

본 사이트에서 수업 자료로 이용되는 저작물은 **저작권법 제25조 수업목적저작물 이용 보상금제도**에 의거, **한국복제전송저작권협회와 약정을 체결하고** 적법하게 이용하고 있습니다. 약정범위를 초과하는 사용은 저작권법에 저촉될 수 있으므로 **수업자료의 대중 공개·공유 및 수업 목적 외의 사용을 금지합니다.**

2014. 03. 24.

동아대학교·한국복제전송저작권협회

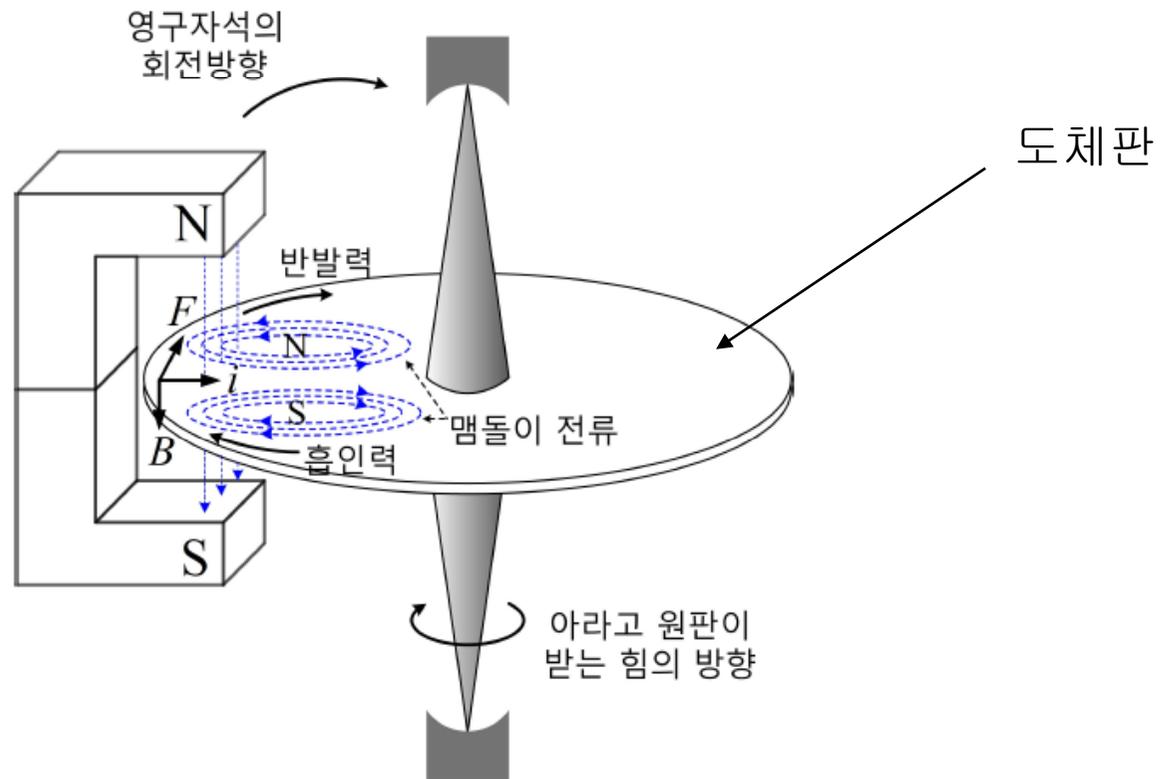
# 유도기

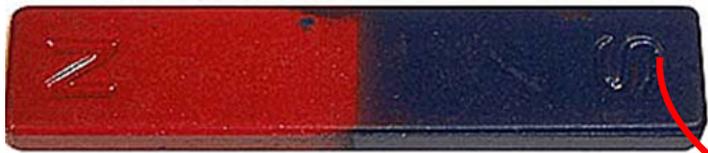
1. 유도기의 원리 및 구조 (Principle and structure of induction machine)
2. 회전자계 (Rotating magnetic field)
3. 유도기의 등가회로 (Equivalent circuit of induction motor)
4. 유도기의 특성 ( Characteristics of induction motor)
5. 유도기의 속도제어 (Speed control of induction motor)
6. 유도기의 회로정수 측정 (Measurement of equivalent circuit parameters of induction motor)

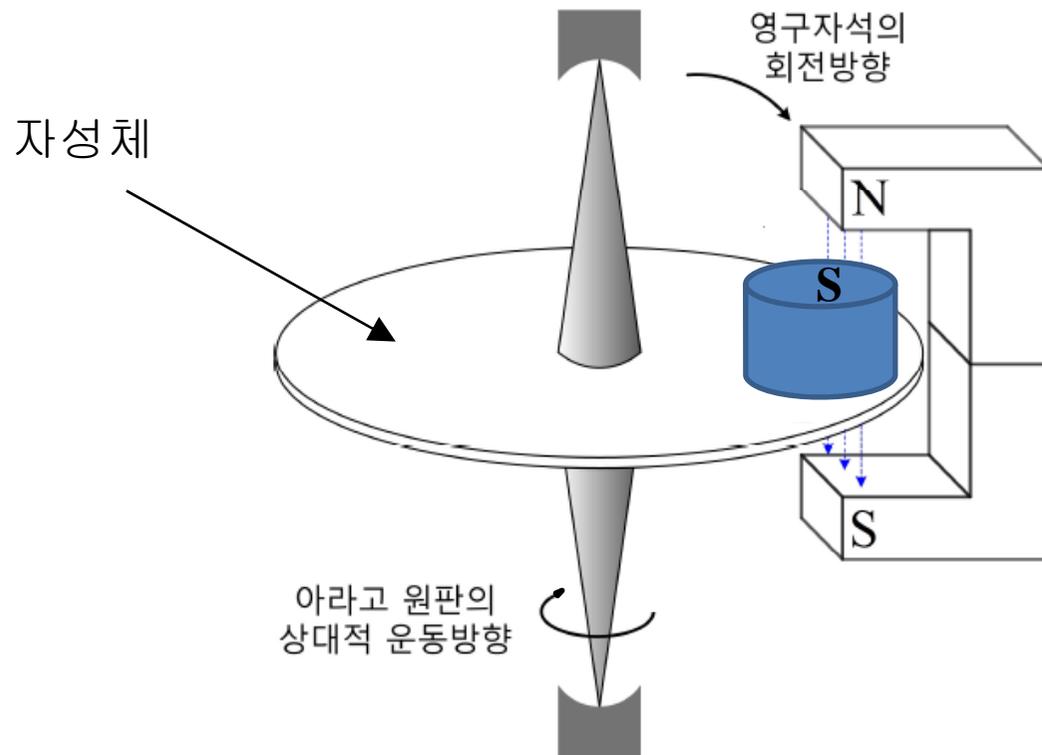
# 1. 유도기의 원리 및 구조

## (1) 유도기의 원리

### 1) 아라고의 원판 (Arago's disk, 1824년)





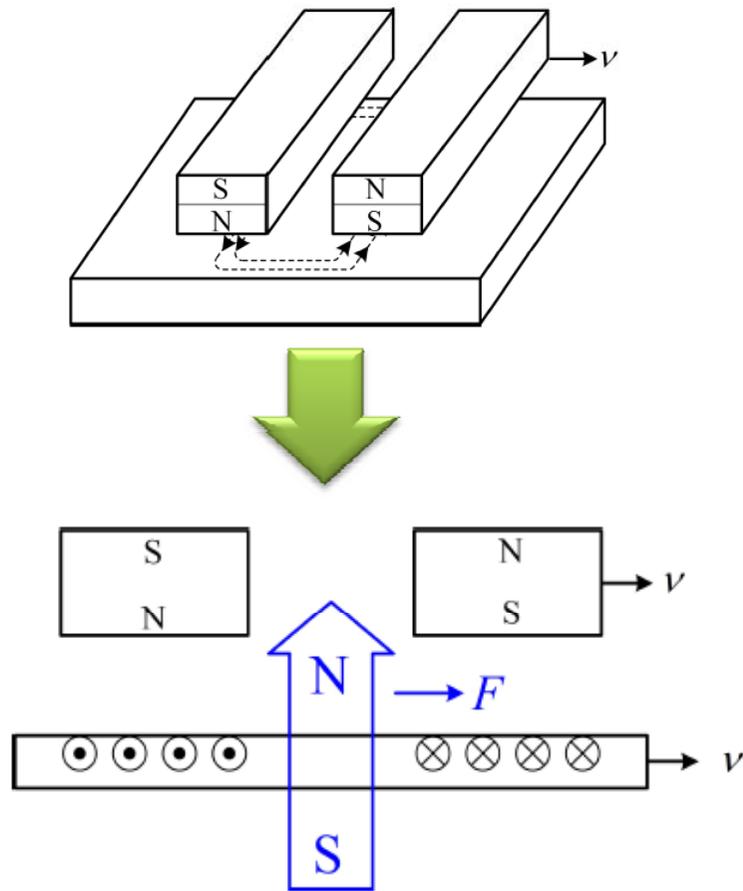


※ 유도기 VS 동기기

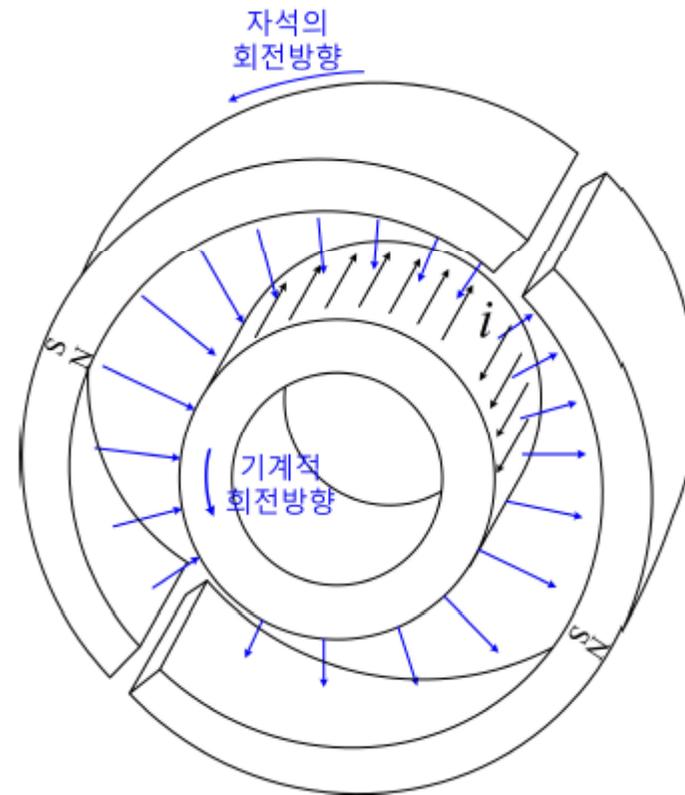
유도기 : 외부 기자력축의 회전속도 > 도체(깁통)의 회전속도

동기기 : 외부 기자력축의 회전속도 = 도체(깁통)의 회전속도 ⇒ 동기속도

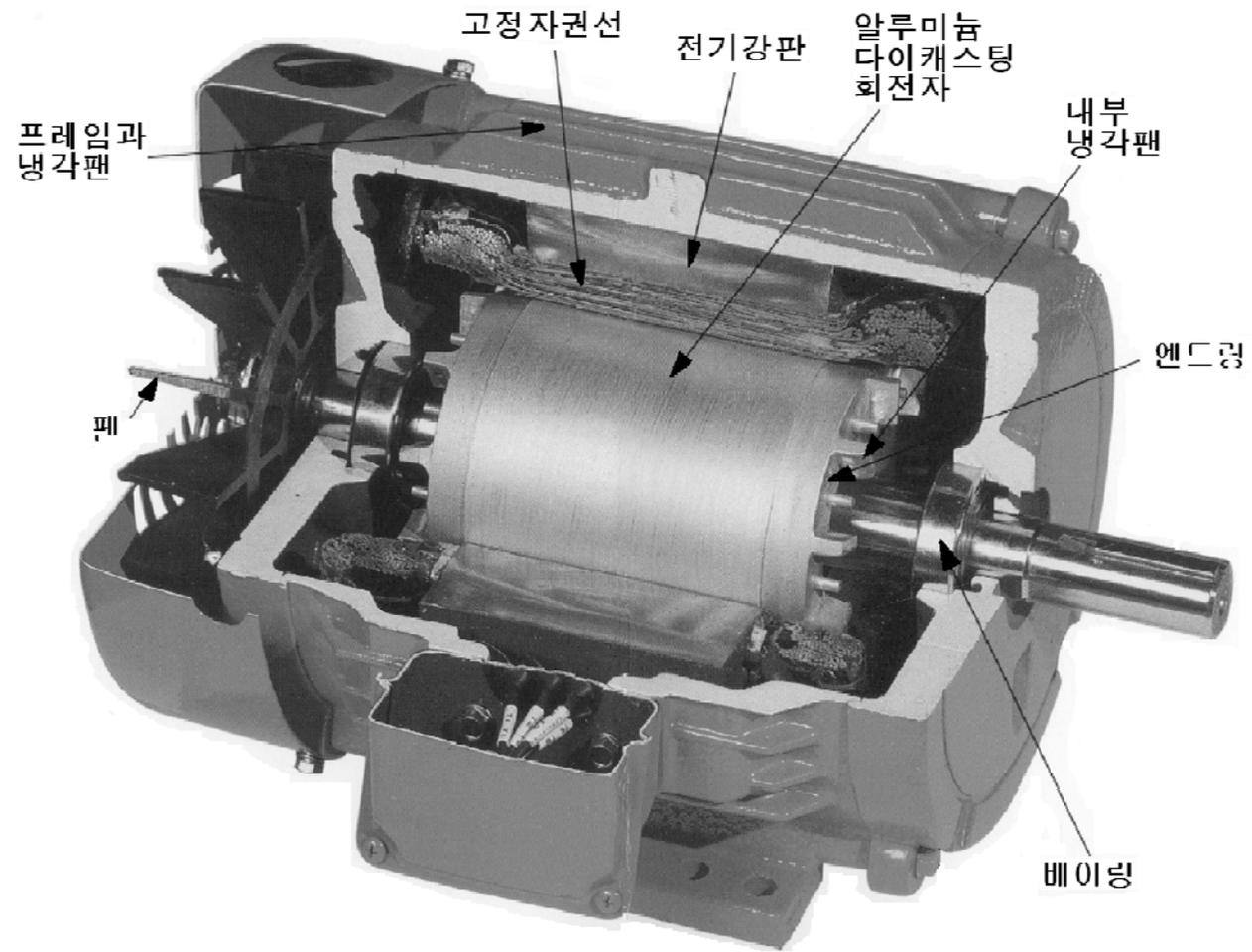
❖ 선형기에서의 동작원리



❖ 회전기에서의 동작원리



## (2) 유도기의 구조

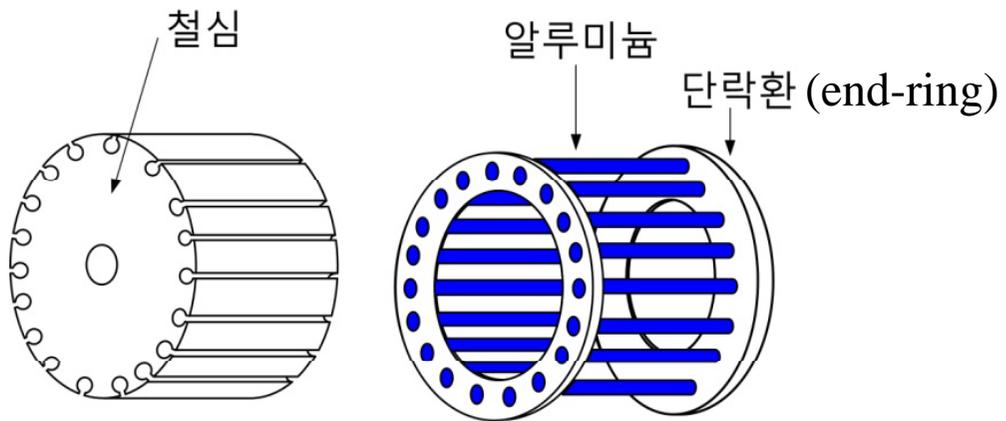


## 1) 고정자 (stator)

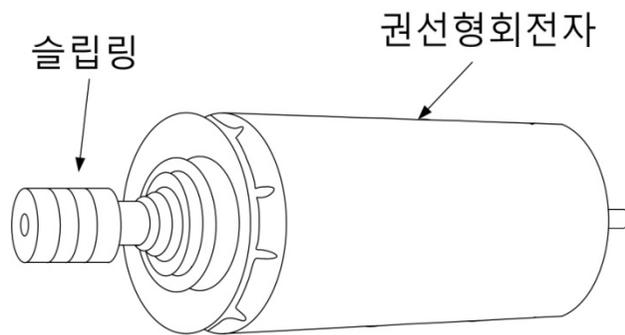


## 2) 회전자 (rotor)

### ① 농형 회전자 (squirrel-cage rotor)



② 권선형 회전자 (wound rotor)

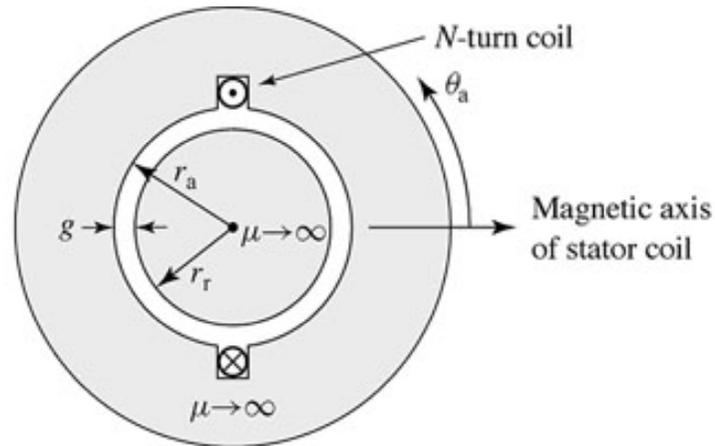


## 2. 회전자계 (rotating magnetic field)

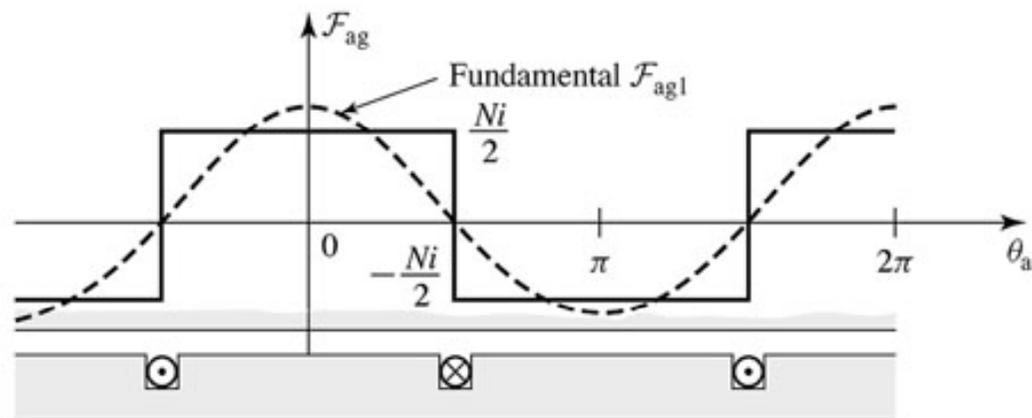
### (1) 단상권선 (single-phase winding) :

#### 1) 그래픽적인 방법

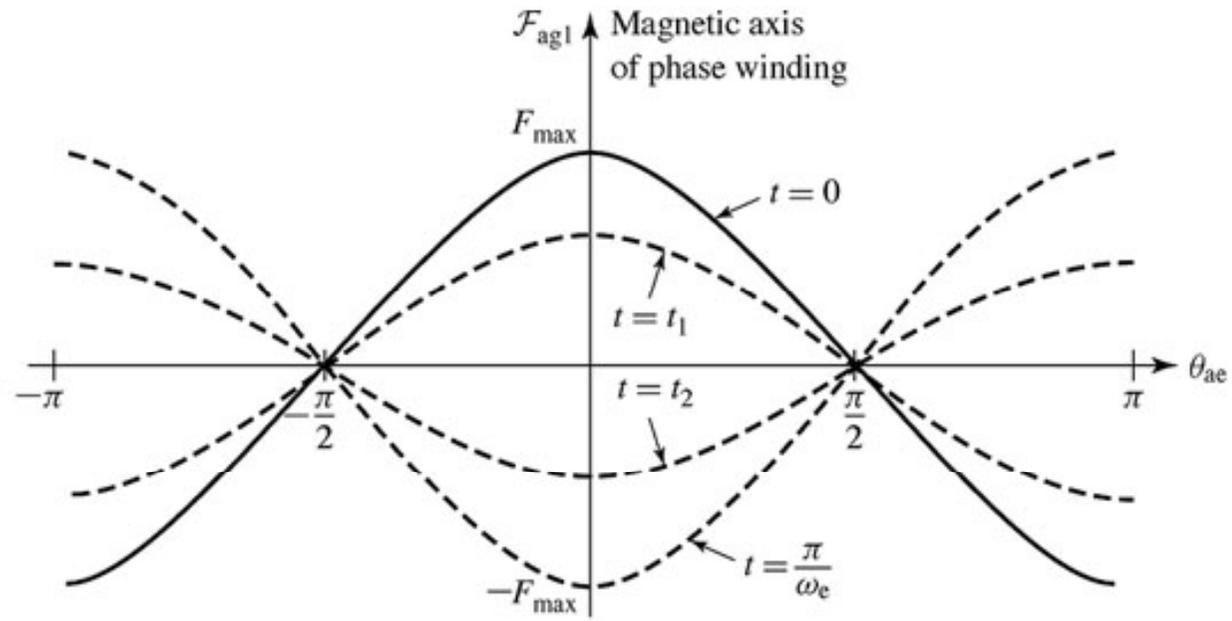
##### ① 단상 고정자



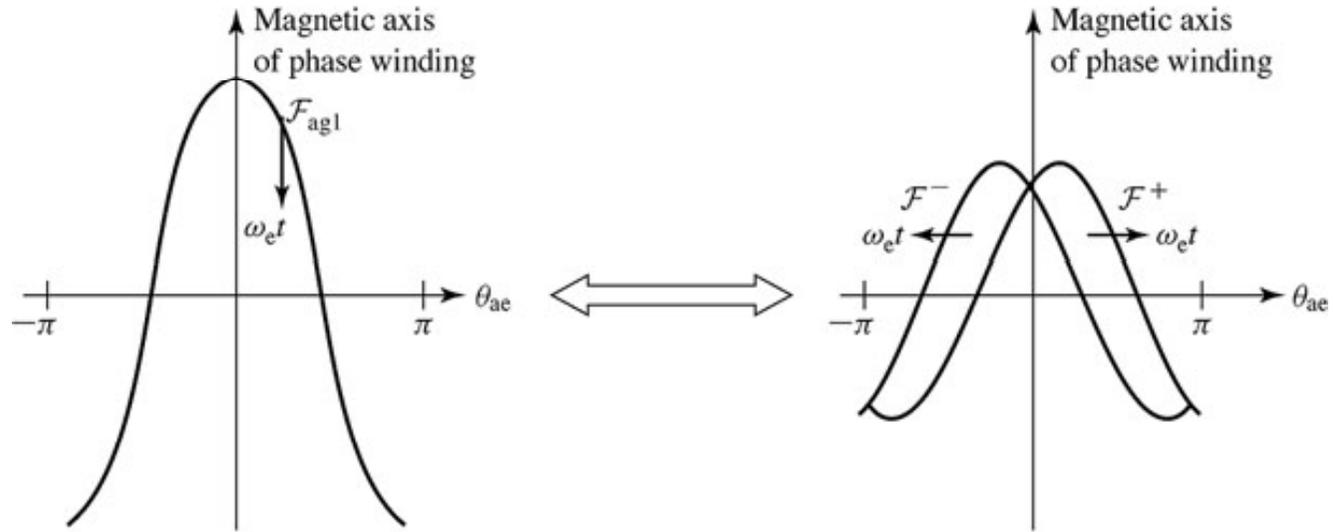
##### ② 위치에 따른 기자력분포



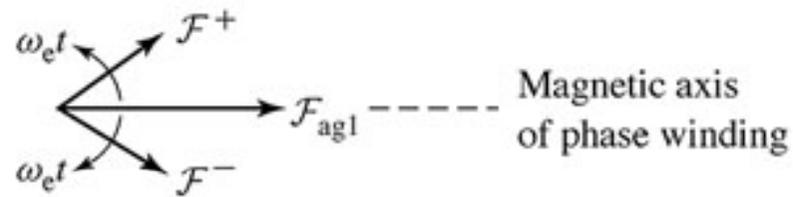
③ 시간에 따른 기자력분포



④ 기자력의 분해 (진행파 (traveling wave))



⑤ 페이지도에 의한 기자력 분해

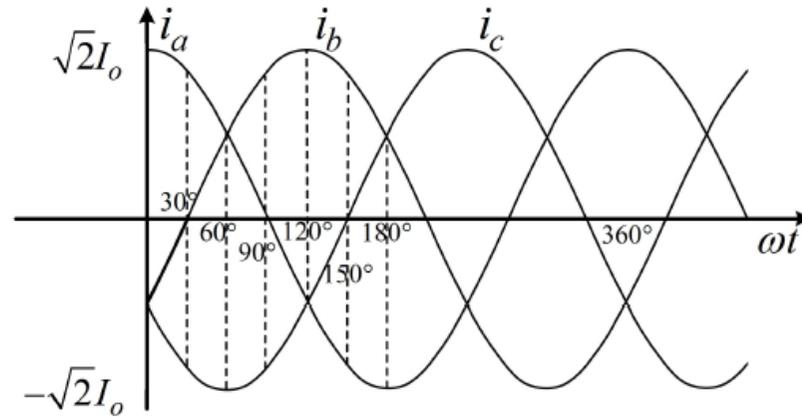
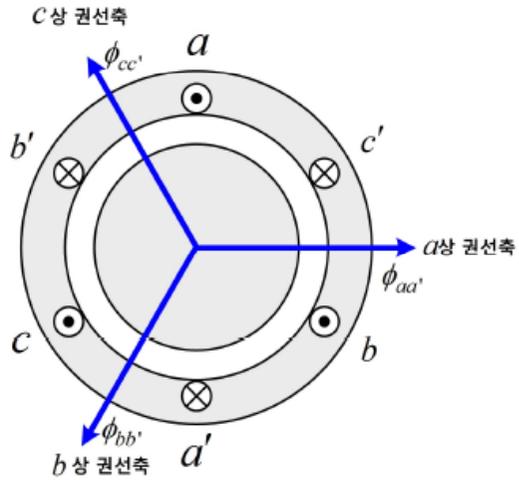


## 2) 해석적인 방법

$$\begin{aligned} F_{ag1} &= (F_{\max} \cos \theta) \cos \omega t \\ &= F_{\max} \left[ \frac{1}{2} \cos(\theta - \omega t) + \frac{1}{2} \cos(\theta + \omega t) \right] \\ &= \frac{1}{2} F_{\max} \cos(\theta - \omega t) + \frac{1}{2} F_{\max} \cos(\theta + \omega t) \\ &= F_{ag1}^+ + F_{ag1}^- \end{aligned}$$

(2) 3상권선 (three-phase winding) :

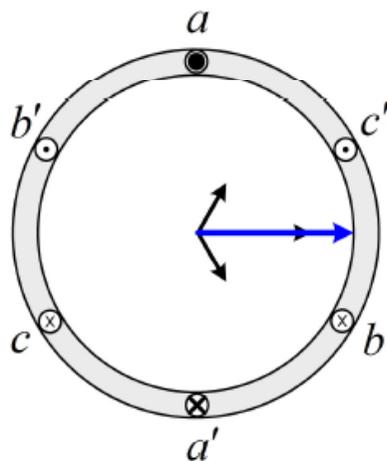
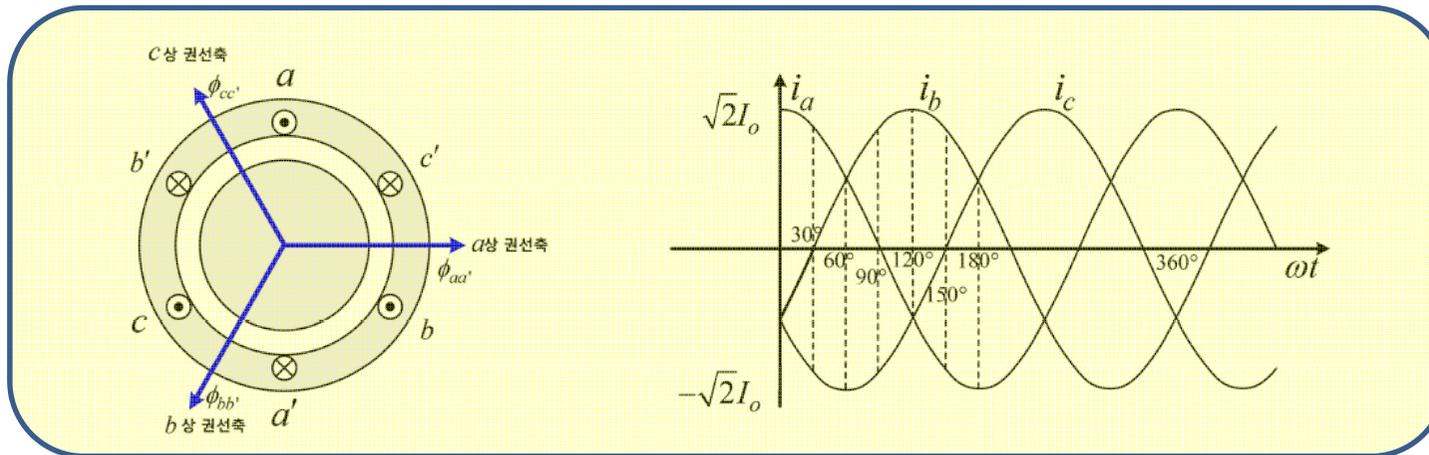
1) 그래픽적인 방법



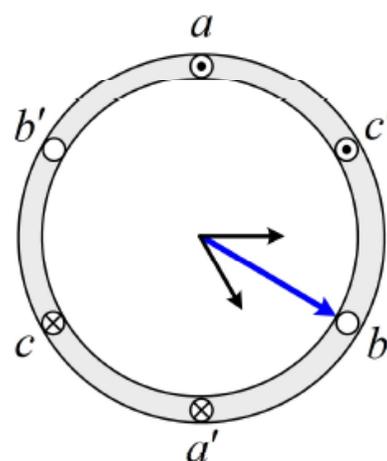
$$i_a = I_m \cos \omega t$$

$$i_b = I_m \cos \left( \omega t - \frac{2}{3} \pi \right)$$

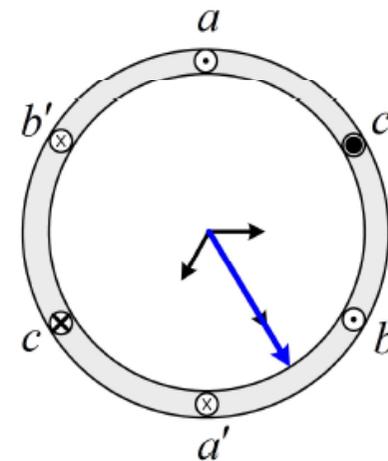
$$i_c = I_m \cos \left( \omega t + \frac{2}{3} \pi \right)$$



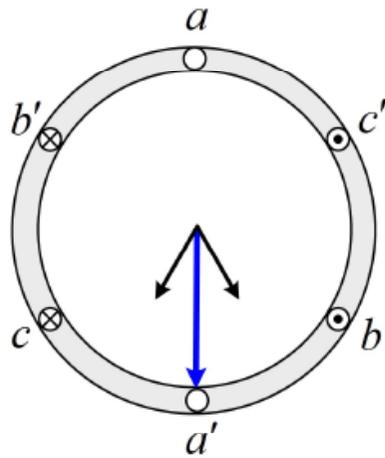
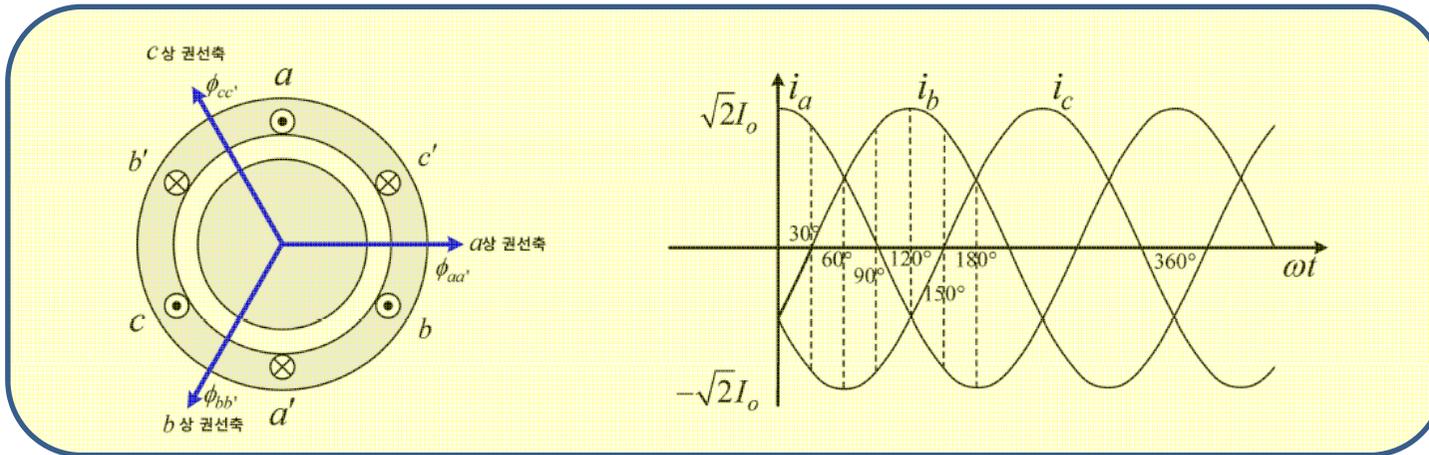
(a)  $\omega t = 0$



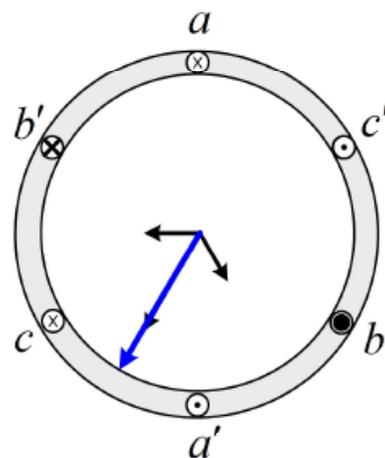
(b)  $\omega t = 30^\circ$



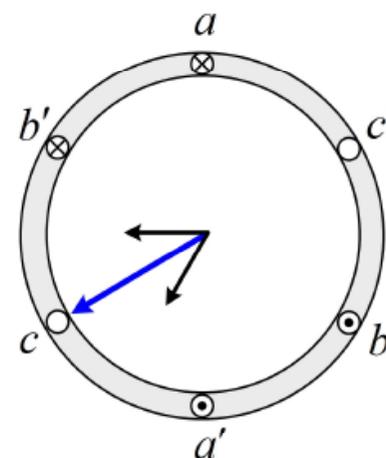
(c)  $\omega t = 60^\circ$



(d)  $\omega t = 90^\circ$



(b)  $\omega t = 120^\circ$



(c)  $\omega t = 150^\circ$

## 2) 해석적인 방법

$$F_{a1} = (F_{\max} \cos \theta) \cos \omega t$$

$$= F_{a1}^+ + F_{a1}^-$$

$$F_{b1} = \left( F_{\max} \cos \left( \theta - \frac{2}{3} \pi \right) \right) \cos \left( \omega t - \frac{2}{3} \pi \right)$$

$$= F_{b1}^+ + F_{b1}^-$$

$$F_{c1} = \left( F_{\max} \cos \left( \theta + \frac{2}{3} \pi \right) \right) \cos \left( \omega t + \frac{2}{3} \pi \right)$$

$$= F_{c1}^+ + F_{c1}^-$$

$$\therefore F(\theta, t) = F_{a1} + F_{b1} + F_{c1}$$

$$= \left[ \frac{1}{2} F_{\max} \cos(\theta - \omega t) + \frac{1}{2} F_{\max} \cos(\theta + \omega t) \right]$$

$$+ \left[ \frac{1}{2} F_{\max} \cos(\theta - \omega t) + \frac{1}{2} F_{\max} \cos \left( \theta + \omega t - \frac{4}{3} \pi \right) \right]$$

$$+ \left[ \frac{1}{2} F_{\max} \cos(\theta - \omega t) + \frac{1}{2} F_{\max} \cos \left( \theta + \omega t + \frac{4}{3} \pi \right) \right]$$

$$\begin{aligned}\therefore F(\theta, t) &= F^+(\theta, t) \\ &= F_{a1}^+ + F_{b1}^+ + F_{c1}^+ \\ &= \frac{3}{2} F_{\max} \cos(\theta - \omega t)\end{aligned}$$

공간적으로 120도 위상차(전기각)가 나고 시간적으로 120도 위상차를 갖는 3상권선에 의한 합성 기자력의 크기는 일정하고 정방향으로 일정속도(동기속도)로 회전한다.

### (3) 동기속도 (synchronous speed) 및 슬립 (slip)

#### 1) 동기속도

$$\omega_s = \frac{p}{2} \omega_m \text{ [rad / s]}$$

$$n_s = \frac{120}{p} f \text{ [rpm]}$$

$p$  : pole number

$\omega_m$  : mechanical speed

$f$  : voltage frequency

#### 2) 슬립

$$\text{Slip} = s = \frac{n_s - n_r}{n_s} \times 100 \text{ [%]}$$

$$s = 1$$

$$s = 0$$

$$n_r = (1 - s) \times n_s \text{ [rpm]}$$

$n_s$  : 동기속도

$n_r$  : 회전자 속도

ex) six-pole motor, supply frequency (3phase) 60 Hz

rotor speed at full load 1140 rpm

a) 동기속도

$$n_s = \frac{120f}{p} = \frac{120}{6} \times 60 = 1200 \text{ rpm}$$

b) 슬립

$$s = \frac{1200 - 1140}{1200} \times 100 = 5\%$$

c) 슬립=0.02일때 회전자 속도

$$\begin{aligned} n_r &= (1 - s) \times n_s \\ &= (1 - 0.02) \times 1200 = 1176 \text{ rpm} \end{aligned}$$

### 3. 유도기의 등가회로

#### (1) 유도기 기동시 (정지시)

{ 고정자 : back-emf  $E_s, f_s$   
회전자 : generated voltage  $E_r, f_r = f_s$

$$\frac{E_r}{E_s} = \frac{N_r}{N_s} \quad (\text{winding factor가 같은 경우})$$

## (2) 고정자 등가회로

$$v_s = R_s i_s + \frac{d\lambda_s}{dt} \quad (1)$$

$$\lambda_s = N_s (\phi + \phi_{\ell s}) \quad \phi : \text{mutual flux} \quad (2)$$

$\phi_{\ell s} : \text{leakage flux}$

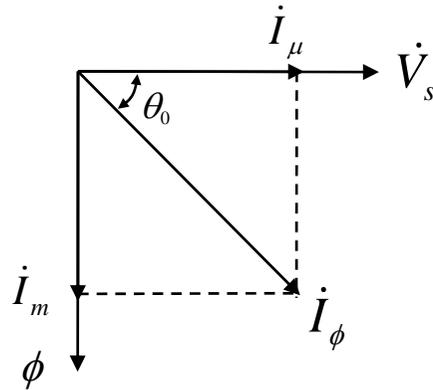
(2)  $\rightarrow$  (1)

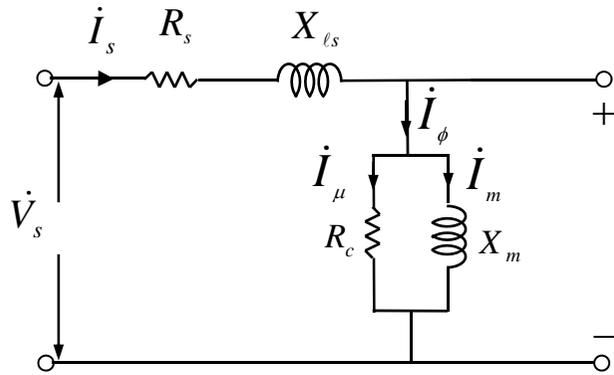
$$\begin{aligned} v_s &= R_s i_s + N_s \frac{d\phi_{\ell s}}{dt} + N_s \frac{d\phi}{dt} \\ &= R_s i_s + L_{\ell s} \frac{di_s}{dt} + L_m \frac{di_s}{dt} \\ &= R_s i_s + L_{\ell s} \frac{di_s}{dt} + e_s \end{aligned} \quad (3)$$

- ① 2차측 (회전자)이 open되었을 경우  
(고정자에서 회전자로 에너지 전달이 없는 경우)

$$\begin{aligned}\dot{I}_s &= \dot{I}_\phi \\ &= \dot{I}_m + \dot{I}_\mu\end{aligned}$$

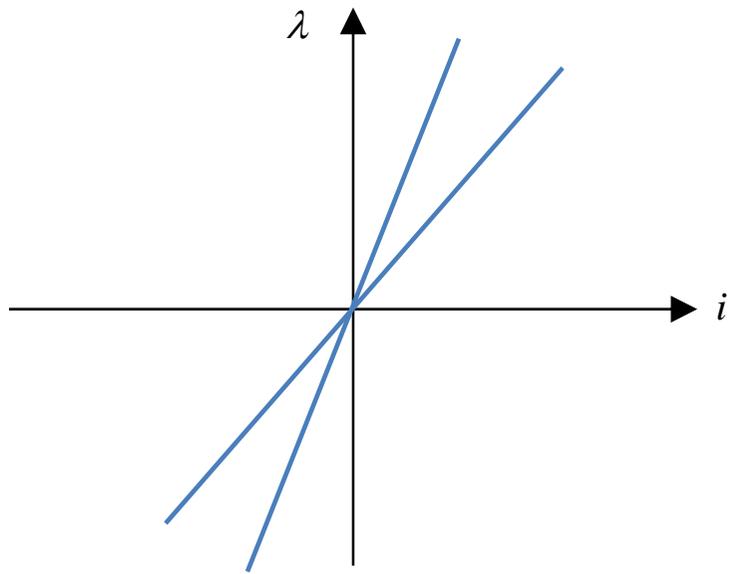
$$\begin{aligned}\dot{I}_m \\ \dot{I}_\mu\end{aligned}$$





② 2차측 (회전자)에 부하가 연결되거나 short된 경우  
(고정자에서 회전자로 에너지 전달 )

※ 유도전동기와 변압기  $\lambda-i$  특성



①  $L_m$  (유도기)     $L_m$  (변압기)

②  $L_{ls}$  (유도기)     $L_{ls}$  (변압기)

### (3) 회전자 등가회로

슬립주파수 (slip frequency)

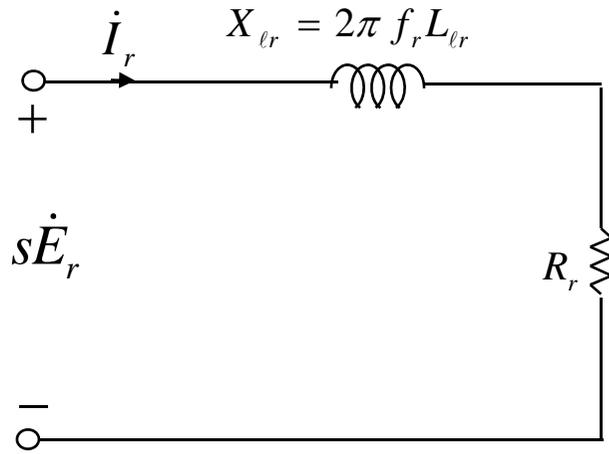
= 회전자 회로의 주파수  $f_r$

= 회전자 전류 주파수

= 회전자 유기전력의 주파수

=  $sf_s$

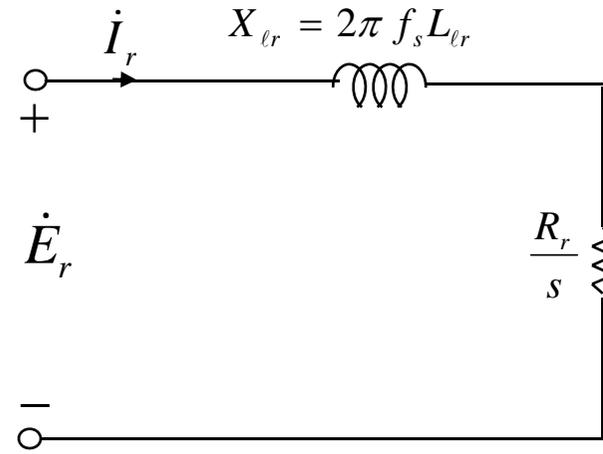
$$f_r = sf_s$$



< 회전자측에서 본 등가회로 >

$$s\dot{E}_r = L_{lr} \frac{di_r}{dt} + i_r R_r$$

등가회로 주파수 :



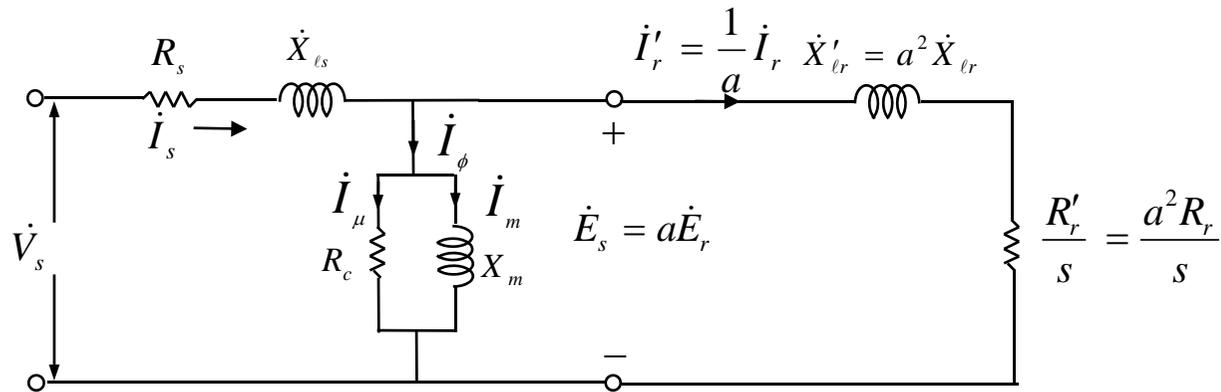
< 고정자측에서 본 등가회로 >

$$\dot{E}_r = L_{lr} \frac{di_r}{dt} + i_r \frac{R_r}{s}$$

등가회로 주파수 :

#### (4) 유도기의 전체 등가회로

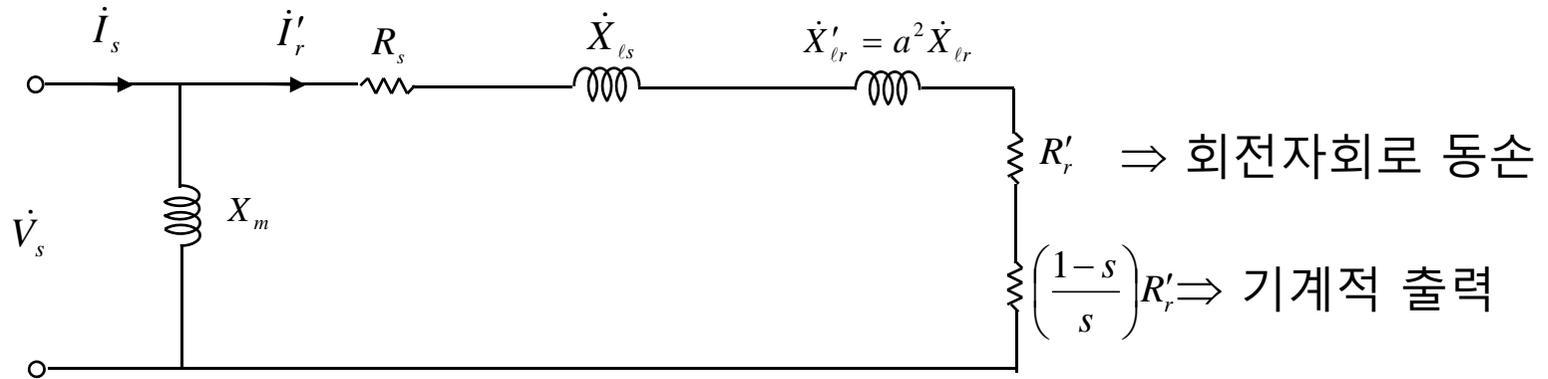
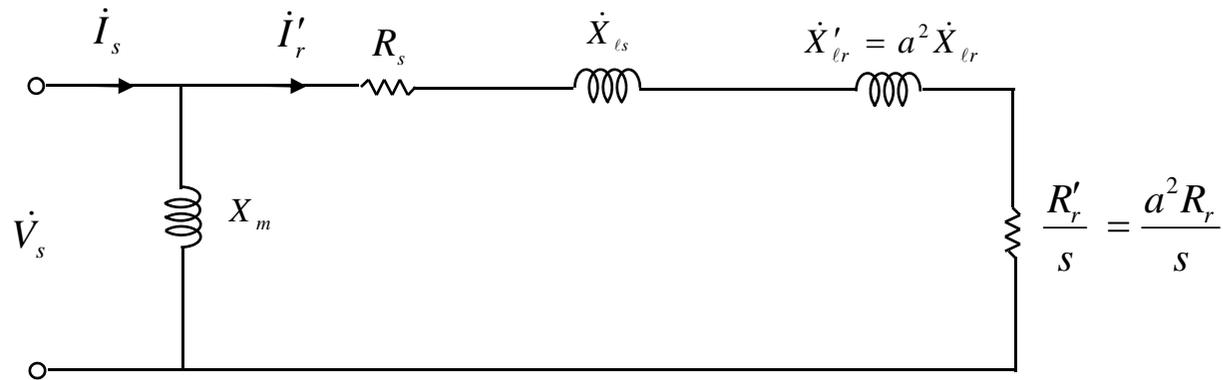
고정자 및 회전자의 사용주파수 동일 => 권수비를 고려한 등가회로 결합



$$a = \frac{N_s}{N_r} : \text{턴수비}$$



- 철손은 일정 => 철손저항 제거하고 효율계산시 고려
- Exciting branch를 왼쪽으로 이동



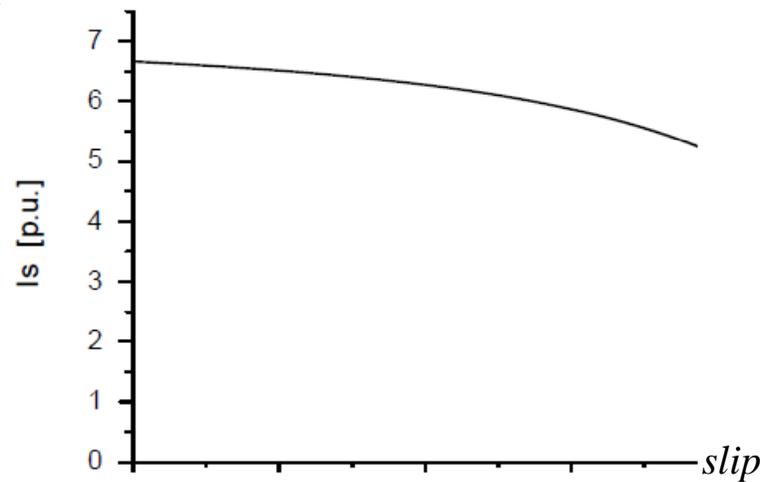
## 4. 유도기의 특성

### (1) 고정자 전류

- 입력 임피던스

$$\dot{Z}_s = R_s + jX_{\ell s} + \left[ X_m // \left( \frac{R_r}{s} + jX_{\ell r} \right) \right] = |\dot{Z}_s| \angle \theta_s$$

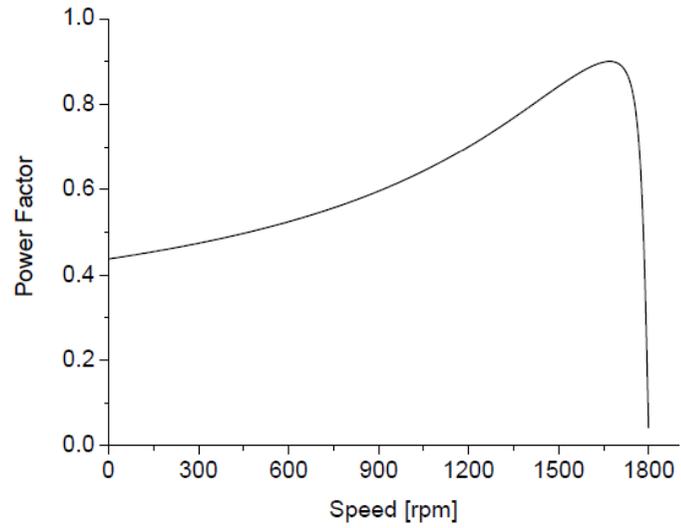
$$\dot{I}_s = \frac{\dot{V}_s}{\dot{Z}_s} = \dot{I}_\phi + \dot{I}$$



$$\frac{R_r}{s} \rightarrow \infty$$

## (2) 입력 역률

$$p.f = \cos\theta_s$$



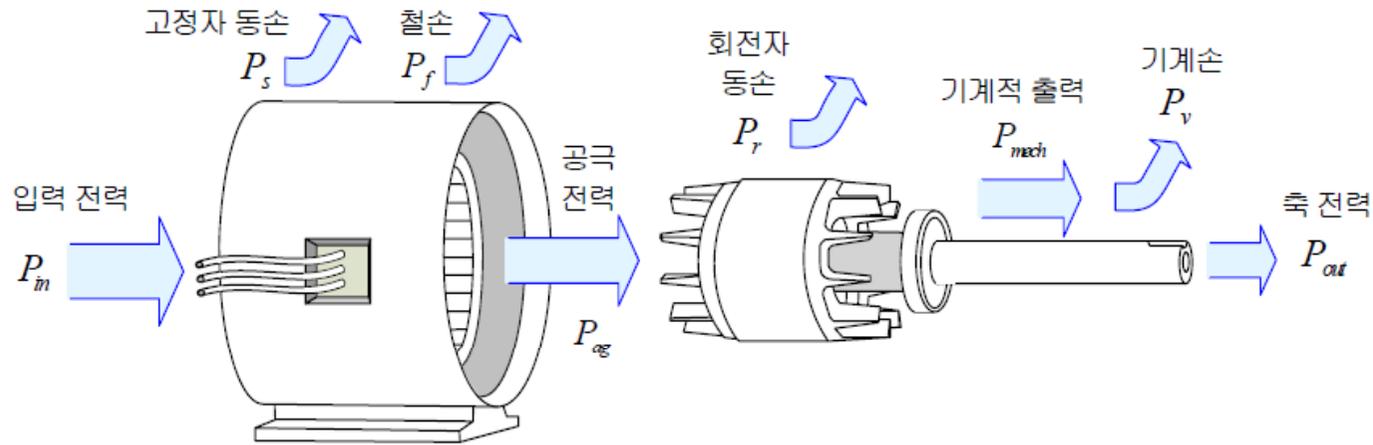
경부하 (light load) : small slip

중부하 (heavy load) : increased slip

### (3) 회전자 전류

$$\dot{I}_r = \frac{\dot{V}_s}{\left(R_s + \frac{R_r}{s}\right) + j(\dot{X}_{\ell s} + \dot{X}_{\ell r})}$$

#### (4) 출력토크

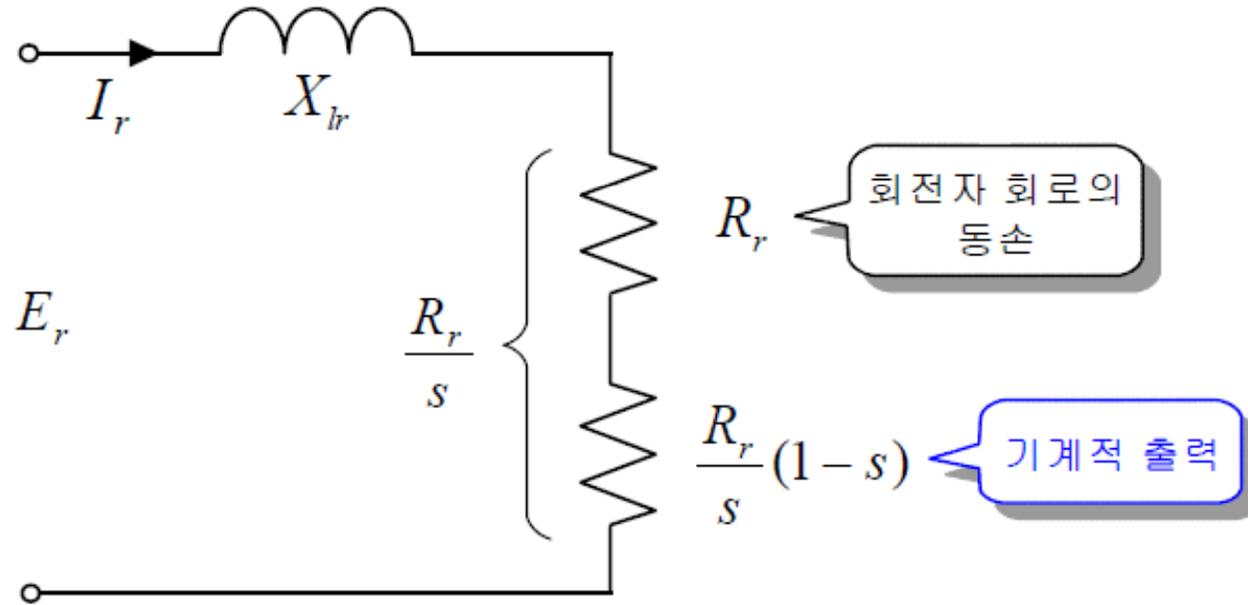


공극전력 ( $P_{ag}$ ) : 고정자로부터 공극을 거쳐 회전자로 입력되는 전력

$$\begin{aligned}
 P_{ag} &= I_r^2 \frac{R_r}{s} \\
 &= I_r^2 \left[ R_r + \frac{1-s}{s} R_r \right] \\
 &= I_r^2 R_r + \left( \frac{1-s}{s} \right) I_r^2 R_r \\
 &= P_r + P_{mech}
 \end{aligned}$$

$$P_r = I_r^2 R_r = s P_{ag} \quad (6)$$

$$P_{mech} = \left( \frac{1-s}{s} \right) I_r^2 R_r = (1-s) P_{ag} \quad (7)$$



$$\begin{aligned}
P_{mech} &= T_{mech} \cdot \omega_{mech} \\
&= T_{mech} \cdot (1-s)\omega_s
\end{aligned} \tag{8}$$

From (7), (8)

$$\begin{aligned}
T_{mech} &= \frac{1}{(1-s)\omega_s} P_{mech} \\
&= \frac{1}{(1-s)\omega_s} \frac{(1-s)}{s} I_r^2 R_r \\
&= \frac{1}{\omega_s} I_r^2 \frac{R_r}{s}
\end{aligned} \tag{9}$$

(5)  $\Rightarrow$  (9)

$$T_{mech} = \frac{1}{\omega_s} \frac{V_s^2}{\left(R_s + \frac{R_r}{s}\right)^2 + (X_{\ell s} + X_{\ell r})^2} \frac{R_r}{s} \tag{10}$$

$$T_{mech} \propto V_s^2$$

① 정격속도 부근 (slip이 작은경우)

$$R_s + \frac{R_r}{s} \gg X_{\ell s} + X_{\ell r}, \quad \frac{R_r}{s} \gg R_s$$

$$\therefore T_{mech} \approx \frac{1}{\omega_s} \frac{V_s^2}{R_r} s$$

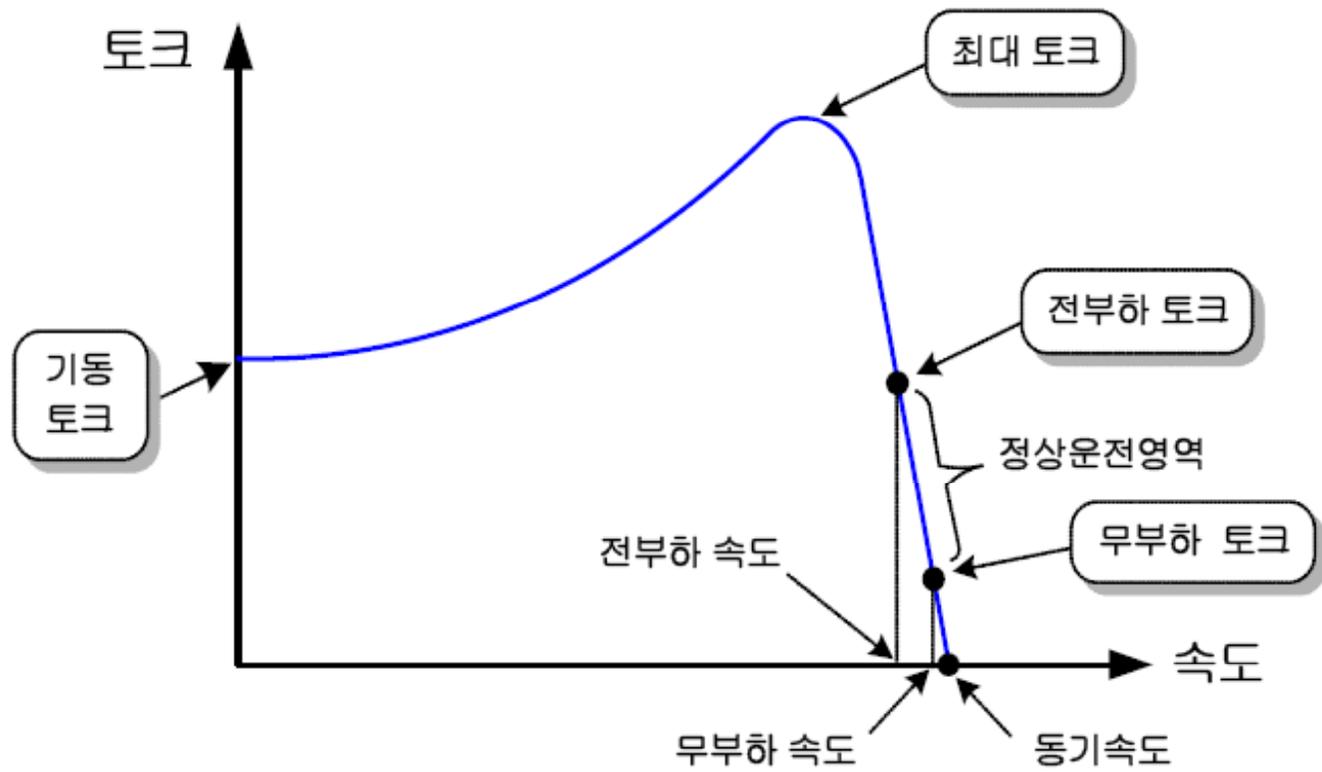
$$T_{mech} \propto s$$

② 저속운전 영역 (slip이 큰경우)

$$R_s + \frac{R_r}{s} \ll X_{\ell s} + X_{\ell r}$$

$$\therefore T_{mech} \approx \frac{1}{\omega_s} \frac{V_s^2}{(X_{\ell s} + X_{\ell r})^2} \cdot \frac{R_r}{s}$$

$$T_{mech} \propto \frac{1}{s}$$



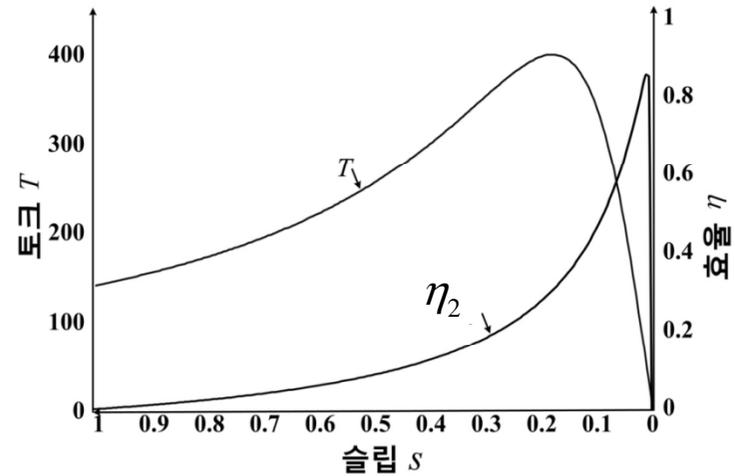
## (5) 효율

- 전기적 입력에 대한 축출력의 비

$$\eta = \frac{P_{out}}{P_{in}}$$

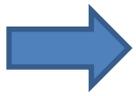
- 2차측 출력을 기준으로한 2차측 효율

$$\eta_2 = \frac{P_{mech}}{P_{ag}} = (1-s)$$



※ 회전자 저항에 따른 토크-속도 특성

- 기동시 : 회전자 저항이 커야
- 동기속도 근처 : 회전자 저항이 작아야



권선형 유도기 :

농형 유도기 : ????

(1) 심구형 (deep-bar) 농형 유도기

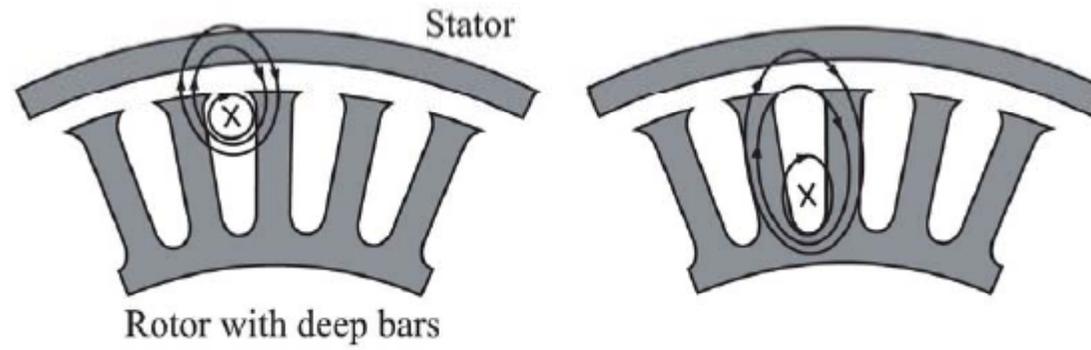


(a) 일반형



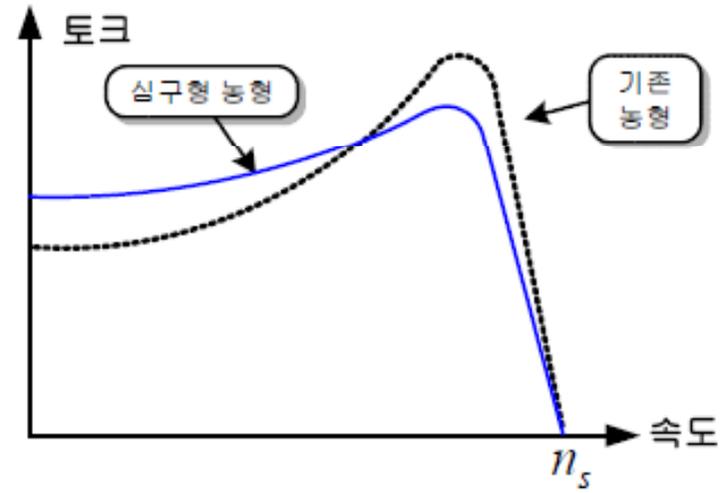
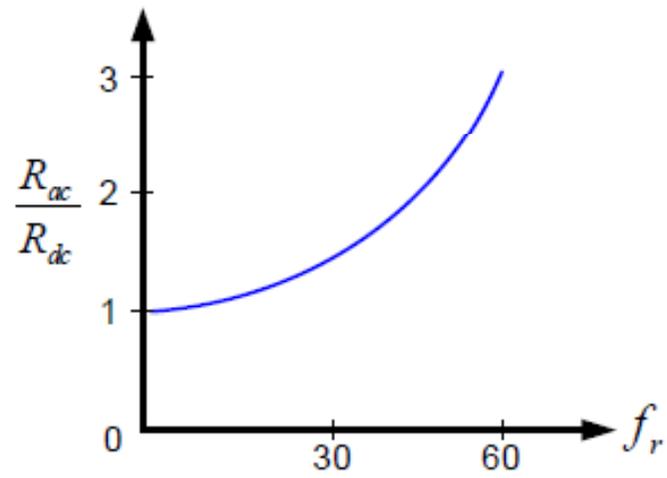
(b) 심구형

① 기동시



심구형도체 표면의 누설자속 << 심구형 도체 하층부 누설자속

② 정격운전시



## (2) 이중농형 (double-cage rotor) 유도기

