전기모터
메카트로닉스 시스템의 구성

Model of 기계 시스템

ECU

인터페이스 회로 (시그нал 컨디셔닝) → 마이컴 → 인터페이스 회로 (드라이빙 회로)

센서

액츄에이터 (구동기)

기계 시스템
Electric Motors: DC Motor

**Physical Basis: Lorentz force**

In physics, the Lorentz force is the force on a point charge due to electromagnetic fields. It is given by the following equation in terms of the electric and magnetic fields:

\[
F = q[E + (v \times B)],
\]

where
- \(F\) is the force (in newtons)
- \(E\) is the electric field (in volts per metre)
- \(B\) is the magnetic field (in teslas)
- \(q\) is the electric charge of the particle (in coulombs)
- \(v\) is the instantaneous velocity of the particle (in metres per second)
- \(\times\) is the vector cross product

The magnetic force component of the Lorentz force manifests itself as the force that acts on a current-carrying wire in a magnetic field. In that context, it is also called the Laplace force.

Electric Motors: DC Motor

Physical Basis: Fleming’s left hand rule for motors

The bottom line is that Fleming's left hand rule is used for electric motors, while Fleming's right hand rule is used for electric generators.

Fleming's left hand rule → Electric motor

Fleming's right hand rule → Generator

http://en.wikipedia.org/wiki/Fleming's_left_hand_rule_for_motors
http://www.magnet.fsu.edu/education/tutorials/java/handrules/index.html
Electric Motors: DC Motor

Physical Basis: Magnetic Line of Force

Right hand grip rule: Prediction of direction of field \( (B) \), given that the current \( I \) flows in the direction of the thumb. [http://en.wikipedia.org/wiki/Right-hand_rule](http://en.wikipedia.org/wiki/Right-hand_rule)

The interaction of the two magnetic fields (the magnetic field of the current-carrying wire and the magnetic field of the permanent magnet) produces a resultant field known as catapult field as shown in the figure above.

The non-uniform field produces the catapult force from the stronger field to the weaker field. [http://www.one-school.net/Malaysia/UniversityandCollege/SPM/revisioncard/physics/electromagnetism/catapultforce.html](http://www.one-school.net/Malaysia/UniversityandCollege/SPM/revisioncard/physics/electromagnetism/catapultforce.html)

Since the magnetic field lines of force are no longer straight lines, but curved to run under the electrical conductor, they are under tension (like stretched elastic bands), with energy stored up in the magnetic field. [http://en.wikipedia.org/wiki/Fleming's_left_hand_rule_for_motors](http://en.wikipedia.org/wiki/Fleming's_left_hand_rule_for_motors)
Electric Motors: DC Motor

**Direct Current (DC) Motor**

![Diagram of Stator and Rotor]

If a current carrying coil is placed in a magnetic field, a pair of forces will be produced on the coil. This is due to the interaction of the magnetic field of the permanent magnet and the magnetic field of the current carrying coil.

http://www.oneschool.net/Malaysia/UniversityandCollege/SPM/revisioncard/physics/electromagnetism/catapultforce.html
Electric Motors: DC Motor

**Commutator**

Electric motor converts **electrical energy to kinetic energy**. It consist a rectangular coil of wire placed between 2 permanent magnets. The coil are soldered to a copper split ring known as **commutator**. 2 carbon brushes are held against the commutator. The function of the **commutator** is to **change the direction of the current in the coil** and hence change the direction of the couple (the 2 forces in opposite direction) in every half revolution. This is to make sure that the coil can **rotate continuously**.

[http://www.oneschool.net/Malaysia/UniversityandCollege/SPM/revisioncard/physics/electromagnetism/catapultforce.html](http://www.oneschool.net/Malaysia/UniversityandCollege/SPM/revisioncard/physics/electromagnetism/catapultforce.html)

**Direct Current Electric Motor**

[http://youtu.be/Xi7o8cMPI0E](http://youtu.be/Xi7o8cMPI0E)

E-mail: hogijung@hanyang.ac.kr

http://web.yonsei.ac.kr/hgjung
Electric Motors: DC Motor

브러시 직류 모터의 구조

- 회전자는 코일 권선 (armature coil)을 갖고 있으며,
- 고정자는 영구자석 (계자극, field pole)이나 전자석 (field coil)으로 구성될 수 있다.
- 정류자 (commutator)

![Diagram of DC Motor](image)
Electric Motors: DC Motor

계자코일을 갖는 브러시 직류모터 [3]

(a) 직권형 (series wound motor)
(b) 분권형 (shunt wound motor)
(c) 복권형 (compound wound motor)
(d) 타려형 (separately excited motor)
Electric Motors: BLDC Motor [1]

http://ccie-accreditation.org/anonymizer-wind-inrunner-bldc/

http://dev.emcelettronica.com/you-use-bldc-motor-you-should-understand-how-it-works-brushless-dc-motors-roll

E-mail: hogijung@hanyang.ac.kr
http://web.yonsei.ac.kr/hgjung
Electric Motors: BLDC Motor [1]

http://www.open-sport.org/Buzz/assets_c/2011/05/4-pole-bldc-motor021804-5.html
Electric Motors: BLDC Motor [1]

Fig. 14. Stator winding dispositions. (a) Nonoverlapping winding. (b) Overlapping winding.

http://www.bavaria-direct.co.za/models/images/CD_Star_diagram.gif

Fig. 13. Schematic of PM brushless drive.
Electric Motors: BLAC Motor [1]

A 3-phase power supply provides a rotating magnetic field in an induction motor.

A symmetric **rotating magnetic field** can be produced with as few as three coils. The three coils will have to be driven by a **symmetric 3-phase AC sine current system**, thus each phase will be shifted 120 degrees in phase from the others.

Sine wave current in each of the coils produces sine varying magnetic field on the rotation axis. Magnetic fields add as vectors.

Vector sum of the magnetic field vectors of the stator coils produces a **single rotating vector** of resulting rotating magnetic field.
Electric Motors: Induction Motor [1]

Physical Basis: Faraday’s Law of Induction

Faraday's law of induction is a basic law of electromagnetism relating to the operating principles of transformers, inductors, and many types of electrical motors and generators. The law states that:

"The induced electromotive force (EMF) in any closed circuit is equal to the time rate of change of the magnetic flux through the circuit."

Or alternatively:

“The EMF generated is proportional to the rate of change of the magnetic flux.”

Electric Motors: Induction Motor [1]

Physical Basis: Lenz’s Law

Lenz's law is a common way of understanding how electromagnetic circuits must always obey Newton's third law and The Law of Conservation of Energy. Lenz's law is named after Heinrich Lenz, and it says:

"An induced current is always in such a direction as to oppose the motion or change causing it“

http://en.wikipedia.org/wiki/Lenz%27s_law

Electric Motors: Induction Motor [1]

Physical Basis: Lenz’s Law

Eddy Current Tubes
http://youtu.be/nrw-i5Ku0mI

MRI MAGIC
http://youtu.be/fxC-AEC0ROk

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http://web.yonsei.ac.kr/hgjung
Electric Motors: Induction Motor [1]

Principle of Operation

The induction motor does not have any permanent magnets on the rotor; instead, a current is induced in the rotor. To achieve this, stator windings are arranged around the rotor so that when energised with a polyphase supply they create a rotating magnetic field pattern which sweeps past the rotor. This changing magnetic field pattern induces current in the rotor conductors. These currents interact with the rotating magnetic field created by the stator and in effect causes a rotational motion on the rotor.

AC Induction Motor
http://youtu.be/UsT-qWAzTHg
Electric Motors: Induction Motor [1]

Structure

The most common rotor is a squirrel-cage rotor. It is made up of bars of either solid copper (most common) or aluminum that span the length of the rotor, and those solid copper or aluminium strips can be shorted or connected by a ring or some times not, i.e. the rotor can be closed or semiclosed type. The rotor bars in squirrel-cage induction motors are not straight, but have some skew to reduce noise and harmonics.


Animation of a squirrel-cage AC motor

Squirrel Cage Motors.MPG
http://youtu.be/3MbP4t920Is

http://web.yonsei.ac.kr/hgjung
Electric Motors: SR Motor [1]

Physical Basis: Magnetic Reluctance

Magnetic reluctance, or magnetic resistance, is a concept used in the analysis of magnetic circuits. It is analogous to resistance in an electrical circuit, but rather than dissipating magnetic energy it stores magnetic energy. In likeness to the way an electric field causes an electric current to follow the path of least resistance, a magnetic field causes magnetic flux to follow the path of least magnetic reluctance.

Variation of reluctance is the principle behind the reluctance motor (or the variable reluctance generator) and the Alexanderson alternator. Another way of saying this is that the reluctance forces strive for a maximally aligned magnetic circuit and a minimal air gap distance.

http://en.wikipedia.org/wiki/Magnetic_reluctance
Electric Motors: SR Motor

직선 운동 기계 [4]

인덕턴스 $L$, 쇄교자속 $\lambda$, 전기자 전류 $i$, 자기저항 $R$

$$L = \frac{\lambda}{i}, \quad e = \frac{d\lambda}{dt}, \quad R \propto \frac{1}{L}$$

자계 에너지 변화량 $dW_f$가 전기 에너지 변화량 $dW_e$과 같다고 가정하면,

$$dW_f = dW_e = Pdt = iedt = id\lambda$$

$$W_f = \int_0^i id\lambda$$

자계 에너지

$$W_f' = \int_0^i \lambda di$$

Coenergy
직선 운동 기계 [4]

코일에 전류 $i$를 흘리면, 운동자가 $x_1$에서 $x_2$로 움직인다.

자기저항이 큰 공극이 작아지면, 동일한 전류 $i$로 더 큰 쇄교자속을 얻을 수 있다.
직선 운동 기계 [4]

운동자가 매우 빨리 움직인 경우
쇄교자속 $\lambda$의 변화는 없다고 가정.
동작점은 $A \rightarrow C \rightarrow B$와 같이 이동.

$d\lambda = 0$ 이므로, 전기 에너지 변화 $(id\lambda)$는 없으며, 이동에 필요한 기계에너지는 모두 자계 에너지가 공급. 이는 OAC의 면적.

$$dW_m = -dW_f$$

힘은 거리당 한 일이므로,

$$f_m = \frac{\partial W_m}{\partial x} = -\frac{\partial W_f}{\partial x} (i, x), \lambda = \text{constant}$$

따라서, 힘의 방향은 자계 에너지가 감소하는 방향이다.
Electric Motors: SR Motor

직선 운동 기계 [4]

운동자가 매우 빠르게 움직인 경우

쇄교자속 $\lambda$의 변화는 없다고 가정.

$$f_m = \frac{\partial W_m}{\partial x} = - \frac{\partial W_f(i,x)}{\partial x}, \lambda = \text{constant}$$

$$W_f = \int i \, d\lambda = \int \frac{\lambda}{L(x)} \, d\lambda = \frac{\lambda^2}{2L(x)} = \frac{1}{2} L(x)i^2$$

$$f_m = - \frac{\partial}{\partial x} \left( \frac{1}{2} \frac{\lambda^2}{L(x)} \right), \lambda = \text{constant}$$

$$= \frac{\lambda^2}{2L(x)^2} \frac{\partial L(x)}{\partial x} = \frac{1}{2} i^2 \frac{\partial L(x)}{\partial x}$$

자기 회로에서 힘은 인덕턴스가 증가하는 방향으로 작용한다.
직선 운동 기계 [4]

운동자가 매우 느리게 움직인 경우
전류 \( i \)의 변화는 없다고 가정.
동작점은 \( A \rightarrow B \)와 같이 이동.
전기 에너지 변동량은
\[
dW_e = eidt = id\lambda = i(\lambda_2 - \lambda_1)
\]
와 같는데, 이는 ABEF의 면적과 같다.
자계 에너지 변동량은 OBE면전에서 OAF의 면적을 뺀 것과 같다.
기계 에너지 변동량은
\[
dW_m = dW_e - dW_f = dW_f'
\]
이는 OAB의 면적과 같다. 따라서, 힘의 방향은 coenergy가 증가하는 방향이다.

그림 1.17 \( \lambda - i \) 곡선 (운동자가 매우 느리게 이동)
Electric Motors: SR Motor

직선 운동 기계 [4]

운동자가 매우 느리게 움직인 경우 전류 \( i \)의 변화는 없다고 가정. \( W_f = W_f' \)인 선형 시스템 가정.

\[
f_m = \frac{\partial W_m}{\partial x} = \frac{\partial W_f'(i, x)}{\partial x} = \frac{\partial W_f(i, x)}{\partial x}, \quad i = \text{constant}
\]

\[
W_f = \int i d\lambda = \int \frac{\lambda}{L(x)} d\lambda = \frac{\lambda^2}{2L(x)} = \frac{1}{2} L(x) i^2
\]

\[
f_m = \frac{\partial W_f}{\partial x} = \frac{\partial}{\partial x} \left( \frac{1}{2} L(x) i^2 \right), \quad i = \text{constant}
\]

\[
= \frac{1}{2} i^2 \frac{\partial L(x)}{\partial x}
\]

자기 회로에서 힘은 인덕턴스가 증가하는 방향으로 작용한다. 인덕턴스와 자기저항은 역수 관계이므로, 자기 회로에서 힘은 자기 저항이 감소하는 방향으로 작용한다.
Electric Motors: SR Motor [1]

Structure

The **stator** consists of multiple salient (i.e., projecting) electromagnet poles, similar to a wound field brushed DC motor.

The **rotor** consists of soft magnetic material, such as **laminated silicon steel**, which has multiple projections acting as salient magnetic poles through magnetic reluctance.

The number of rotor poles is typically less than the number of stator poles, which minimizes torque ripple and prevents the poles from all aligning simultaneously—a position which can not generate torque.

Electric Motors: SR Motor [1]

Principle of Operation

When a rotor pole is equidistant from the two adjacent stator poles, the rotor pole is said to be in the "fully unaligned position". This is the position of maximum magnetic reluctance for the rotor pole.

In the "aligned position", two (or more) rotor poles are fully aligned with two (or more) stator poles, (which means the rotor poles completely face the stator poles) and is a position of minimum reluctance.

When a stator pole is energized, the rotor torque is in the direction that will reduce reluctance. Thus the nearest rotor pole is pulled from the unaligned position into alignment with the stator field (a position of less reluctance.)
Electric Motors: SR Motor [1]

**Principle of Operation**

In order to sustain rotation, the stator field must rotate in advance of the rotor poles, thus constantly "pulling" the rotor along.

Some motor variants will run on 3-phase AC power.

Most modern designs are of the switched reluctance type, because electronic commutation gives significant control advantages for motor starting, speed control, and smooth operation (low torque ripple).

[Diagram showing phase waveforms and a switched reluctance motor structure]

Electric Motors: SR Motor [1]

Simulation of a Switched Reluctance Motor

http://youtu.be/LXJUYumwh-k
Electric Motors: SR Motor [1]

Step Motor
Stepper motors have multiple "toothed" electromagnets arranged around a gear-shaped piece of iron.

To make the motor shaft turn, first one electromagnet is given power, which makes the gear's teeth magnetically attracted to the electromagnet's teeth. When the gear's teeth are aligned to the first electromagnet, they are slightly offset from the next electromagnet. When the next electromagnet is powered and the first is turned off, the gear rotates slightly to align with the next one, and from there the process is repeated.

Each of those small rotations is called a "step," with a specific number of steps making a full rotation. In this way, the motor can be turned by a precise angle.

http://keebraparkshs.eq.edu.au/EUREKA2009-tidalpower/BackgroundInformation.htm
## Electric Motors

<table>
<thead>
<tr>
<th>Rotor</th>
<th>Commutation</th>
<th>Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>No commutation</td>
<td>AC</td>
</tr>
<tr>
<td></td>
<td>Electro mechanical</td>
<td>DC</td>
</tr>
<tr>
<td>Magnet</td>
<td>Electronic</td>
<td>DC</td>
</tr>
<tr>
<td>Copper</td>
<td>Stator coils driven by line voltage</td>
<td>BLAC motor</td>
</tr>
<tr>
<td></td>
<td>Motor has a commutator to switch power to rotor coils</td>
<td>Induction motor (Squirrel cage)</td>
</tr>
<tr>
<td></td>
<td>Switches power to stator coils, rotor position by sensing, either by discrete sensors, or feedback from coils, or open loop</td>
<td>Electronic switches</td>
</tr>
</tbody>
</table>

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

**Fig. 1.** Energy management systems of an engine-based HEV 
(a) without dc-dc converter and (b) with dc-dc converter.

**Fig. 2.** Energy management systems of the FCV (a) without dc-dc converter and (b) with dc-dc converter.
DC–DC Converter [2]

Fig. 3. Power converter sizing for (a) high-voltage fuel cell supplemented with low-voltage battery and (b) low-voltage fuel cell supplemented with high-voltage battery.
DC–DC Converter [2]

**Fig. 6.** Basic isolated bidirectional dc–dc converter configurations. (a) LV current source and HV voltage source. (b) LV voltage source and HV current source.
**Torque-Speed Profile**

**Ideal Torque-Speed Profile for Traction [5]**

The ideal torque (power)-speed profile for traction application is the constant power in all the speed ranges. A well-controlled electric motor drive has the torque-speed profile close to the ideal one as below.

\[
P = \frac{W}{t} = \frac{F x}{t} = F \frac{x}{t} = F v
\]

원운동일 때,

\[
P = F v = F \frac{r \theta}{t} = Fr \frac{\theta}{t} = T \omega
\]
브러시 직류 모터의 Torque-Speed Profile [3]

자속밀도 $B$, 도선의 길이 $L$, 도선의 폭 $b$, 전류 $i$일 때, $N$개의 도선이 받는 토크

$$T = N B i L = N B b L i = k_i i$$

전기코일이 자기장에서 회전하면 전자기 유도가 발생한다. 이때, 역기전력(back e.m.f) $v_b$는 코일에 링크된 자속의 변화율에 비례하므로, 회전속도 $\omega$에 비례한다.

$$v_b = k_v \omega$$

전기자 코일의 인덕턴스를 무시한다면,

$$i = \frac{V - v_b}{R} = \frac{V - k_v \omega}{R} \quad T = k_i i = \frac{k_i}{R} (V - k_v \omega)$$
브러시 직류 모터의 Torque-Speed Profile [3]

\[ T = k_i i = \frac{k_i}{R} (V - k_v \omega) \]

Constant power가 아님에 유의할 것.
DC 모터 구동계의 수학적 모델 [6]

계자 전류제어 모터
전기자 전류제어 모터
발생토크
\[ T_m(t) = K_1 \phi_i(t) = K_1 K_f i_f(t) = K_m i_a(t) \]
\[ T_m(s) = K_m I_a(s) \ldots (1) \]
전기기에 가해진 전압이 \( V_a \), 역기전력 전압 (back-emf voltage) 이 \( V_b \) 라 할 때,
\[ V_a(s) = (R_a + L_a s) I_a(s) + V_b(s) \]
\[ V_b(s) = K_b \omega(s) \text{ 이므로,} \]
\[ V_a(s) = (R_a + L_a s) I_a(s) + K_b \omega(s) \ldots (2) \]
모터의 회전 운동방정식은
\[ J_m s \omega(s) + b_m \omega(s) = T_m(s) - T_L(s) \ldots (3) \]
디지털 모터 구동계의 수학적 모델 [6]

식(2)로부터
\[ V_a(s) = (R_a + L_a s)I_a(s) + K_b \omega(s) \]
\[ I_a(s) = \frac{V_a(s) - K_b \omega(s)}{R_a + L_a s} \]

이것을 식(1)에 대입하면,
\[ T_m(s) = K_m I_a(s) = K_m \frac{V_a(s) - K_b \omega(s)}{R_a + L_a s} \]

이것을 식(3)에 대입하면,
\[ J_m s \omega(s) + b_m \omega(s) = T_m(s) - T_L(s) = K_m \frac{V_a(s) - K_b \omega(s)}{R_a + L_a s} - T_L(s) \]
DC 모터 구동계의 수학적 모델 [6]

이것을 $\omega(s)$에 대해 풀면,

$$J_m s \omega(s) + b_m \omega(s) = K_m \frac{V_a(s) - K_b \omega(s)}{R_a + L_a s} - T_L(s)$$

$$\omega(s)(J_m s + b_m)(R_a + L_a s) = K_m (V_a(s) - K_b \omega(s)) - T_L(s)(R_a + L_a s)$$

$$\omega(s)\{[J_m s + b_m](R_a + L_a s) + K_m K_b\} = K_m V_a(s) - T_L(s)(R_a + L_a s)$$

$$\omega(s) = \frac{K_m V_a(s) - T_L(s)(R_a + L_a s)}{(J_m s + b_m)(R_a + L_a s) + K_m K_b}$$

$$= \frac{K_m}{(J_m s + b_m)(R_a + L_a s) + K_m K_b} V_a(s) - \frac{(R_a + L_a s)}{(J_m s + b_m)(R_a + L_a s) + K_m K_b} T_L(s)$$

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DC 모터 구동계의 수학적 모델 [6]

[그림 4.20] 모터의 공급전압과 출력토큰 및 속도와의 관계
참고자료


