切換式(開關式)磁阻馬達之驅動控制與應用

(Driving controls and applications of Switched-Reluctance Motors)

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98.02.12-23

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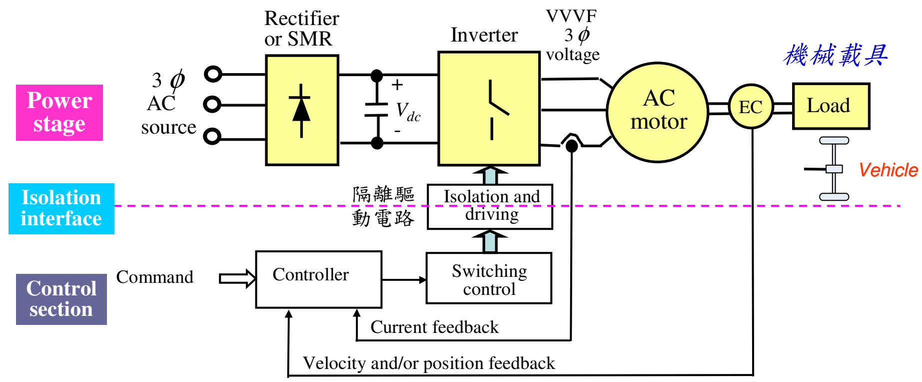
馬達驅動系統 (Motor Drive)簡介

- 為一含*馬達、機械載具、轉換器、控制器、感測與轉換*等之整合系統，唯有馬達本身之適當設計與驅動系統組件間之妥善搭配，始可得優良之運轉控制性能。



- Requirements: low cost, reliable, miniaturization, smaller volume and weight (modularization and integration), higher efficiency (energy saving), low vibration and acoustic noise, etc.

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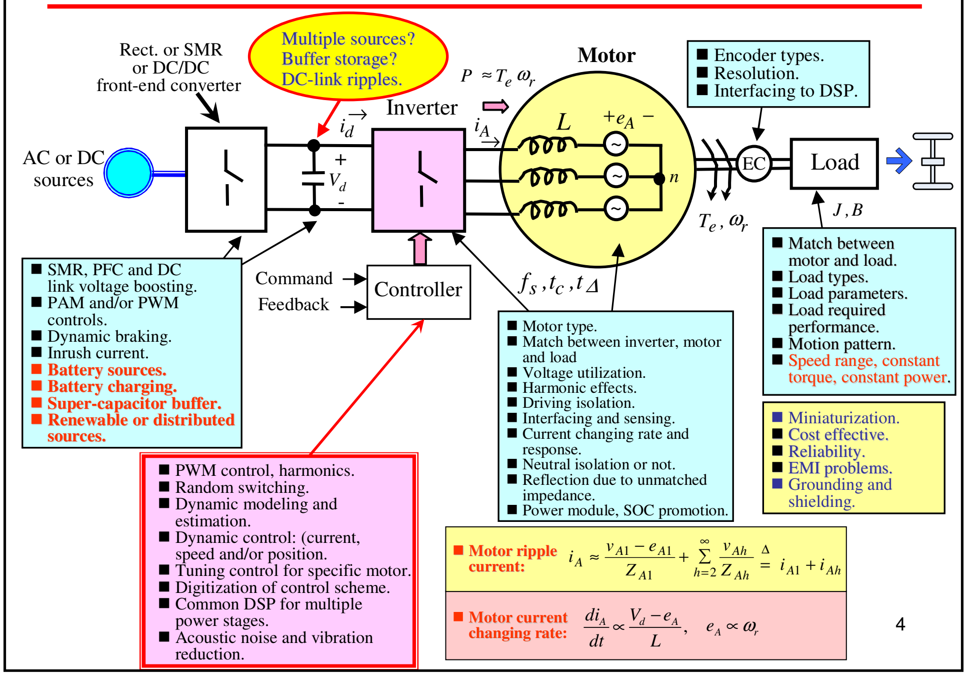
馬達驅動系統關鍵事務 (Key Issues of Motor Drives)



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Key Components and Issues of Motor Driven Plant

- Motor:
  - ☒ DC brush motor (DCM) (Least used).
  - ☒ Induction motor (IM).
  - ☒ Permanent-magnet synchronous motor (PMSM).
  - ☒ Switched-reluctance motor (SRM).
- Power electronic converter and its switching control:
  - ☒ DC/DC converters (DCM).
  - ☒ Inverters (Sine-wave, square-wave) (IM, PMSM).
  - ☒ Asymmetric bridge converter (Unipolar square-wave) (SRM).
- Power sources: AC mains, battery or renewable sources.
- Energy management technology.

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The motors employed in some typical HEVs

- Asynchronous (Induction motor)
  - BOSCH
  - SIEMENS
  - CONTINENTAL TEMIC…
- Permanent magnets (Permanent-magnet synchronous motor)
  - TOYOTA
  - HONDA
  - AISIN
  - HITACHI…
- Reluctance (Switched-reluctance motor)
  - VISTEON
- Wound rotor
  - VALEO
  - HITACHI
  - DENSO
  - BOSCH

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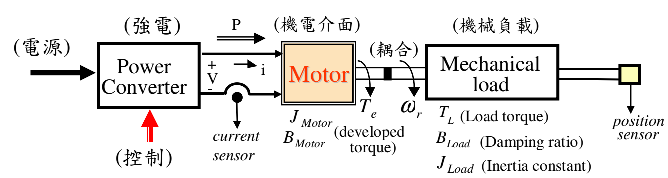
www.euripides2008.de/download/vortraege/Balle_EURIPIDES.pdf

Table 1 Electric propulsion adopted in the automotive industry.

HEV Model	Propulsion System
 PSA Peugeot-Citroën / Berlingo (France)	Dc Motor
 Holden /ECOmmodore (Australia)	Switched Reluctance Motor
 Nissan/Tino (Japan)	Permanent Magnet Synchronous Motor
 Honda/Insight (Japan)	Permanent Magnet Synchronous Motor
 Toyota/Prius (Japan)	Permanent Magnet Synchronous Motor
 Renault/Kangoo (France)	Induction Motor
 Chevrolet/Silverado (USA)	Induction Motor
 DaimlerChrysler/Durango (Germany/USA)	Induction Motor
 BMW/X5 (Germany)	Induction Motor

Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study
IEEE Trans. Vehicular Technology, vol. 55, no. 6, pp. 1756-1764.

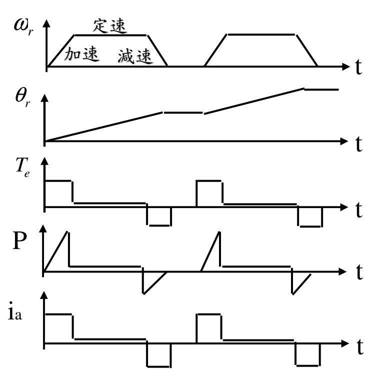
Converter - Motor - Mechanical load 間之配合 (以直流馬達為例)



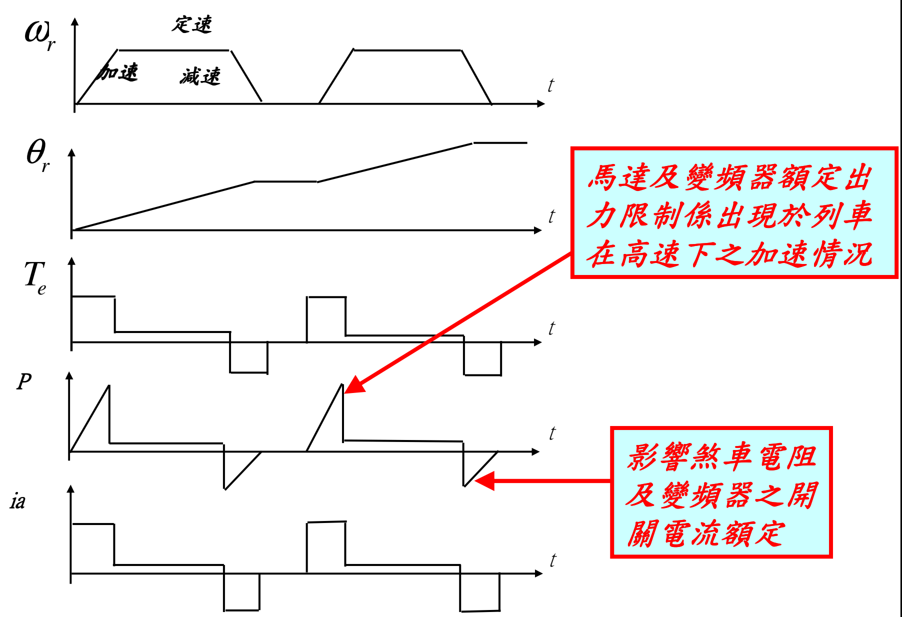
Motor drive產生轉矩必須於全速度範圍均滿足負載之轉矩要求且有較佳之驅動特性

Motor : Electrical power to mechanical power conversion: $P = T_e \omega_r$

Mechanical dynamic equation : $T_e = T_L + B\omega_r + J(d\omega_r / dt)$



- 負載在各運轉情況下所需之轉矩,馬達均應有能力提供.
- 馬達所需之電流ia係由電源流經換流器供給，故在負載在各運轉情況下均應注意功率元件之額定。
- 馬達之Te：與ia,av成正比。
  馬達之銅損:與ia,rms 之平方成正比。
  馬達之換向能力:與ia,max 有關。
  電晶體之電流額定: ia,max, ia,av, ia,rms。
- 馬達與換流器之電壓及功率額定:
  ω_r >rated : Constant power operation via field weakening。



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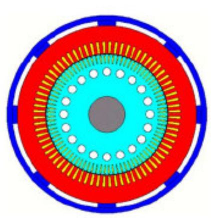
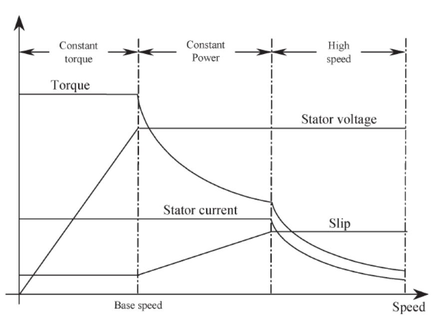
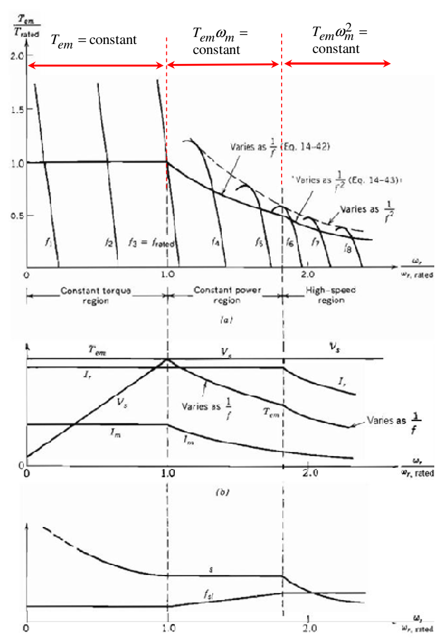
一些常用馬達轉矩-速度特性

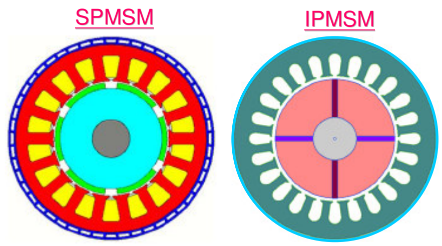
- Induction motor (IM)

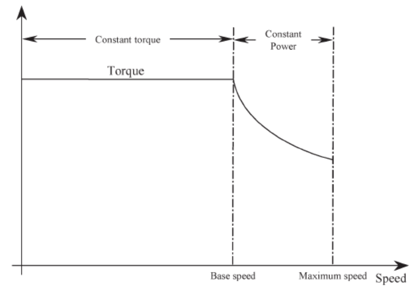






Permanent-Magnet Synchronous Motor (PMSM)





■ ***Key features of PMSMs:***

☒ Advantages:

☒ Limits: inherent narrow constant-power region.

Improvements:

(a) the use of proper types of PMSMs.
(b) suitable field-weakening by excitation setting.
(c) field-weakening via commutation advanced shift.
(d) voltage boosting.

IEEE Trans. Vehicular Technology, vol. 55, no. 6, pp. 1756-1764.

Torque-speed characteristics of SPMSM and IPMSM

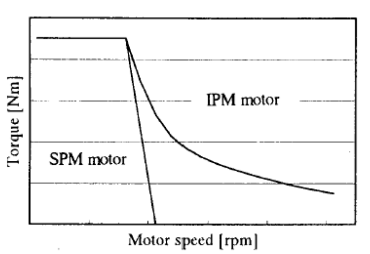


Fig.7 Torque curves of SPM motor and IPM motor

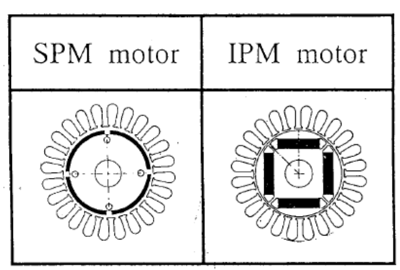
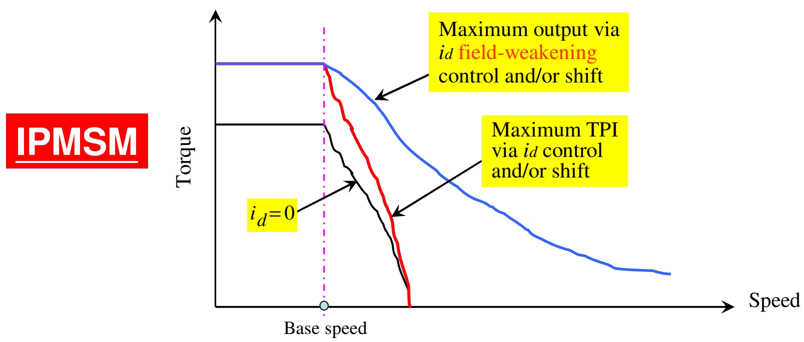


Fig.8 The structures of an SPM motor and an IPM motor

Control alternatives of IPMSM for yielding different torque-speed characteristics



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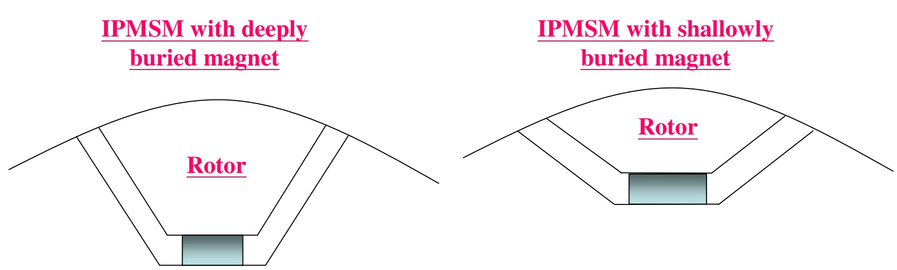
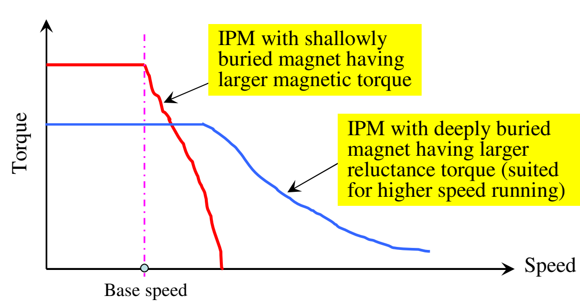
Rotor design alternatives of IPMSM for yielding different torque-speed characteristics





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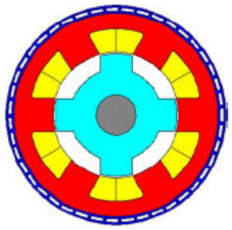
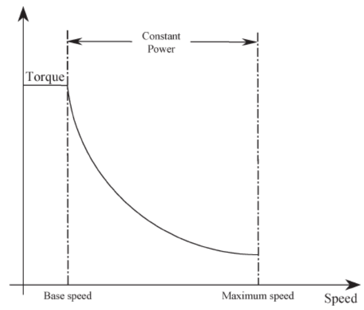
Switched-Reluctance Motor (SRM)





- ***Key features of SRM:***

  ☒ Advantages: simple and rugged, fault-tolerant operation, simple control, good torque-speed characteristic with wide constant-power region.

  ☒ Disadvantages: Higher torque ripple, vibration and acoustic noise.

  Improvements:

  (a) field-weakening via commutation advanced shift.
  (b) voltage boosting.

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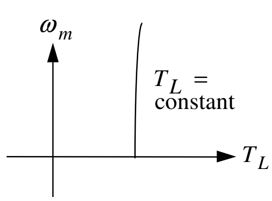
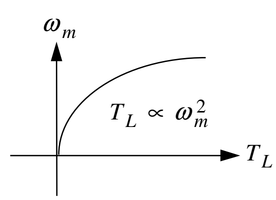
一些常用負載轉矩-速度特性

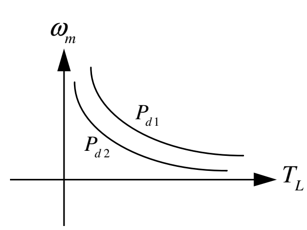
- Constant torque loads (low-speed elevator): $T_L = \text{constant}, P \propto \omega_m$



- Fan, blower and centrifugal pump: $T_L \propto \omega_m^2, P \propto \omega_m^3$



- Constant power loads (Coiler drive): $T_L \propto 1/\omega_m$



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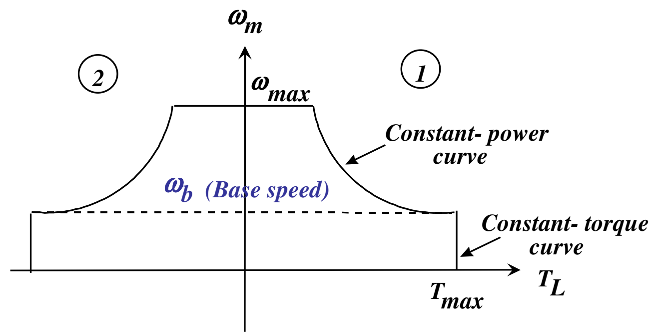
Torque-Speed Characteristics of Transportation Drives

- Freight train hauled by diesel-electric locomotives
- Commercial road delivery vehicles.
- Other systems: (a) subway trains, (b) streetcars, (c) trolley buses.



Envelope of speed-torque characteristics.

Electric Vehicles

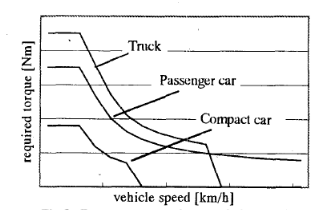


Fig.2 Constant power characteristics required for different types of vehicles

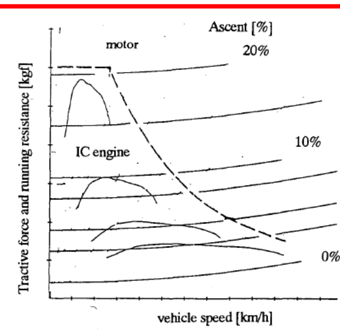


Fig.3 Tractive force vs speed diagram of IC engine with transmission and DC shunt wound motor.

- *Key features of EV load and drives:*
  - ☒ A wide speed range is critical for passenger car.
  - ☒ Internal combustion engine needs speed transmission (gear box) to modify the torque-speed patterns under different speed ranges, whereas the motor may possess adequate torque-speed profile via field-weakening. And regenerative braking is achievable for motors.

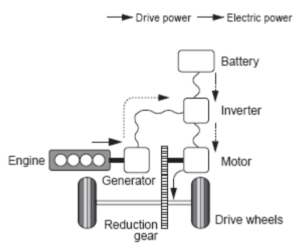
Yamada, E. and Zhengming Zhao, "Applications of electrical machine for vehicle driving system," Power Electronics and Motion Control Conference, 2000. Proceedings. IPEMC 2000. The Third International, vol. 3, pp.1359-1364, 2000.

Types of Hybrid Electric Vehicles (HEV)

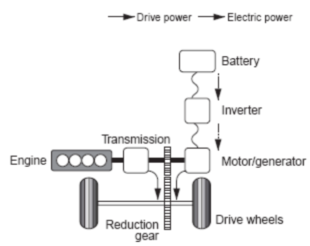
Definition:

Automobile hybrid systems combine two motive power sources, such as an internal combustion engine and an electric motor, to take advantage of the benefits provided by these power sources while compensating for each other's shortcomings, resulting in highly efficient driving performance. Although hybrid systems use an electric motor, they do not require external charging, as do electric vehicles.

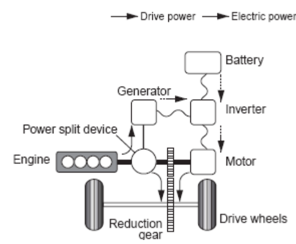
Series HEV



Parallel HEV



Series/parallel Hybrid HEV



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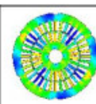
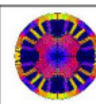
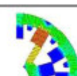
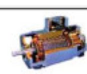
"Toyota Hybrid System THS II" www.toyota.co.jp/en/tech/environment/ths2/SpecialReports_12.pdf

Comparative evaluation of commonly used motors for EV

TABLE II
ELECTRIC-PROPULSION SYSTEMS EVALUATION

Propulsion Systems / *Characteristics*	 DC	 IM	 PM	 SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	 **22**	 **27**	 **25**	 **23**

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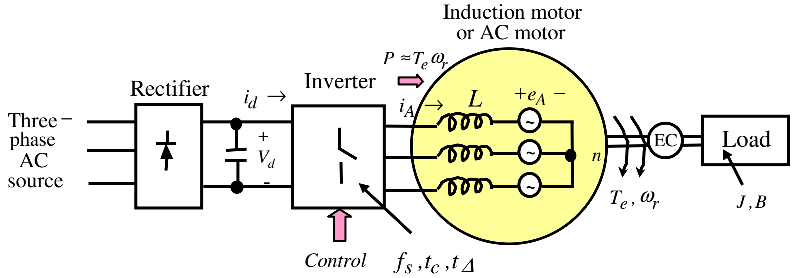
Key Parameters of an Inverter-Fed Motor Drive



- **Consideration Factors:**

  (a) Armature ripple current.
  (b) Switching losses.
  (c) Dead-time in converter transfer function.
  (d) DC link voltage capability and boosting.

- *Adverse effects of armature ripple current : (i) increase losses; (ii) cause torque ripple, vibration and acoustic noise, (iii) EMI)*
- *How to reduce armature ripple current*

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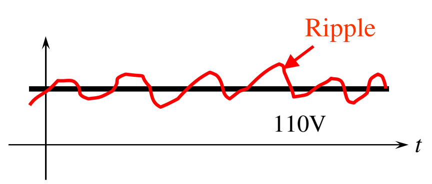
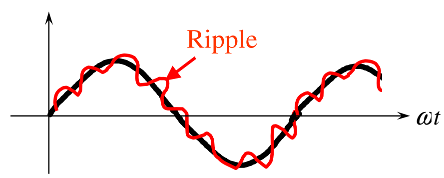
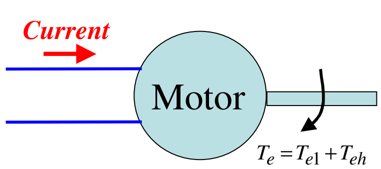
Ripple Torque due to Non-ideal Current Waveforms

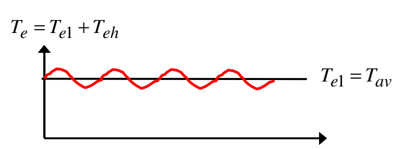
DC current:



AC current:







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Effect of Ripple Current on Mechanical Torque and Speed

- The speed of an inverter-fed motor:

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

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

$$T_{eh} \downarrow or (J/B) \uparrow or (f_1) \uparrow or (m_f) \uparrow \Rightarrow \omega_{rh} \downarrow$$

- ***Effects of torque ripple (speed ripple):***
  driving performance is degraded:
  the generation of vibration, acoustic noise, etc.

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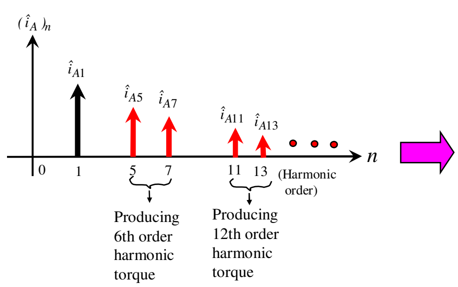
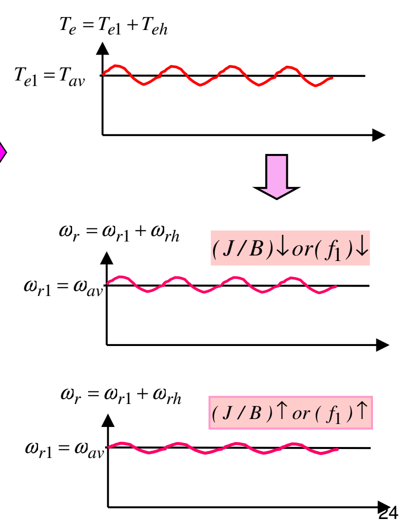
The effects of ripple current on torque and speed

- *Example: Six-step inverter-fed induction motor:*





- ***Inverter output waveform: depends on the employed switching approach.***

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Classification of PWM Methods

- 方波切換或稱六塊波切換 (Six-step switching)
- 脈寬調制(Pulse-Width Modulation, PWM)：又分：
  - (a) 方波 PWM (Square-wave PWM)
  - (b) 正弦波 PWM (Sinusoidal PWM, SPWM)
  - (c) 修正式 SPM (Modified SPWM)
  - (d) 規則取樣 PWM (Regular Sampled PWM, RSPWM)
  - (e) 諧波注入式 PWM (Harmonic Injection PWM, HIPWM)
  - (f) 最佳 PWM (Optimum PWM)
  - (g) 選擇諧波消去 PWM (Selective Harmonic Elimination PWM)
  - (h) 電流控制 PWM (Current-Controlled PWM)
    - ☒ 磁滯控制 (Hysteresis control)，或稱 Bang-Bang control，或 ON/OFF control，或Adaptive Current control。
    - ☒ 定頻控制 PWM (Fixed-Frequency PWM control)，或稱 Subharmonic PWM control，或 Ramp Comparison PWM control。
- 空間向量調制 PWM (Space Vector Modulated PWM, SVMPWM):
  - (a) Current control
  - (b) Flux and Torque control
  - (c) 其他控制法則
- Discontinuous PWM (DPWM):
  DPWM3, DPWMMAX, DPWMMIN,
  GDPWM (DPWM0, DPWM1, DPWM2)
- 隨機切換 (Random switching)

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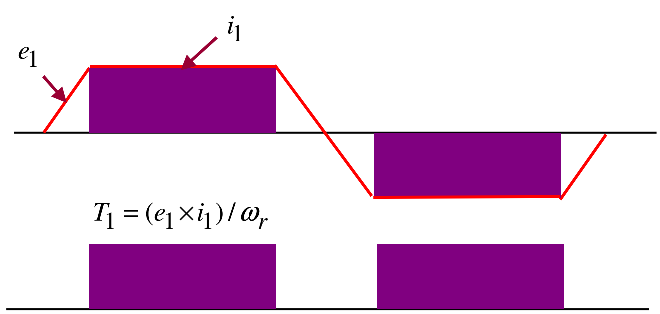
Typical waveforms of some commonly used motors

➢ **Square-wave BDCM**



$$P_m = \sum e_k i_k = T_e \omega_r \quad \Rightarrow \quad T_e = T_L + B\omega_r + J\frac{d\omega_r}{dt}$$

- Ideal case: torque is ripple-free, speed is ripple-free.
- Actual case: back-EMF and current waveforms are far from ideal >> the ripple torque and hence the speed ripple exit.
- The back-EMF waveform depends on the winding type and the permanent-magnet pole shape.
- Remedies: machine design and electronic approaches.

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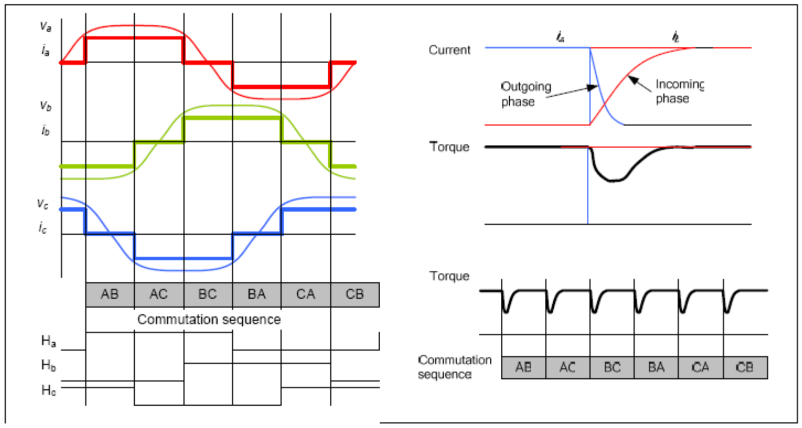
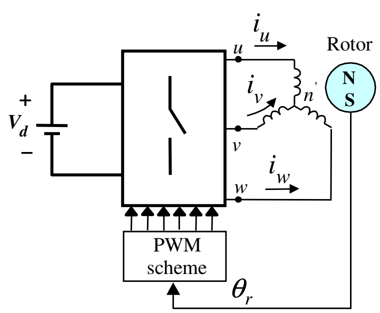
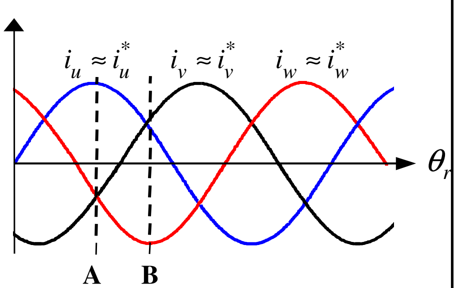
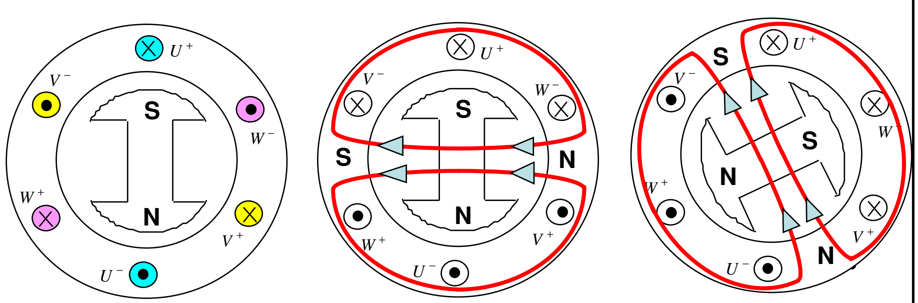


Fig. 2: (a) Trapezoidal Drive waveforms (b) Current And Torque At Commutation

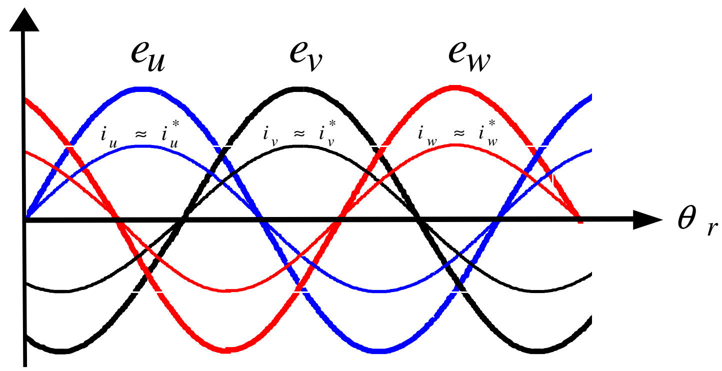
➢ Sine-wave BDCMs





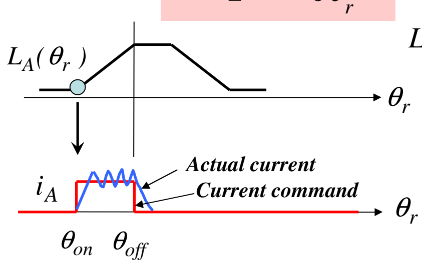


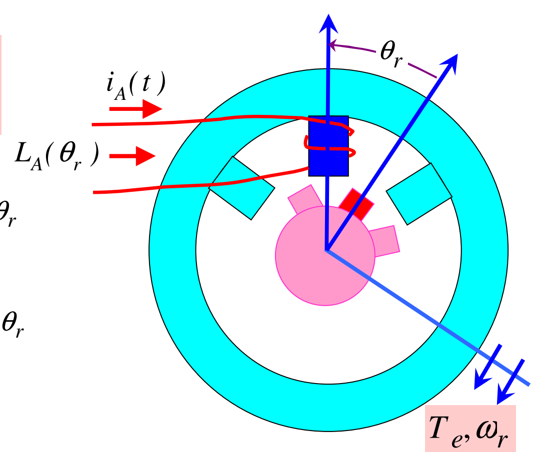
$$P = e_a i_a + e_b i_b + e_c i_c = \text{constant} = T_e \omega_r$$



➢ Switched reluctance motor

$$T_A = \frac{1}{2} i_A^2 \frac{\partial L_A(\theta_r)}{\partial \theta_r}$$





- **Switched reluctance motor:**
  - **The winding excitation is applied according to the sensed rotor position.**
  - **Absolute rotor position sensing is required.**

發電機與電動機(馬達)之分類

- 發電機與電動機在結構上一樣，僅作用方式不同。兩者在機械結構上，均具有定子(Stator)與轉子(Rotor)；在電磁作用上，具有磁場繞組(Field winding)與電樞繞組(Armature winding)。磁場繞組與電樞繞組設置於定子與轉子之方式有兩種方式：

Case 1: 如直流機

磁場繞組 → 定子

電樞繞組 → 轉子

Case 2: 如同步機

磁場繞組 → 轉子

電樞繞組 → 定子

- 發電機與電動機在作用之方式上為：

電動機	發電機
在磁場中之導體通以電流, 產生力進而使承載導體之轉子產生轉矩.	在磁場中之導體被外力帶動, 產生電動勢, 可供給電負載產生電流.

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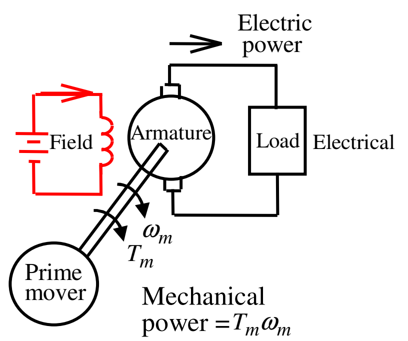
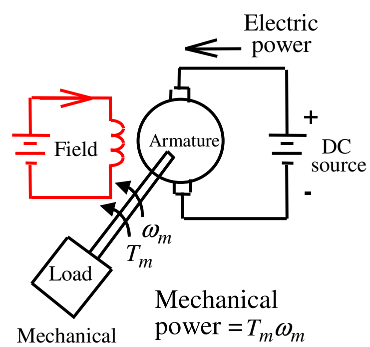
以直流電機為例

直流發電機 (DC generator)



直流電動機 (DC motor)



- **Generator: $e = B\,l\,v$**
- **Motor: $f = B\,l\,i$**

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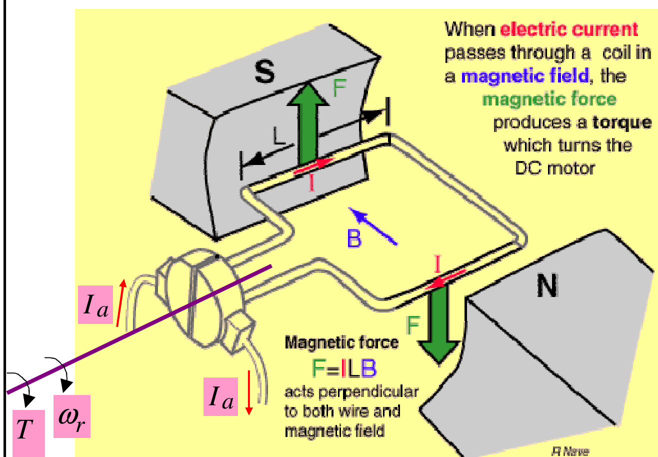
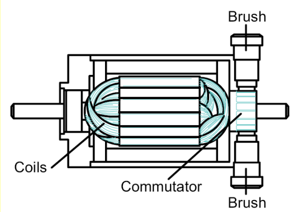
Structure and Developed Torque of a DC Motor (with brush)

- Torque generating capability of a DC Motor is the best among all motors, since the flux and armature conductor current are kept in quadrature in nature.



$$T = K_a \Phi I_a$$



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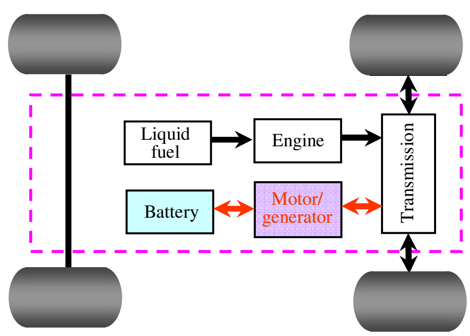
發電機與電動機(馬達)運轉模式兼具之應用場合

- 抽蓄水力發電廠 (Pumped-storage plant)
- Hybrid electric vehicles (HEVs)
  - Electric machine: motor/generator, starter/generator
  - Example: parallel HEV:

Five possible modes:

- Engine only traction
- Electric only traction
- Hybrid traction
- Regenerative braking
- Battery charging from engine



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常用馬達之綜合比較特性與應用

■ 旋轉電機分類

直流機:
- 永磁式 (Permanent-magnet, PM)
- 他激式(Separately excited)
- 自激式 (Self excited)
  - 並激 (Shunt excited)
  - 串激 (Series excited)
  - 複激 (Compound)
    - 連接方式
      - 長並聯(Long shunt)
      - 短並聯(Short shunt)
    - 激磁方式
      - 差複激(Differential compound)
      - 助複激 (Cumulative compound)
        - 欠複激 (Under-compound)
        - 平複激 (Flat-compound)
        - 過複激 (Over-compound)

馬達驅動控制性能追求之對象：

■ 並激馬達：IM, BDCM (PMSM)

■ 串激馬達：SRM

交流機:
- 同步機(Synchronous machine)
  - 三相
  - 單相
- 感應馬達 (Induction motor)
  - 三相
    - 繞線式(Wound-rotor or slip-ring)
    - 鼠籠式(Squirrel-cage)
  - 單相 (鼠籠式)
    - 分相馬達(Split-phase motor)
    - 電容馬達(Capacitor motor):
      Capacitor-start
      Capacitor-run
      Capacitor-start capacitor-run
    - 蔽極馬達(Shaded-pole motor)
    - 萬用(普用)馬達(Universal motor) (即串激馬達)
    - 其他

特殊電機:

- 步進馬達 (Stepping motor)
- 切換式磁阻馬達 (Switched-reluctance motor (SRM):
  (為具有轉子位置感測之可變磁阻步進馬達)
- 直流無刷馬達 (Brushless DC motor, BDCM)
  (為具有轉子位置感測之同步馬達)
  - 速度驅動 (方波式)
  - 位置伺服驅動 (弦波式)
- 直接驅動馬達 (Direct drive (DD) motor)：
  Possess high and smooth torque at low speed, no gears are required.
- 線性馬達 (Linear motor)
- 超音波馬達 (Ultrasonic motor)
- 其他馬達

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Applications of motors

- 直流有刷馬達: without rotor position sensing
  Excitation type: Integral-hp drives, traction drives, steel machinery, paper machinery.
  PM-type: (Lower ratings) Automotive auxiliaries, aircraft auxiliaries, small position servos, speed servos.
- 感應馬達 (Scalar control): without rotor speed sensing
  Three-phase squirrel-cage: Pumps, fans, compressors, general industrial speed drives, traction, electric vehicles, elevators.
  Three-phase wound-rotor type: High-power industrial drives with limited speed range and/or high starting torque requirement.
  Single-phase squirrel-cage: Low-cost industrial and domestic appliances.
- 感應馬達 (Vector control): with rotor speed sensing (incremental type):
  vector control is necessary for high-performance speed drives and position servo drives.
- 傳統同步馬達: without rotor position sensing
  High-power industrial drives, fans, compressors, tractions.
- 直流無刷馬達(PM-type PMSMs with absolute rotor position sensing) (lower ratings)
  Square-wave: computer peripherals, office machinery, small fan, potable tools, air conditioners, domestic appliances, electric vehicles, elevators.
  Sine-wave: Servo drives, motion control devices, advanced home appliances.
- 步進馬達: without rotor position sensing to perform positioning control
  Low-power computer peripherals, motion control devices.
- 開關式磁阻馬達: with absolute rotor position sensing
  Low-cost wide speed drives, domestic appliances, aerospace applications.

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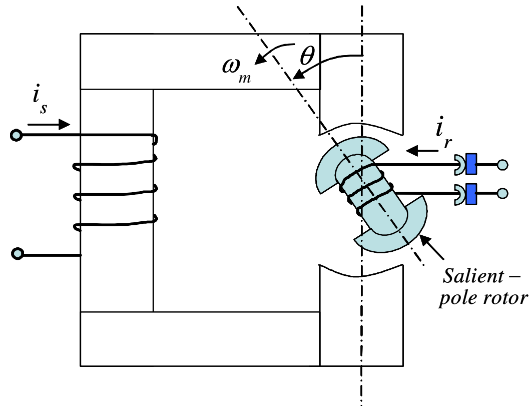
Unified Operation Principles of Electric Motors

- An elementally rotating electromagnetic device:
  One phase winding on stator and one winding on rotor

$$W_f = \frac{1}{2} L_{ss} i_s^2 + \frac{1}{2} L_{rr} i_r^2 + L_{sr} i_s i_r$$



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The electromagnetic developed torque

$$T = \frac{1}{2} i_s^2 \frac{\partial L_{ss}}{\partial \theta} + \frac{1}{2} i_r^2 \frac{\partial L_{rr}}{\partial \theta} + i_s i_r \frac{\partial L_{sr}}{\partial \theta}$$

Reluctance torques due to the variations of self-inductances with rotor position

Torques due to the variation of mutual inductance with rotor position (excitation torque)

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- The stator and rotor currents can be DC or AC.
- For single-phase motor, there is no starting torque and the pulsating torque exists.
- If the rotor is not equipped with winding, i.e., $i_r = 0$, then

$$T = \frac{1}{2} i_s^2 \frac{\partial L_{ss}}{\partial \theta}$$

- The rotor should have ***saliency***. The synchronous reluctance motor, variable reluctance stepping motor and switched-reluctance motor belong to this type. To obtain better torque generating capability, the winding current waveform switching control should be made in accordance with the pattern of L_{ss} , which is nonlinear function of rotor position, current level and frequency.

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- If the rotor is non-salient or *cylindrical* type: $T = i_s i_r \frac{\partial L_{sr}}{\partial \theta}$

Thus the doubly-excited operation should be adopted. The slip rings and brushes are used for AC motors, and the commutators and brushes are used for DC motors. The winding currents for various types of motors are:

DC motor: i_s and i_r are all DC currents.

AC excited synchronous motor: i_s is AC and i_r is DC.

AC permanent synchronous motor: i_s is AC, rotor is equipped with permanent magnet. ***BDCM*** is basically a PMSM with inverter commutation being made according to the sensed rotor position.

AC induction motor: i_s is AC, i_r is induced AC current with frequency smaller than those of i_s .

Switched-reluctance motor: a kind of synchronous motor with singly excited unipolar square-wave winding currents.

- ***Each type of motor possesses its key parameters affecting the motor driving performance, and they can be properly tuned to yield better performance.***

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直流馬達(有刷) (DC Motors)

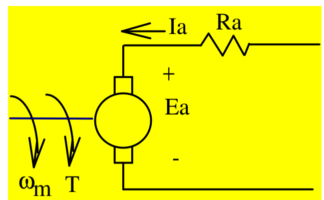
- **Two basic equations:**

$$E_a = K_a \Phi \omega_m \begin{cases} \text{Generator : Generated voltage} \\ \text{Motor : Back emf (Lenz's law)} \end{cases}$$

$$T = K_a \Phi I_a \begin{cases} \text{Motor: Generated torque} \\ \text{Generator: Retarding torque (Lenz's law)} \end{cases}$$

- Torque generating capability is excellent

$$E_a I_a = T\,\omega_m \,(Neglecting\ losses)$$



- 機電整合主導公式
- 馬達及轉換器之象限：
  - Forward driving and regenerating braking
  - Backward driving and regenerating braking

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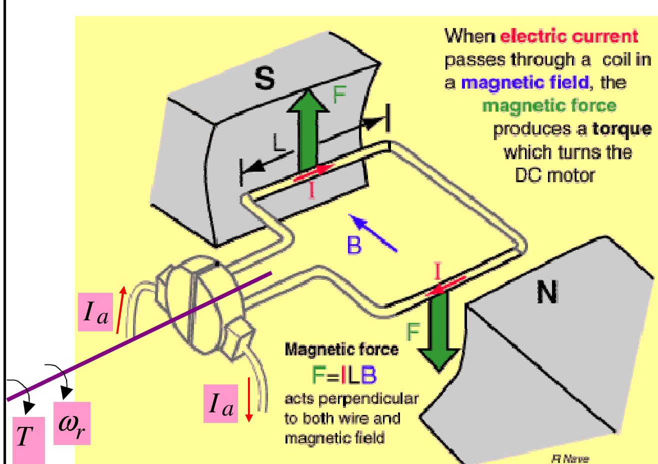
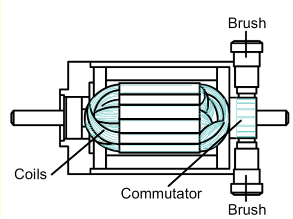
Structure and Developed Torque of a DC Motor (with brush)

- Torque generating capability of a DC Motor is the best among all motors, since the flux and armature conductor current are kept in quadrature in nature.



$$T = K_a \Phi I_a$$



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Series Motor

- Universal motor: AC and DC are all okay.
- Large developed torque (large starting torque):

$$T = K_t I_a^2$$

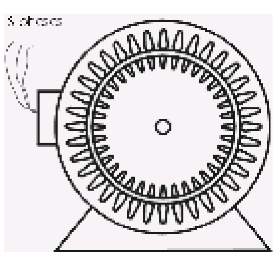
- Speed will be dangerously large at light load.

$$\omega_m = \frac{V_t}{\sqrt{K_{sr}}\sqrt{T}} - \frac{R_a + R_{sr} + R_{ae}}{K_{sr}}, \quad K_a \Phi = K_{sr} I_a$$

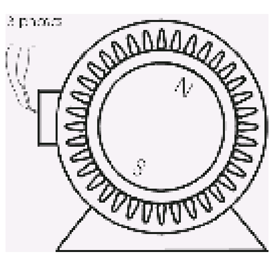
$$\omega_m \propto 1/\sqrt{T}, T = 0\,(No\ load) \Rightarrow \omega_m \rightarrow \infty$$

AC Motors

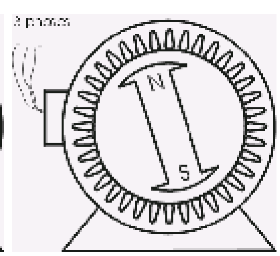
Squirrel-cage induction motor (IM)



Non-salient-pole synchronous motor (SM)



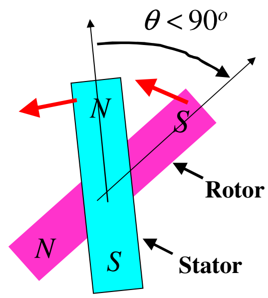
Salient-pole synchronous motor (SM)



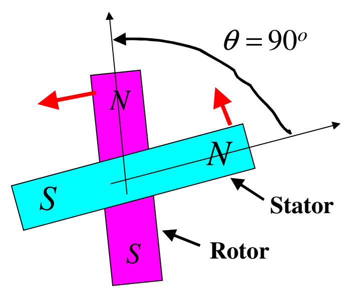
Traditional synchronous motor (SM) vs. brushless DC motor (BDCM)

- BDCM: A permanent magnet synchronous motor with its stator windings being excited according to the sensed rotor position.
- Absolute rotor position sensing or estimation (i.e., sensorless control) is required.

SM



BDCM



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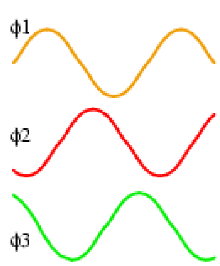
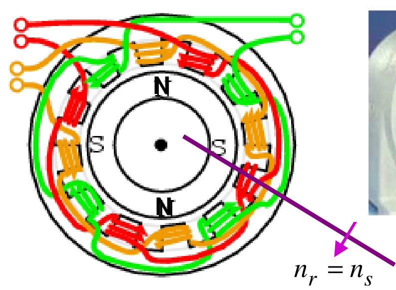
Structures of Synchronous Motors (sine wave type)

- *Armature windings: sinusoidaly distributed*
- *Winding currents: Three-phase armature currents (sinusoidal balance set)*





- Rotating filed produced by stator armature windings:

$$n_s = \frac{120 f}{P} (rpm),\ f = frequency ,\ P = pole\ number$$

- Rotor is equipped with field, and it will run at the same speed.
- The poles of stator and rotor are displaced by a power angle (< 90 degrees)

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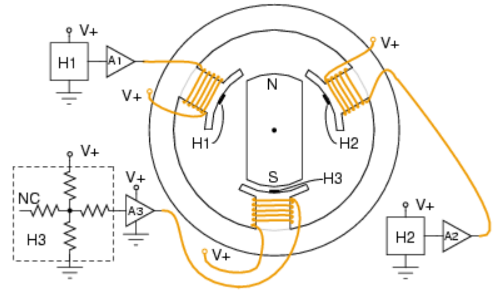
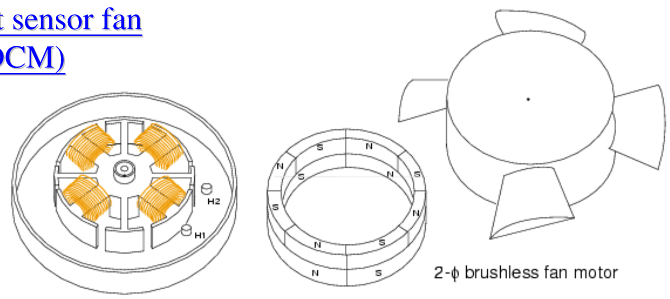
Structures of Brushless DC Motors (BDCMs)
(Square wave type synchronous motors)

Three-phase
Hall-effect sensor
BDCM



Two-phase 4-pole
Hall-effect sensor fan
motor (BDCM)



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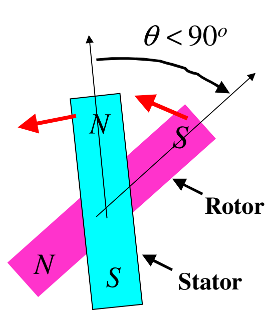
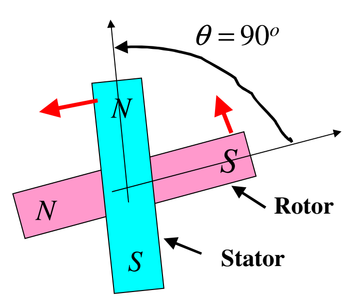
Induction motor: scalar control vs. vector control (field-orientation control)

Scalar control

Vector control
(Predictive control with
proper slip angular speed
being determined)





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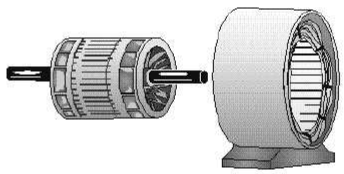
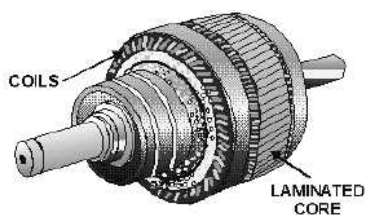
感應馬達之結構簡介

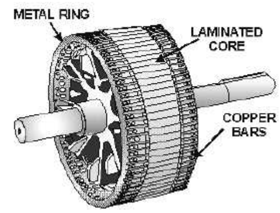
定子及轉子

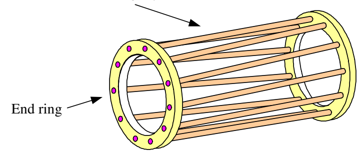


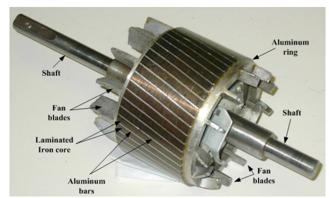
繞線式(滑環式)轉子



鼠籠式轉子

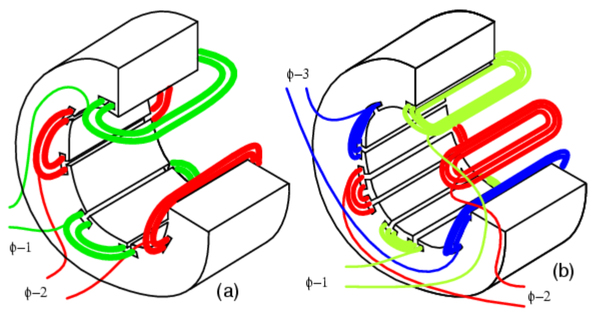






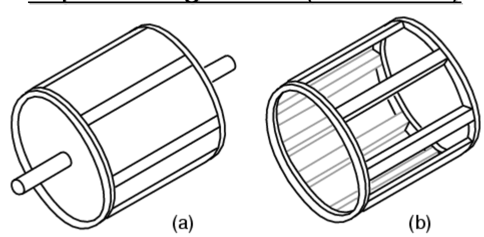
Structures of Induction Motors (IMs)

Stator (two-phase) | Stator (three-phase)



Squirrel-cage rotor (brushless)

(a) Embedded squirrel cage;
(b) Conductive cage removed from rotor.



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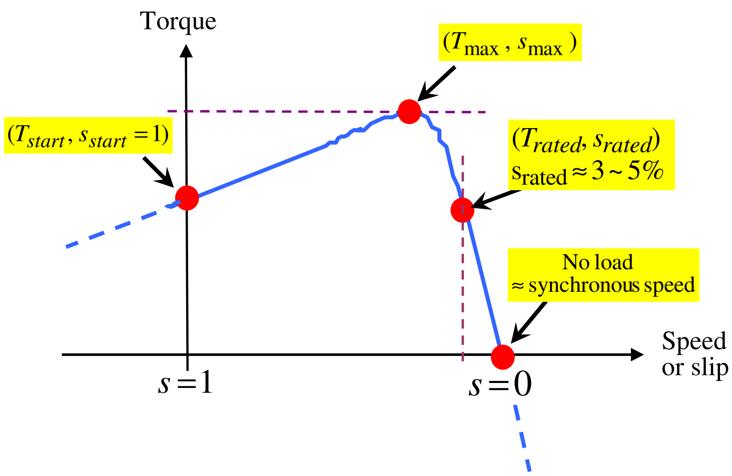
Typical operating points in motoring mode



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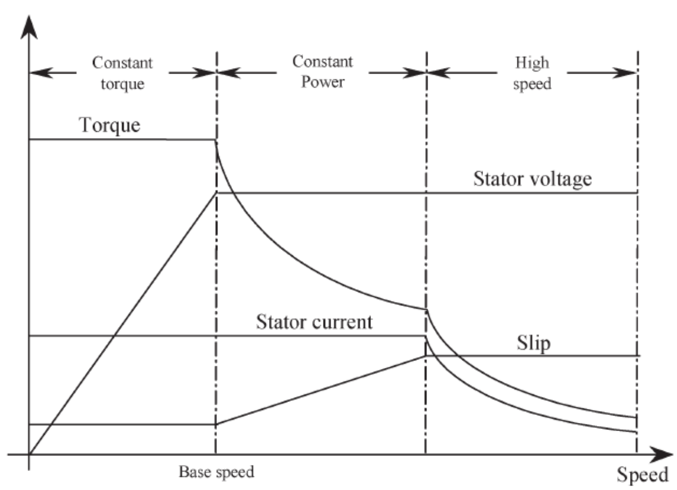
Operating capabilities of induction motor



- Scalar control: proper V/f ratio, voltage boosting in low speed.
- Vector control: suitable field-orientation control with compensation.
- Suitable field-weakening control in high-speed range.
- DC-link voltage boosting.

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不同馬達性能比較(應用於空調機)：

- 四種馬達：IM, SynRM, SPMSM, IPMSM
- 比較之性能：Cogging torque、轉矩特性、效率及損失、成本。
- (i) 齒隙轉矩(Cogging torque)：IPMSM與SPMSM具有Cogging torque，其中IPMSM較大，因其具有凸極效應(Saliency)，在壓縮機負載之應用上，應具有效小之Cogging torque，因需具有低噪音及低振動特性;

(ii) 馬達效率及損失：IPMSM之效率最高，因其除具永磁轉矩外，尚具有磁阻轉矩，其所需之定子電流最小，而具有最小之銅損。SPMSM無磁阻轉矩，其銅損增大。另外，因外包鋼膜上之感生渦流所造成之鐵損，以及較大之氣隙，使其效率稍低。而SynRM因無永磁轉矩，全靠磁阻轉矩而效率較低，但仍比IM高約2~3%；

(iii) 成本：以SynRM為1.0當比較對象，IM、IPMSM、SPMSM分別為其之1.13、1.42、1.5倍。由上之比較可知，欲得高性能高效率之空調運轉操控特性，可選用IPMSM，而如欲得最低成本者，可選用SynRM，只是效率較低，但仍比IM高些。

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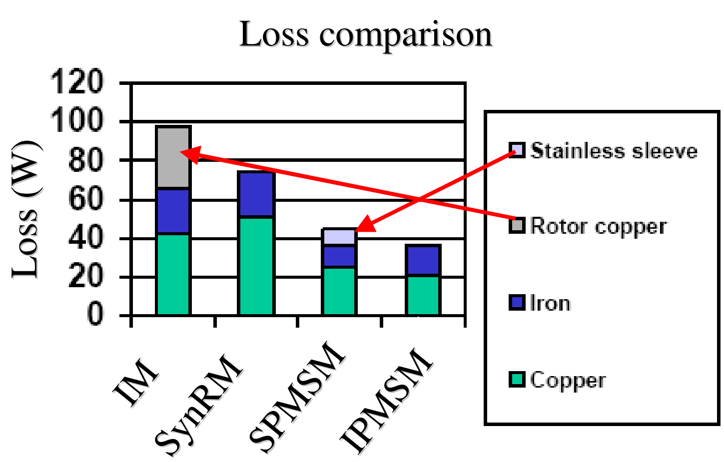
Loss Comparison of Some Commonly Used Motors



www.irf.com/technical-info/whitepaper/imotionapmotorpcimchina06.pdf

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Classification of synchronous motors

PMSM >> PMSM + RM >> SynRM

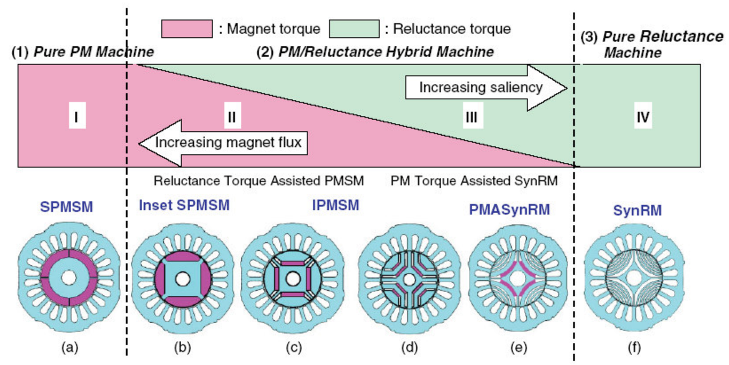

Fig. 2 Classification of synchronous machines by torque generating mechanism

- PMASynRM: Permanent magnet torque assisted SynRM
- SynRM: Synchronous Rluctance Motor

Shigeo Morimoto, "Trend of permanent magnet synchronous machines," IEEJ Trans., 2007; 2: pp. 101-108.

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- **PM-Assisted SynRM rotor**

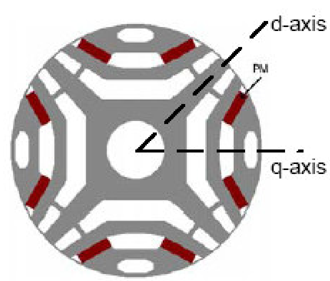
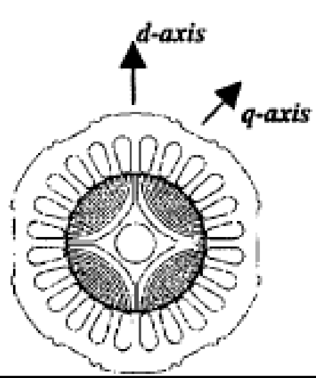


Fig. 1 A four pole PMa-SynRM rotor.

- **SynRM rotor**



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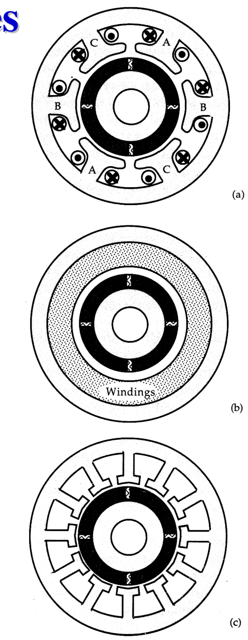
☒ Some typical stator structures

(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。

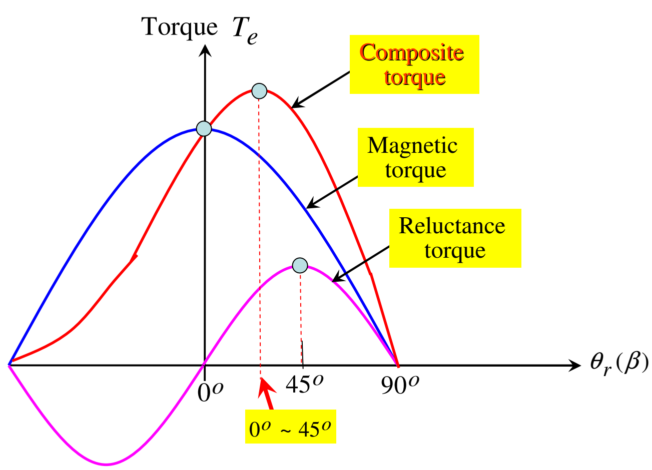
(b) 如圖(b)，沒有slot (Slot-less)，故沒有齒隙轉矩(Cogging torque)，但線圈與後鐵間之熱導低，不利負荷之增加。又因沒有靜子齒，使得氣隙增長成轉子表面至後鐵，為維持適當大之PC值，磁鐵之長度須增長。

(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。



☒ IPMSM

$$T_e = \frac{3}{2}\frac{P}{2}[\lambda_m^r I_{as}\cos\beta - (L_d - L_q) I_{as}^2 \sin\beta\cos\beta]$$
$$= \frac{3}{2}\frac{P}{2}[\lambda_m^r I_{as}\cos\beta + \frac{L_q - L_d}{2} I_{as}^2 \sin 2\beta]$$



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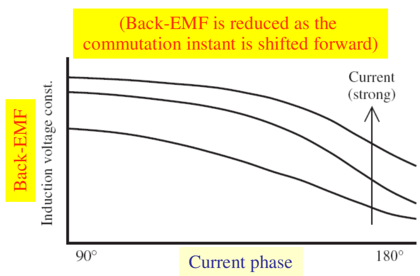
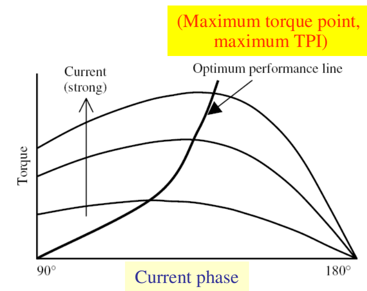
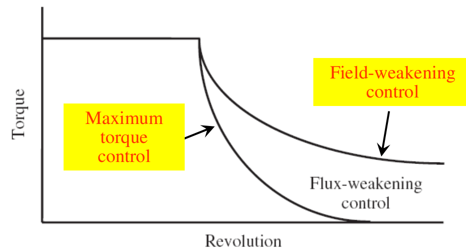
換相前移調控之等值弱磁及轉矩產生能力增進





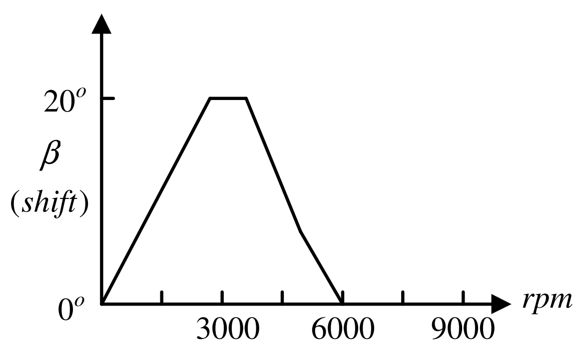
- Maximum torque control:
  The required current is minimum under a particular load.

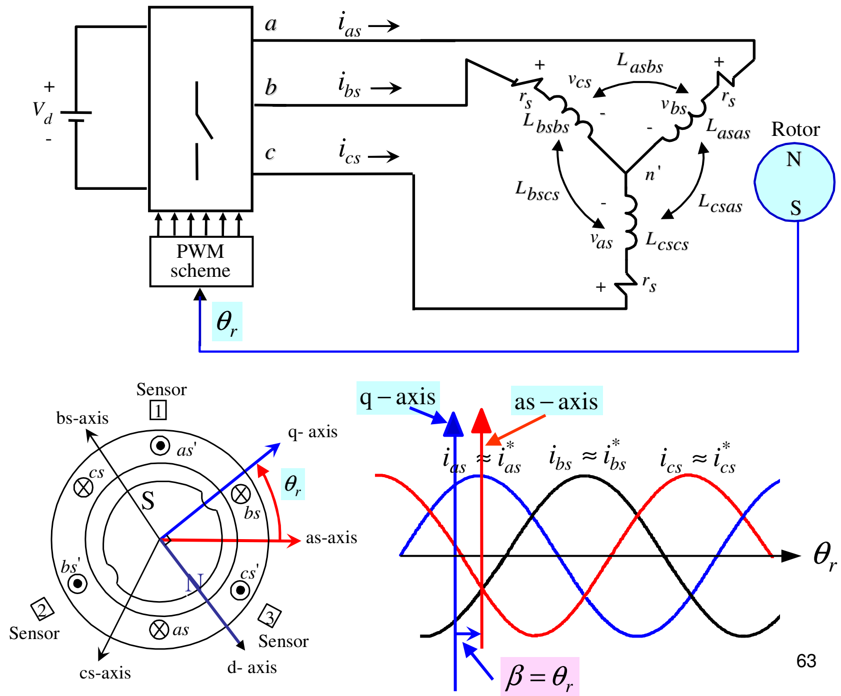


IEEJ Trans 2007; **2**: 162–168

最佳 β 角對轉速之概略關係

- 實際上，β_{max} 與速度、負載、馬達參數等均有關。
- β 角之調控：須特別研究的課題為採用合適之方法及合適之性能評估指標(Performance index)來做換向調控以達到較佳之操控性能。





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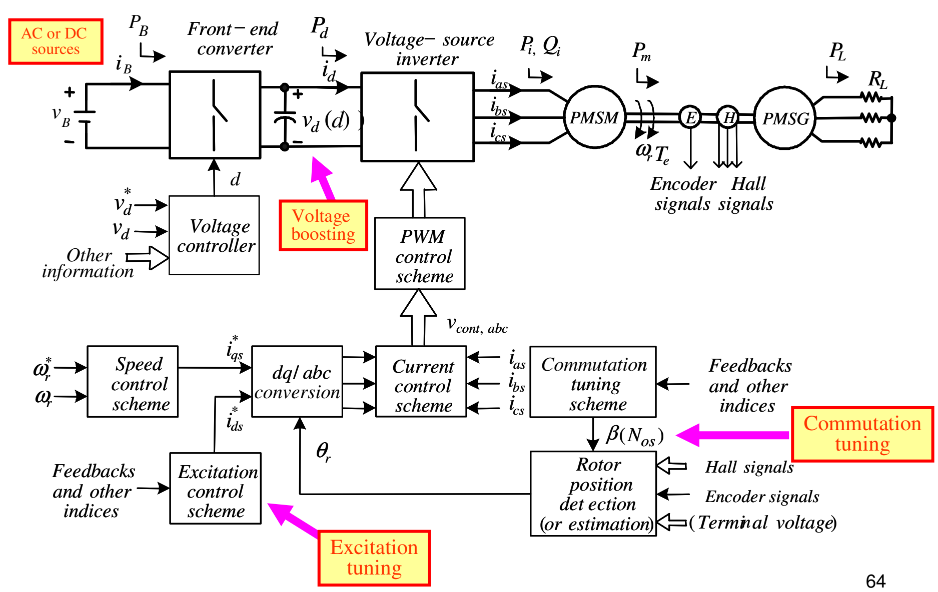
影響PMSM馬達驅動系統操控特性之關鍵因素、參數及事務



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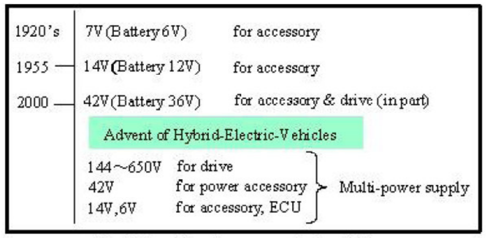
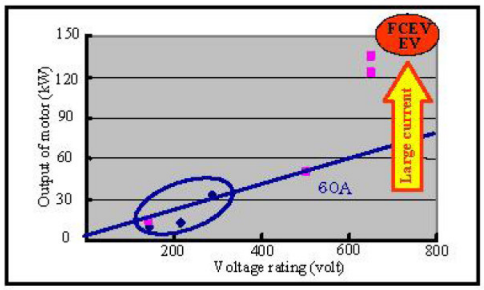
Voltages of Electric Vehicles

Transition of voltages in electric vehicles



Background of high-voltage in HEV



"Trend of high voltage harness technology that supports Hybrid Electric Vehicles."
ieeexplore.ieee.org/iel5/4239117/4239118/04239329.pdf?tp=&isnumber=&arnumber=4239329

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Features of some electric vehicles

TABLE I MAJOR ELECTRIC VEHICLES SEEN IN EVS 13 AND 14.

maker		TOYOTA	NISSAN	HONDA	GM	FORD
name		RAV4-EV	Altra EV	EV Plus	EV 1	Ranger EV
weight		1540kg	1700kg	1615kg	1350kg	2123kg
seating capacity		5	4	4	2	2
speed		125km/h	120km/h	over 130km/h	130 km/h	120 km/h
range		200km (city) 170km (highway)	200km (city, highway)	210km (10-15 mode)	110km (city) 145km (highway)	95km
motor		PM	PM	PM	IM	IM
Battery	type	Ni-MH	Lithium ion	Ni-MH	Lead acid	Lead acid
	capacity	95A×5h 30V	100A×3h 28.8V	95A×3h 12V	53Ah 12V	86A×3h 8V
	voltage	288V	345V	288V	312V	312V

Recent *Trends* of *Electric Vehicle* Technology
mizugaki.iis.u-tokyo.ac.jp/staff/hori/paperPDF/JCTrip.pdf

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THS-II Specifications (Motors and voltages)

Table-3: Application of IPM Motor drives in Japanese Hybrid Electric Vehicles

Year	Company	Brand	Vehicle type	Power	Voltage	km/litre
1997	Toyota	Prius	Sedan	30kW	274V	22
2000	Toyota	Prius-1	Sedan	33kW	288V	22.5
2004	Toyota	Prius-2	Sedan	50kW	500V	25.6
2005	Toyota	Camry	Sedan	60kW	650V	25.0
2005	Toyota	Kluger*	V6-SUV	123kW	650V	17.8
2005	Toyota	Estima*	V6-Van	123kW	650V	18.6
2005	Toyota	Harrier*	V6-SUV	123kW	650V	17.8

* Japanese 4 WD, front motor/generator, 123 kW, 12400 rpm rear motor, 50 kW, nickel metal hydride battery

Table-4: THS specifications [Kamiya, 2005]

System	THS		THS II	
Vehicle	Prius			SUV
E/G	1.5L			3.3L
Launch	1997	2000	2003	2005
DC Bus Voltage	About 274V		500V	650V
Max. Power	30 kW	33 kW	50 kW	123 kW
Max. Torque	305 Nm	350 Nm	400 Nm	333 Nm
Max. Speed	6000 rpm		6700 rpm	12400 rpm

THS II

DC bus voltage 500V/650V

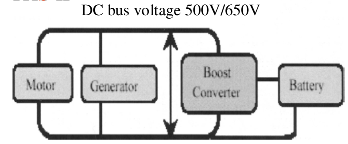

Fig. 8: High voltage drive system using a dc/dc boost converter

ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4510492

Recent R&D Activities of Power Devices for Hybrid Electric Vehicles

Voltage boosting 202V >> 500V (or higher)

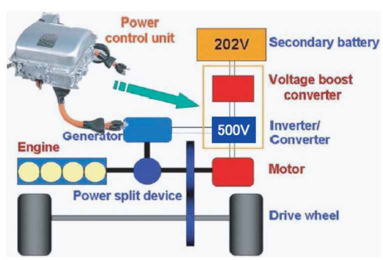

Fig. 5 Schematic view of THS II system of Prius. The power control unit contains an inverter and a DC/DC converter. In THS II, a high-voltage power circuit that increases the voltage up to 500V is added.

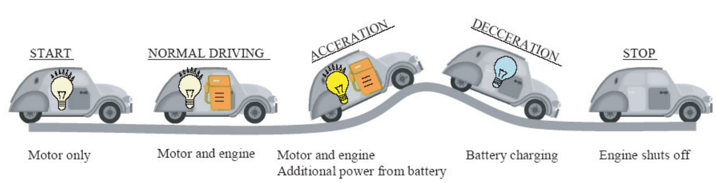

Fig. 6 Schematic view to show how both a gasoline engine and a motor work.

www.tytlabs.co.jp/english/review/rev394epdf/e394_001ishiko.pdf

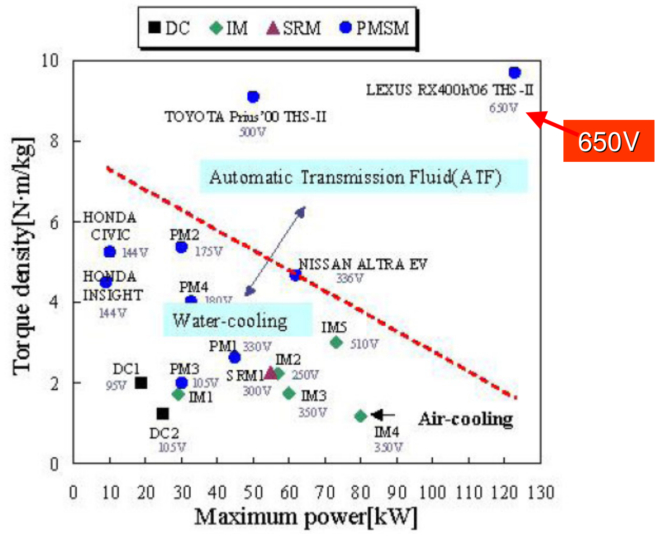

Fig. 6 Maximum power vs. torque density plots
for a variety of traction motors in PEVs and HEVs.

"**Progresses for a Last Decade and Perspectives in Applications Specific Electric Motors and Drives in Japan**," Matsui, Nobuyuki; Power Conversion Conference - Nagoya, 2007. PCC '07, 2-5 April 2007 Page(s):K-17 - K-24.

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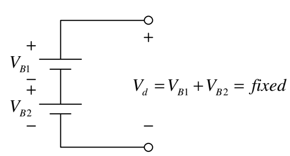
Possible voltage boosting approach: boosted DC-link voltage using front-end converters:

- Series connected voltage boosting circuits

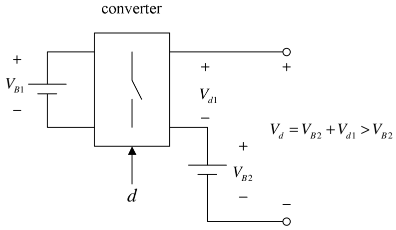
Fixed voltage



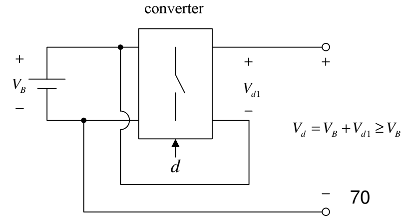
Adjustable voltage – two batteries

Adjustable voltage – single battery

Non-isolated converter



Isolated converter



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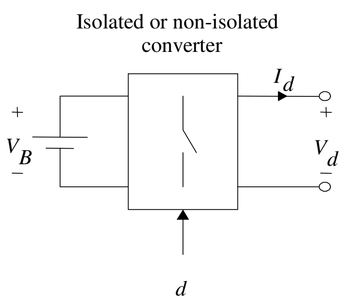
Single-stage voltage boosting circuits

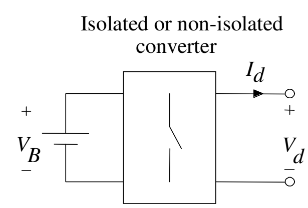


- One-quadrant

$V_d \geq 0,\ I_d \geq 0$

$$V_d = \frac{V_B}{1-d} \text{ or } \frac{d}{1-d} V_B$$

(a)



- Two-quadrant
  - (i) $V_d \geq 0,\ I_d \geq 0$ or $I_d \leq 0$
  - (ii) $I_d \geq 0,\ V_d \geq 0$ or $V_d \leq 0$
- Four-quadrant
  - $V_d \geq 0$ or $V_d \leq 0,\ I_d \geq 0$ or $I_d \leq 0$

(b)

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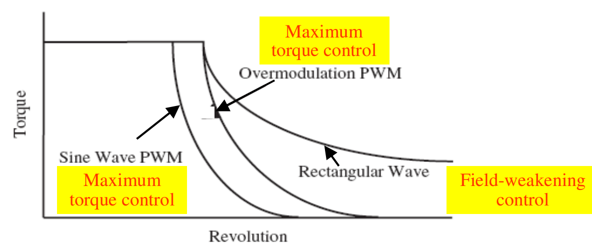
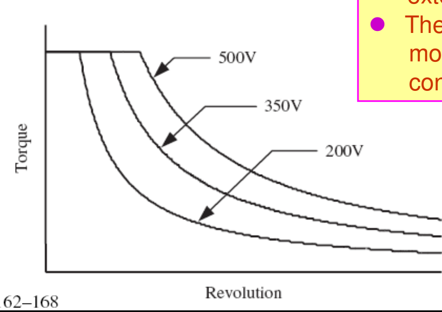
PWM modulation strategies (fixed DC-link voltage)



Boosted DC-link voltages

- The operation range can be extended to higher speeds.
- The ratings of inverter and motor should be properly considered.



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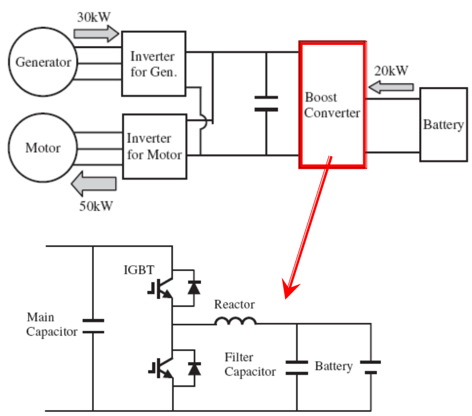
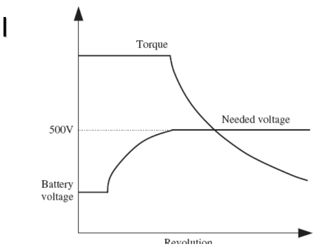
IEEJ Trans 2007; **2**: 162–168

Example: THS (Toyota Hybrid System)-II



Voltage boosting
202V >> 500V
(or higher)



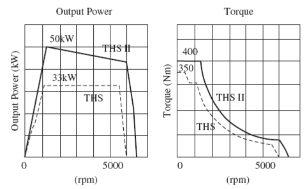


Fig. 17 Motor performance curve

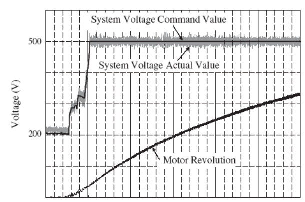


Fig. 18 Full acceleration test

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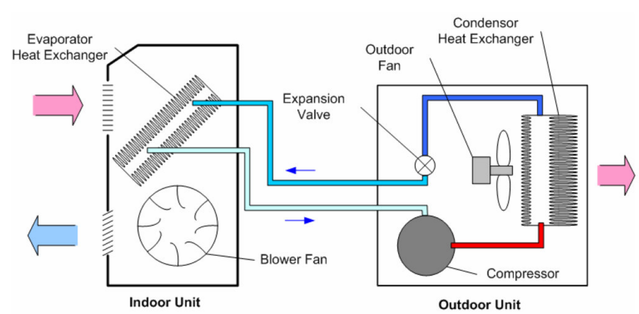
IEEJ Trans 2007; **2**: 162–168

Home air conditioner trends



Trends:

- Motor: Induction motor >> Permanent-magnet synchronous motor (PMSM)
- Vector control >> Sensorless control.
- Square-wave type >> sinewave type.
- Front-end switch-mode rectifier (SMR)>> provide boostable and well-regulated DC-link voltage with good line drawn power quality.
- Common digital control environment for: Outdoor compressor PMSM, outdoor condenser fan motor, front-end switch-mode rectifier (SMR).
- DSP or ASIC + microcontroller, or FPGA + microcontroller.

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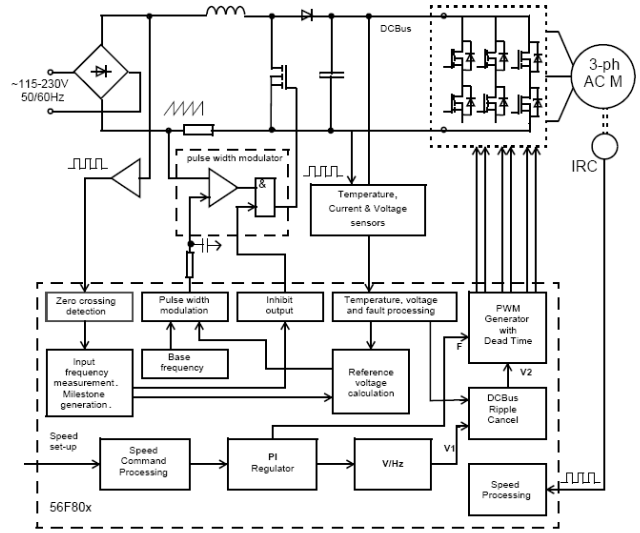
www.irf.com/technical-info/whitepaper/mce_digitalpfc_ac.pdf

SMR (PFC rectifier) + AC motor drive (Common DSP)



Indirect Power Factor. Correction for 3-Phase AC. Motor Control with V/Hz. Speed Open Loop. Application Using a 56F80x. Device.
www.freescale.com/files/product/doc/AN1918.pdf

Example PMSM drive (Hitachi)

Features:

- Sensorless control.
- Sinewave PMSM current.
- Integrated power stages:
  Boost SMR + PMSM inverter.
- DC-link current sensing
- Common DSP.

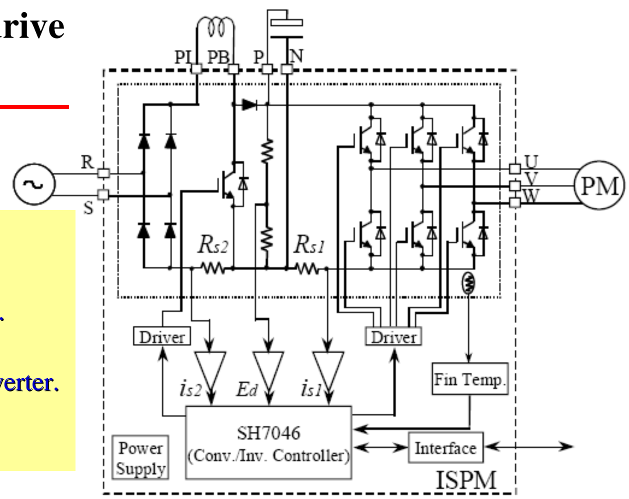
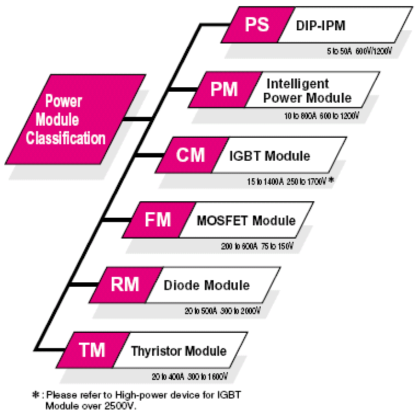
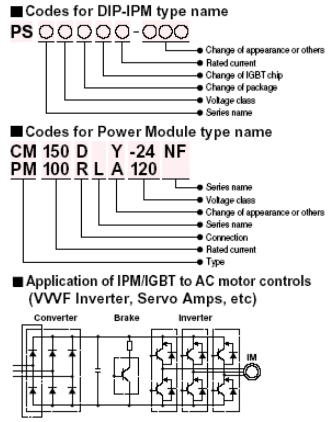


Figure 1. Configuration of proposed PMSM drive system

Sensorless Control and PMSM Drive System for Compressor Applications
Dongsheng Li; Takahiro Suzuki; Kiyoshi Sakamoto; Yasuo Notohara; Tsunehiro Endo; Chikara Tanaka; Tatsuo Ando;
Power Electronics and Motion Control Conference, 2006. IPEMC '06. CES/IEEE 5th International
volume 2, Aug. 2006, Page(s):1-5

Mitsubishi Power Modules





www.**mitsubishi**chips.com/Global/ catalogue/pdf/**power**/general_e/e_05.pdf

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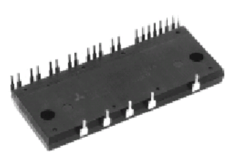
Intelligent Power Module PS21245-E

PS21245-E



INTEGRATED POWER FUNCTIONS

4th generation (planar) IGBT inverter bridge for 3 phase DC-to-AC power conversion.

INTEGRATED DRIVE, PROTECTION AND SYSTEM CONTROL FUNCTIONS

- For upper-leg IGBTs : Drive circuit, High voltage isolated high-speed level shifting, Control circuit under-voltage (UV) protection.
  Note : Bootstrap supply scheme can be applied.
- For lower-leg IGBTs : Drive circuit, Control circuit under-voltage protection (UV), Short circuit protection (SC).
- Fault signaling : Corresponding to a SC fault (Low-side IGBT) or a UV fault (Low-side supply).
- Input interface : 5V line CMOS/TTL compatible, Schmitt Trigger receiver circuit.

MITSUBISHI SEMICONDUCTOR <Intelligent Power Module>

PS21245-E

TRANSFER-MOLD TYPE
INSULATED TYPE

MAXIMUM RATINGS (T_j = 25°C, unless otherwise noted)
INVERTER PART

Symbol	Parameter	Condition	Ratings	Unit
V_{CC}	Supply voltage	Applied between P-N	450	V
$V_{CC(surge)}$	Supply voltage (surge)	Applied between P-N	500	V
V_{CES}	Collector-emitter voltage		600	V
$\pm I_C$	Each IGBT collector current	T_C = 25°C	20	A
$\pm I_{CP}$	Each IGBT collector current (peak)	T_C = 25°C, instantaneous value (pulse)	40	A
P_C	Collector dissipation	T_C = 25°C, per 1 chip	56	W
T_j	Junction temperature	(Note 1)	–20~+150	°C

Note 1 : The maximum junction temperature rating of the power chips integrated within the DIP-IPM is 150°C (@ $T_C \le$ 100°C) however, to ensure safe operation of the DIP-IPM, the average junction temperature should be limited to $T_{j(ave)} \le$ 125°C (@ $T_C \le$ 100°C).

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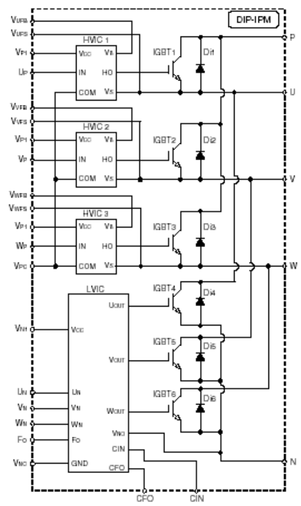
Intelligent Power Module PS21245-E

MITSUBISHI SEMICONDUCTOR <Intelligent Power Module>

PS21245-E

TRANSFER-MOLD TYPE
INSULATED TYPE

Fig. 4 THE DIP-IPM INTERNAL CIRCUIT



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Motor Drivers for Home Appliances

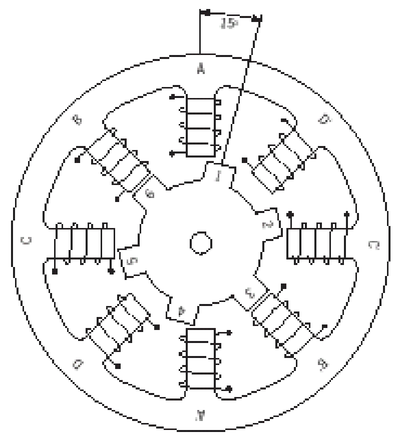
Toshiba Products

Motors are commonly used in home appliances. Traditional AC motors are being replaced by DC motors, which are favorable in terms of control characteristics and efficiencies. Toshiba offers various motor controllers and drivers for brushed DC motors, 3-phase brushless motors, stepper motors and solenoids.
For details, please refer to the *Toshiba Semiconductor System Catalog for Motors and Mechatronics.*

Applications		Part Number	Features
Refrigerators	Cooling fans	TA7262FG	3-phase brushless motor driver; 25 V/1.5 A
		TA8492PG	3-phase brushless motor driver; 25 V/1.5 A; shrink version of TA7262P
		TB6537PG/FG	3-phase PWM sensorless motor controller; 5.5 V/20 mA
		TB6548FG+TA84005FG	3-phase PWM sensorless motor controller/driver; 25 V/1.0 A
		▲TB6575FNG	3-phase PWM sensorless motor controller; 5.5 V/20 mA
	Automatic ice makers	TA7291P/FG/SG	Bridge motor driver; 25 V/2 A (1.2 A)
		TA8409FG/SG	Bridge motor driver; 25 V/1 A
	Switching valves	TA7774PG/FG/FAG	Stepper motor driver; 17 V/0.4 A
Air Conditioners	Indoor fans	TB6520PG+TA8483CP	3-phase sensorless motor controller/driver; 35 V/2.0 A
		TB6539NG/FG	Sine-wave PWM motor controller; 18 V/20 mA
		TB6551FG	Sine-wave PWM motor controller; 12 V/2 mA
		▲TB6556FG	Sine-wave PWM motor controller with an auto lead angle control function; 12 V/2 mA
		▲TB6586FG/AFG	PWM motor controller for 150° commutation; 16.5 V/3 mA
		▲TB6582FG	Sensorless sine-wave PWM motor controller; 16.5 V/2 mA
		☆TB6584FNG	Sine-wave PWM motor controller with an auto lead angle control function; 16.5 V/2 mA
	Outdoor fans	TB6539NG/FG	Sine-wave PWM motor controller; 18 V/20 mA
		TB6551FG	Sine-wave PWM motor controller; 12 V/2 mA
		▲TB6556FG	Sine-wave PWM motor controller with an auto lead angle control function; 12 V/2 mA
		▲TB6581HG	Sine-wave PWM motor driver; 500 V/1.0 A
		▲TB6582FG	Sensorless sine-wave PWM motor controller; 16.5 V/2 mA
		☆TB6584FNG	Sine-wave PWM motor controller with an auto lead angle control function; 16.5 V/2 mA
	Louvers	TA84002FG	2-phase bipolar stepper motor driver; 35 V/1 A
	Filter cleaning – Actuator	▲TB6608FNG	2-phase bipolar microstepping motor driver; 15 V/0.8 A
	Filter cleaning – Fan	▲TB6585FG	Sine-wave PWM motor driver; 45 V/1.8 A
Dishwashers	Pumps	▲TB6575FNG	3-phase PWM sensorless motor controller; 5.5 V/20 mA
Washing Machines	Drying fans	▲TB6575FNG	3-phase PWM sensorless motor controller; 5.5 V/20 mA
		▲TB6588FG	3-phase PWM sensorless motor driver; 50 V/2.5 A
Ventilators	Fan	▲TB6585FG	Sine-wave PWM motor driver; 45 V/1.8 A

Variable reluctance stepping motor vs. Switched reluctance motor

- **Variable reluctance stepping motor**



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SRM Governing Equations

- By neglecting the mutual coupling and assuming the linear magnetic circuit, the per-phase winding voltage equation of a SRM can be written as:

$$v = Ri + L(\theta_r, i)\frac{di}{dt} + \frac{\partial \lambda(\theta_r, i)}{\partial \theta_r}\omega_r = Ri + L(\theta_r, i)\frac{di}{dt} + e(\theta_r, i, \omega_r)$$

- The composite generating torque of a SRM drive can be obtained by summing all per-phase developed torques, and then the motor drive torque equation is:

$$T_e = \sum_{i=1}^{n} T_{ei} = T_L + B\omega_r + J\frac{d\omega_r}{dt}, \quad T_{ei} = \frac{1}{2}\frac{\partial L(\theta_r, i_i)}{\partial \theta_r} i_i^2$$

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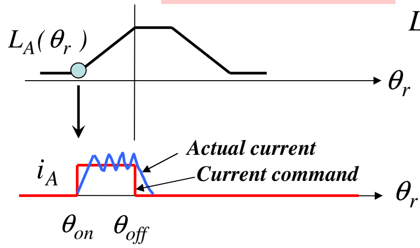
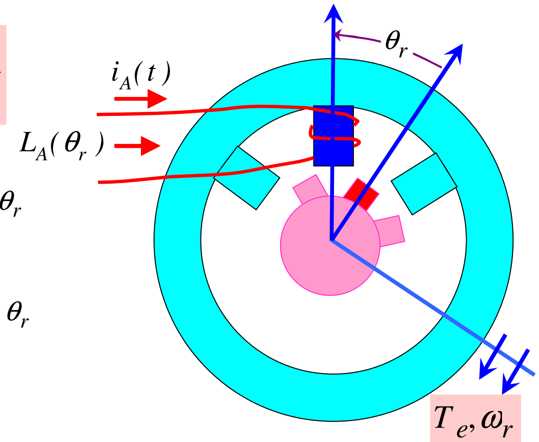
Variable reluctance stepping motor vs. Switched reluctance motor

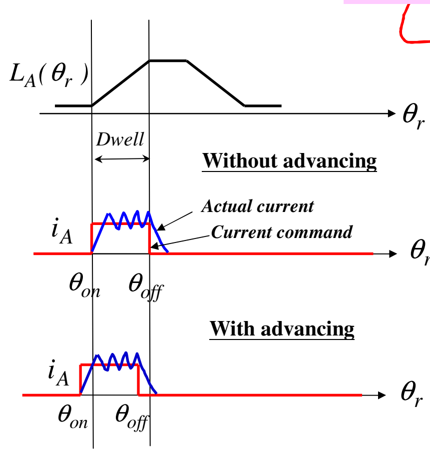
$$T_A = \frac{1}{2} i_A^2 \frac{\partial L_A(\theta_r)}{\partial \theta_r}$$

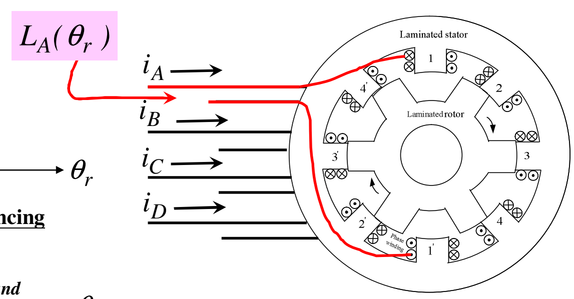


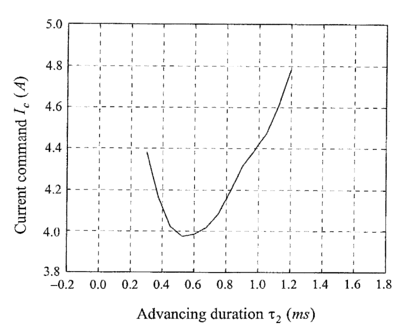


- **Switched reluctance motor:**
  - **The winding excitation is applied according to the sensed rotor position.**
  - **Absolute rotor position sensing is required.**

Commutation Instant Tuning



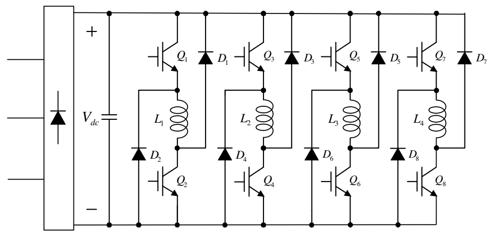




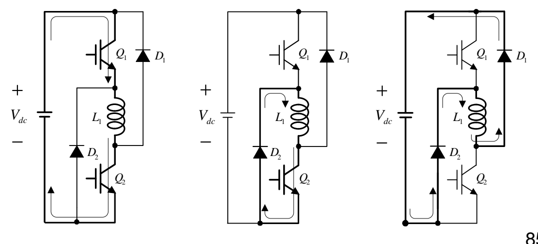
$$T = \frac{1}{2} i_s^2 \frac{\partial L_{ss}}{\partial \theta}$$

Typical converter circuit

- Classical bridge converter circuit



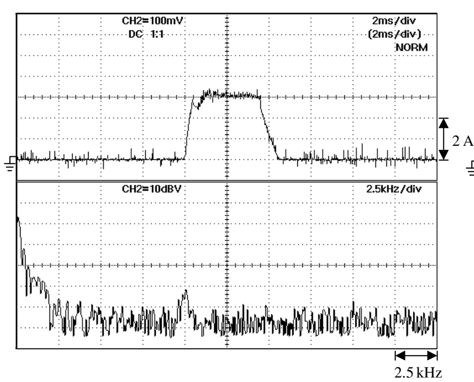
- Operation modes



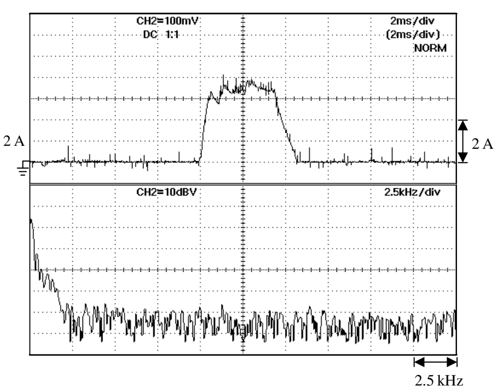
PWM switching with varying frequency

- **Linearly varying switching frequency**

Fixed switching frequency

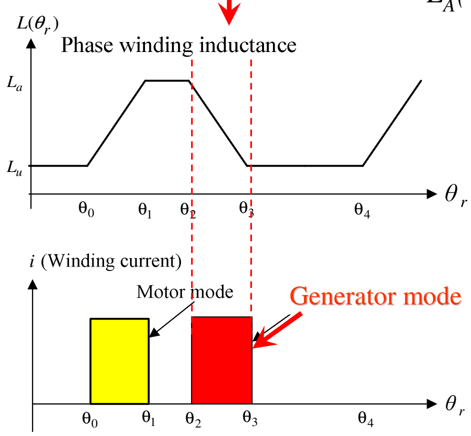


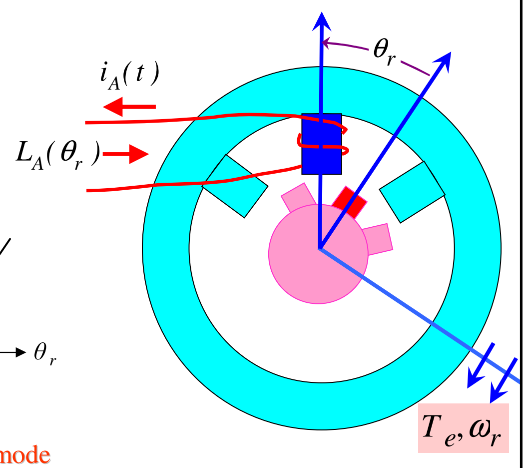
Varying switching frequency



Switched reluctance generator

$$T_A = \frac{1}{2} i_A^2 \frac{\partial L_A(\theta_r)}{\partial \theta_r}$$

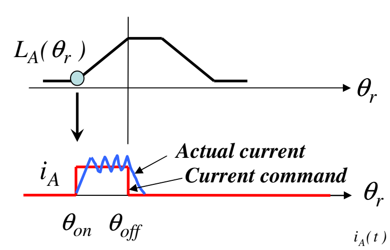


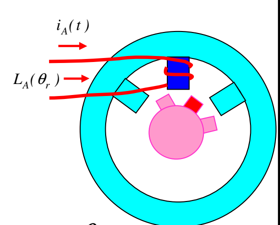


Motoring and generating mode of a switched-reluctance machine

- **Motoring**

$$T_A = \frac{1}{2} i_A^2 \frac{\partial L_A(\theta_r)}{\partial \theta_r} = positive$$





- **Generating**

$$T_A = \frac{1}{2} i_A^2 \frac{\partial L_A(\theta_r)}{\partial \theta_r} = negative$$