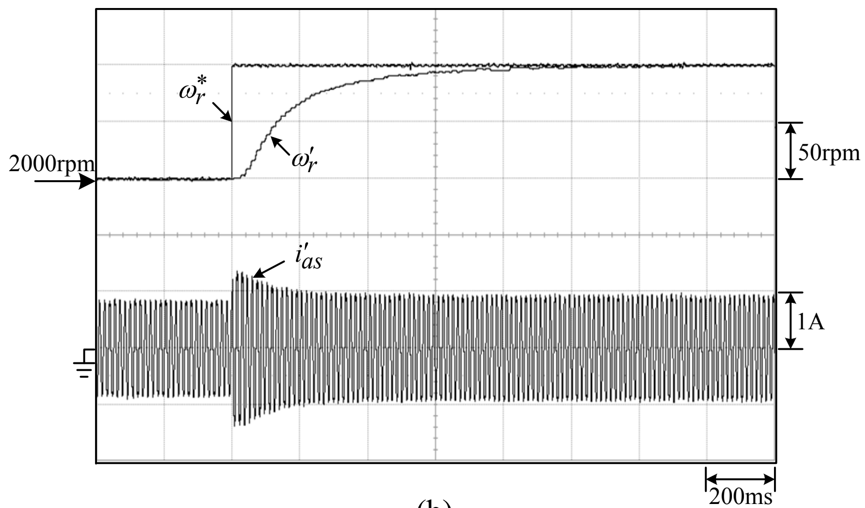
(a)



(a)



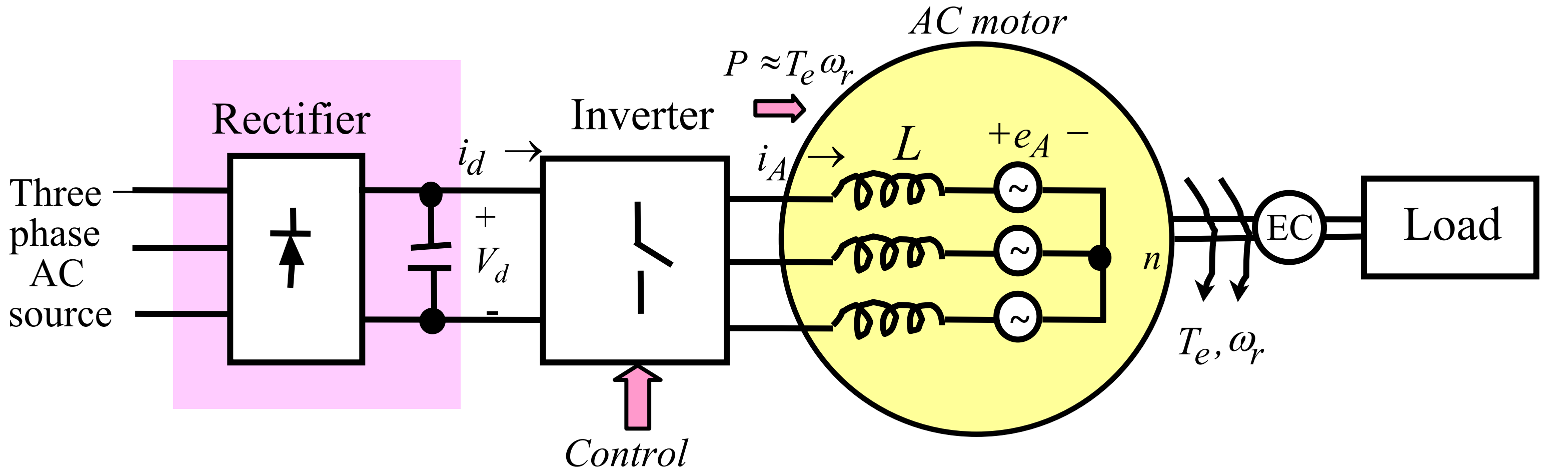
(b)



(b)

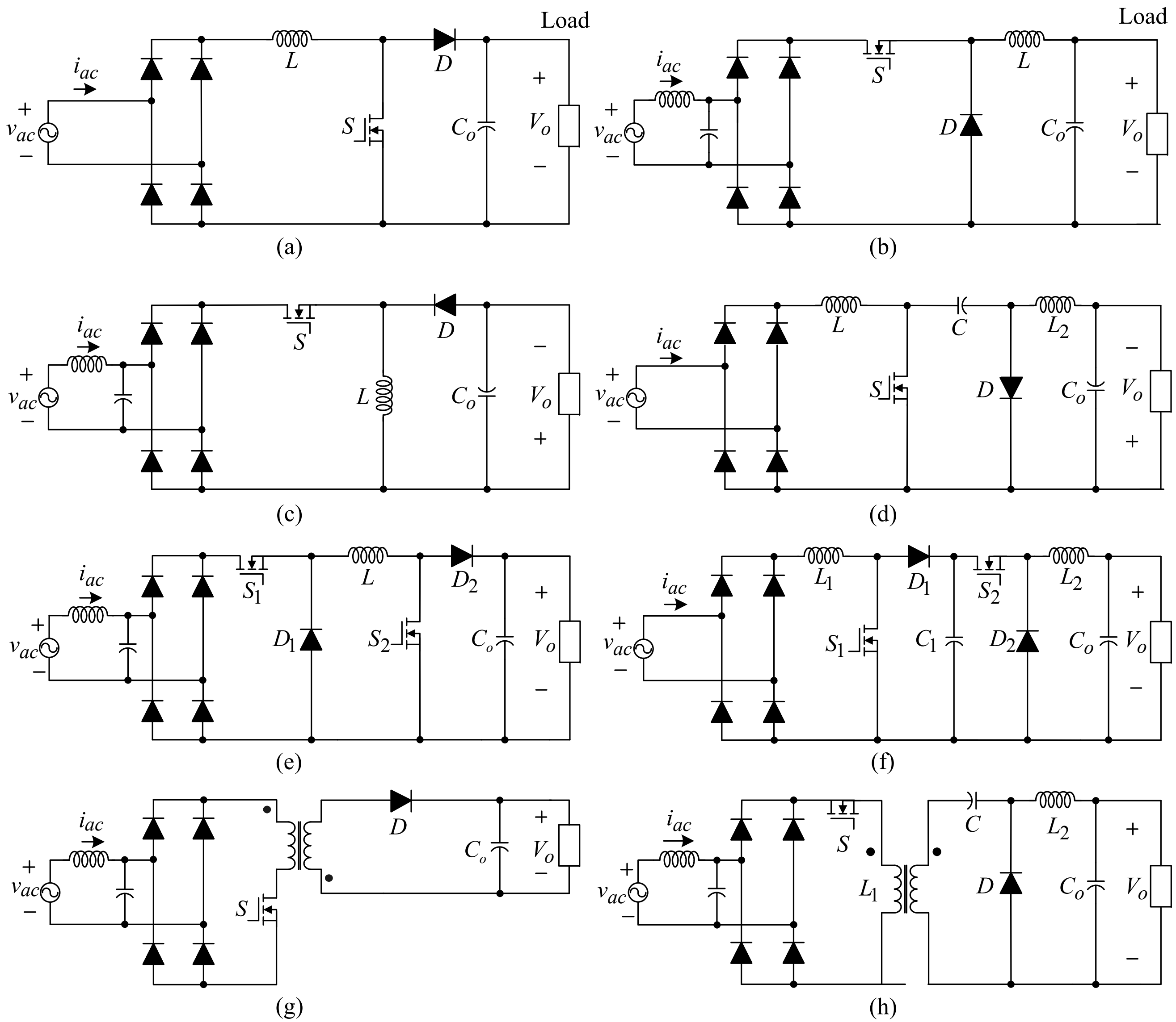
☒ SMR Application examples: Front-end of motor drives

- 對於一變頻器供電之交流馬達而言，雖然變頻器之PWM控制具有變頻變壓控制能力，但在變頻器之前端加裝一**切換式整流器(Switching-mode rectifier, SMR)**以建立直流鏈電壓，更具調壓彈性，可得良好之高速驅動特性，及提升入電之電力品質。(The equipment of SMR front-end: can provide well-regulated and boosted DC-link voltage to improve the operation performance of a motor drive, particularly the high speed operations.)
- 變頻器直流鏈之電壓如為可調變一般稱為 (Pulse-width modulated, PAM) 變頻器，藉由直流鏈電壓之調變可使方波變頻器之輸出成為近乎弦波。然而PAM之操控性能較差，僅適用於速度驅動。但如將PWM佐以PAM，可得較佳之控制彈性及性能。((PAM + PWM) >> can increase the control flexibility and performance of a motor drive.)



Some typical single-phase SMRs:

(a) boost SMR; (b) buck SMR; (c) buck- boost SMR; (d) Ćuk SMR; (e) buck-boost cascade SMR; (f) boost-buck hybrid SMR; (g) flyback SMR; (h) isolated ZETA SMR.



Flyback SMR (Flyback 切換式整流器)

- Isolated buck/boost type
- Perfect one-stage structure
- Lower rating