

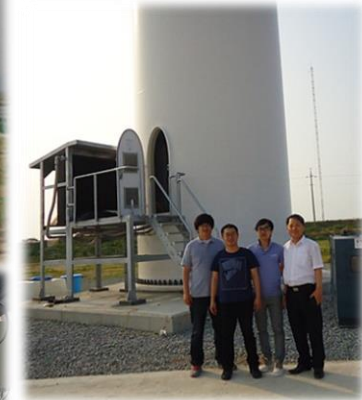
Electric Vehicle Motors for Traction

2015. 5. 29

산업통상자원부, 한국에너지기술평가원 지정 '분산형전원용
스마트 전기기기시스템 설계 및 성능평가 시스템 고급트랙 센터

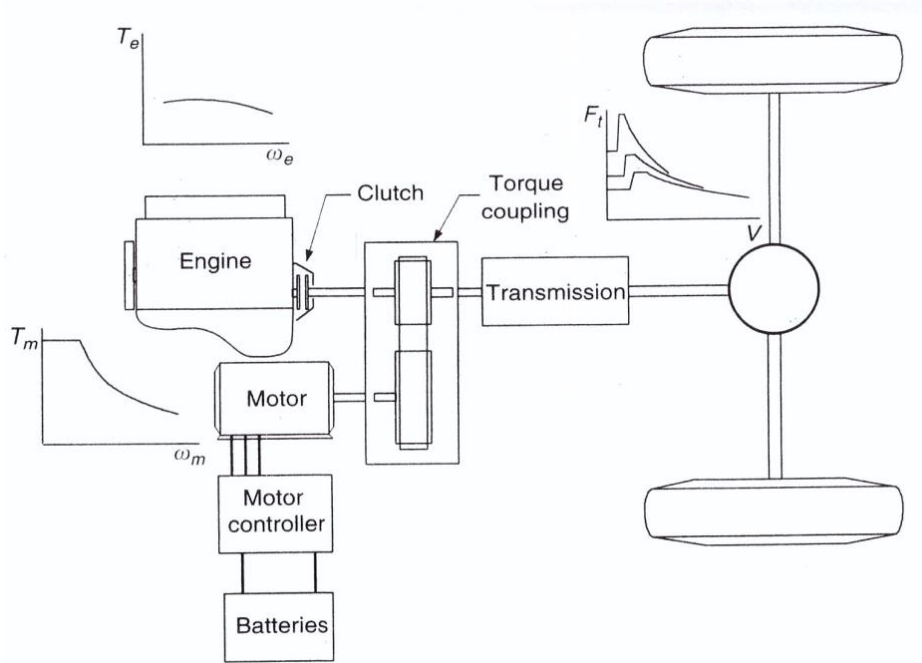
주식회사 셈스하이테크 엔지니어링

장 석 명

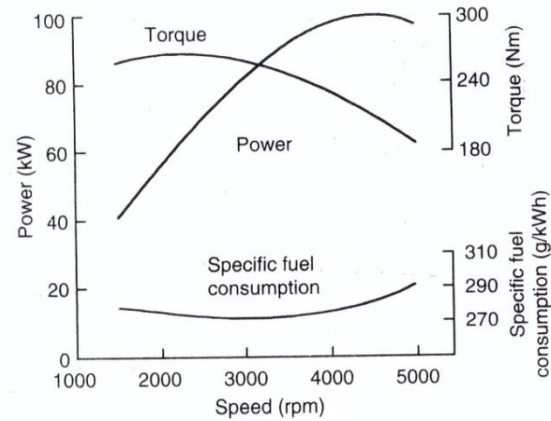


Electric Vehicle Motors for Traction

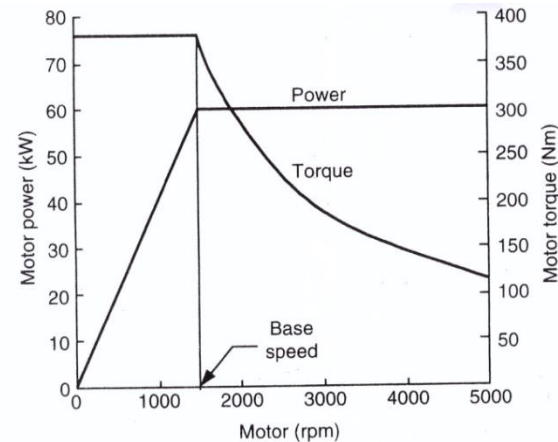
Engine - Electric motor for Tractive Effort



**Torque-Coupling Parallel Hybrid Electric Drive Train
-Two-Shaft Configuration**

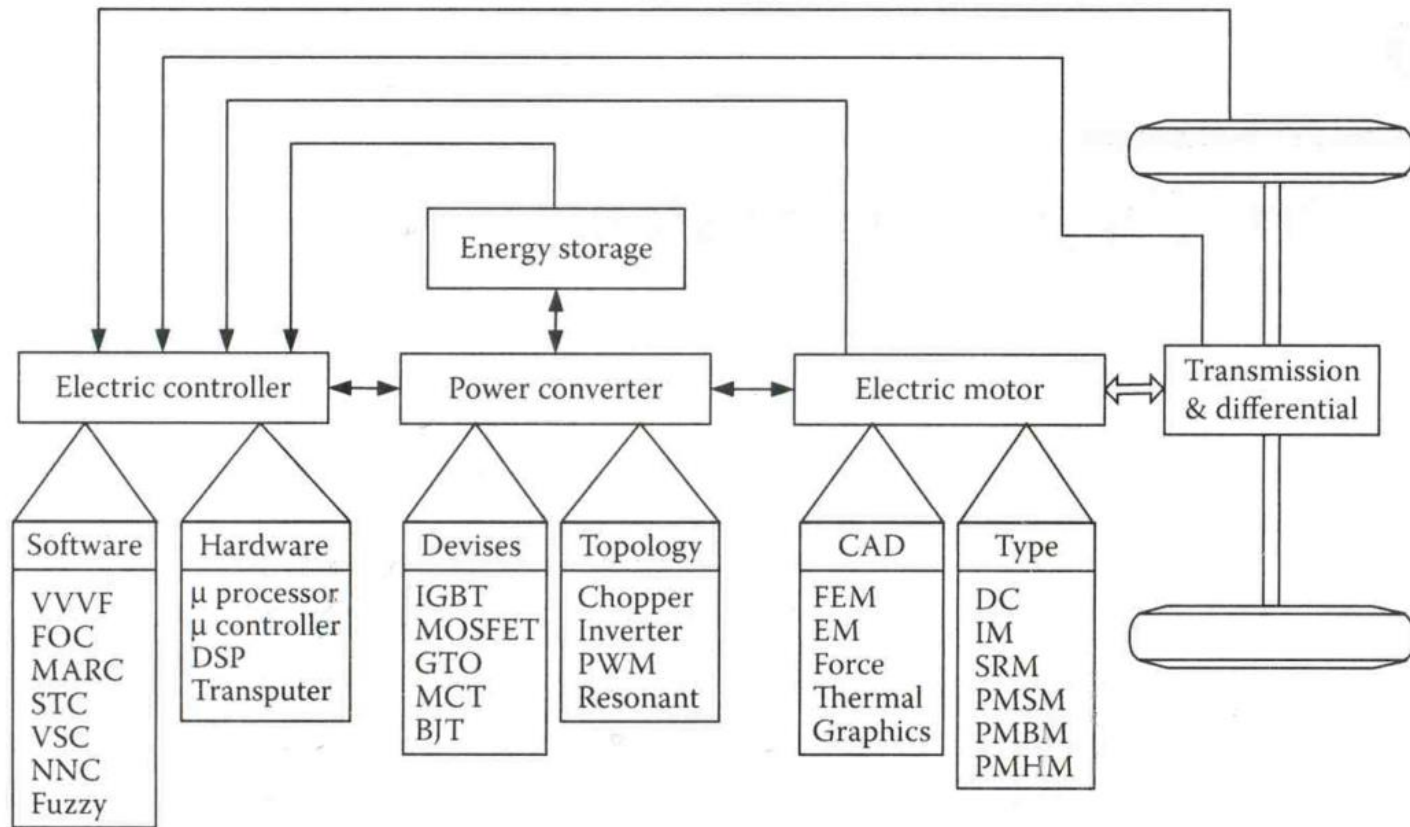


Typical Performance Characteristics of Gasoline Engine



Typical Performance Characteristics of Electric Motors for Traction

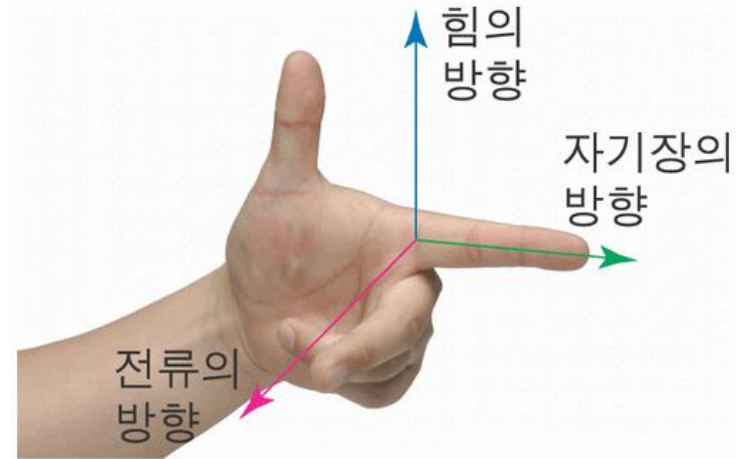
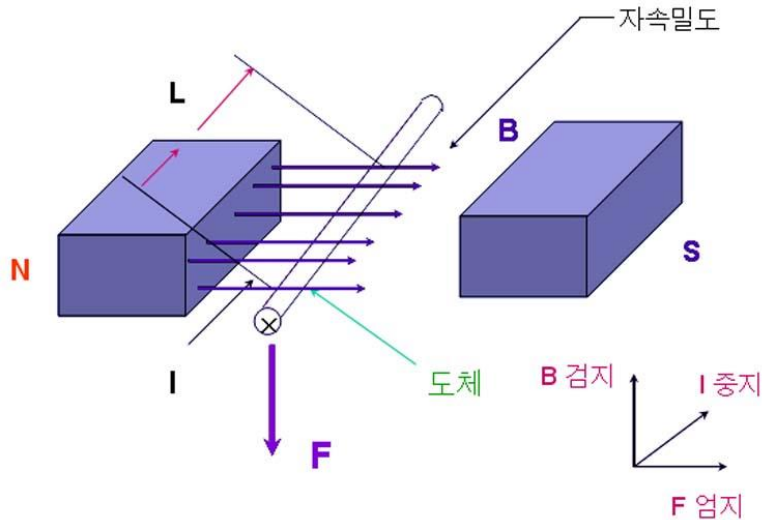
EV Propulsion Systems & Electric motor family tree



Functional block diagram of a typical electric propulsion system

Fleming left hand rule- Motor

플레밍의 왼손법칙(전동기의 원리)



$$F_{[N]} = B_{(T)} \cdot I_{(A)} \cdot L_{(m)}$$

- F : 회 전 력 N
- I : 전 류 . A
- B : 자 속 밀 도 T. Wb / m^2
- L : 유효도체 길이. m

왼손법칙은 오른쪽손의 법칙과 반대되는 개념으로 전선에 전류를 흐르게 하면 도체에 힘(토크)이 발생하며 이것이 모터의 운동에너지가 된다.

Brushed Motor : Torque-Speed 특성 (V_s, Φ 가변제어)

$$T = \frac{K_m \Phi E_s}{R_a} - \frac{(K_m \Phi)^2}{R_a} \omega \quad E_s : \text{Supply Voltage}$$

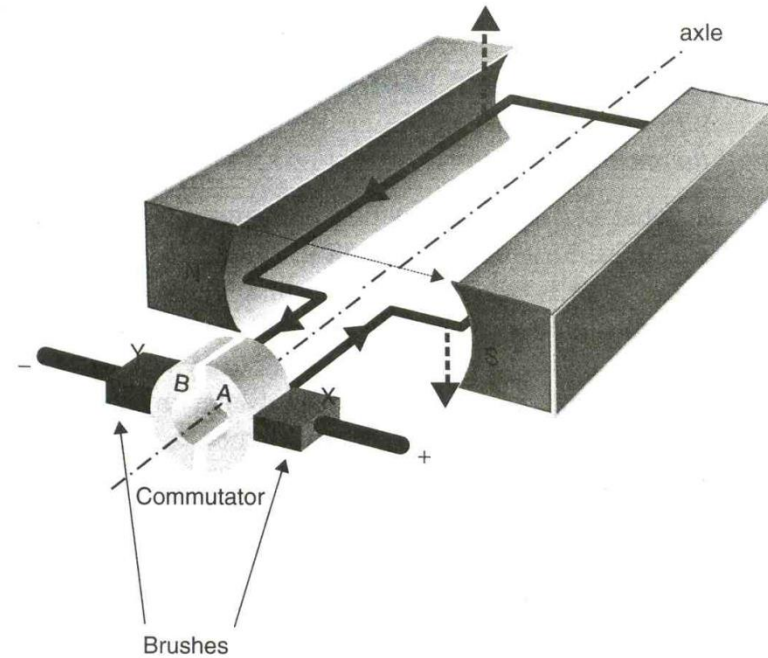
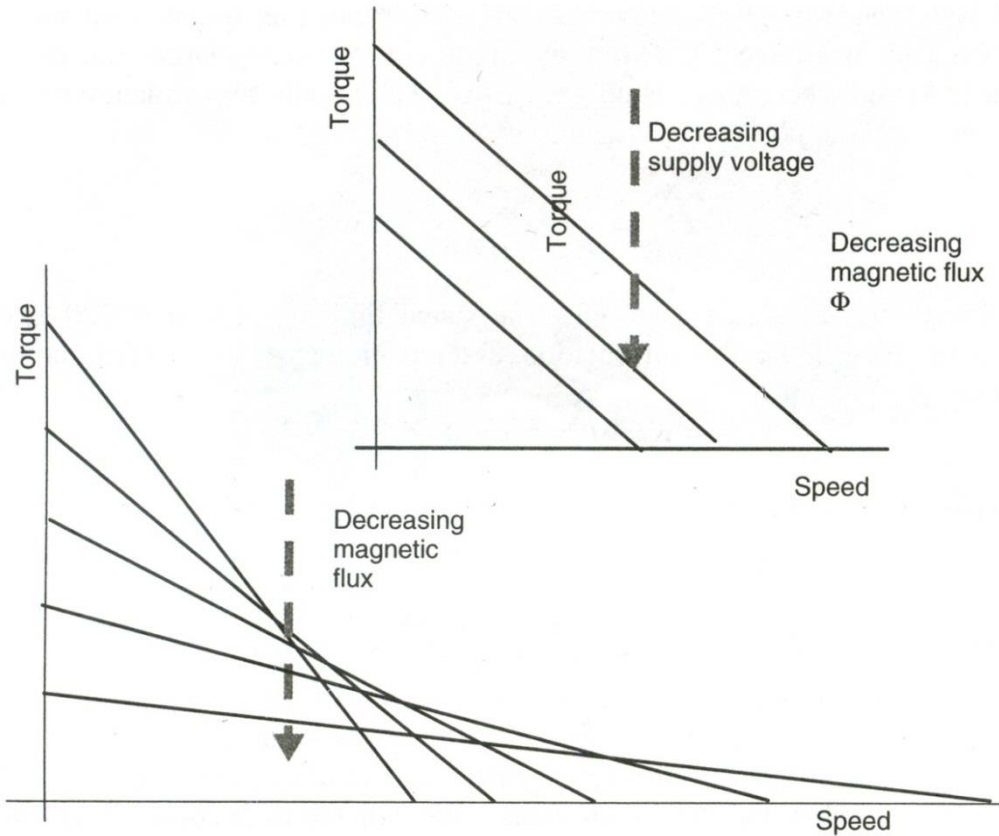
Brushless Motor : Torque-Speed 특성

$$\omega_r(s) = \frac{K_T}{(R_s + sL_s)(sJ + B) + K_T K_E} V_t(s) - \frac{R_s + sL_s}{(R_s + sL_s)(sJ + B) + K_T K_E} T_L(s)$$

How changing the supply voltage and the magnetic field strength affects the torque speed characteristic of the DC motor

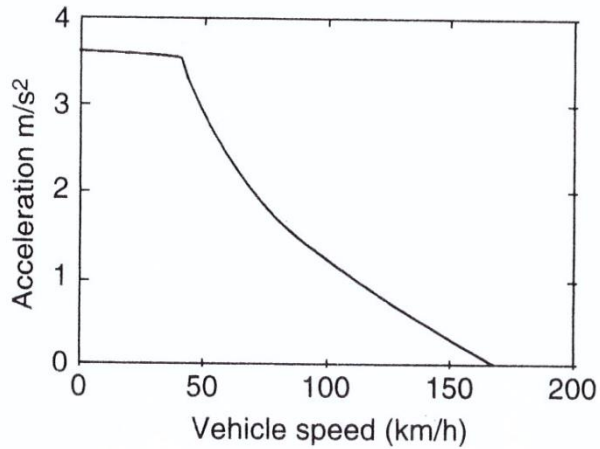
출처; Electric vehicle technology'Wiely 2003.

DC motor의 Torque-speed 특성

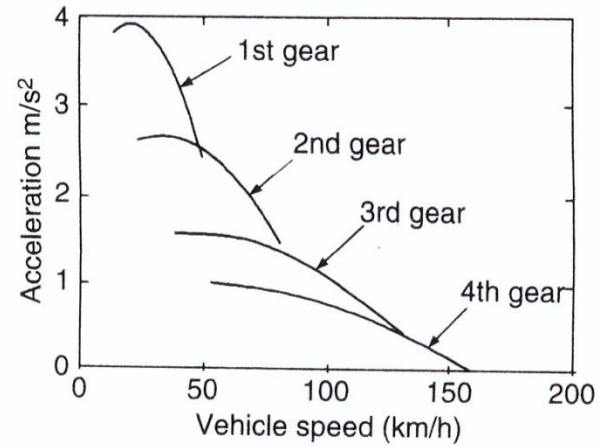


How changing the supply voltage and the magnetic field strength affects the torque speed characteristic of the DC motor

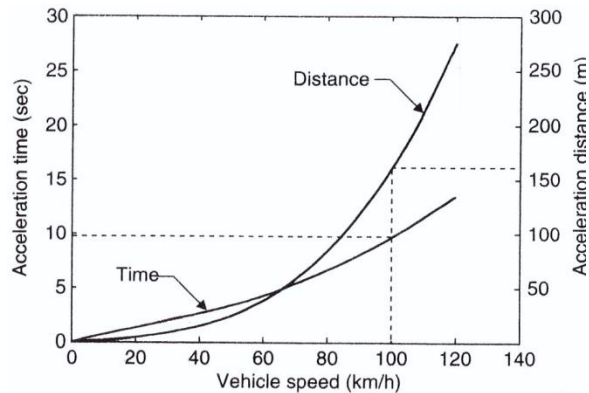
출처; Electric vehicle technology'Wiely 2003.



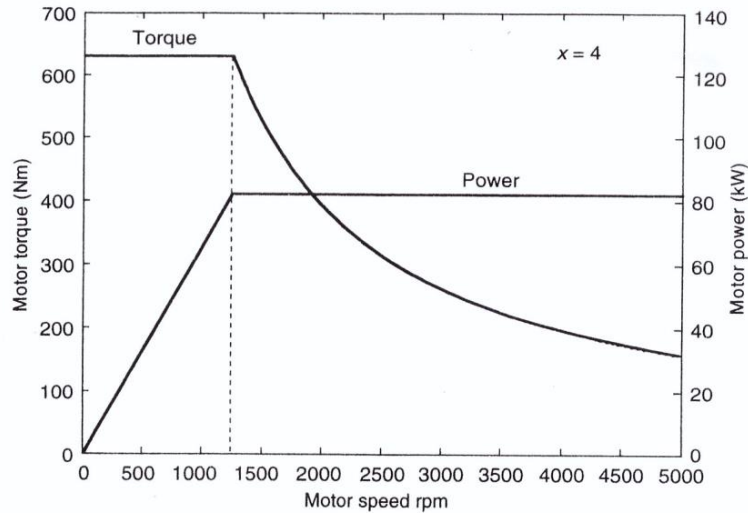
Acceleration of an Electric Machine-powered Vehicle with Single-gear Transmission



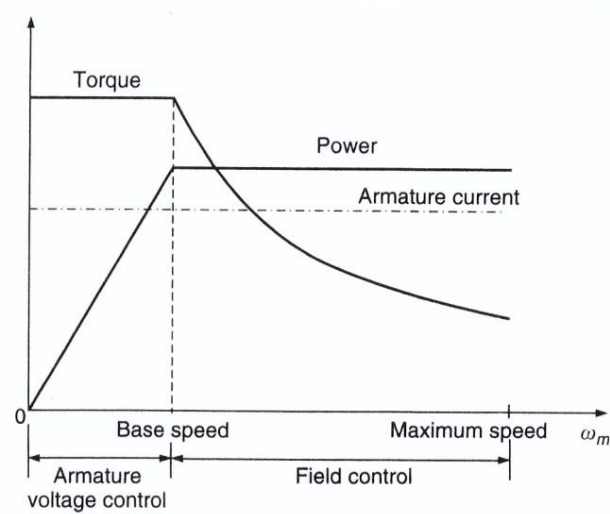
Acceleration of a Gasoline Engine-Powered Vehicle with Four-gear Transmission



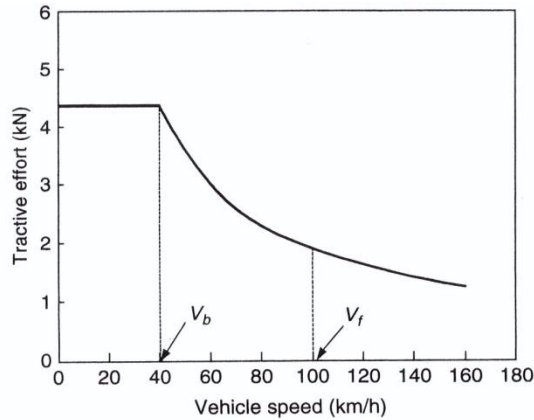
Accelerating Time and Distance vs. Vehicle Speed



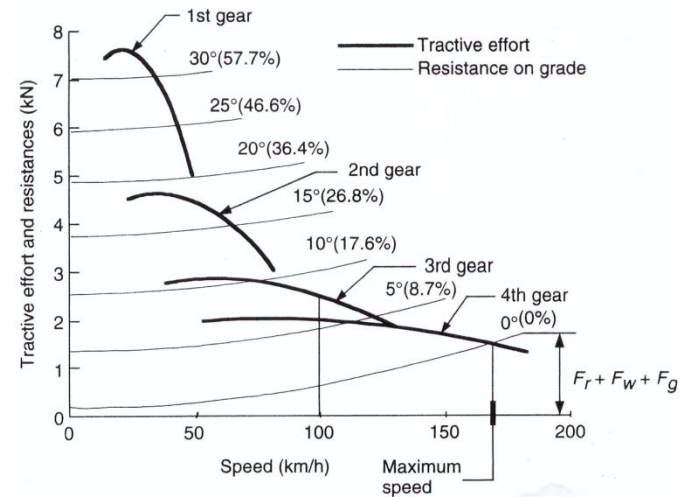
Characteristics of Traction Motor vs. Motor rpm and Vehicle Speed



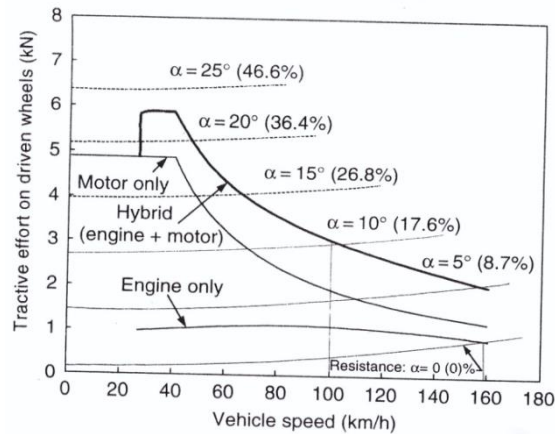
Torque and Power Limitations in Combined Armature Voltage and Field Control



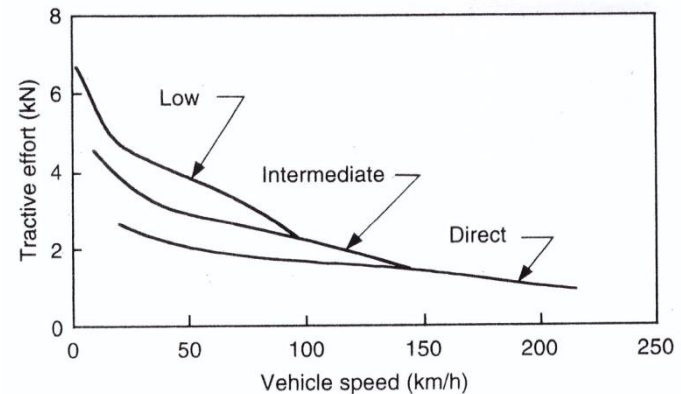
Acceleration of an Electric Machine-Powered Vehicle with Single-gear Transmission



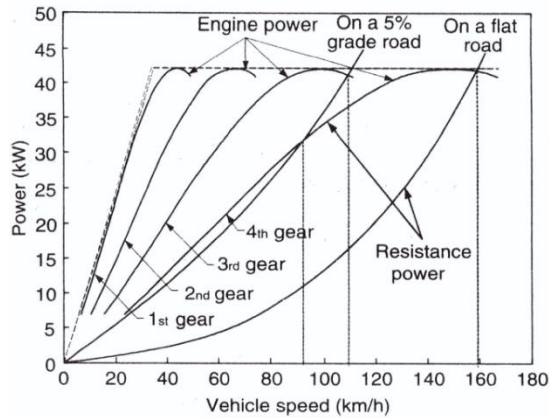
Tractive Effort of a Gasoline Engine-Powered Vehicle with Multispeed Transmission and its Resistance



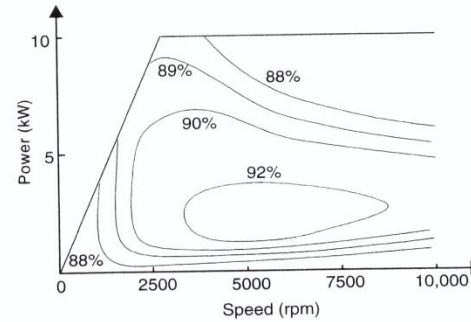
Tractive Effort and Resistance on Slope road vs. Vehicle Speed



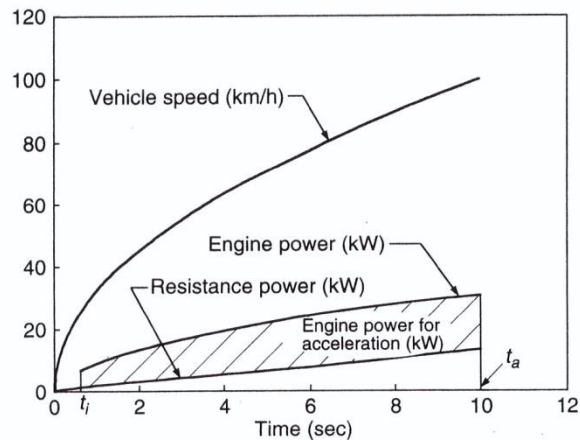
Tractive Effort –speed Characteristics of a Passenger Car with Automatic Transmission



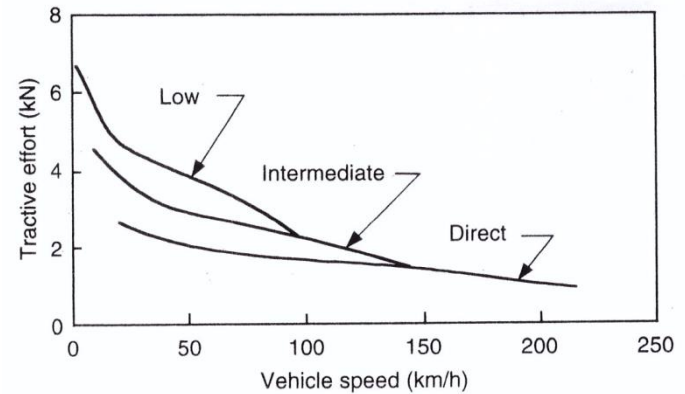
Engine Power Required at Constant Speed on a Flat Road and a 5% Grade Road



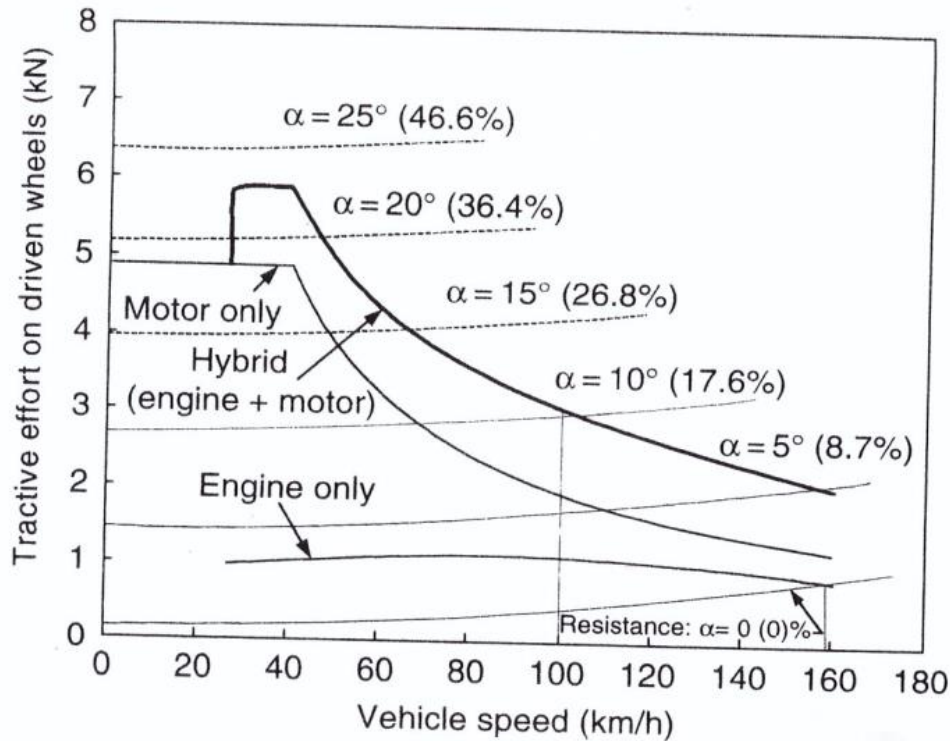
Optimal Efficiency Profiles of a PM Hybrid Motor Drives



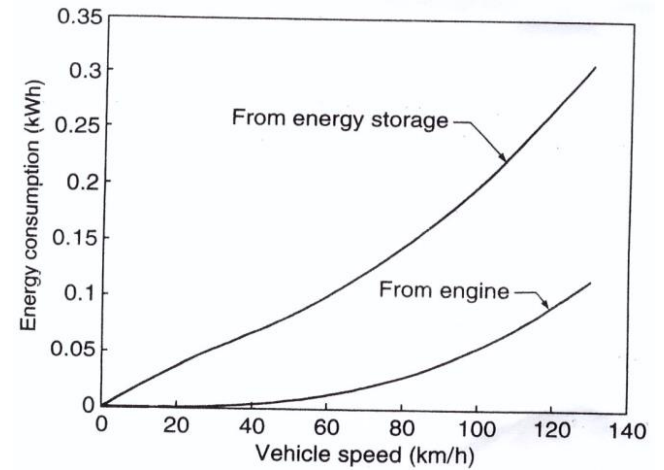
Vehicle Speed , Engine Power , and Resistance Power vs. Acceleration Time



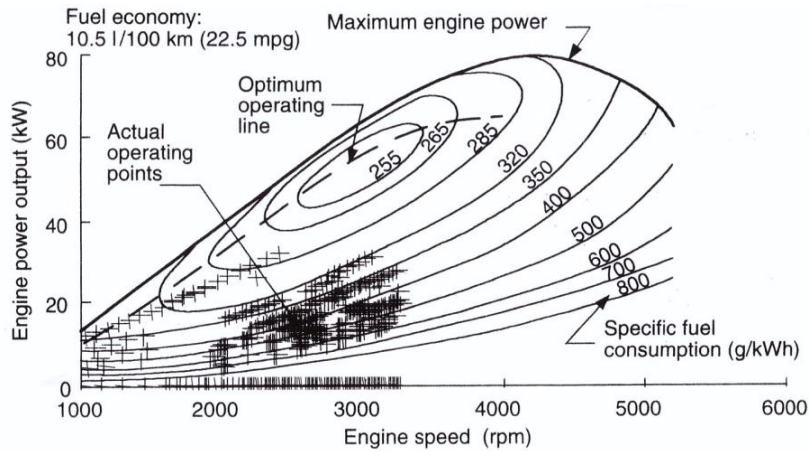
Tractive Effort –speed Characteristics of a Passenger Car with Automatic Transmission



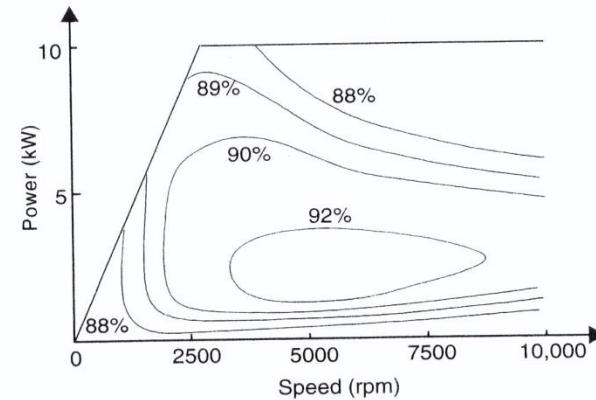
Tractive Effort and Resistance on Slope road vs. Vehicle Speed



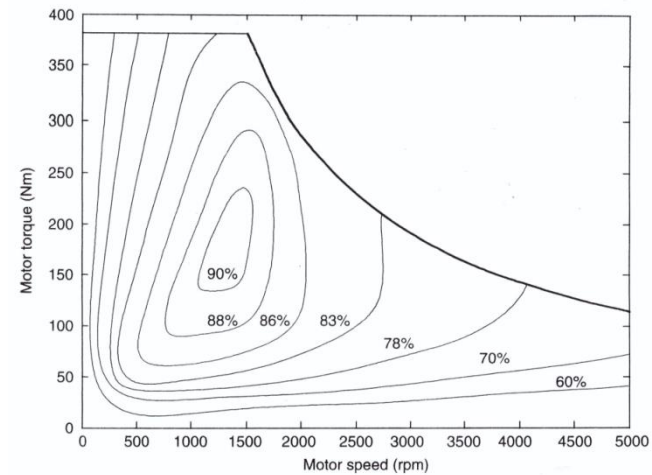
Energies Drawn from the Energy Storage and Engine in the Acceleration Period



Fuel Economy and Engine Operating Points in EPA FTP75 Highway Drive Cycle Overlapped on Engine Fuel Consumption Characteristics Map



Optimal Efficiency Profiles of a PM Hybrid Motor Drives

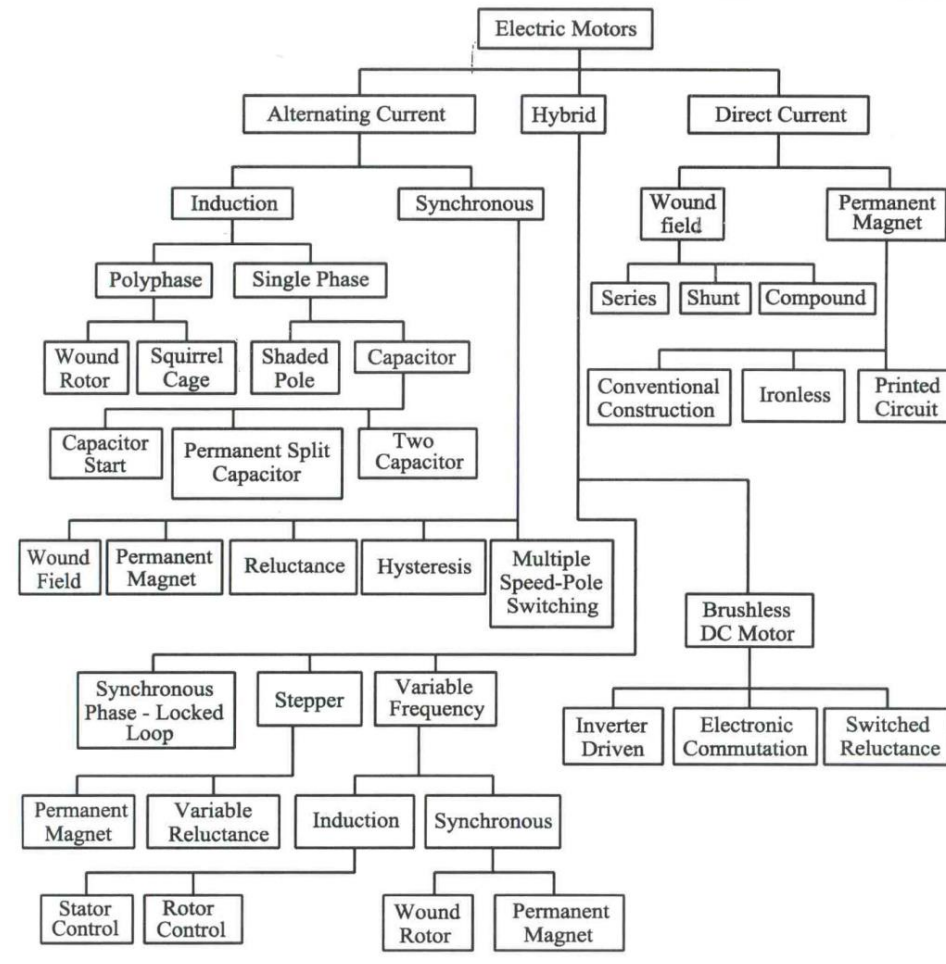


Typical Electric Motor Efficiency Characteristics

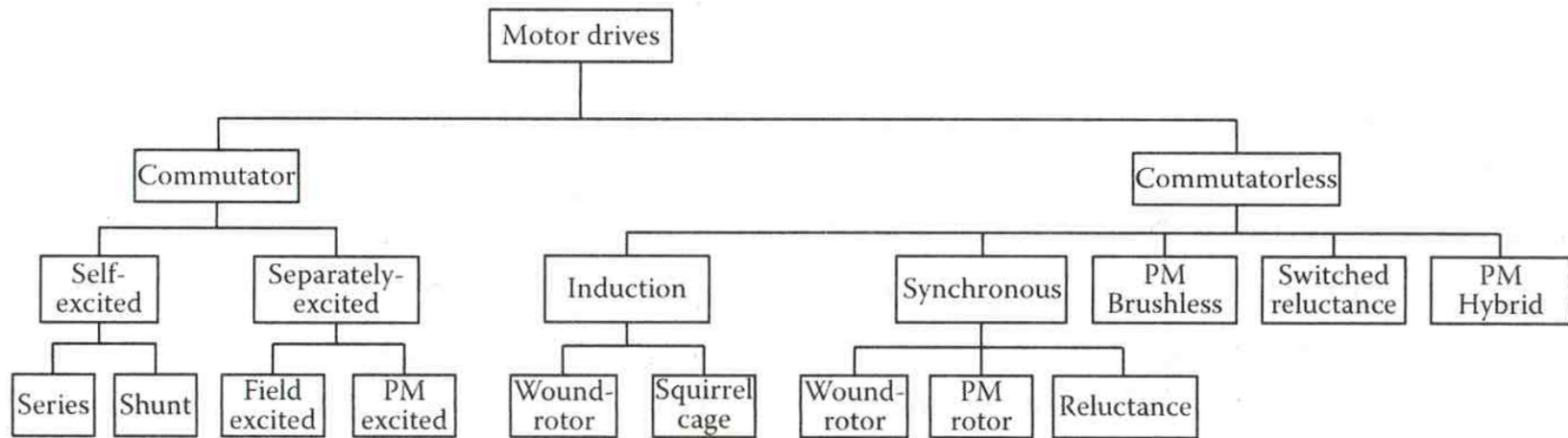
Electric motor family tree

- Robert C. Perrine, SR. "Design Handbook for Motors and Tachometer" Magna Physics Publishing Div. of Motorsoft, Inc. 2000
- After Sidney Davis, "Wide World of Electric Motor/Subsystems," Design Engineering, May 1982, p.51

Electric motor family tree



Electric motor family tree



Classification of electric motor drives for EV and HEV applications

Evaluation of four types of motor drives for EVs

	DC motor	IM	BLDC motor	SRM
Efficiency	2	4	5	4.5
Weight	2	4	4.5	5
Cost	5	4	3	4
Total	9	12	12.5	13.5

각각 5점 만점으로 가장 높은 효율, 낮은 중량, 최저 비용을 나타냄
즉,

- DC 전동기는 저가격으로 EV용으로 계속 사용가능
- BLDC 전동기는 효율성에서 가장 우수
- SRM의 무게가 가장 작음

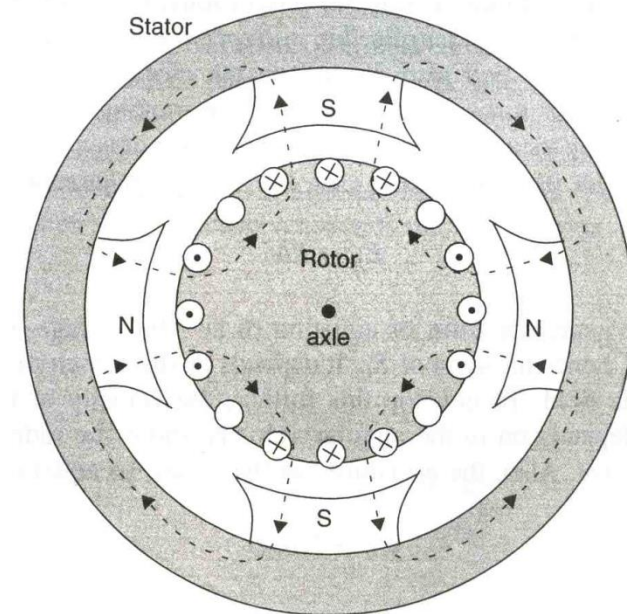
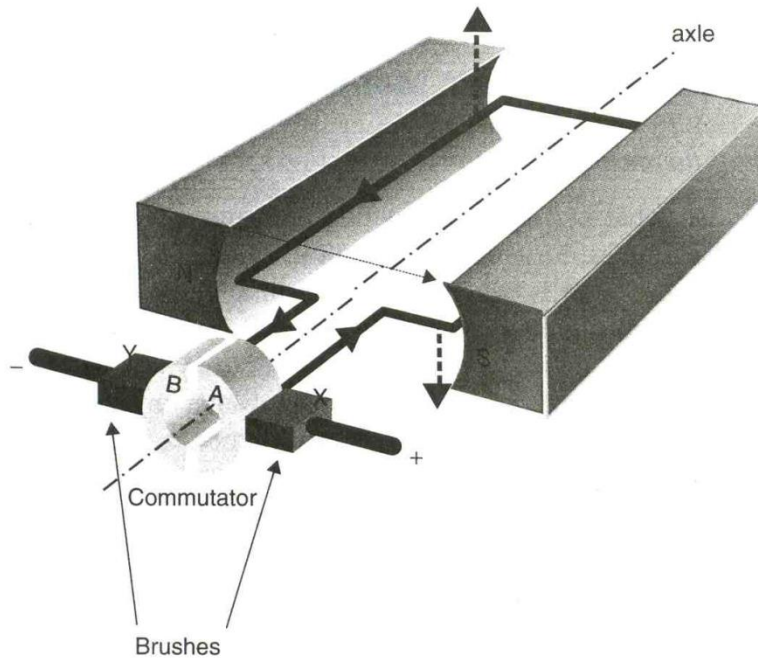
세가지 조건을 모두 합한 결과 EV용으로는 SRM이 가장 적절함.

SRM은 냉각과 최대속도, 耐久고장성과 신뢰성 면에서도 다른 전동기와 비교하여 우위에 있다

자료 : 'Selection of Electric Motor Drives for Electric Vehicles'
2008 Australasian Universities Power Engineering Conference (AUPEC'08)

Brushed DC Electric motor

Brushed DC Motor Drives

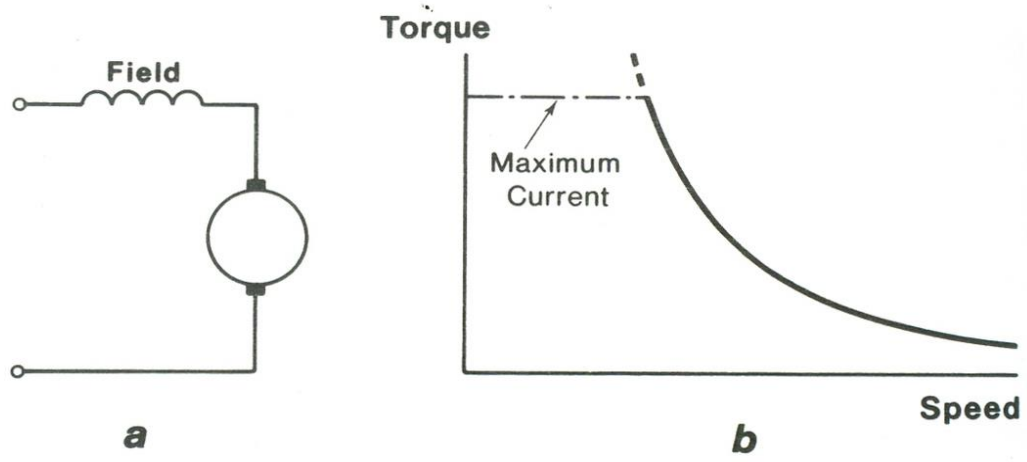


(a)
⊕ Current going down into page
⊙ Current coming up out of page
∅ No current
(b)

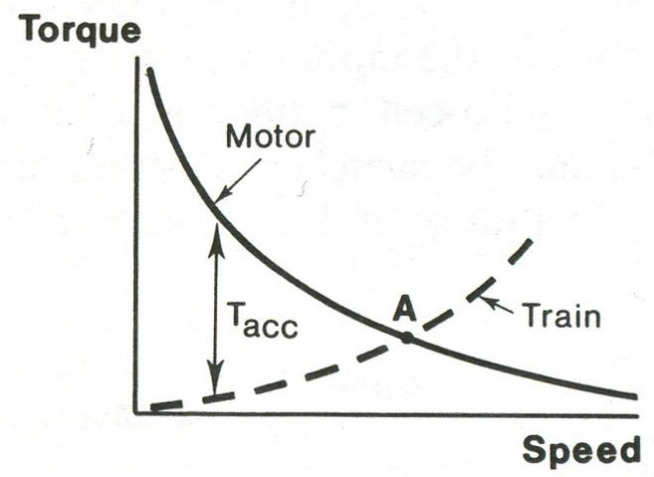
Diagram to explain the operation of the simple permanent magnet DC motor

Cross-section through a four-pole DC motor

Series connected DC motor –torque-speed 특성

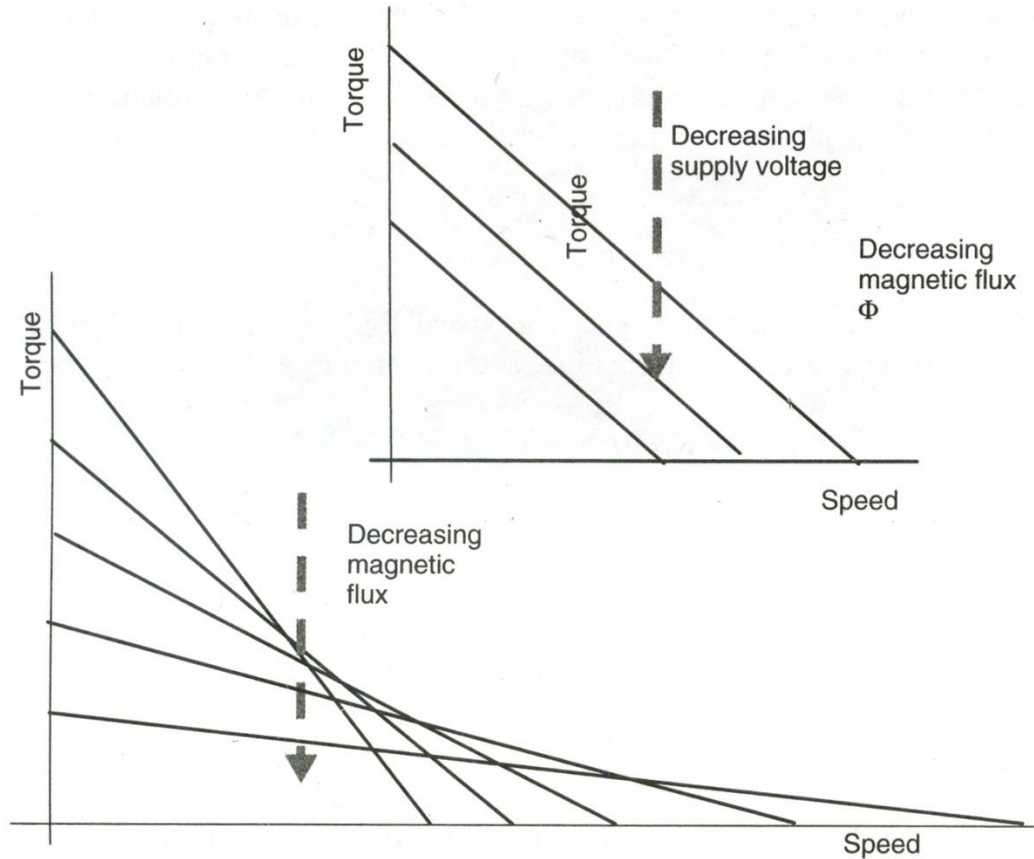


Series-connected DC motor and steady-state torque-speed curve



Torque-speed curve illustrating the application of a series-connected DC motor to traction

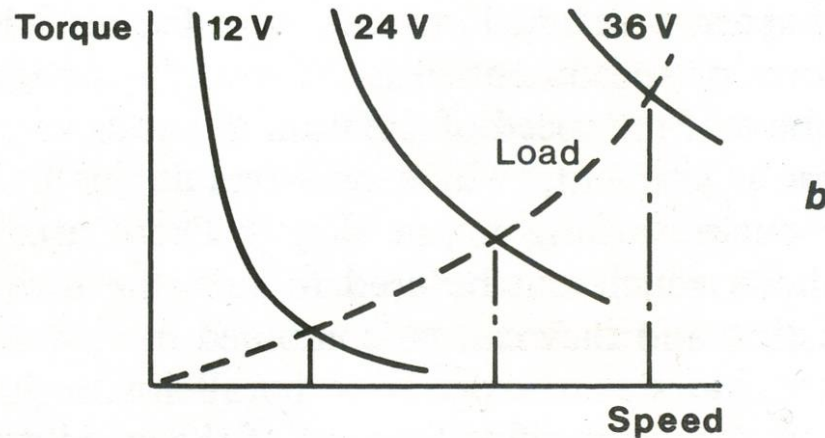
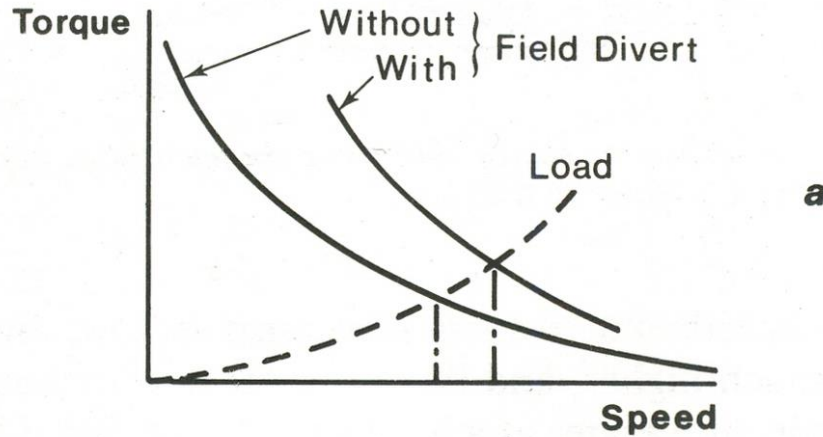
DC motor의 Torque-speed 특성



How changing the supply voltage and the magnetic field strength affects the torque speed characteristic of the DC motor

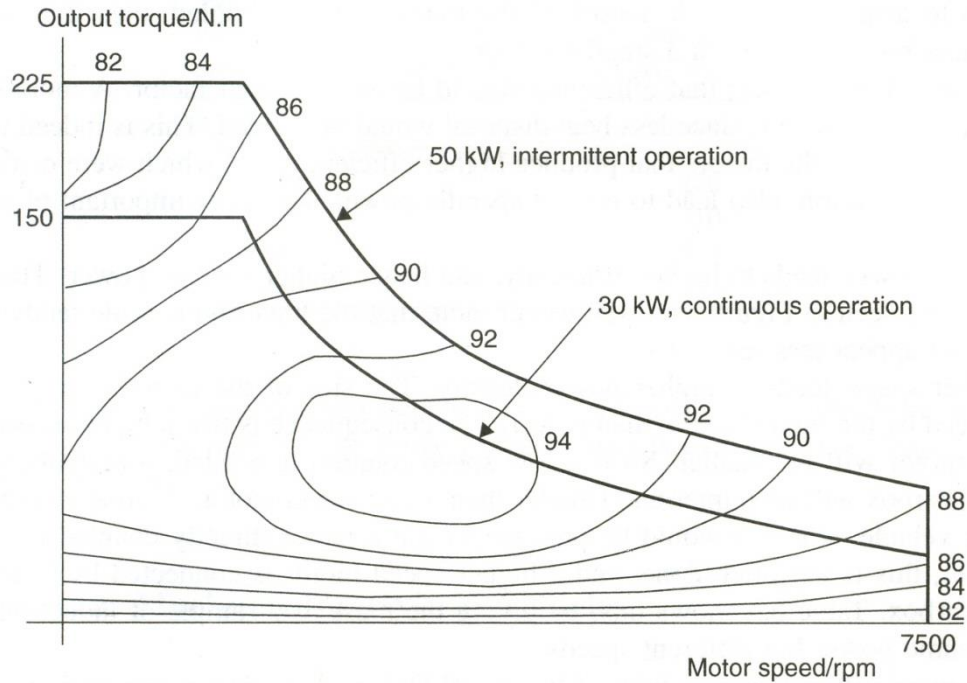
출처; Electric vehicle technology'Wiely 2003.

DC motor의 Torque-speed 특성



Series motor characteristics with (a) field divert control and (b) series/parallel switching

Efficiency map for BLDC Motor

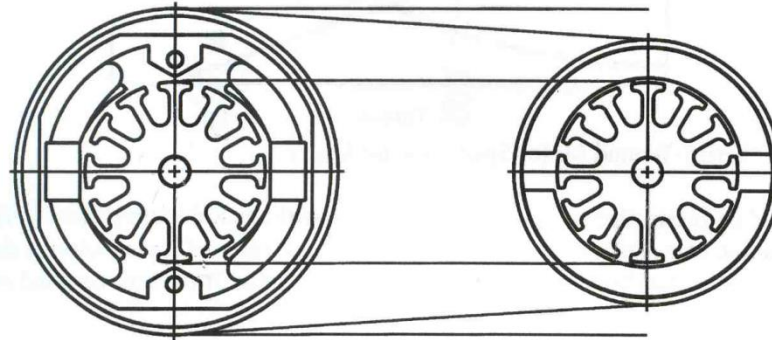


The efficiency map for 30kW BLDC motor. This is taken from manufacturer's data, but note that in fact at zero speed the efficiency must be 0%
Maximum efficiency 94%

출처; [Electric vehicle technology'Wiely 2003.](#)

PM Brushed DC Electric motor

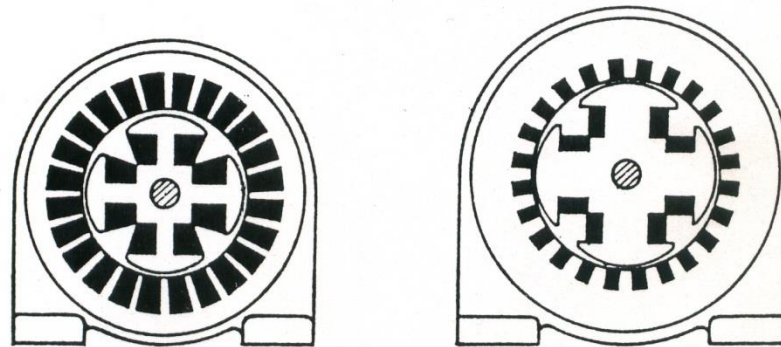
Evaluation of four types of motor drives for EVs



(a) Wound Field Motor

(b) Permanent Magnet Motor

Motor cross-sections



(a)

(b)

동기계와 철기계

A New Approach was Needed

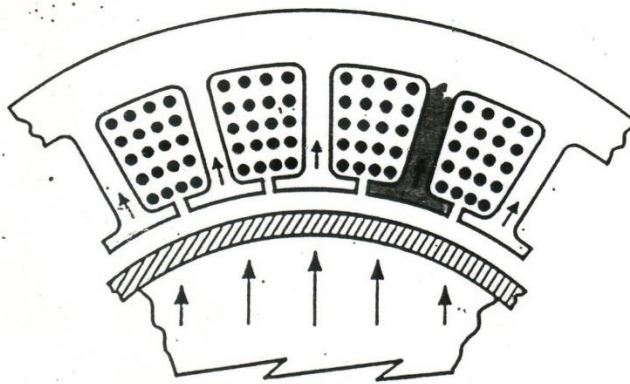
HIGHER ENERGY DENSITY

→ INCREASED FLUX

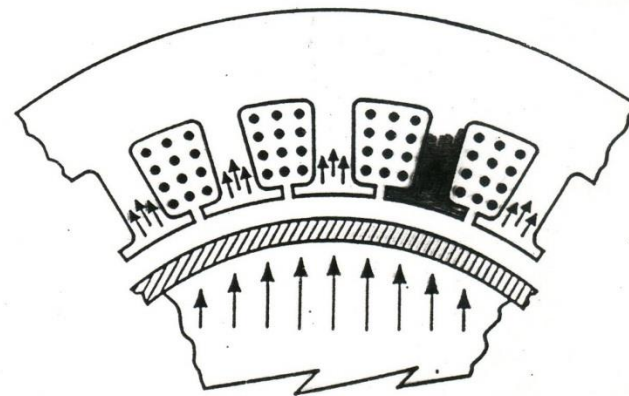
→ WIDER TEETH

→ LESS SLOT AREA

→ PERFORMANCE PLATEAU



**LOW-ENERGY
MAGNET**



**HIGH-ENERGY
MAGNET**

B-15839

Permanent Magnet Brushless DC motor Drives

Electric Machine 출력

$$P = \left(\frac{p}{a} \phi Z n \right) (I_a) \times 10^{-3} \text{ [kW]}$$

$$= \pi^2 \quad ac \quad B_{av} \quad D^2 L \quad n$$

Electric loading

Magnetic loading

Volume loading

Speed loading

초전도/copper

초강력 PM, 자성체

체적 대형화

초고속화

①

②

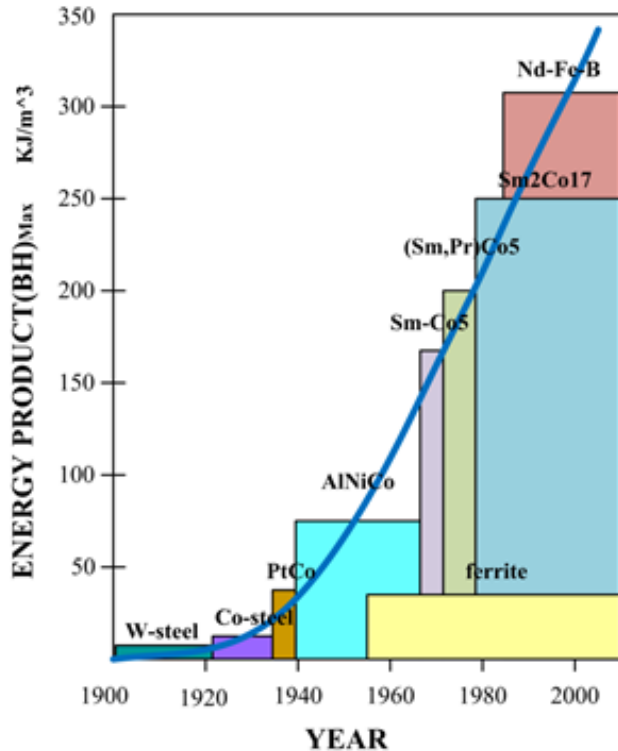
③

④

항목	전동기 고출력화 4가지 방안	전동기 타입
1	ampere, conductor를 크게 하는 방법	초전도 기기 Electric loading
2	자속밀도를 크게 하는 방법	강한 자석 기기 Magnetic loading
3	부피를 크게 하는 방법	초대형 자성체 기기 Volume loading
4	속도를 크게 하는 방법	초고속 기기 (컴팩트화)

1.3 영구자석 EXCITER-LESS 발전기

(1) ENERGY PRODUCT - 전기기기 COMPAACT/ LIGHTWEIHT



Magnet Volume: $V_m [m^3]$
 Energy Product: $[B_m H_m] [kJ/m^3]$

$$V_m = A_m l_m = \left(\frac{B_g l_g}{B_m}\right) \left(\frac{-H_g l_g}{H_m}\right) = \frac{B_g^2 V_g}{\mu_o [B_m H_m]} [m^3]$$

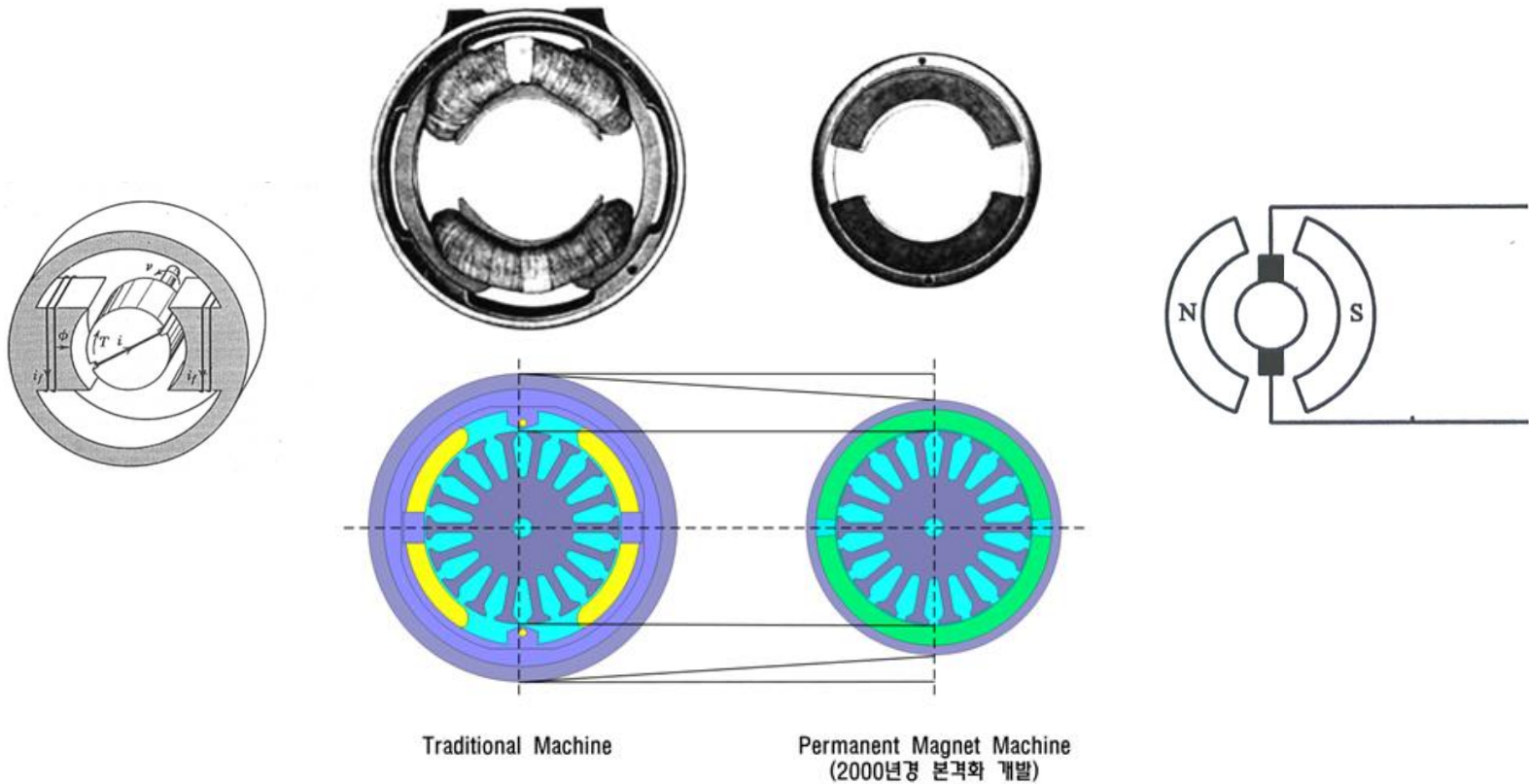
Energy Product 가 클 수록
 Compact, Lightweight

출처 : KISTI 기술정보분석보고서, "Nd-Fe-B계 영구자석의 개발 동향", 2003
 J. R. Hendershot JR and THE MILLER, "Design of Brushless Permanent Magnet Motors", 1994

Energy Product가 W-steel 은 5인데 비해
 NdFeB 는 320 이므로 자성체의 부피가 1/64로 감소
 영구자석 재질별 에너지 밀도

1.3 영구자석 EXCITER-LESS 발전기

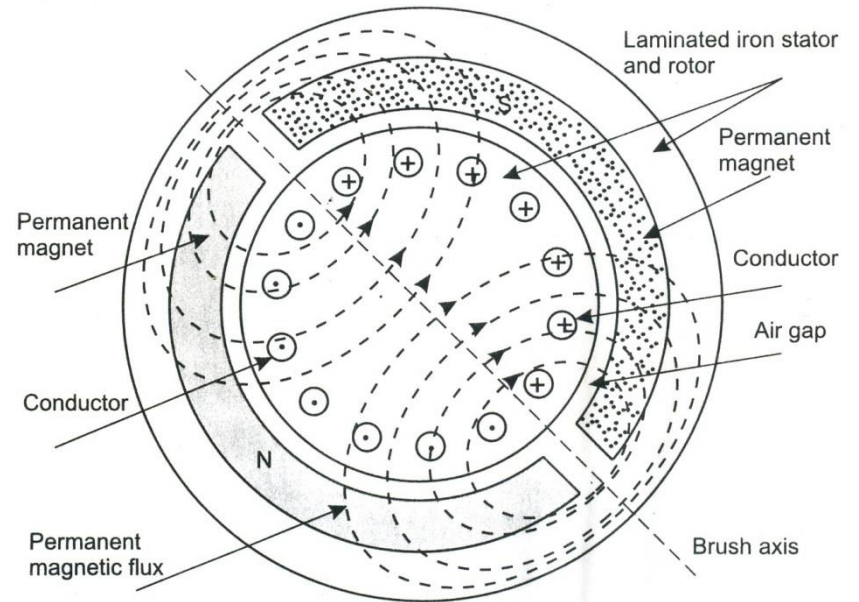
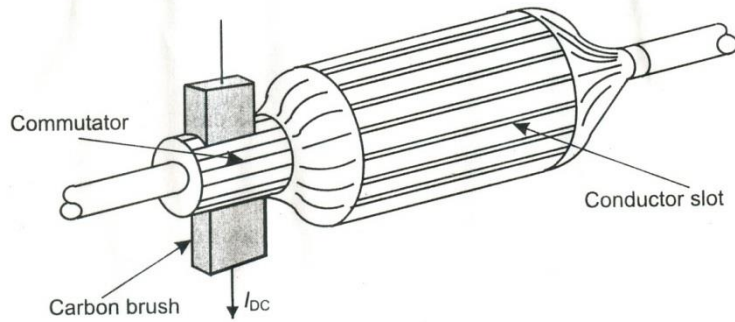
(1) ENERGY PRODUCT - 전기기기 COMPAACT/ LIGHTWEIHT



- Rf 1; I M.Gottlieb'Electric Motors & Control Techniques using electronics to increase motor efficiency and to conserve energy' Tab Books Inc.1982
- Rf 2: R C.Perrine, SR'Design Handbook for PM Motors and Tachometers 'Magna Physics Pub. Div.of Motorsoft, 1994

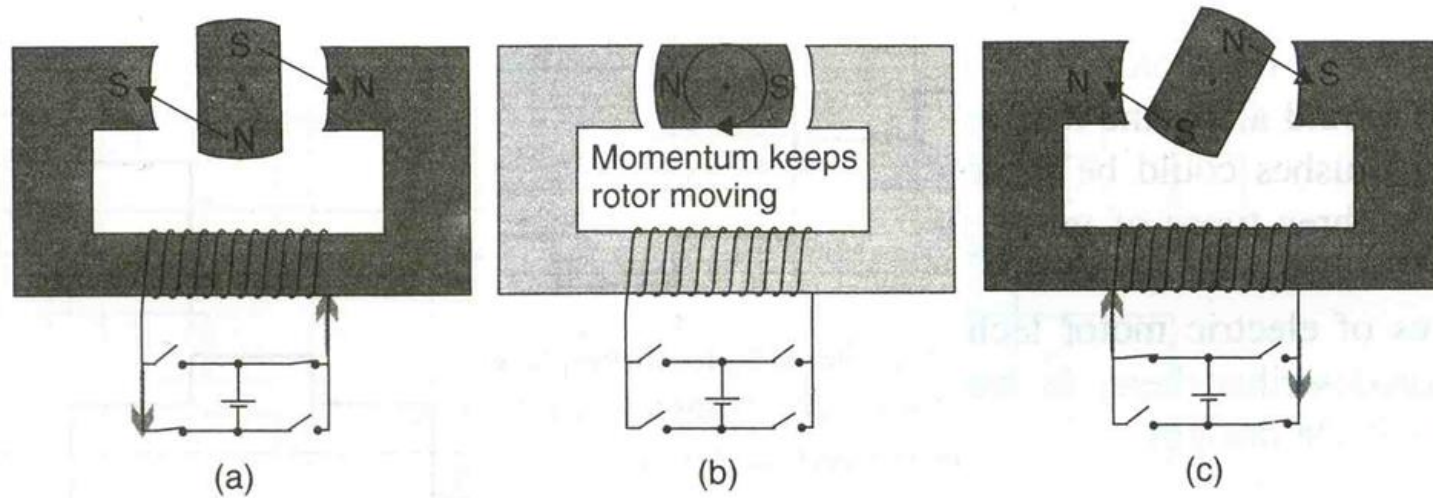
기존의 권선형 기기와 영구자석형 기기의 크기 비교

PM DC Motor

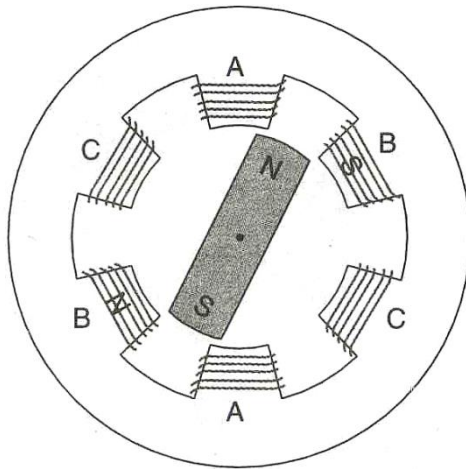


Cross-section and rotor of a two-pole, permanent magnet DC motor

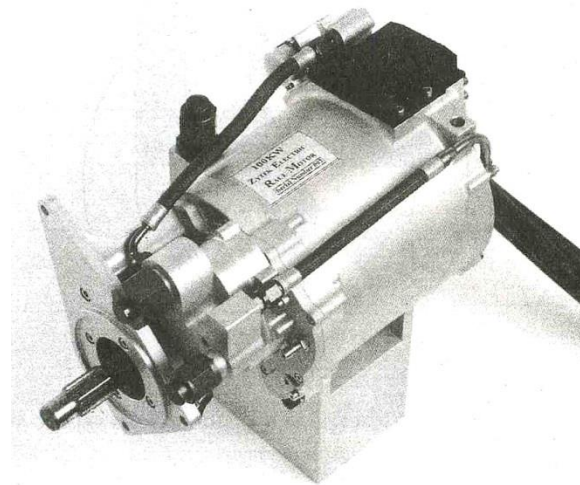
PM BLDC motor drives



The basis of operation of the brushless DC motor

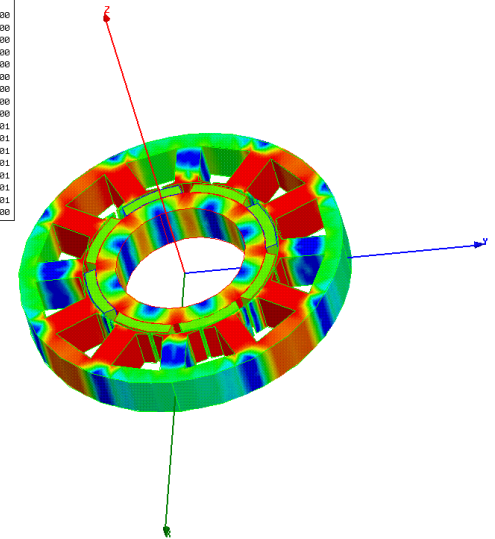
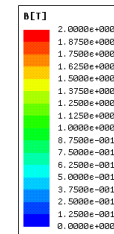
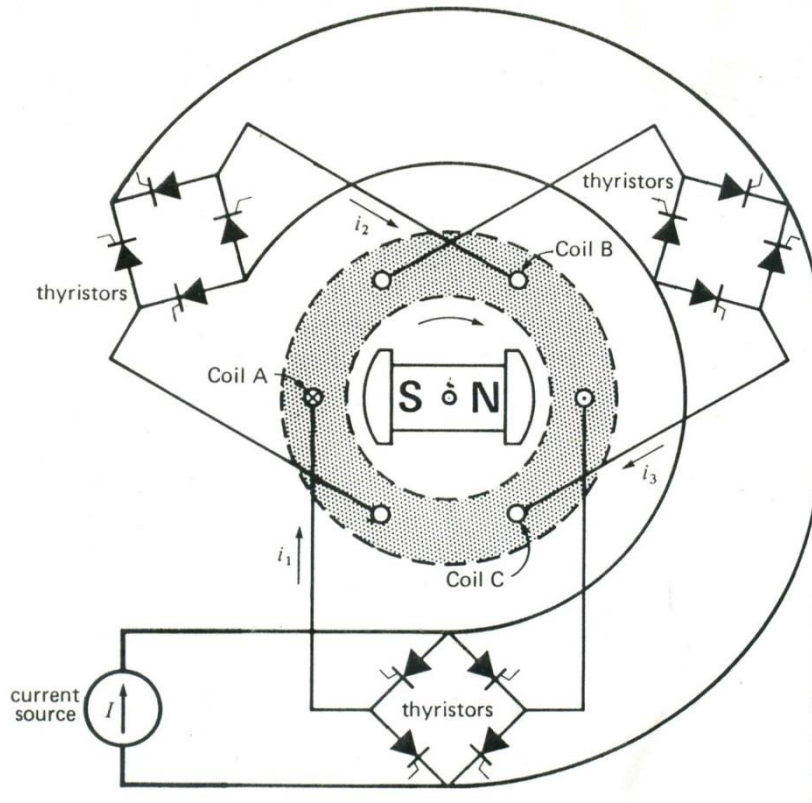


An arrangement of three coils



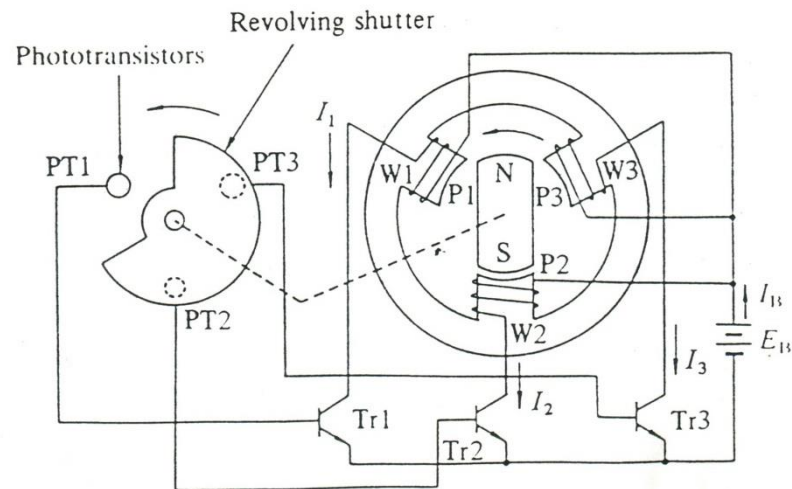
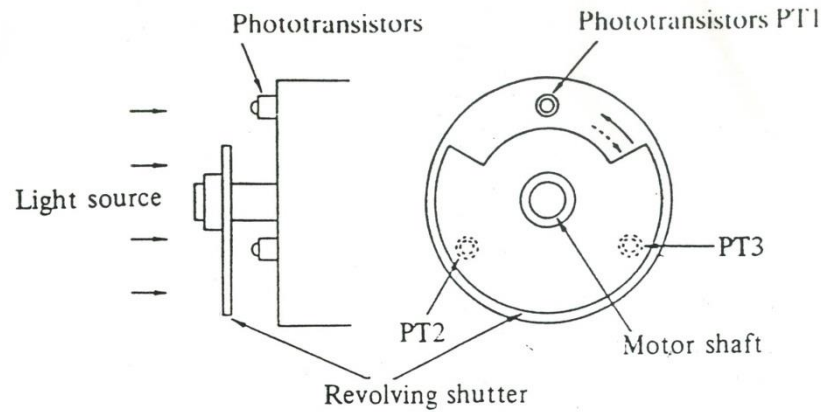
100kW, oil cooled BLDC motor

PM BLDC motor drives



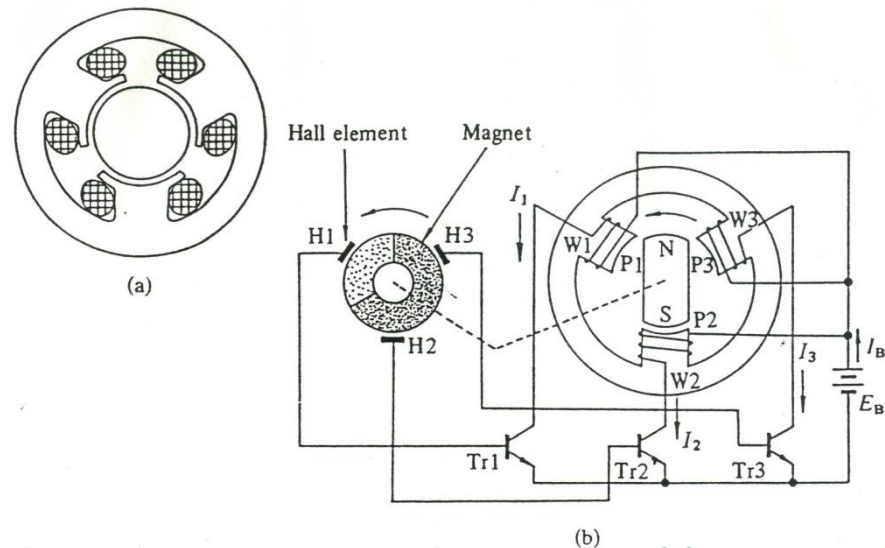
The armature is now the stator, and the switches have been replaced by thyristors.

PM BLDC motor drives

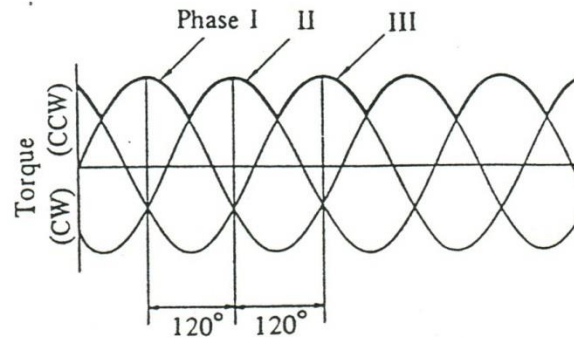


Three-phase unipolar-driven brushless DC motor

PM BLDC motor drives

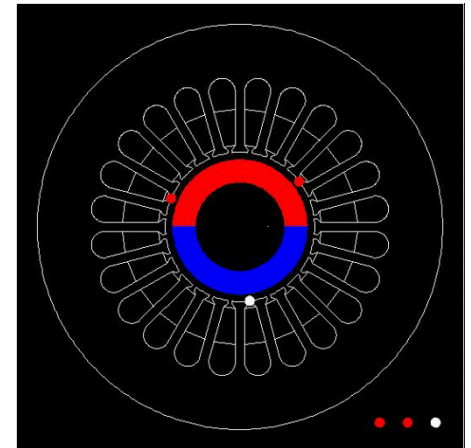
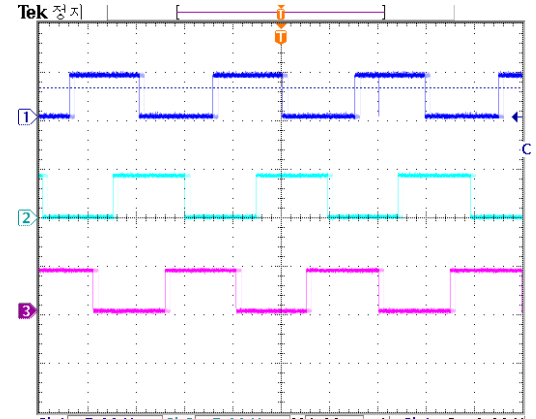
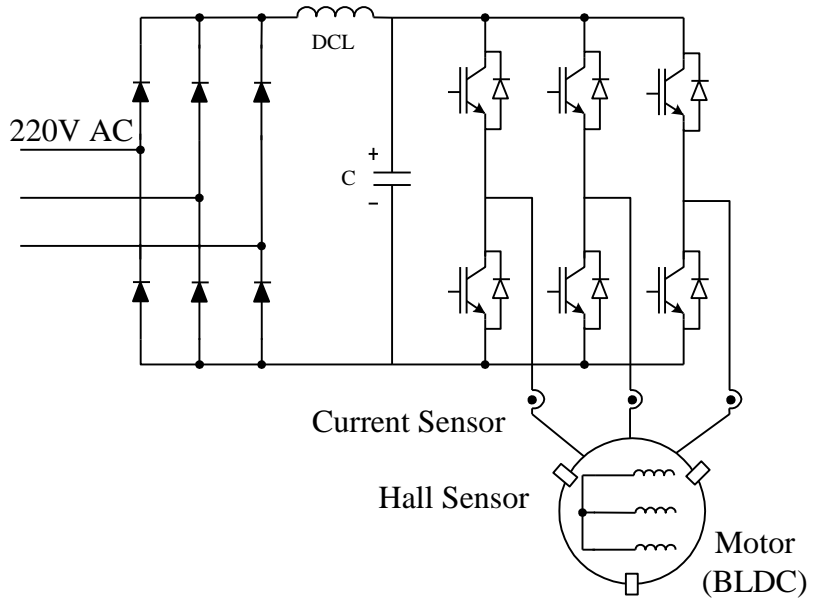


Principles of a three-phase unipolar motor: (a) cross-section, (b) principles of operation



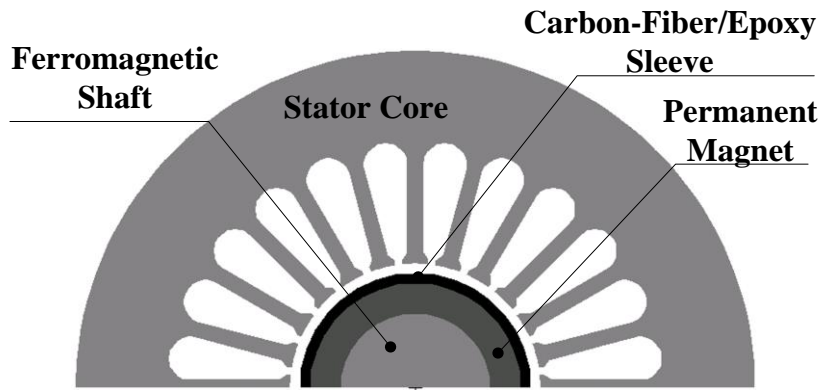
Relationship between torque and reboiling angle when a direct current flows in each phase

드라이버를 고려한 동특구동 성 해석



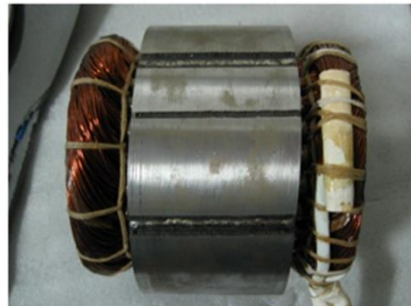
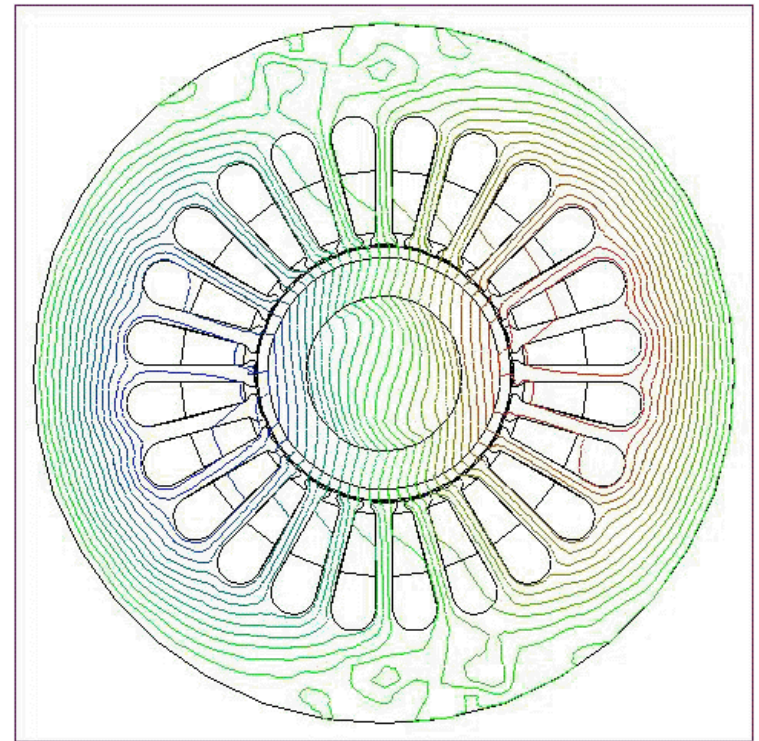
시작기 모델 설계 / 해석 / 제작

시작기 모델 설계/해석/제작



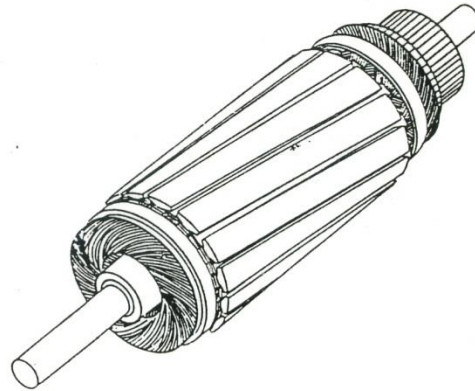
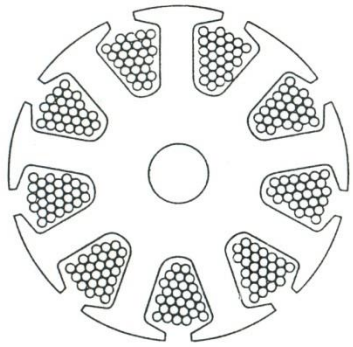
1차년도 시작기 모델

부하시 등자속선 분포특성

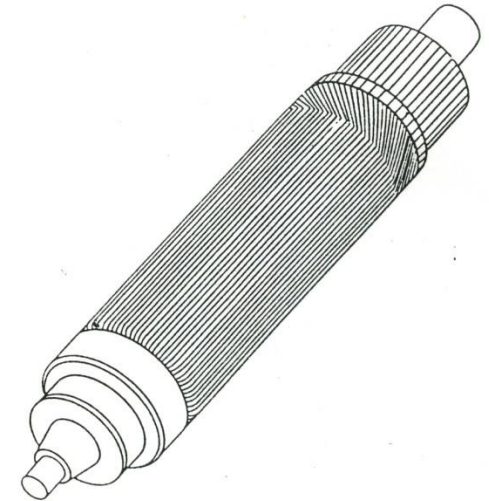
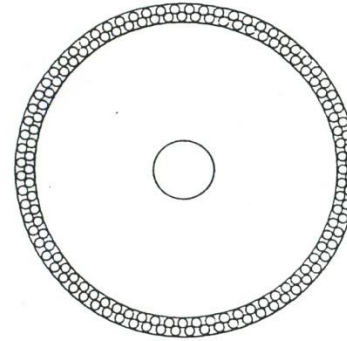


Rotor Types

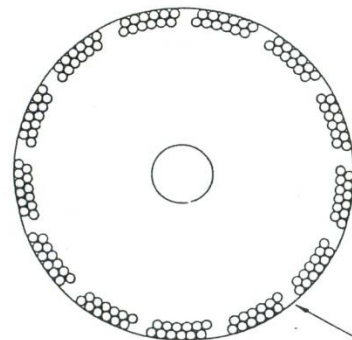
Slot – Slotless rotor



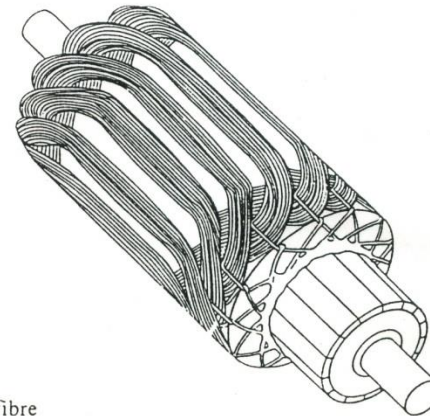
Slotted rotor



Slotless rotor

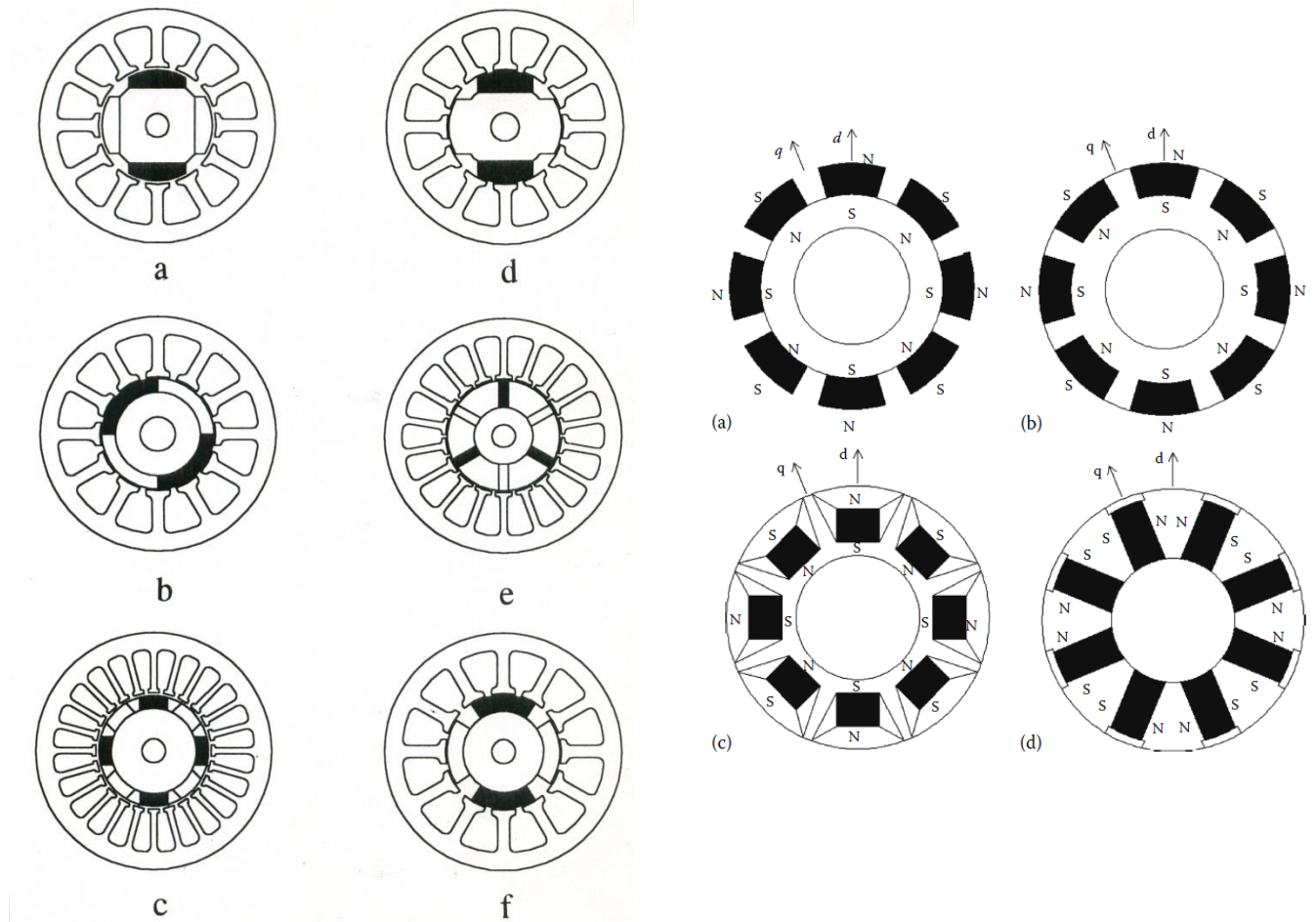


Glass fibre



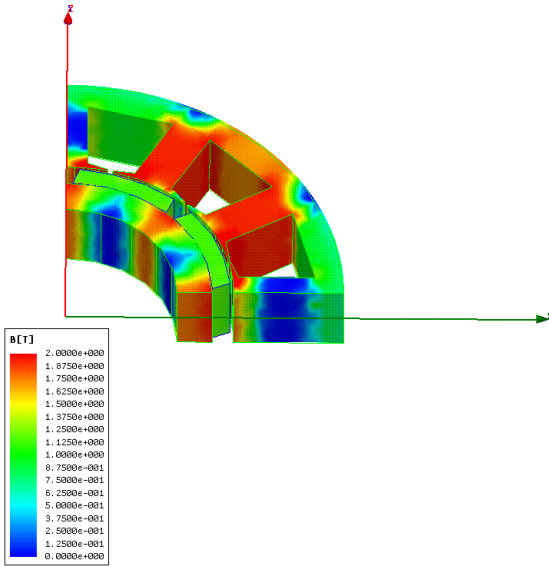
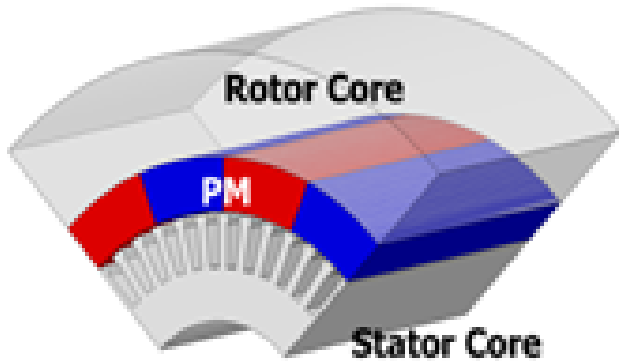
Moving-coil rotor

PM BRUSHLESS ROTORS



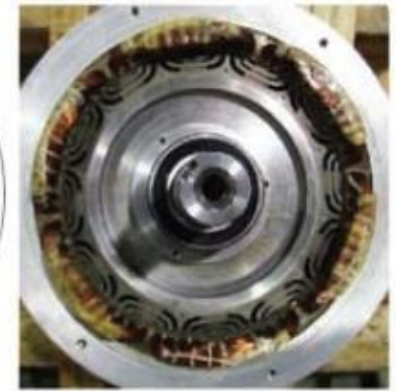
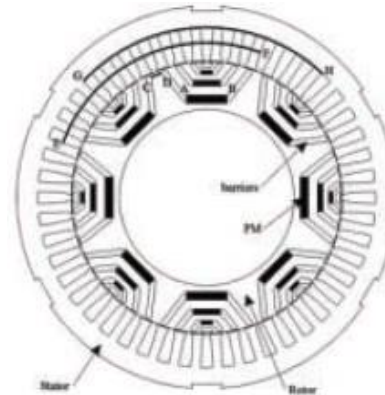
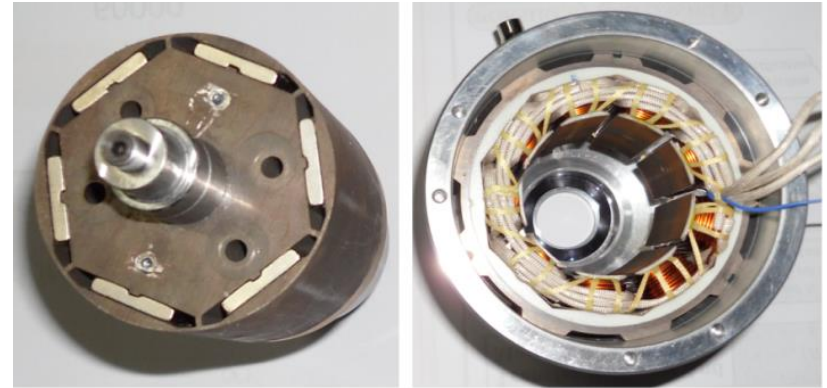
Examples of interior-rotor brushless permanent-magnet rotors

(2) 회전자 - 외전형(OUTER ROTOR TYPE), 내전형(INNER ROTOR TYPE), 표면부착형(SURFACE MOUNTER PM TYPE), 매입형(INTERIOR PM TYPE) 개념



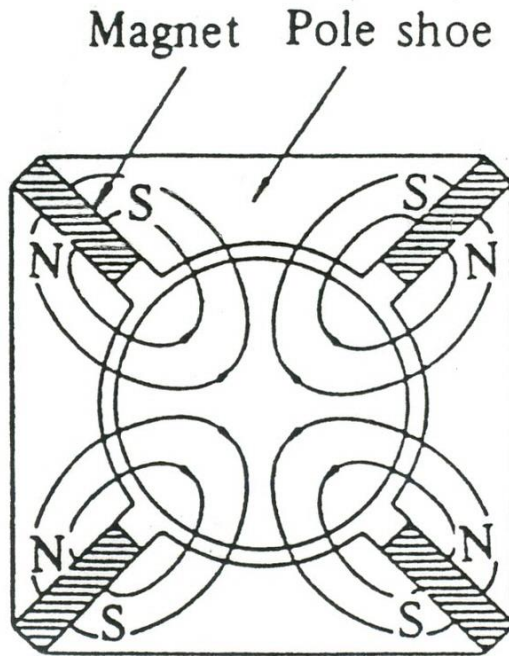
Time=10s1

영구자석 표면부착형 계자 내전형 발전기(SPMG)

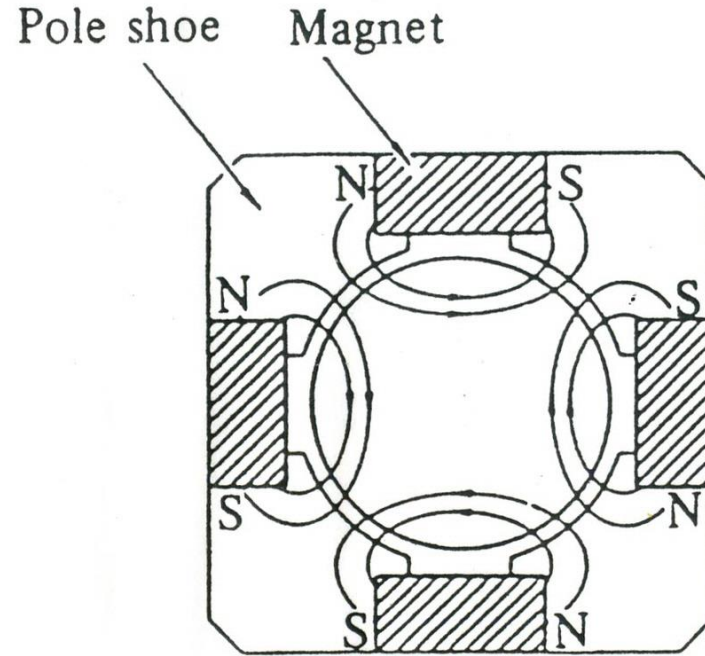


영구자석 매입형 계자 내전형 발전기(IPMG)

PM Field Systems



(a)

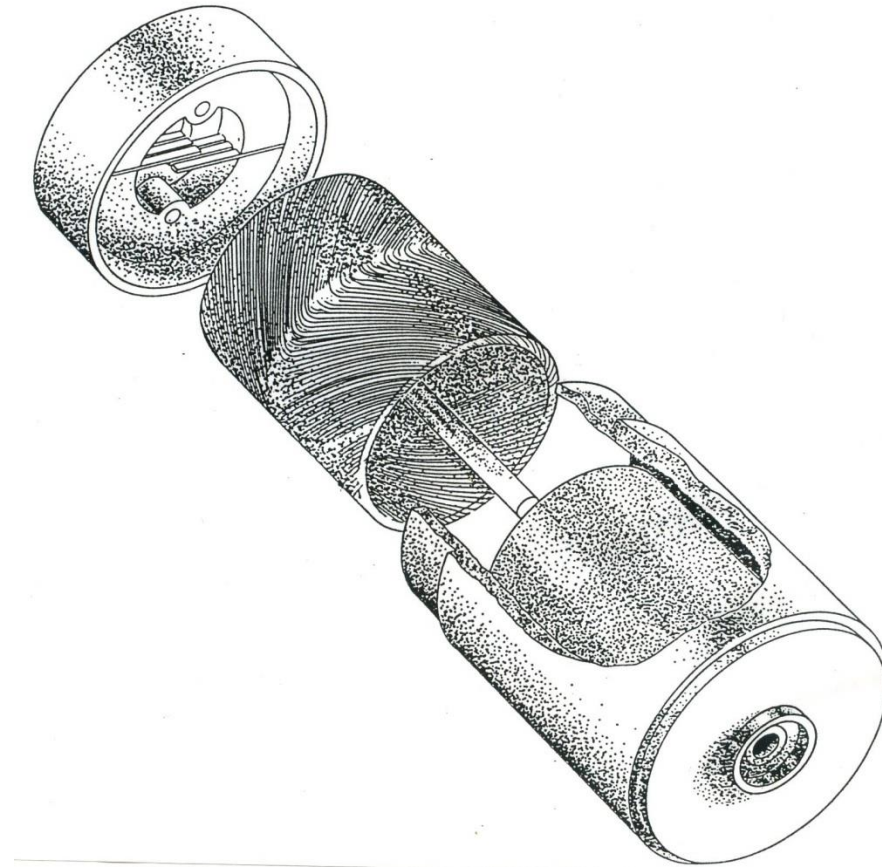


(b)

Comparison of (a) a field system using samarium-cobalt magnets and (b) the one Alnico magnets.

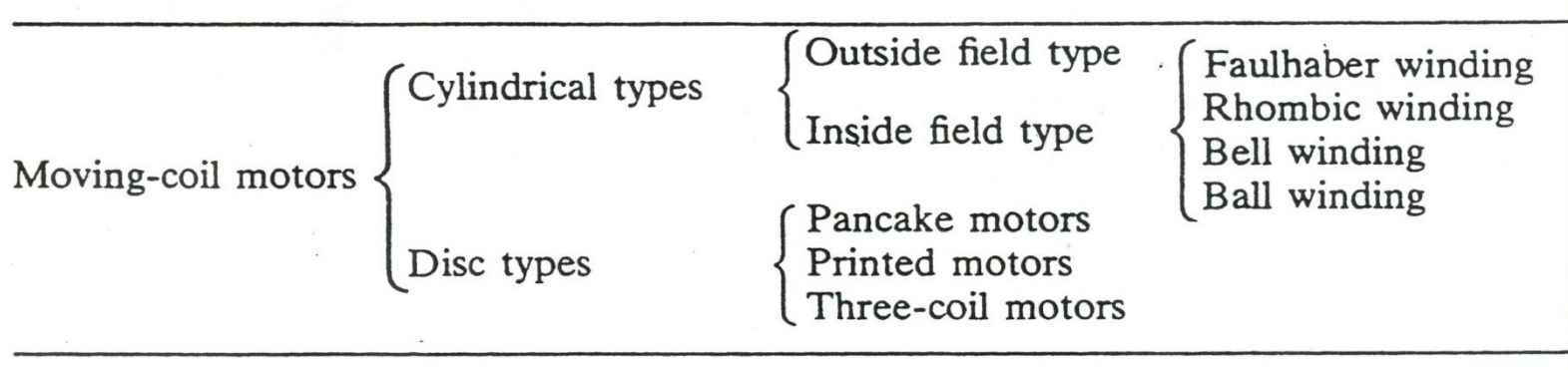
Moving Coil –coreless –Motors

Moving-coil (coreless) motors



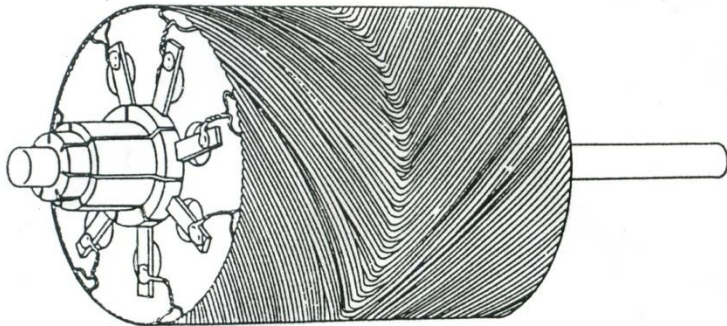
As explained in the previous chapter the armature structures of DC motors can be classified into the three fundamental types: slotted, slotless, and moving-coil motors, which are also known as coreless motors, have recently progressed and are now used in a variety of applications, This chapter will focus on an explanation of the characteristics of moving-coil motors.

Moving coil motor

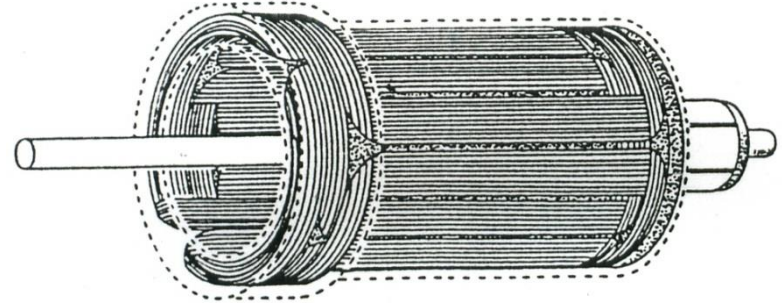


Classification of moving-coil motors

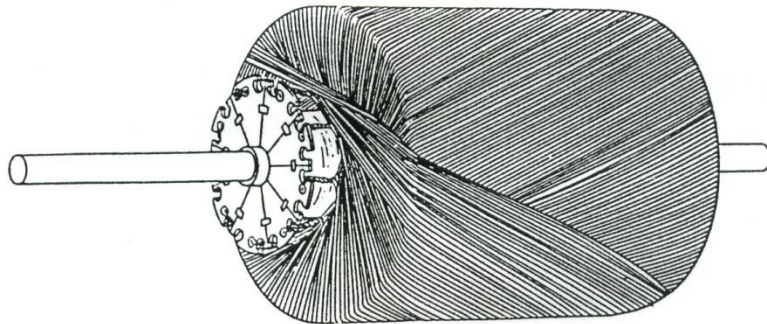
Coreless rotor



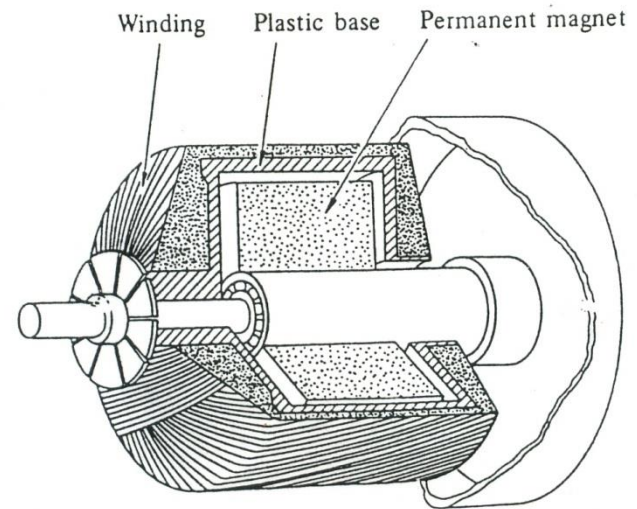
Rhombic winding rotor



Structure of a bell winding rotor. (The dashed line indicates the resinated part.)



Coreless rotor of the ball winding method



Cutaway view of a ball winding rotor

Permanent Magnet Brushless DC motor Drives

장 점

- 높은 효율 및 높은 출력 밀도
- 영구자석 사용으로 magnetic poles의 불필요
- 열 방출이 용이함
- Conduction angle 제어를 사용하여 속도범위가 3-4배 길어짐

단 점

- 영구자석의 가격이 비쌈
- 자석의 기계적 강도는 큰 토크를 구출하기 어려움
- 자석의 고정 강도에 따라 최대속도의 제한 발생
- 자석과 회전자계가 반대방향으로 약 계자에 의한 성능 저하

Brushed DC Motor Drives

- 전동기의 속도는 전압의 변화로 조절
- 출력에 따라 2, 4 또는 6극을 사용
- 직권과 분권이 있음

장 점

- 낮은 속도에서 높은 토크가 가능
(견인에 적절함)
- 제어가 쉽다. (특히 분권전동기)
- 약 계자 동작에 적합
- 가격이 저렴함

단 점

- 낮은 효율 및 신뢰성
- 큰 기기 사이즈 및 무게
- 정류자와 브러쉬에 의한 높은 유지보수비 발생
- 최대속도의 제한 (정류자와 브러쉬의 마찰)



부하조건 및 제어방식에 따른 EV용 motor 정격결정

H A. Toliyat et al 'Handbook of Electric Motors' Marcel Dekker,2004

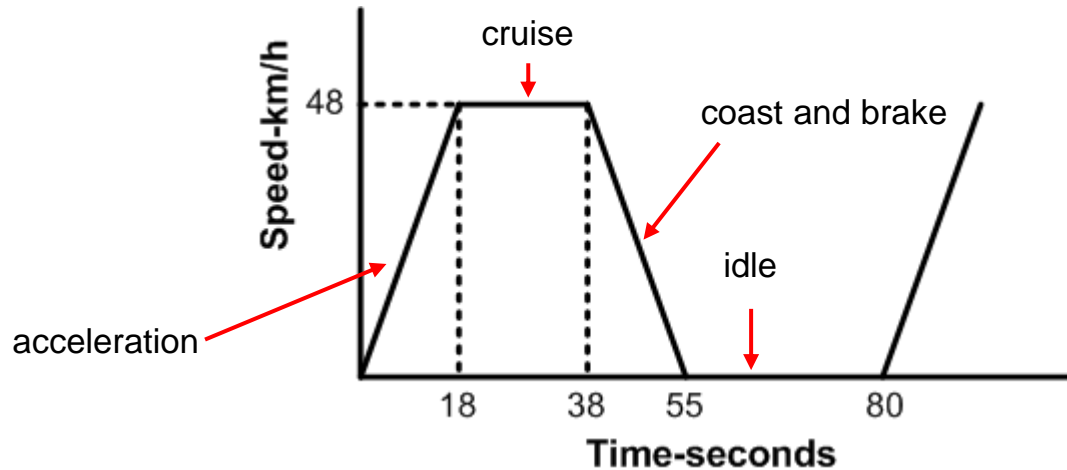


❖ EV용 모터(DC 모터), 드라이브 설계에 고려해야 할 사항

1. 모터 타입, 직권 or 분권
2. 분권일 때
 - a. 계자 자속이 일정한가? 변화하도록 제어되는가?
 - b. 전기자 전압이 chopper 또는 스위치에 의해 제어 되는가?
 - c. 변속 기억비 (Transmission gear ratio)
 - d. 회생제동이 사용되는가?
3. Tire size.
4. System voltage.
5. Vehicle performance
 - a. 최대 가속 (Maximum acceleration)
 - b. 최대 경사로에서의 최대 속도
 - c. 정속 주행 속도 (Cruise speed)
 - d. 평지에서의 최대 속도
 - e. 회생제동

EV 속도 프로파일- 부하 계산

❖ 전기 자동차의 속도 프로파일 예시. (cruise 구간에 5초 동안 10% 경사로 주행)



❖ 전기자동차용 모터의 정격출력 결정

→ 1~5의 부하조건을 충족할 수 있는 충분한 power를 제공해야 함.

1. 공기역학(Aero-dynamic)에 의한 drag
2. 경사의 변화 (Change of grade)
3. 주행 저항 (Rolling resistance)
4. 가속 요구조건 (Acceleration requirements)
5. 기어, 베어링, 구동렬에서 발생하는 기계적 손실

EV 부하 계산

공기역학(Aero-dynamic)에 의한 drag

$$P_d = \frac{18.357}{10^6} (C_d A) (km/h)^3 \text{ (hp)}$$

C_d Drag coefficient
 A Frontal area - m²
 km Speed - kilometer per hour

경사의 변화 Change of grade

$$P = \frac{3.72}{10^5} (W) (km/h) (\%) \text{ (hp)}$$

W Vehicle weight - kg
 $\%$ Percent grade

주행 저항 Rolling resistance due to tire friction

$$P = \frac{3.72}{10^5} (W) (km/h) (100\mu) \text{ (hp)}$$

Typical friction coefficient between tire and road

$$0.012 < \mu < 0.017$$

가속 요구조건 Acceleration requirements

$$P_a = \frac{38.029}{10^5} (W) (a) (km/h) \text{ (hp)}$$

a Acceleration rate - m/s²

EV Motor의 정격

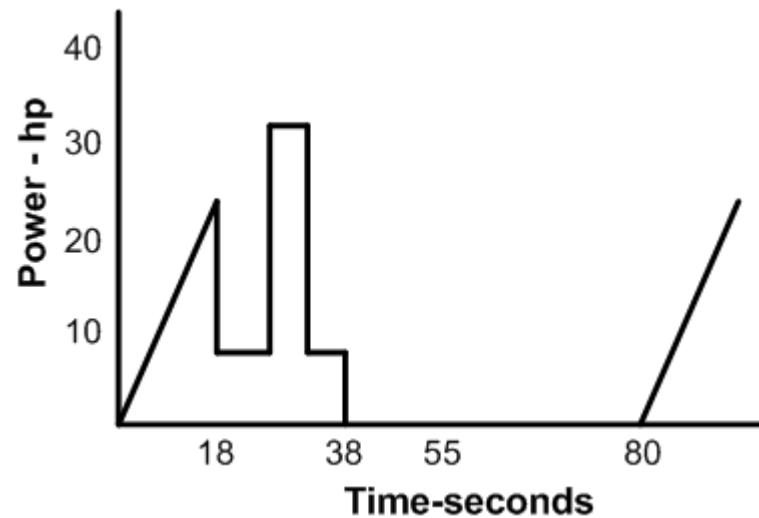
❖ 속도 프로파일 각 구간에서의 모터 요구 출력 계산결과

- 정속 주행구간에서의 10% 경사로 주행
- 구동률 효율(drive-train efficiency): 95%

Drag coefficient $C_d = 0.3$
 Frontal area - m^2 $A = 1.8 m^2$
 Vehicle weight $W = 1360.7 kg$
 friction coefficient between tire and road $\mu = 0.012$

Mode	Speed in time	Power req.
Accelerating	0-48 km/h in 18s	25.58 hp
Cruising	48 km/h	6.51 hp
Grade climbing	10% at 48 km/h	31.77 hp
Top speed	88 km/h	27.67 hp

	계산	책	차이
accel	22.64144	25.58	2.938556
cruise	4.011444	6.51	2.498556
grade	28.31144	31.77	3.458556
top speed	12.09617	27.67	15.57383



EV용 DC 모터의 정격결정

❖ 모터 정격 결정시 최대부하 뿐만 아니라 지속부하의 측면에서도 고려되어야 함.

- 최대부하 : 31.77 hp at Grade climbing

- 지속부하 : RMS power

$$P_{rms} = \sqrt{\frac{\sum (p)^2 \times \text{time}}{\text{running time} + \text{standstill time} / k}}$$

$$P_{rms} = \sqrt{\frac{\int_0^{18} \left(\frac{25.58}{18}\right)^2 t^2 dt + 6.51^2 \times 15 + 31.77^2 \times 5}{38 + 17 + 25 / 4}} = 12.5 \text{ hp}$$

DC 모터의 특성방정식/특성곡선

❖ 특성방정식: DC Series motor

$$E = K(I_f)\omega \quad \text{Open circuit voltage}$$

$$T = K(I_f)I_a \quad \text{Torque (N-m)}$$

직류전동기에서 역기전력상수 = 토크 상수 = $K(I_f)$

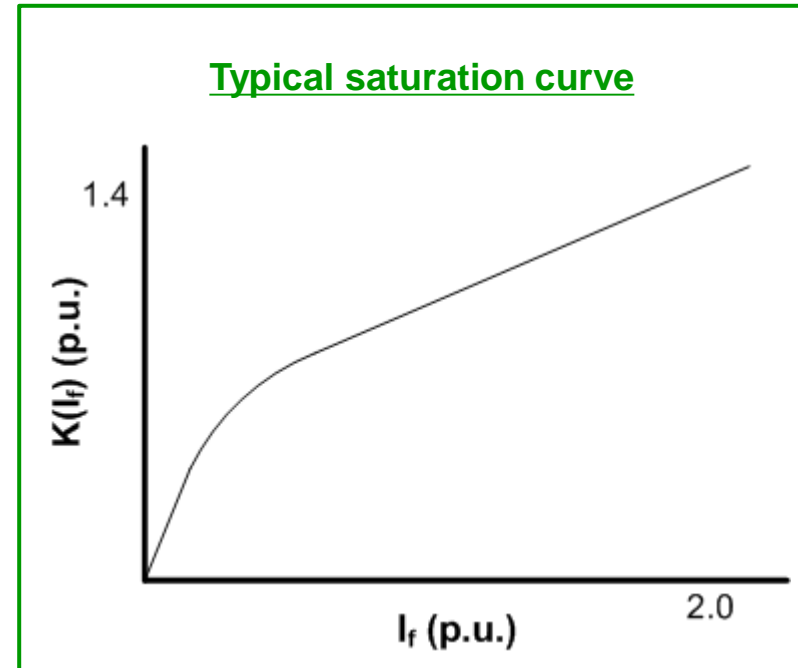
$$K(I_f)_{pu} = \left(\frac{T}{I_a}\right)_{pu} = \left(\frac{E}{\omega}\right)_{pu} = 0.95I_f^{0.454}$$

$$T_{pu} = 0.95I^{1.454} \quad (I_a = I_f = I \text{ in a series motor})$$

$$\omega_{pu} = \frac{V - IR}{0.95I^{0.454}} \quad (V = V_{avg(pu)})$$

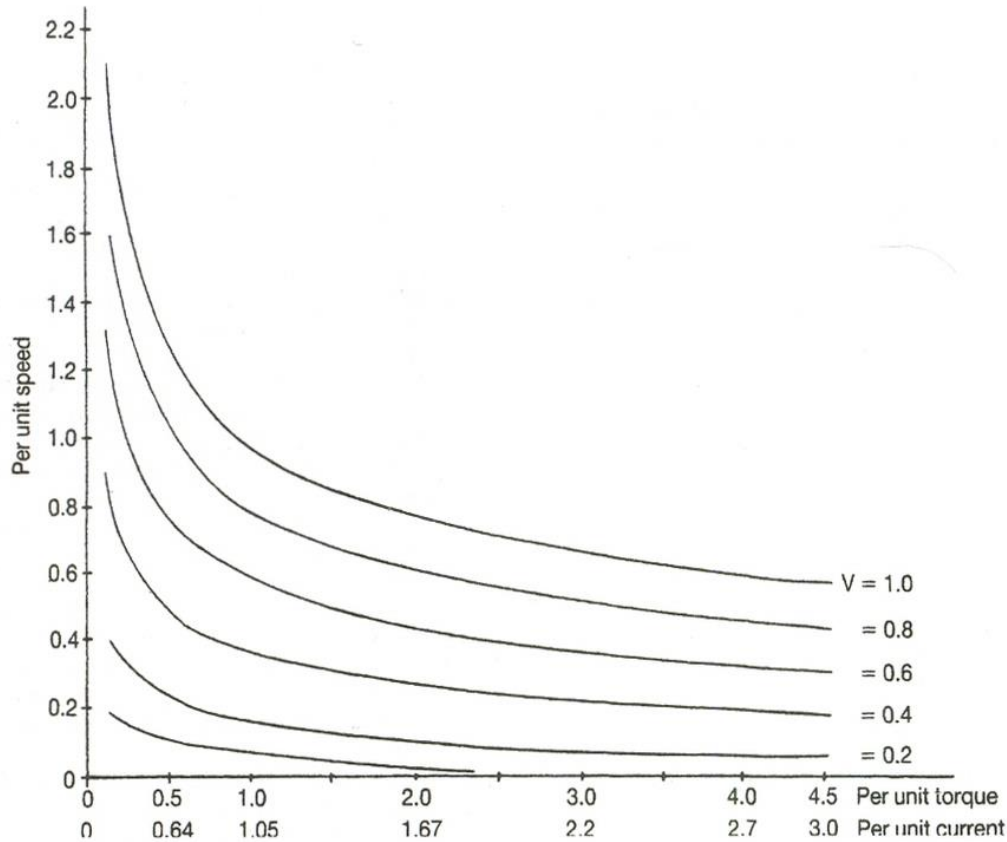
$$P_{pu} = (T_{pu})(\omega_{pu})$$

$$(R = 0.045 pu)$$

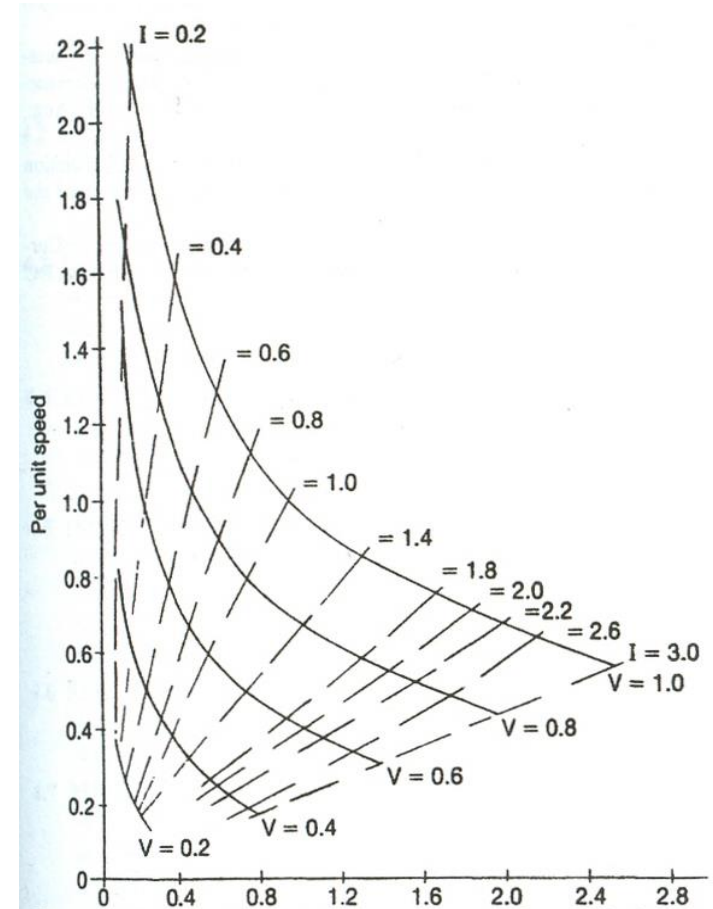


DC 모터의 특성방정식/특성곡선

Per-unit speed VS per-unit torque
for typical series motor



Per-unit speed VS per-unit power
for typical series motor



부하조건을 고려한 EV용 DC 모터의 정격

$$\omega_m = \frac{0.6Gv}{D}$$

D Tire diameter
 G Gear ratio
 v Vehicle velocity

rpm



$$N = 5.229 \frac{G}{D} (\text{km/h})$$

Tire diameter : 0.6 m
 Vehicle gear differential : 5.21/1
 Motor speed : 88 km/h



$$N = 4000 \text{ rpm}$$

'Cut and try' process

- Case 1 >** Motor rated speed = 5000 rpm → 4000 rpm : 0.8 pu speed
 Net power at top speed : 27.67 hp
 Speed=0.8pu, V=1.0 pu → Power=1.45 pu, I=1.5 pu
 Motor size : 27.67/1.45 = 20 hp
- Case 2 >** Motor rated speed : 4000 rpm → 1.0 pu speed
 Power = 0.95 pu
 Motor size : 27.67/0.95 = 30 hp

주행을 고려한 EV용 DC motor 정격결정

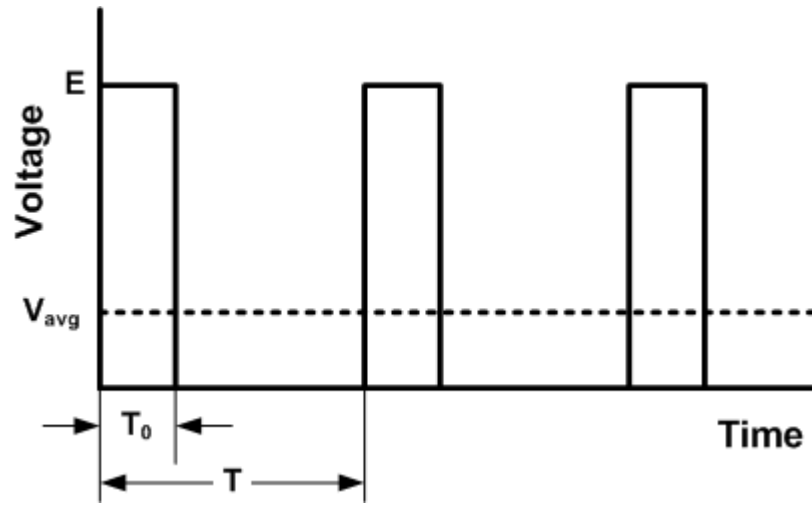
Case 1 > 20-hp, 5000-rpm Motor

Condition	Speed	Power	Voltage	Current
Top speed	0.8	1.45	1.0	1.5
Cruise	0.44	0.33	0.42	0.8
Accelerating	0.44	1.28	0.7	2.1
Grade climbing	0.44	1.59	0.75	2.6

Case 2 > 30-hp, 4000-rpm Motor

Condition	Speed	Power	Voltage	Current
Top speed	1.0	0.95	1.0	1.0
Cruise	0.55	0.22	0.4	0.5
Accelerating	0.55	0.85	0.68	1.4
Grade climbing	0.55	1.06	0.73	1.6

Chopper drive를 사용한 제어기의 출력전압



E Source voltage

T_0 ON time T Period

T_0 / T Duty cycle

$f = 1 / T$ Frequency

$$V_{avg} = E(T_0 / T)$$

전류 변화량 $\Delta i = \frac{E}{Lf} \left(1 - \frac{T_0}{T}\right) \frac{T}{T_0}$ amperes

Δi 증가 \rightarrow 전류의 고조파 성분 증가 \rightarrow Joule loss 증가 \rightarrow 발열 증가, 효율 감소

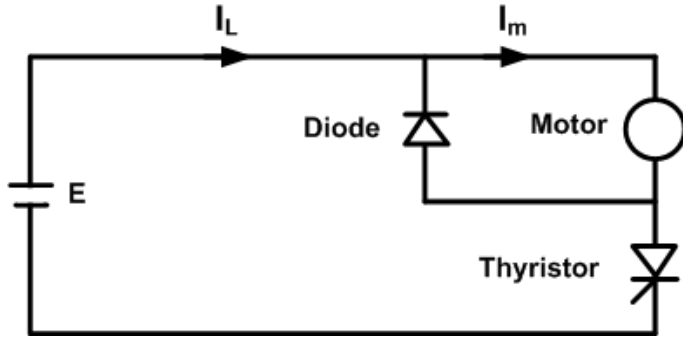
즉, 모터의 회로 인덕턴스 L 와 chopper 주파수 f 에 따라 모터의 효율이 달라짐.

$L, f \downarrow \rightarrow \Delta i \uparrow$ Efficiency \downarrow

$L, f \uparrow \rightarrow \Delta i \downarrow$ Efficiency \uparrow

Chopper drive를 사용한 제어기의 출력전압

Basic chopper circuit



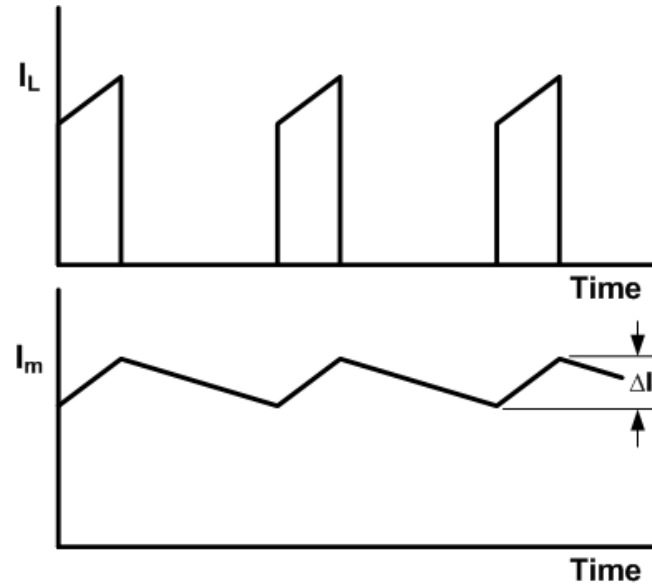
Turn on 시 시간에 대한 전류 변화량
(회로의 저항 성분 무시)

$$\frac{di}{dt} = \frac{E - V_{avg}}{L} = \frac{E}{L} \left(1 - \frac{T_0}{T} \right)$$

시간에 대한 전류 변화량의 최대값을 제한시켜야 함. (V_{avg} 의 최소값 제한)

모터와 chopper drive 사이의 상관관계와 모터 구동 효율에 대한 관점에 있어서
회로 인덕턴스 L 는 매우 중요한 요소임.

Source current & Motor current



회로 인덕턴스 = 전기자 인덕턴스 + 계자 인덕턴스

전기자 인덕턴스
$$L = \frac{K_1 Z^2 l (h_1 + h_2)}{3Qa^2 b}$$

계자 인덕턴스
$$L = \frac{K_2 h n^2 l p}{g a^2}$$

Z	Armature inductors
l	Stack length
Q	Number of slots
a	Number of parallel paths in armature
b	Slot width
h_1	Depth of copper in slot
h_2	Depth from top of tooth to top of conductor in slot
h	Pole height
n	Number of pole turns
p	Number of poles in series
g	Air gap length

상수 K_1, K_2 의 값을 명확하게 하는 것이 불가능하기 때문에, 위 식들은 모터 설계에 있어서 인덕턴스 값이 어떤 요소들에 의해서 어떤 식으로 변화하는지에 대한 정보만을 제공함.

Chopping Frequency-인덕턴스

❖ 회로 인덕턴스에 영향을 주는 요인

1) Chopper 주파수

주파수 증가 → 표피효과(skin effect) & 와전류(eddy current) 증가
와전류에 의해 생성된 역자계는 전체 자속을 감소시킴 → 회로 인덕턴스 감소

2) 모터 전류 (입력전류)

전류 증가 → 계자 자속이 전기자 철심을 포화시킴 → 회로 인덕턴스 감소

일정 chopper 주파수: no-load → full load, 인덕턴스 20% 감소

일정 부하 전류: chopper 주파수 20 Hz → 600 Hz, 인덕턴스 20% 감소

3) 보상권선의 유무, 정류자 권선, end turn, 브러쉬 이동 등

모터의 회로 인덕턴스- 저항이 변화하며,

그에 따라 모터의 성능이 바뀐다-motor 설계 시 구동 방법을 고려한 설계 필요

❖ 인덕턴스 per-unit 값 C_x 에 근거한 모터 인덕턴스의 예측

$$L_{base} = \frac{E}{I\omega_{base}}$$

E, I Rated voltage and current

$$\omega_{base} = \frac{N}{60} \left(\frac{p}{2} \right) 2\pi = \frac{Np}{19.1}$$

N Speed p Number of poles

$$L = L_{base} C_x$$

- Typical values of C_x

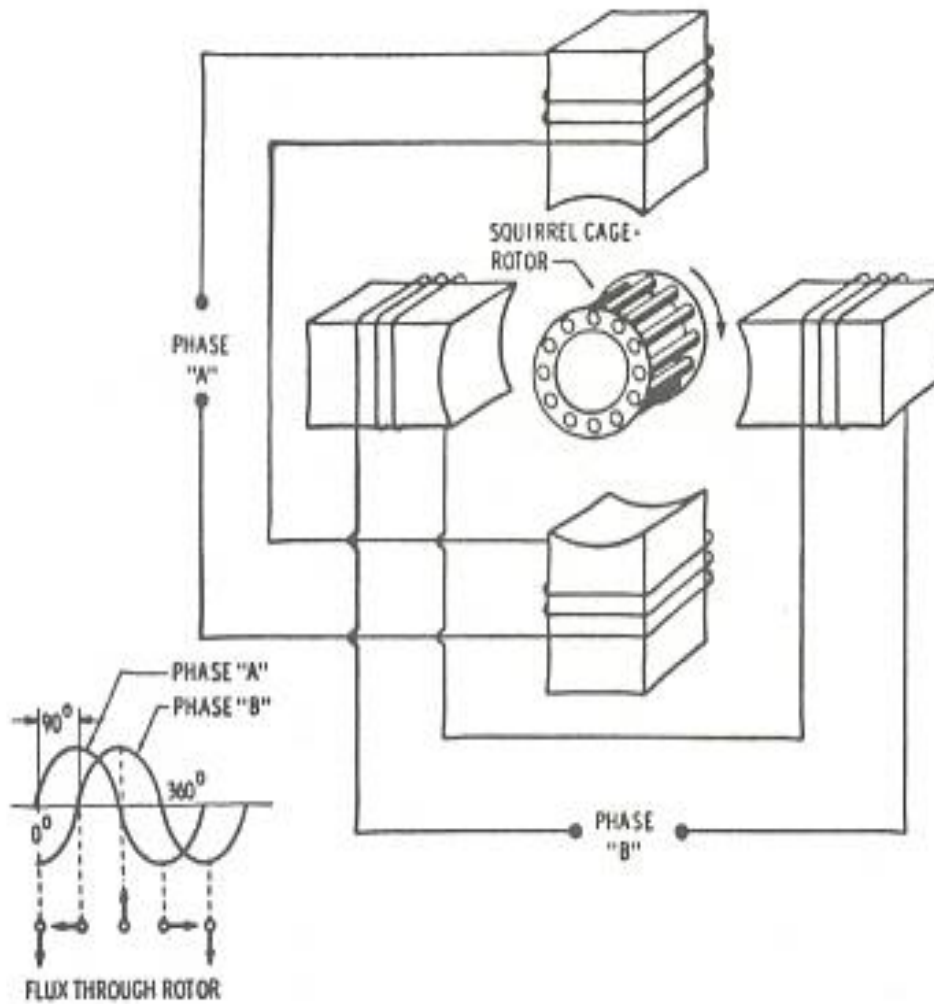
Shunt wound (compensating windings) $0.06 < C_x < 0.4$

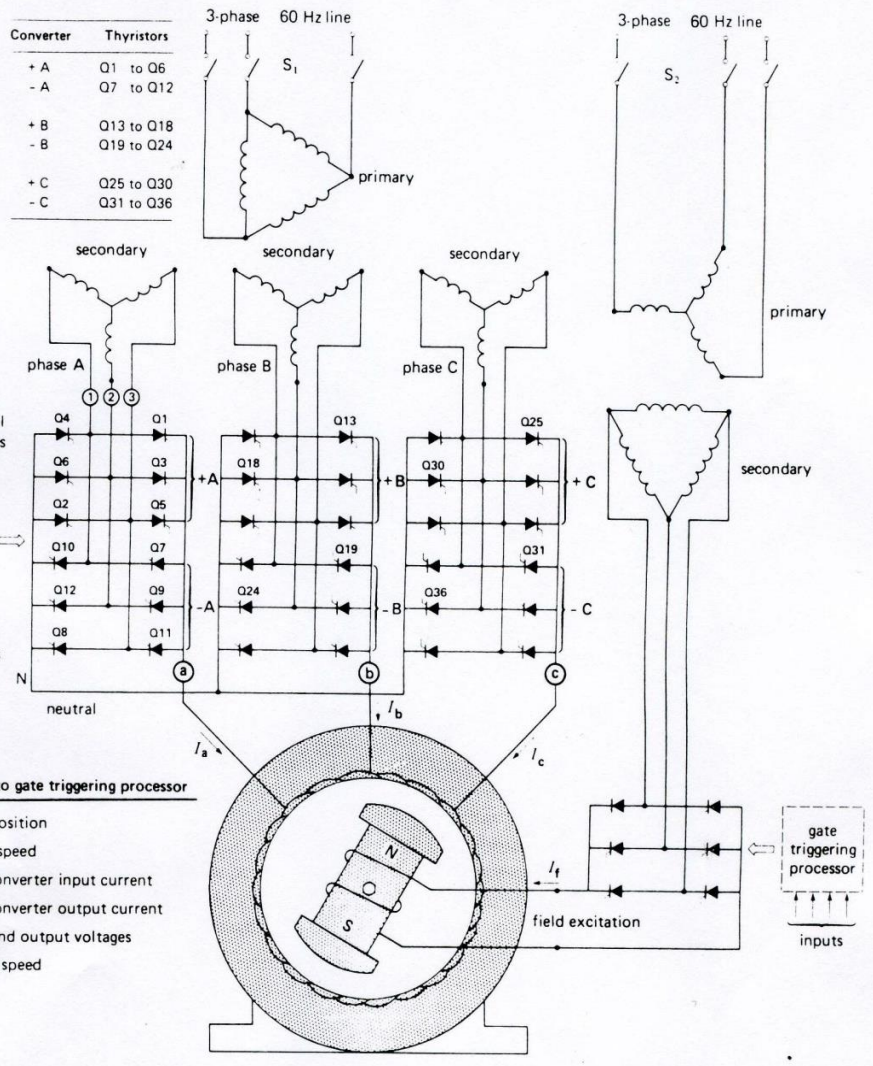
Shunt wound (non-compensated) $C_x \approx 0.35$

Series-wound (non-compensated) $C_x \approx 0.35$

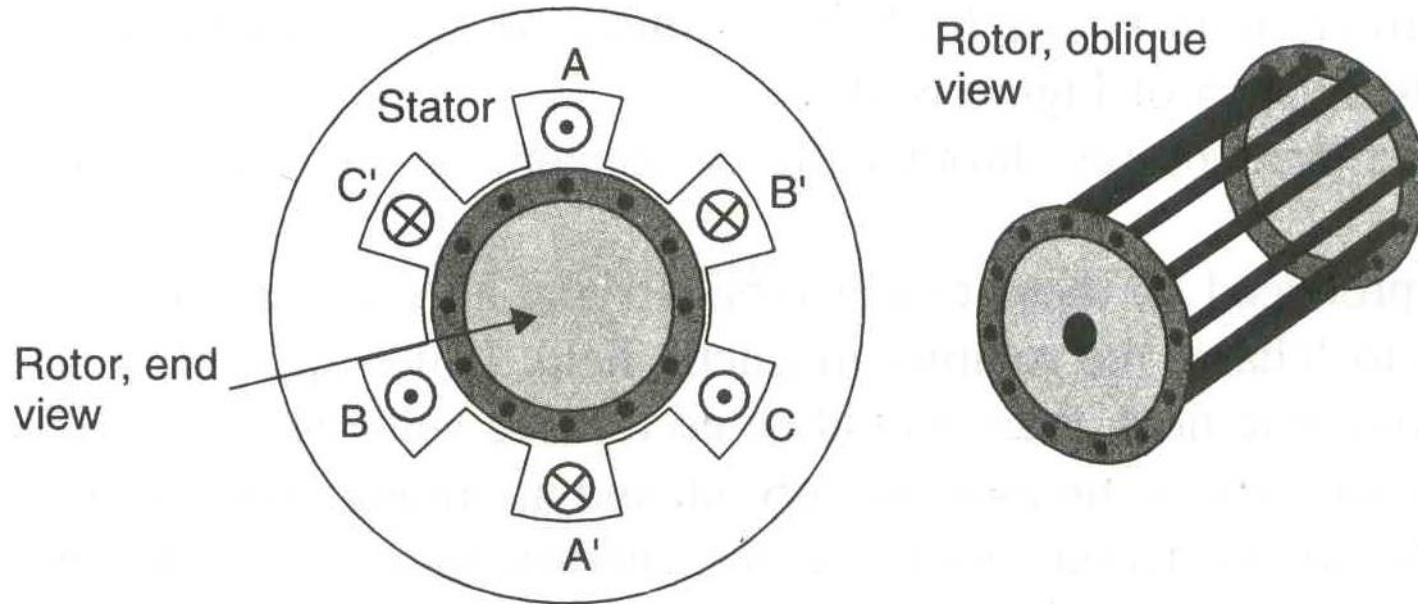
보상권선의 사용은 C_x 를 감소시킴 → 인덕턴스 감소

IM



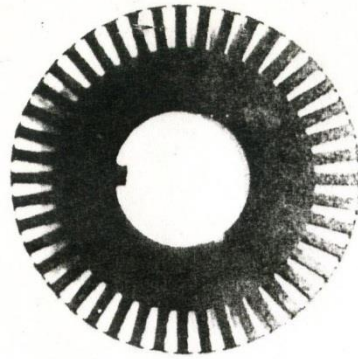


Induction Motor Drives

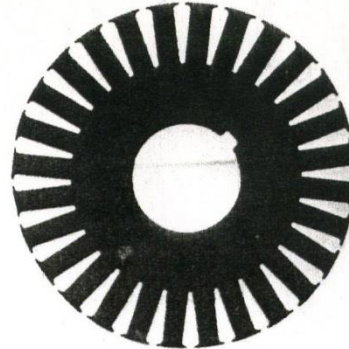


The stator and rotor of an induction motor

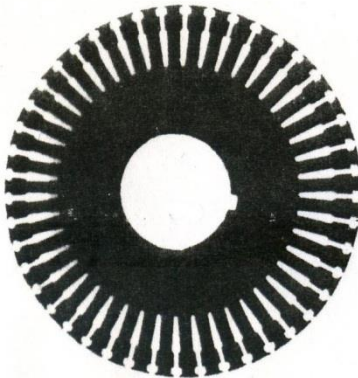
Induction Motor Drives



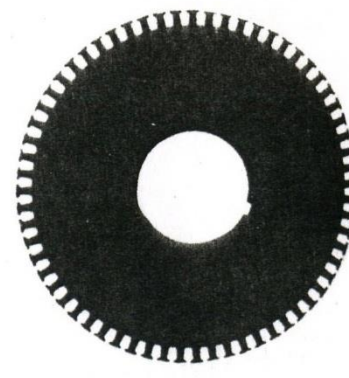
(a)



(b)

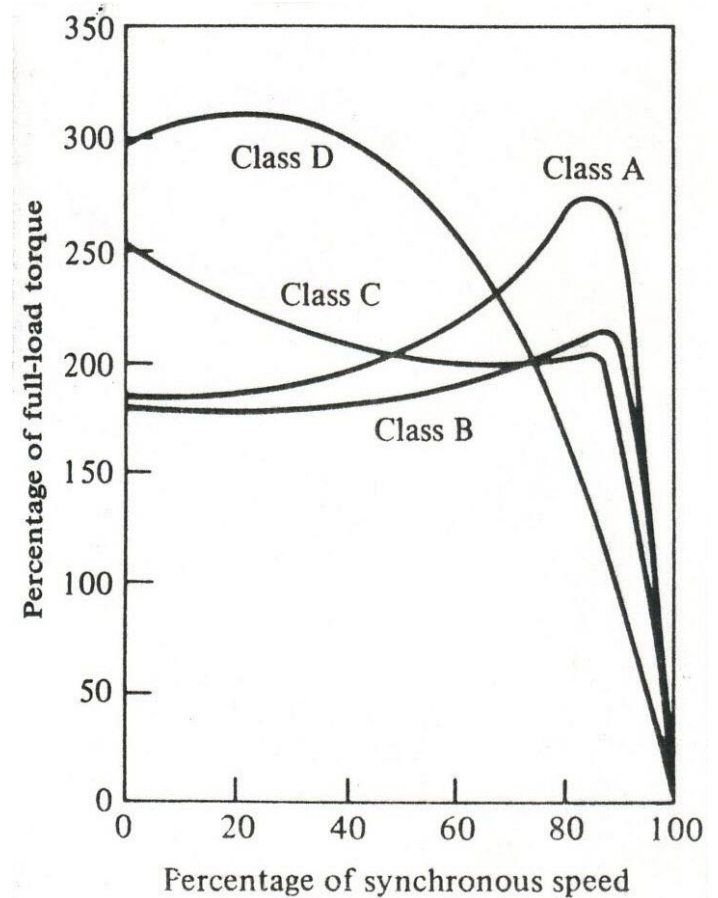


(c)



(d)

Laminations from typical squirrel-cage induction motor rotors, showing the cross section of the rotor bars: (a) NEMA design class A—large bars near the surface. (b) NEMA design class B—large, deep rotor bars. (c) NEMA design class C—double-cage rotor design. (d) NEMA design class D—small bars near the surface. (Courtesy of MagneTek, Inc.)



Rotor Type



Solid Rotor



Squirrel-cage Rotor



Commutator Rotor

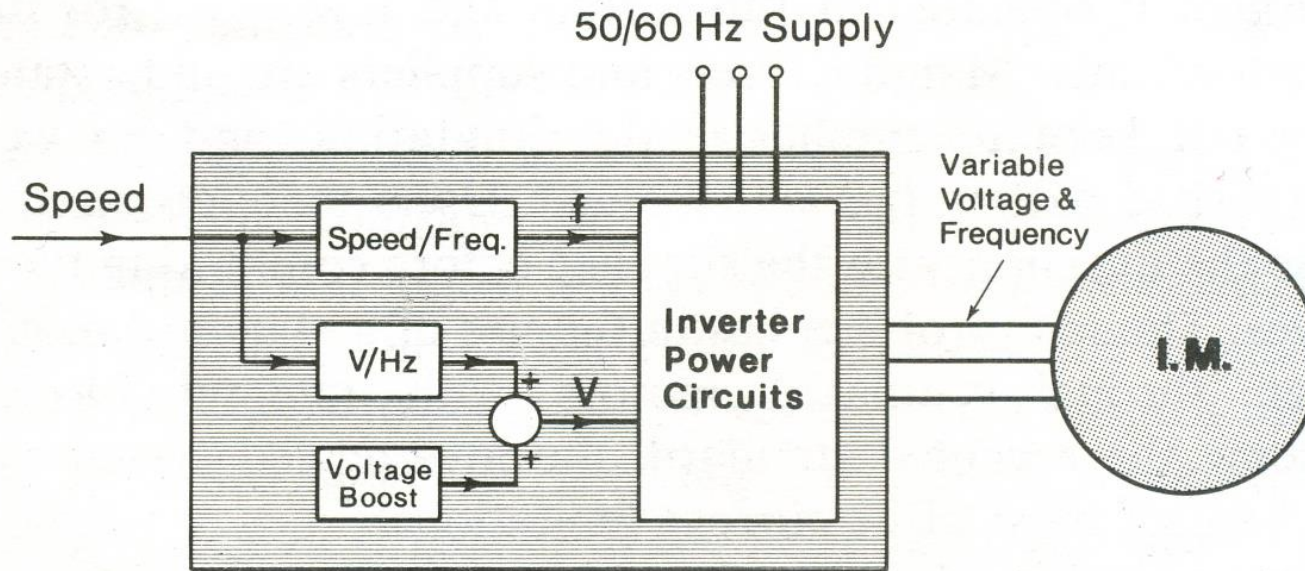


Wound-field Rotor

Les Manz 'Applying Adjustable-speed drives to three-phase induction
NEMA frame motors'
IEEE Trans.on Industry Applications, vol.33, no.2, 1997

NEMA 규격 3상 IM의 인버터 구동 concept

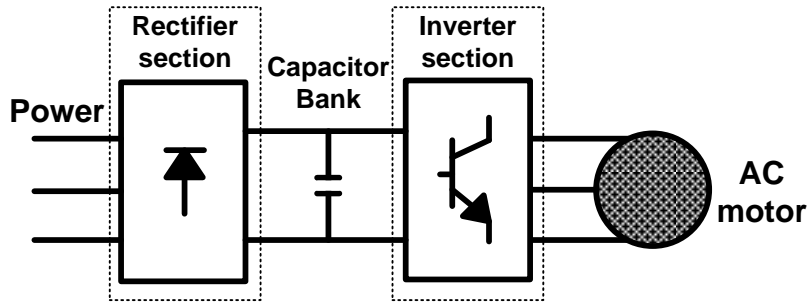
Les Manz'Applying Adjustable-speed drives to three-phase induction NEMA frame motors'IEEE Trans.on Industry Applications, vol.33, no.2, 1997



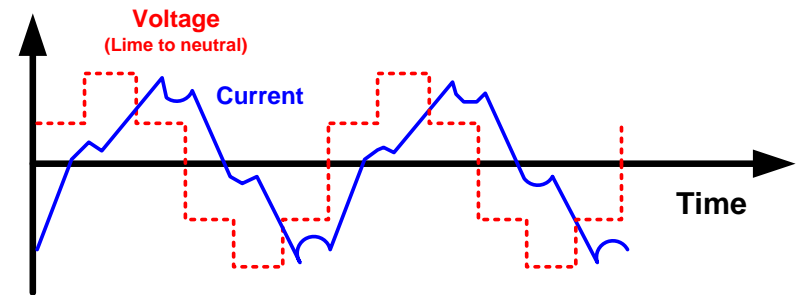
Schematic diagram of open-loop inverter-fed induction motor speed controlled drive

NEMA 규격 3상 IM의 인버터 구동시의 고조파 및 Torque 특성

- ❖ 가변속 구동 : ASD (Adjustable speed drive)
- ❖ 전압원 인버터 : VSI (Voltage-source inverter)



ASD block diagram



Voltage and current from a VSI-type ASD

- Rectifier section : 3상 AC 입력전원을 정류하여 DC 전원으로 변환
- Capacitor bank : DC 전원을 저장
- Inverter section : DC 전원에서부터 가변전압 가변주파수(VVVF)의 AC 전원으로 변환

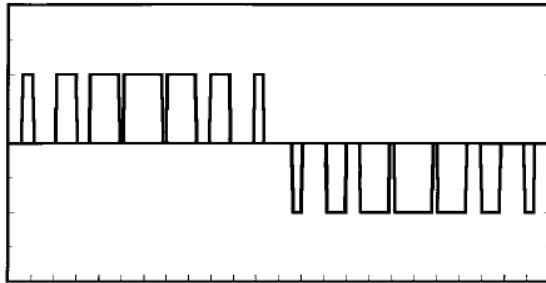
유도 전동기의 가변속 구동시의 전압-전류파형-고조파스펙트럼

❖ PWM (pulse width modulation) inverter를 사용한 가변속(ASD) 구동

: 전압의 peak 값은 유지하면서, 펄스 폭을 조정하여 전압의 RMS 값을 조정

: PWM inverter의 출력전압과 전류는 기본파 외에 고조파 성분을 가지고 있음.

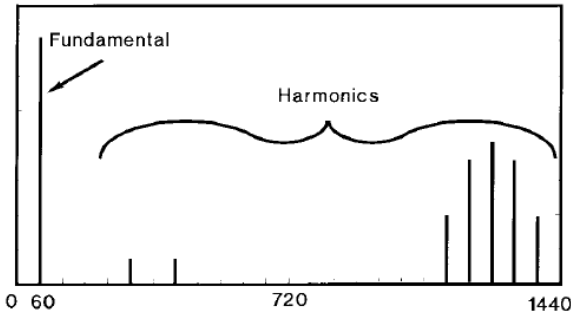
- 인버터 출력 선간 전압과 출력 전류는 같은 차수의 고조파를 가지고 있음
- 전류는 전압과 모터 임피던스에 의해 결정됨.



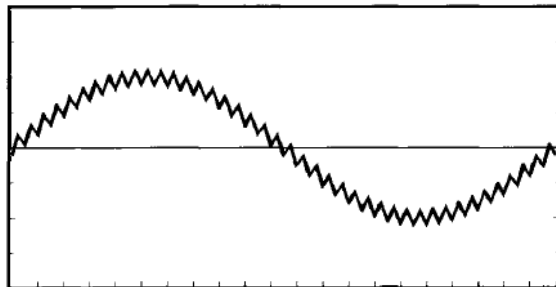
Voltage from a PWM ASD



Spectral analysis



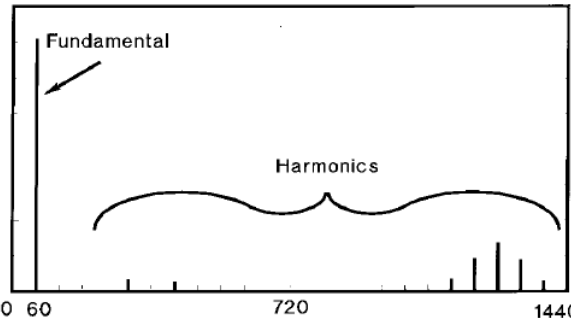
Spectral analysis of a PWM ASD's voltage



Line current in PWM ASD

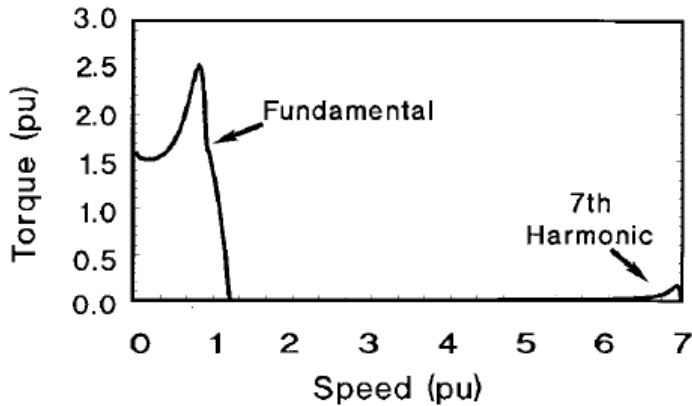


Spectral analysis

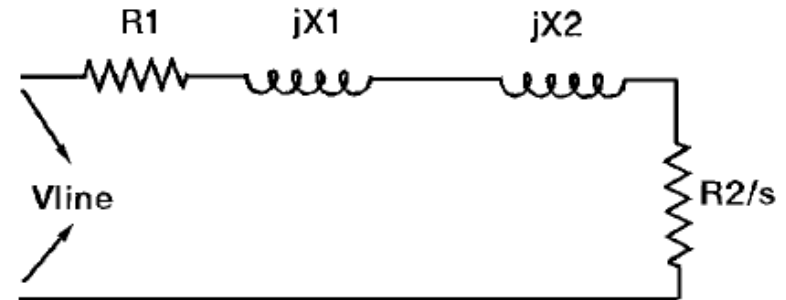


Spectral analysis of a PWM ASD's current

NEMA 규격 3상 IM의 인버터 구동시의 고조파영향



Speed-torque curves showing both fundamental and seventh harmonic torques



Approximate per-phase induction motor equivalent circuit

기본파 60 Hz $n_s=1800$ rpm

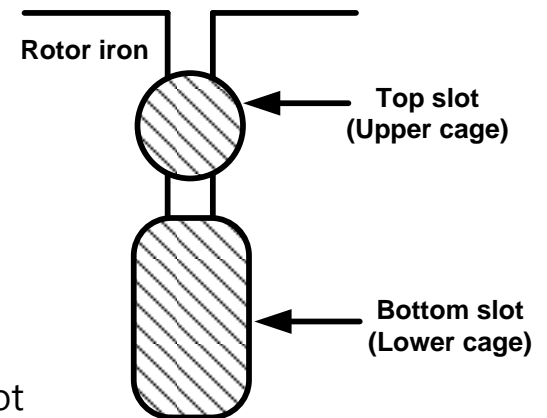
7고조파 $60 \times 7 = 420$ Hz $n_s=12,600$ rpm (7pu)

정지; $s=1.0$ $f' = sf = 60.0$ Hz : crowds the current into the top slot

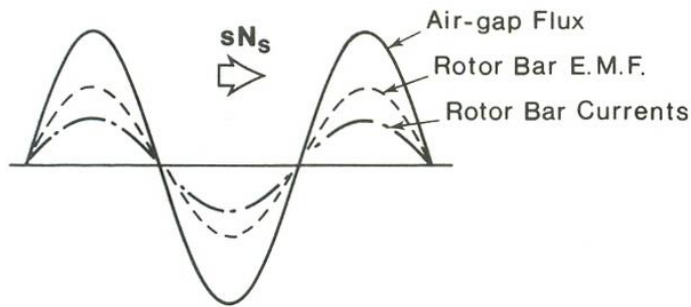
고속운전; $s=0.011$ $f' = sf = 0.67$: allows both slots

60 Hz 운전시; $s=0.859$ 의 7고조파 슬립 주파수

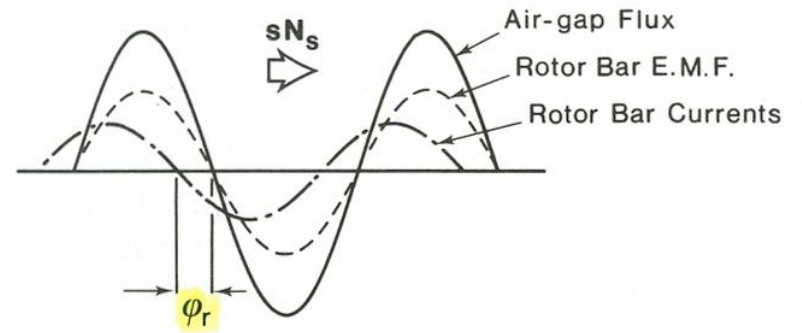
$7 \times f' = 7 \times sf = 361$ Hz Crowds the current into a portion of the top slot



NEMA 규격 3상 IM의 인버터 구동시-슬립에 따른 역률변화



Pattern of air-gap flux, and induced EMF and current in cage rotor bars at low values of slip

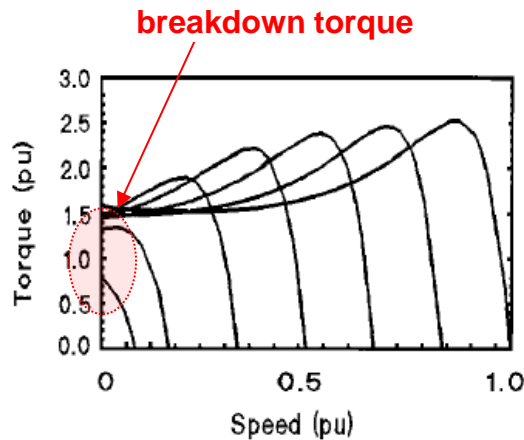


Pattern of air-gap flux, and induced EMF and current in cage rotor bars at high values of slip

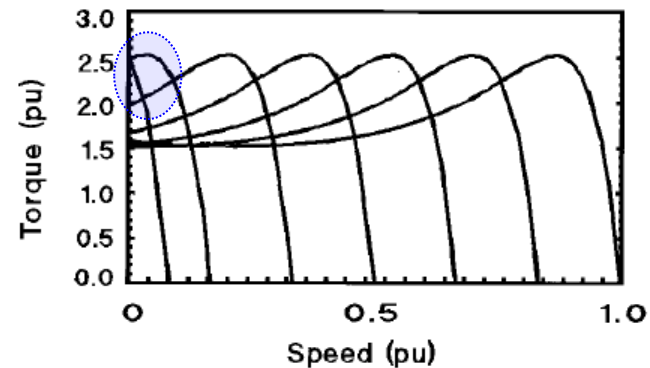
ASD를 사용한 유도 전동기의 Torque-speed 제어

❖ 유도 전동기의 주파수에 따른 Torque-Speed curve

- 저속에서 고정자 임피던스에 의한 전압강하가 크게 나타남에 따라 토크 감소
- 저속에서 토크를 증가시키기 위해 V/F ratio를 boost 시킴

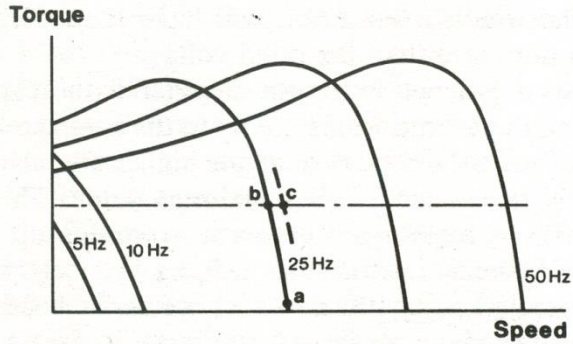


Speed-torque curve as frequency changes.
Constant V/F without boost

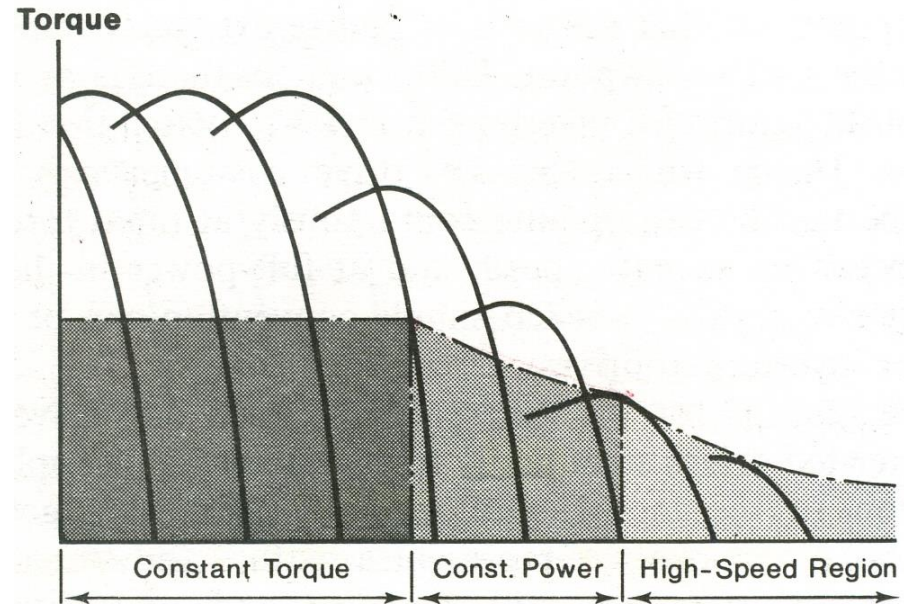


Speed-torque curve as frequency changes.
Constant V/F with boost

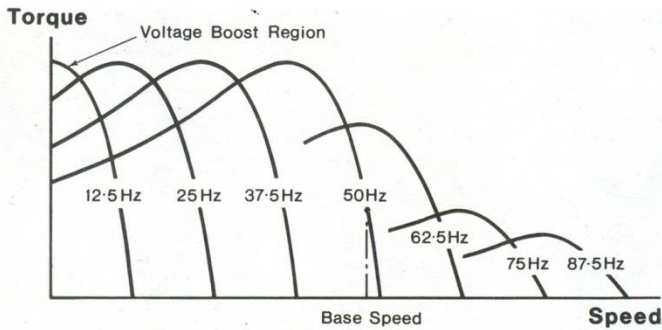
3상 IM의 torque-speed특성 과 운전제어



Torque-speed curves for inverter-fed induction motor with constant voltage/frequency ratio



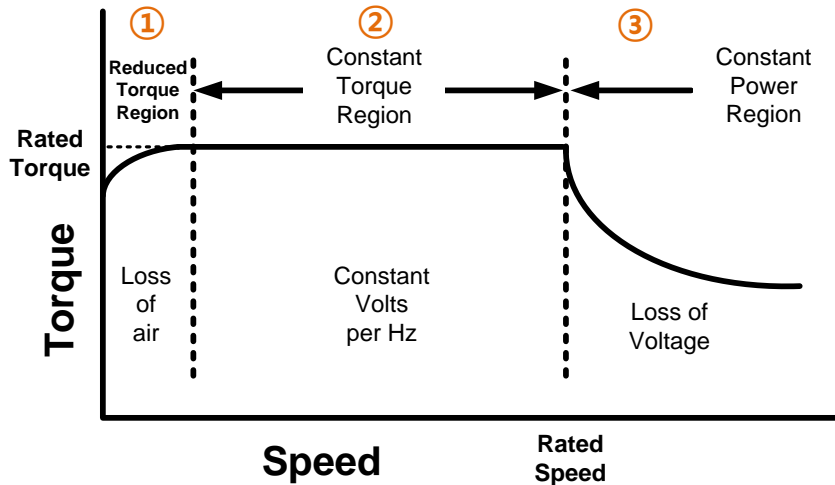
Constant torque, constant power and high-speed region



Typical torque-speed curves for inverter-fed induction motor with low-speed voltage boost, constant voltage/frequency ratio from low speed up to base speed, and constant voltage above base speed

유도 전동기의 주행-Torque-Speed 곡선

❖ 유도 전동기의 이론적 Torque-Speed 곡선



Theoretical capability curve

① Reduced Torque region: @ low speed

Rotor end ring의 cooling fan저속 - 냉각효과 저하
- Torque reduction

② Constant Torque region: @ Accelerating

V/F constant ratio - 일정토크로 구동 - 가속
정격속도(rated speed)에서 최대 상전압

③ Constant power region: @ Cruising

Sf일정제어-제한된 입력전압에서 모터 속도를 정격속도
이상으로 증가시키기 위한 약계자 제어 수행.

→ 입력전원의 고조파 성분에 의한 손실로 인해 실제 곡선의 형태가 달라짐.

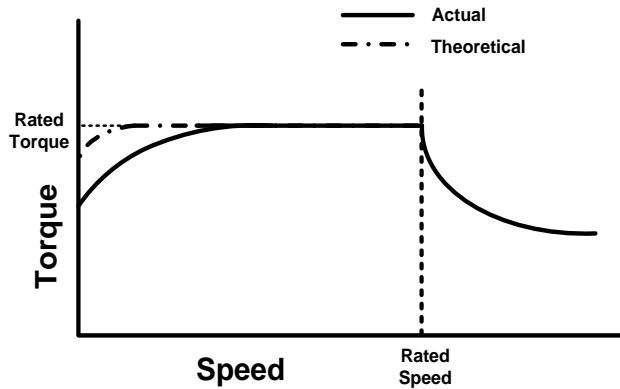
ASD에서의 고조파 손실에 의한 Torque-speed 특성 영향

❖ **Core loss** : 철손을 구성하는 손실들이 주파수의 비례 또는 제곱에 비례하여 증가하므로, 고조파의 영향이 크게 작용

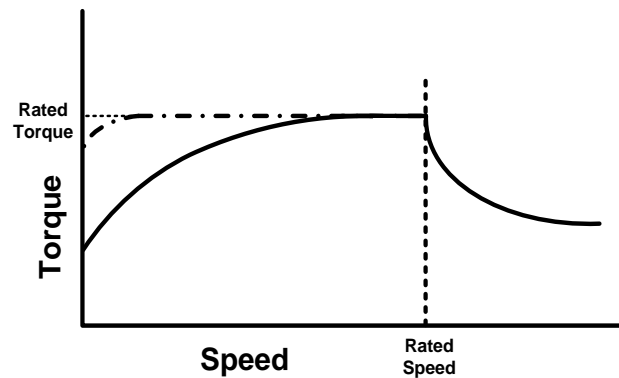
$$P_{core} = P_h + P_e + P_a = k_h f B^n + k_e f^2 B^2 + k_a f^{1.5} B^{1.5}$$

P_h 히스테리시스 손실 P_e 와전류 손실 P_a 이상와전류 손실

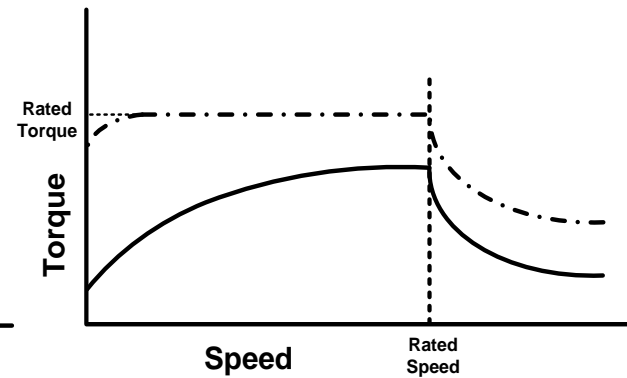
❖ **Theoretical Torque-Speed curve VS Actual Torque-speed curve**



Slight deviation



Moderate deviation



Considerable deviation

Chopping Frequency-인덕턴스

❖ 회로 인덕턴스에 영향을 주는 요인

1) Chopper 주파수

주파수 증가 → 표피효과(skin effect) & 와전류(eddy current) 증가
와전류에 의해 생성된 역자계는 전체 자속을 감소시킴 → 회로 인덕턴스 감소

2) 모터 전류 (입력전류)

전류 증가 → 계자 자속이 전기자 철심을 포화시킴 → 회로 인덕턴스 감소

일정 chopper 주파수: no-load → full load, 인덕턴스 20% 감소

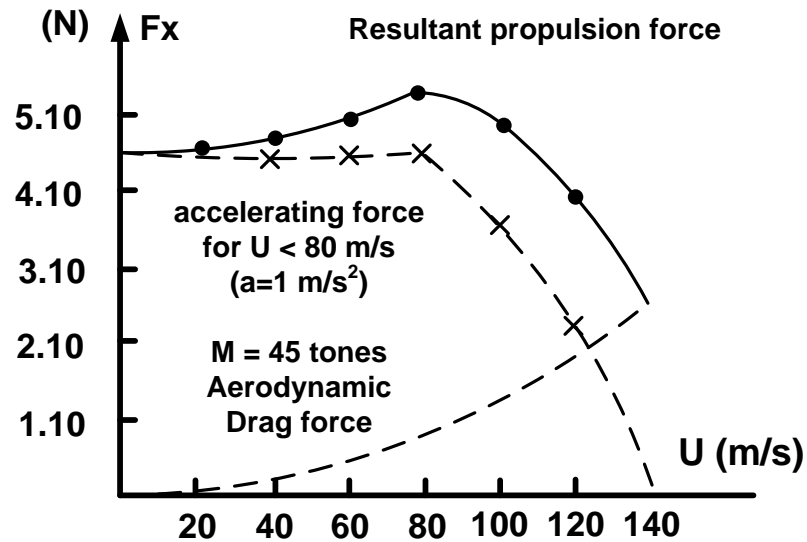
일정 부하 전류: chopper 주파수 20 Hz → 600 Hz, 인덕턴스 20% 감소

3) 보상권선의 유무, 정류자 권선, end turn, 브러쉬 이동 등

모터의 회로 인덕턴스- 저항이 변화하며,

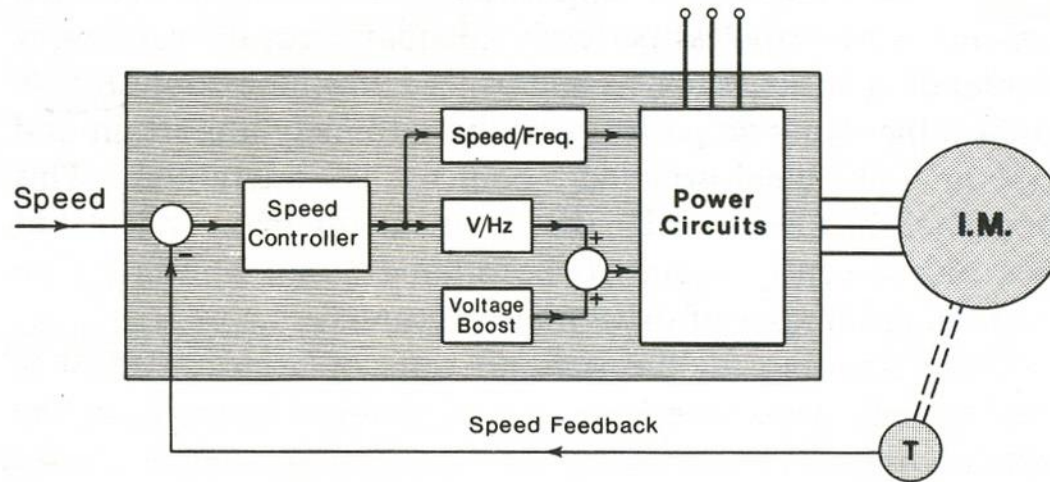
그에 따라 모터의 성능이 바뀐다-motor 설계 시 구동 방법을 고려한 설계 필요

차량추진용 motor의 정격산정시 손실을 고려하는 사례



Typical propulsion force profile for a 45-tones Maglev

NEMA 규격 3상 IM의 인버터 구동시의 closed loop control



Schematic diagram of closed-loop inverter-fed induction motor speed controlled drive with tacho feedback

3상 4극 IM의 Efficiency

Power, kW	Minimum efficiency, %
1.1	83.8
2.2	86.4
4	88.3
7.5	90.1
15	91.8
30	93.2
55	96.2
90	95.0

The minimum efficiency of four-pole three-phase induction motors (even if they are not IM, for all motor types) to be classified as Class 1 efficiency under EU regulations. Efficiency measured according to IEC 36.2

출처: Electric vehicle technology/Wiely 2003.

Induction Motor Drives

- 전동기의 속도는 전압의 주파수 변화로 조절
- Field orientation control (FOC)은 자계 제어로부터 토크 제어를 분리함
- 정격 속도 이상의 속도 범위 동작은 자속의 약화에 의하여 조절

장 점

- 간단한 구조, 신뢰성, 낮은 유지비
- 어려운 환경에서 동작 가능한 능력
- 브러시가 없어 DCmotor보다 최대속도 높음 (속도 향상으로 고출력 가능)

단 점

- 제어기 가격이 비쌈
- 임계 속도에서 breakdown torque 발생
- Breakdown torque로 인한 출력의 제한 발생
- 고속 범위에선 효율이 낮아짐

Application

- 강한 강성을 요구하는 곳
- 부하변동이 있는 곳
- 진동 및 소음이 적은 곳
- 고속 모터
- 터빈 발전기
- 2상 서보 모터
- 역운전이 필요한 곳
- 높은 온도 속 구동에서 신뢰성을 요하는 곳
- 군용장비
- 화학 무기
- Gyro 모터
- Eddy current break

Gas compressor, pump,
turbocharger

Advantages

- 기계적으로 높은 강성
- 정상 상태에서의 안정도
- 높은 신뢰성
- 모든 Speed 영역에서의 선형적인 토크 특성

Disadvantages

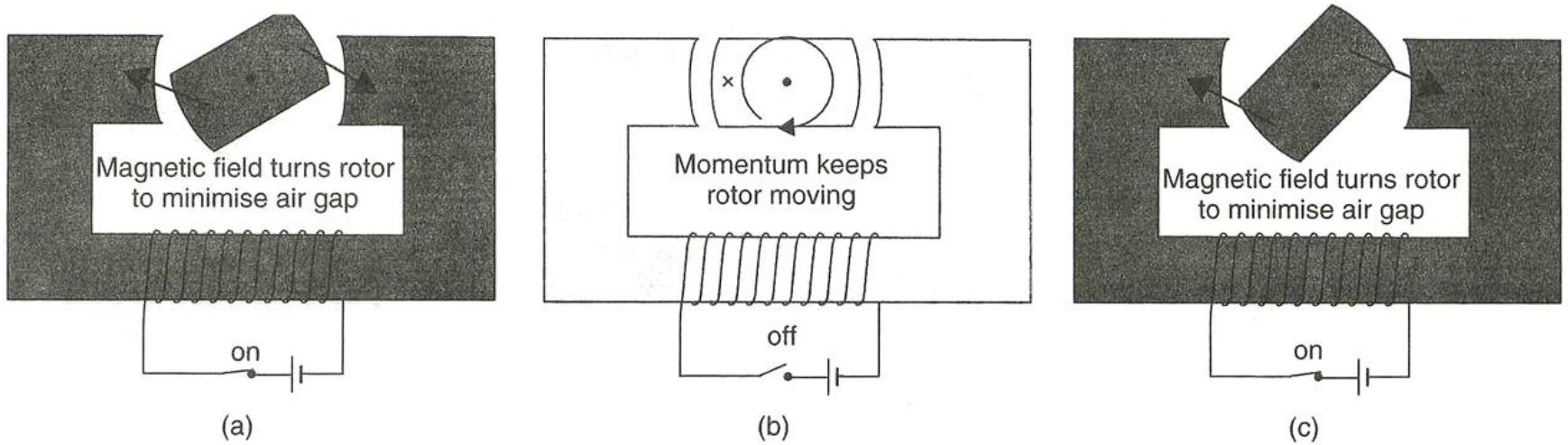
- 높은 Impedance
- 낮은 출력
- 낮은 효율
- 같은 Size의 Cage형과 비교해 높은 부하 Slip발생

Impedance 감소법

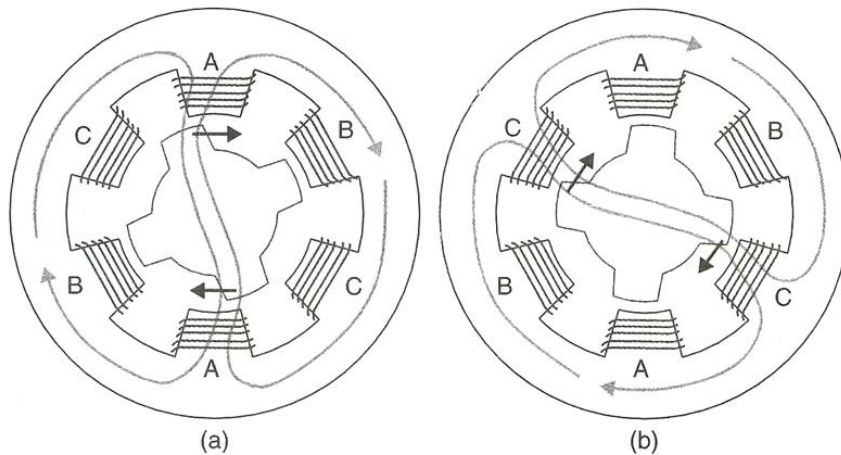
- 높은 투자율, 낮은 전도율을 갖는 강자성체로 Rotor 제작
- 적절한 강자성체와 높은 전도율을 갖는 비자성체의 재질로 Layer
- 최적의 system을 사용해 높은 Impedance의 영향 상쇄

SRM

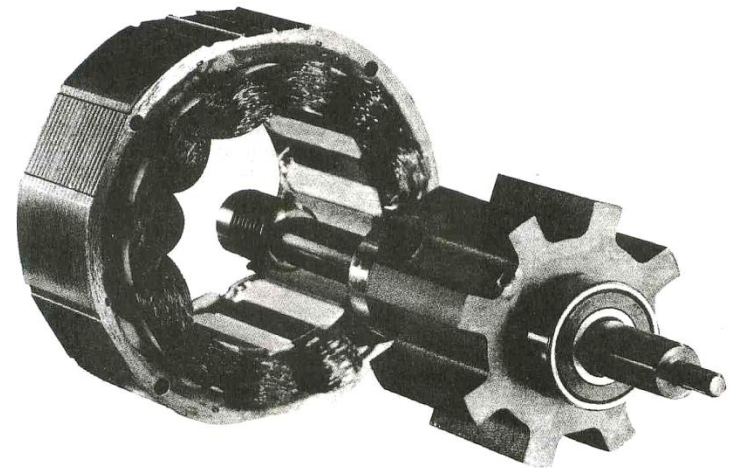
Switched Reluctance Motor Drives



The principle of operation of the switched reluctance motor

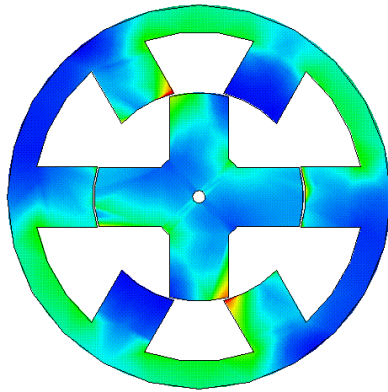
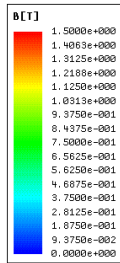


The operation of an SRM with a four salient pole rotor

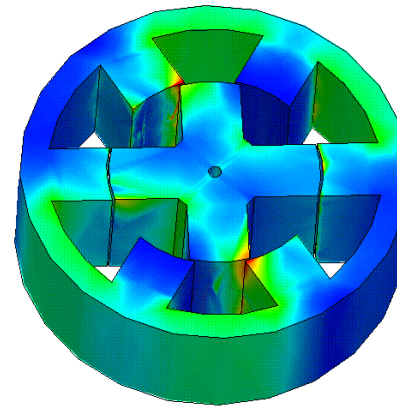
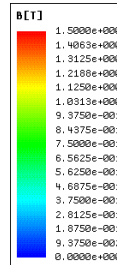


The rotor and stator from an SRM

Synchronous reluctance motor



Time=0.0025s



Time=0.0025s

Switched Reluctance Motor Drives

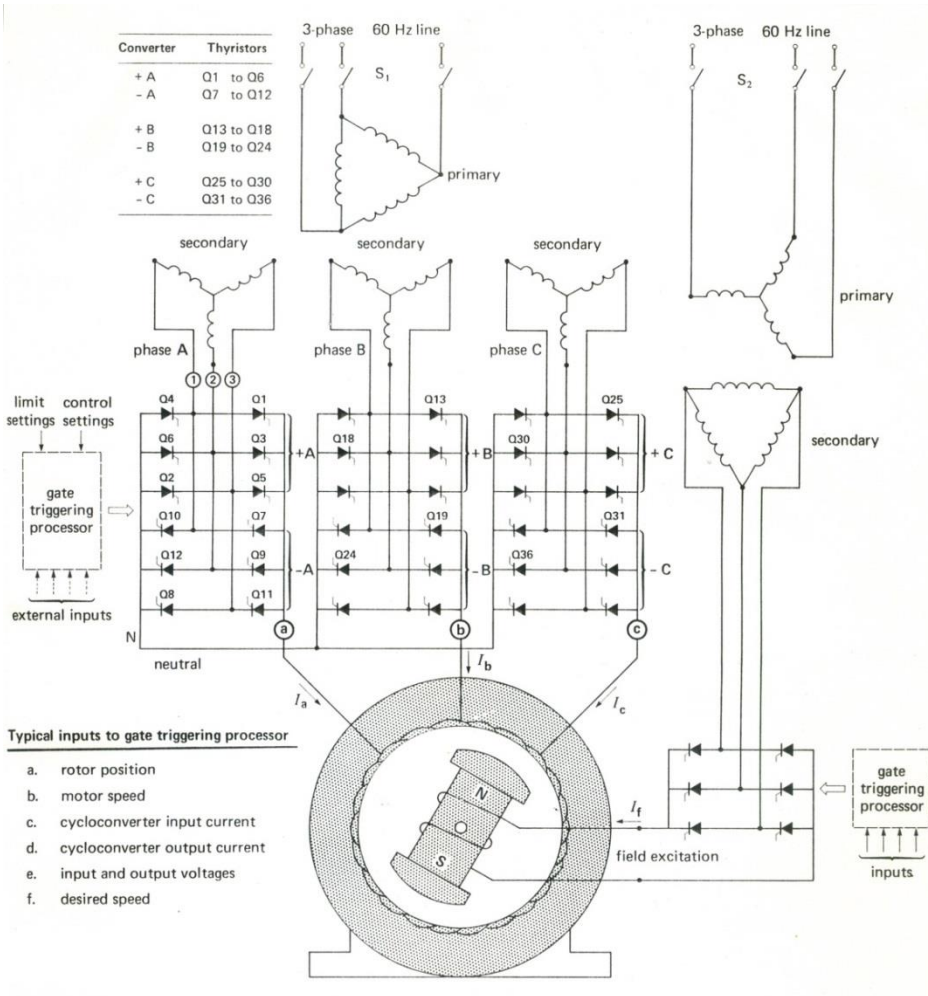
장 점

- 간단하고 견고한 구조
- 결함중의 작동
- 간단한 제어와 뛰어난 토크-속도특성
- 매우 긴 일정출력범위로 동작 가능
- 높은 기동 토크와 높은 토크-관성 비
- 빠른 가속과 고속 동작이 가능
- 회전자에 권선 또는 자석이 없어 냉각이 쉽고 온도에 둔감함

단 점

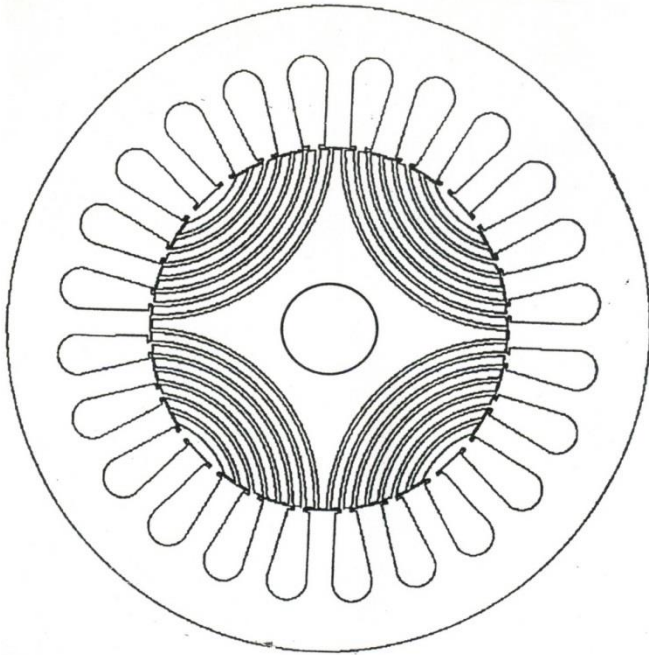
- 토크리플이 큼
 - 소음 발생
- # 단점사항이 EV용 전동기 응용에 금지될만한 사항은 아님

Synchronous motor drive concept

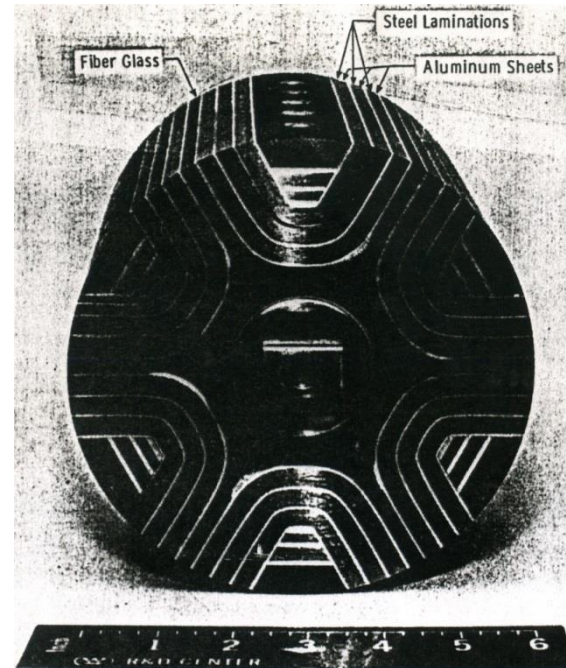


Cycloconverter driving a commutatorless dc machine. The output voltage associated with phase A is a slowly changing sine wave having a frequency of 6Hz, which is 10 times less than the supply frequency. Thyristors Q1 to Q12 are triggered so as to track the desired sine wave as closely as possible. This produces the saw-tooth output voltage shown in Fig. 22-30. The power factor at the input to the motor is assumed to be unity. The corresponding power factor at the input to the cycloconverter is less than unity, owing to the delayed firing angles.

Synchronous reluctance motor

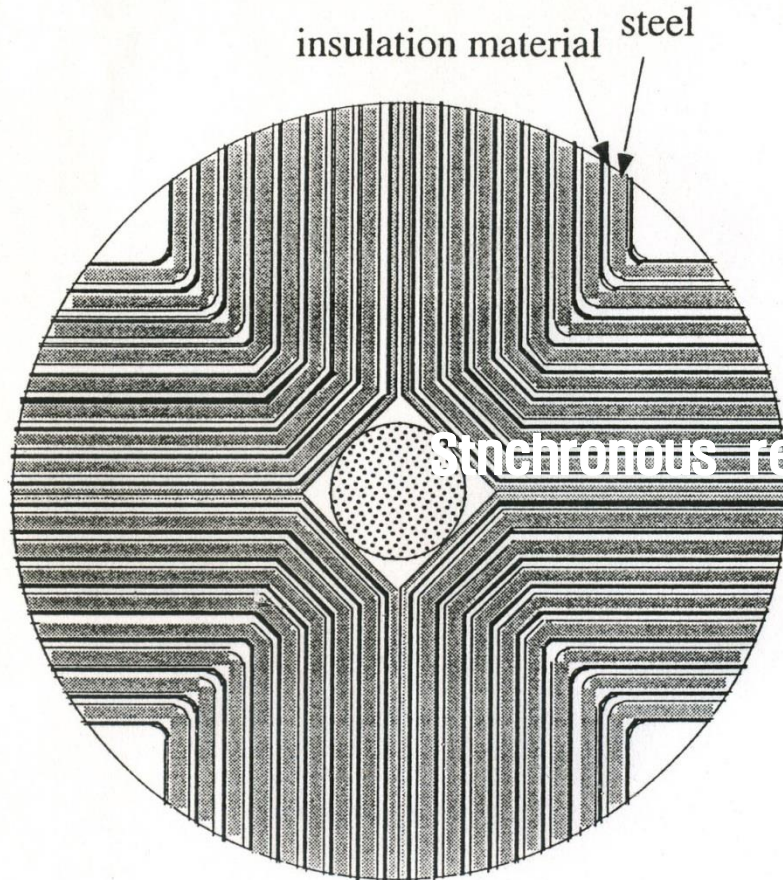


A synchronous reluctance motor with 24 stator slots

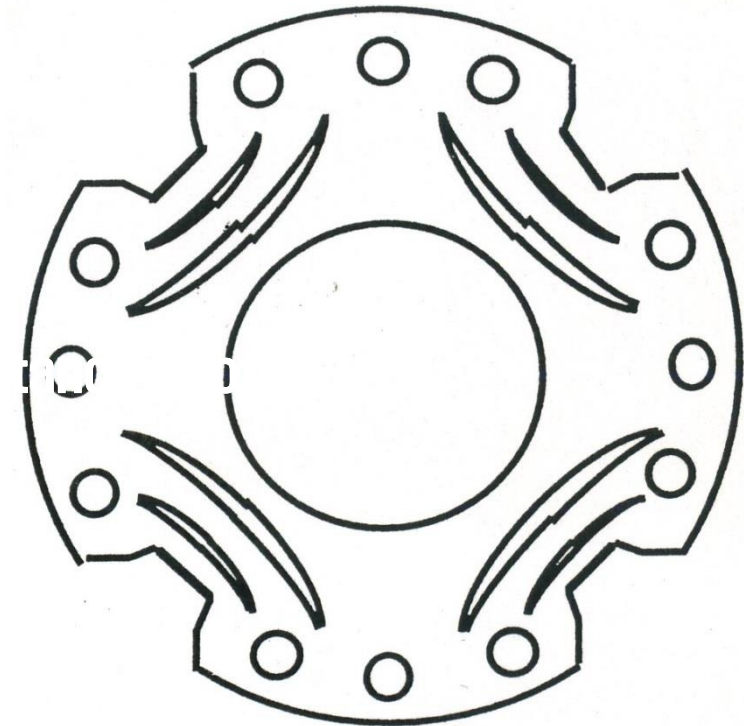


An ALA rotor showing laminated construction

Synchronous reluctance motor



Modern axially laminated rotor for synchronous reluctance machine

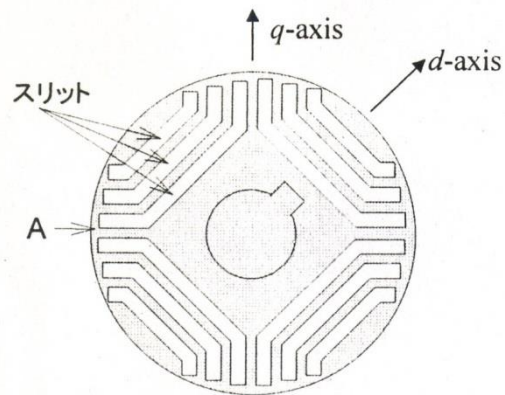


Flux barrier type rotor of reluctance motor of the sixties

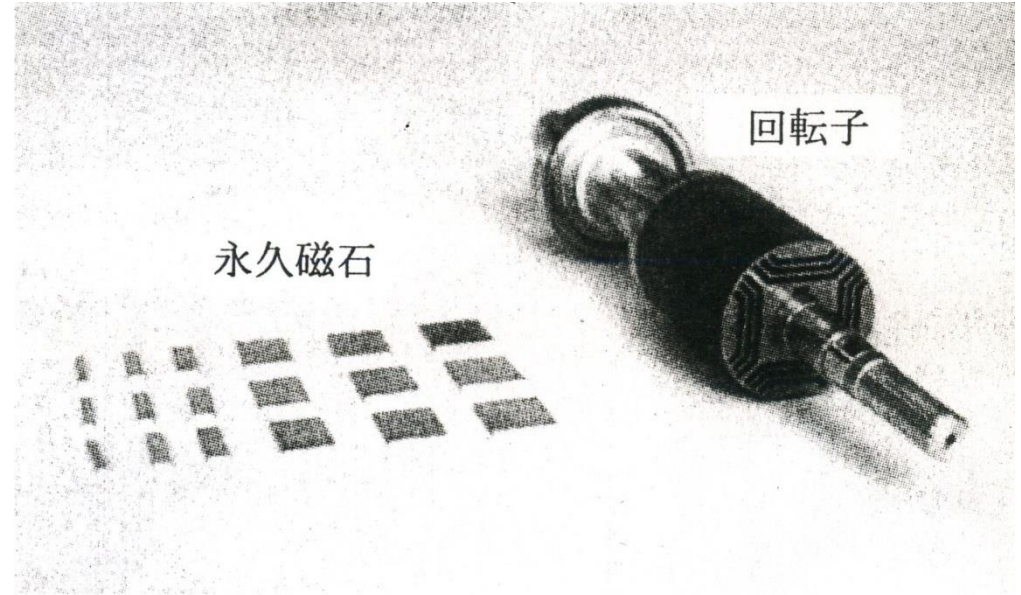
PM Assisted Synchronous reluctance motor

Specifications of prototype motors.

極対数	2
固定子外径	73 mm
固定子内径	30.5 mm
回転子外径	29.9 mm
エアギャップ長	0.3 mm
積厚	45.3 mm
定格電流	2.4 A
電機子抵抗	1.00 Ω

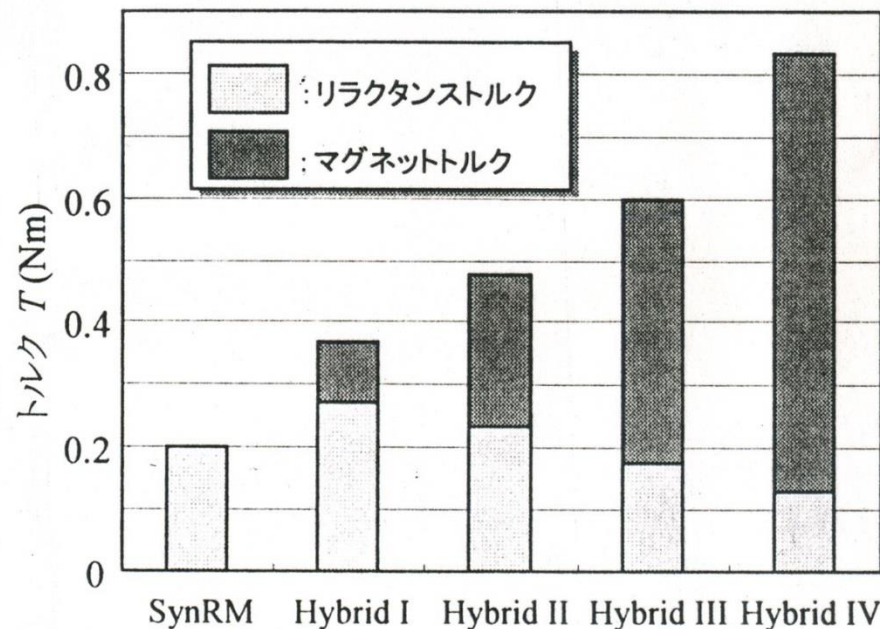
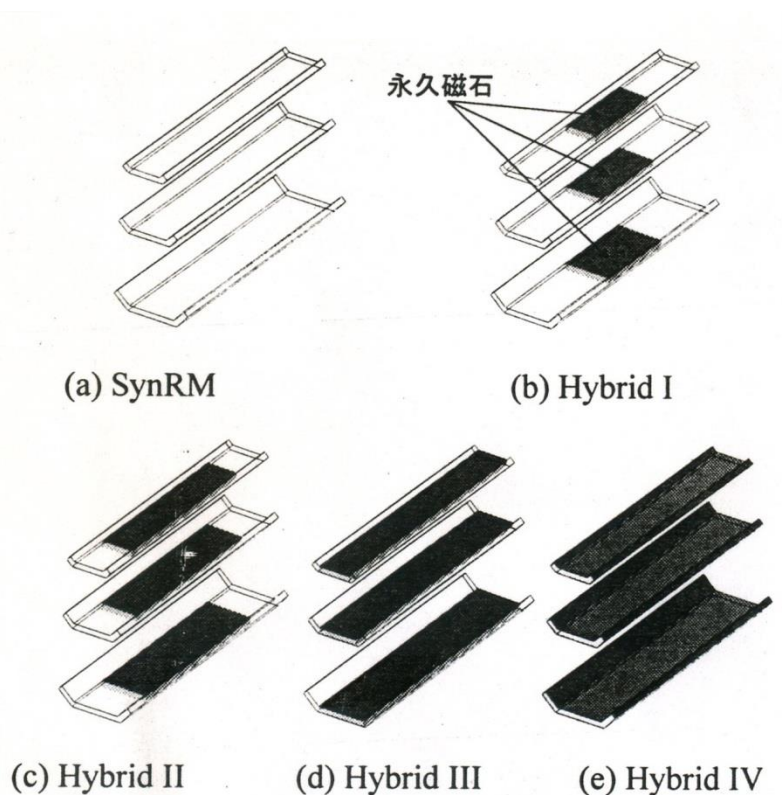


Cross-section of rotor.



Photograph of rotor and permanent magnet for prototype motor

PM Assisted Synchronous reluctance motor



Reluctance torque and magnet torque
in maximum torque production. ($I_e=2.4$ A)

Arrangement of permanent magnets in slit per pole

Switched Reluctance Motor Drives

- ...

장 점

- 간단하고 견고한 구조
- 결합중의 작동
- 간단한 제어와 뛰어난 토크-속도특성
- 매우 긴 일정출력범위로 동작 가능
- 높은 기동 토크와 높은 토크-관성 비
- 빠른 가속과 고속 동작이 가능
- 회전자에 권선 또는 자석이 없어 냉각이 쉽고 온도에 둔감함

단 점

- 토크리플이 큼
 - 소음 발생
- # 단점사항이 EV용 전동기 응용에 금지될만한 사항은 아님

전기 자동차 용 DC 모터

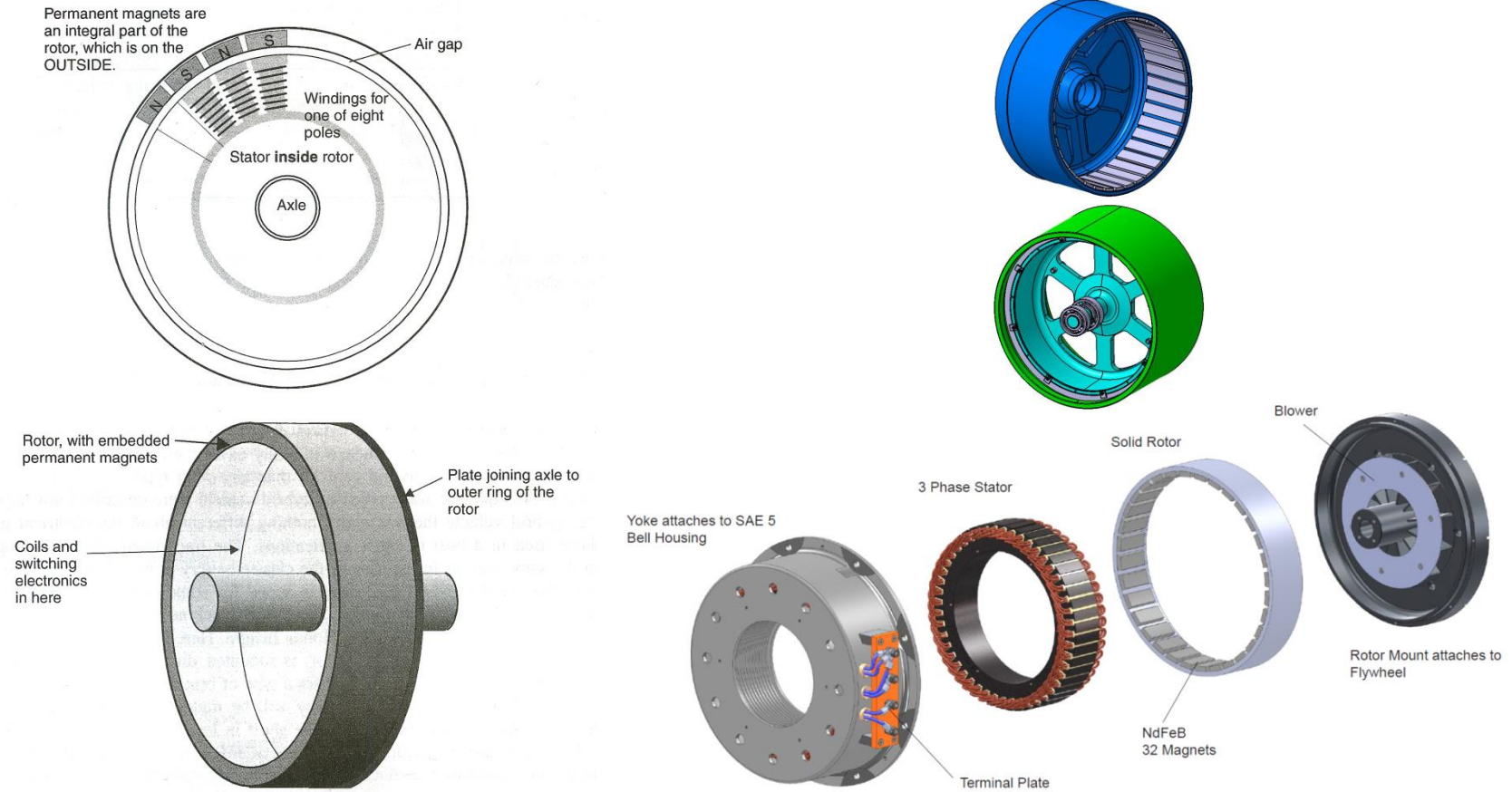


Diagram of inside out electric motor

Motor Type 선정

전기 자동차 용 DC 모터의 설계

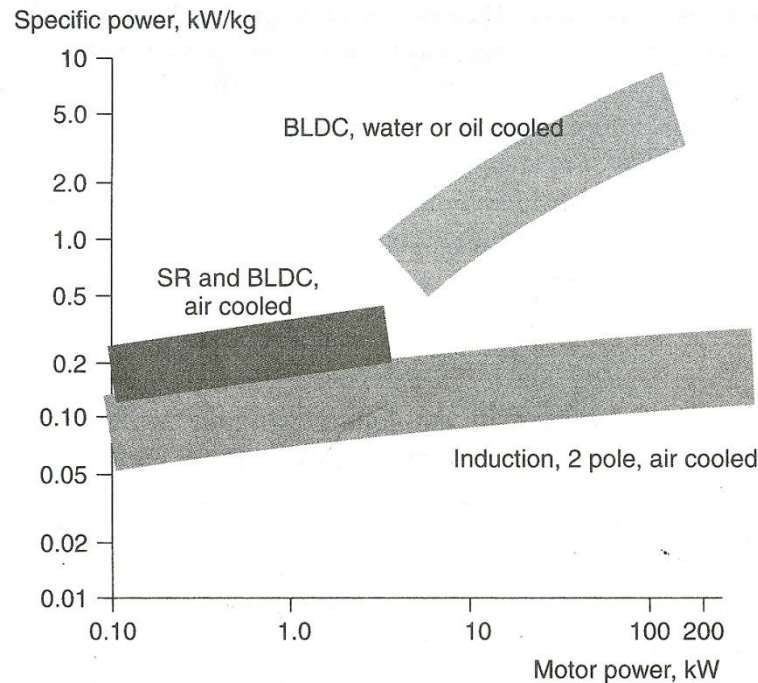


Chart to show the specific power of different types of electric motor at different powers. The power here is the continuous power. Peak specific powers will be about 50% higher. Note the logarithmic scales (this chart was made using data from several motor manufacturers.)

출처; Electric vehicle technology'Wiely 2003.

Power range for motors and drives

Motors							
	W		kW			MW	
	10	100	1	10	100	1	10
3-ph. Induction							
1-ph. Induction							
3-ph. Reluctance							
3-ph. Exc. Synch.							
3-ph. P.M. Synch.							
Conventional D.C.							
Ironless rotor D.C.							
Brushless D.C.							
Switched Rel.							
Stepping							

Controlled-Speed Drives						
	W		kW		MW	
	10	100	1	10	100	1
Variable Freq.* Cage Ind. Mot.						
Slipping Ind. Mot.						
Variable Freq. Synch. Motor						
Closed-loop Synch. Motor						
Conventional D.C.						
Brushless D.C.						
Switched Rel.						

Power ranges for the most common types of motor and drive.

*In the low and medium power ranges most of these drives use variable frequency inverters of the type discussed in Chapters 2 and 7, but in the higher power ratings (of a few hundred kW or more) and especially where a restricted speed range is acceptable, a cycloconverter is used to provide the variable-frequency supply

자료; Austin Hughes' Electric Motors and Drives' Newness

Evaluation of four types of motor drives for EVs

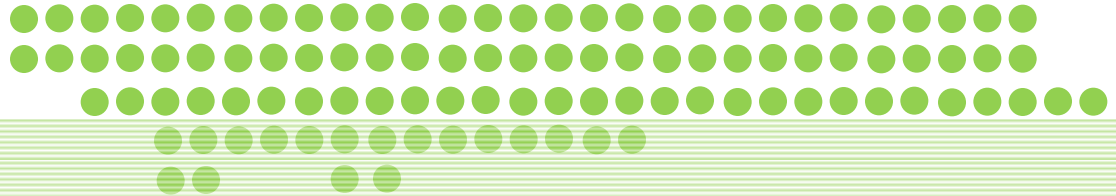
Index	DC motor	IM	BLDC motor	SRM
Efficiency	2	4	5	4.5
Weight	2	4	4.5	5
Cost	5	4	3	4
Total	9	12	12.5	13.5

- 각각 5점 만점으로 가장 높은 효율, 낮은 중량, 최저 비용을 나타냄
- DC 전동기는 가장 낮은 가격으로 EV용으로 계속 사용될 것이다
- BLDC 전동기는 효율성에서 가장 우수하다
- SRM은 가장 적은 무게를 갖는다

세가지 조건을 모두 합한 결과 EV용으로는 SRM이 가장 적절한 선택이다.

SRM은 냉각과 최대속도, 내고장성과 신뢰성 면에서도 다른 전동기와 비교하여 우위에 있다

자료 : 'Selection of Electric Motor Drives for Electric Vehicles'
2008 Australasian Universities Power Engineering Conference (AUPEC'08)



COMPARISON OF AC DRIVES FOR ELECTRIC VEHICLES - A REPORT ON EXPERT'S OPTION SURVEY -

L.CHANG, IEEE AES SYSTEMS MAGAZINE, AUGUST 1994

Background

- 배터리 기술 외에도, 차량 추진기술은 전기자동차의 범위와 성능에 영향을 미치는 또 다른 요소
- EV 추진시스템을 선택하는 것에서, 단가, 신뢰성, 효율, 유지보수, 내구성, 무게, 크기 및 소음 등의 기준이 주요 고려 사항
- DC모터는 낮은 안정성, 낮은 효율, 높은 운영비용, 큰 사이즈, 속도 제한으로 인해 EV에서는 AC모터 구동이 적합
- 최근에 Switched Reluctance Motor (SRM)도 EV에 대한 구동원으로 제안

Type		IM Drive		BLDC Drive	
		Motor	Converter	Motor	Converter
Parameters					
	Efficiency(%)	<1987	90.0-92.0	94.5	93.5-96.0
	1987-92	91.7-97.0	95.0	96.3-97.0	96.0
Power Density(kW/kg)	<1987	0.43-0.86	0.49-1.30	0.57-1.02	0.81-1.44
	1987-92	1.00	1.70	1.64-3.30	1.79
Cost(\$US/kW)	<1987	\$21-\$26	\$81-\$223	\$29-\$55	\$75-\$223
	1987-92	\$16-\$30	\$38-\$177		\$51-\$70
Size(l/kW)	<1987	0.12-0.57	0.72-1.33	0.15	
	1987-92	0.65	0.47	0.12	

Table 1. 기존의 EV용 AC Motor drive의 비교

BLDC Drive - 높은 효율, 높은 출력 밀도, 컴팩트한 사이즈

IM Drive - 고속 운전 가능, 단가가 저렴

SRM Drive - 낮은 단가, 작은 사이즈, 높은 안정성 > EV 구동의 대안 가능성

Motor	IM		SRM		BLDC	
	Scale	Deviation	Scale	Deviation	Scale	Deviation
Parameters	Scale	Deviation	Scale	Deviation	Scale	Deviation
Efficiency	8.1	0.8	8.2	0.9	9.1	0.8
Reliability	9.0	0.6	8.9	0.9	7.5	1.0
Power Density	7.7	1.4	7.9	0.9	8.6	1.1
Torque Ripple	6.8	2.5	7.6	2.1	7.5	2.1
Overload Capacity	8.5	0.9	7.8	1.0	7.9	1.4
Size	8.1	1.2	7.6	0.9	7.5	1.5
Cost	7.1	1.5	7.4	1.6	8.3	1.8
Max Speed	8.2	1.1	8.7	1.5	7.0	1.5

Table 2. IM, SRM, BLDC의 상대적 비교
23개국 전문가들의 설문조사 결과

IM – 낮은 효율, 높은 신뢰성, 낮은 출력밀도, 낮은 토크리플
높은 과부하용량, 큰 크기, 낮은 단가, 중간/높은 최대속도

SRM – 중간/낮은 효율, 중간 신뢰성, 중간 출력밀도, 높은 토크리플
중간/낮은 과부하용량, 중간/낮은 단가, 높은 최대속도

BLDC – 높은 효율, 낮은 신뢰성, 높은 출력밀도, 작은 크기
높은 단가, 낮은 최대속도

Converter	IM		SRM		BLDC	
	Scale	Deviation	Scale	Deviation	Scale	Deviation
Parameters	Scale	Deviation	Scale	Deviation	Scale	Deviation
Efficiency	8.4	0.5	8.6	0.9	8.8	0.6
Power Device	IGBT	0.5	IGBT	0.4	IGBT	0.3
Complexity	8.4	0.8	8.2	1.0	8.5	0.7
Power Density	7.9	0.8	8.2	1.2	8.5	1.0
Size	7.9	0.9	7.9	1.5	7.9	1.4
Cost	8.5	0.8	7.8	1.5	7.9	1.0

Table 3. IM, SRM, BLDC 컨버터의 비교
23개국 전문가들의 설문조사 결과

IM 컨버터 - 낮은 효율, 중간/높은 제어복잡성, 낮은 출력밀도, 높은 단가

SRM 컨버터 - 중간 효율, 낮은 제어복잡성, 중간 출력밀도, 낮은/중간 단가

BLDC 컨버터 - 고 효율, 중간/높은 제어복잡성, 높은 출력밀도, 낮은/중간 단가

EV 추진 시스템 선택 시 고려해야 할 기준

- 단가, 효율, 신뢰성, 유지보수 측면, 고속 구동, 넓은 속도범위 크기, 토크리플, 소음

낮은 단가, 높은 신뢰성, 넓은 속도범위, 위치센서 없이 구동가능,
낮은 토크리플, 낮은 소음 - 응답자의 72% IM 선호

작은 크기, 작은 중량, 고 효율, 높은 제어능력 - 응답자의 17% BLDC 선호

높은 신뢰성, 낮은 단가, 구조적 단순함, 고속 구동 - 응답자의 11% SRM 선호

Motor	IM		SRM		BLDC	
	Value	Deviation	Value	Deviation	Value	Deviation
Parameters	Value	Deviation	Value	Deviation	Value	Deviation
Efficiency(%)	93.4	1.8	93	2.8	95.2	1.6
Power Density(kW/kg)	0.7	0.5	0.7	0.6	1.2	1.1
Torque Ripple(%)	7.3	6.3	24.0	14.5	10.0	4.1
Overload Capacity(%)	243	56	186	57	212	54
Size(l/kW)	1.8	1.6	2.6	1.8	2.3	1.6
Cost(\$US/kW)	19.0	6.9	20.0	7.5	32.0	19.2
Max Speed(rpm)	12700	6300	12400	8260	9400	4670

Table 4. IM, SRM, BLDC의 양적 비교

Motor	IM		SRM		BLDC	
	Value	Deviation	Value	Deviation	Value	Deviation
Parameters	Value	Deviation	Value	Deviation	Value	Deviation
Efficiency(%)	95.0	2.1	96.1	2.0	95.9	1.9
Power Density(kW/kg)	1.8	1.2	1.3	0.2	1.7	0.6
Size(l/kW)	1.6	1.2	1.0	0.0	0.9	0.3
Cost(\$US/kW)	85	11	65	51	98	37

Table 5. IM, SRM, BLDC 컨버터의 양적 비교

Conclusion

- 전기자동차에 대한 관심이 커짐에 따라 고 효율, 높은 신뢰성, 낮은 단가를 갖는 AC drive에 대한 연구 및 개발이 요구됨
- IM drive와 BLDC drive는 기존의 EV에 적용, SRM drive는 대안으로 제안됨
- 대다수의 전문가에 따르면 IM drive는 낮은 단가, 높은 신뢰성, 높은 속도, 위치센서 없이 구동 가능, 낮은 토크리플과 노이즈를 이유로 EV 구동 시스템으로 적합
- BLDC drive는 소형화, 경량화 가능, 높은 효율을 이유로 EV 구동 시스템으로 적합