

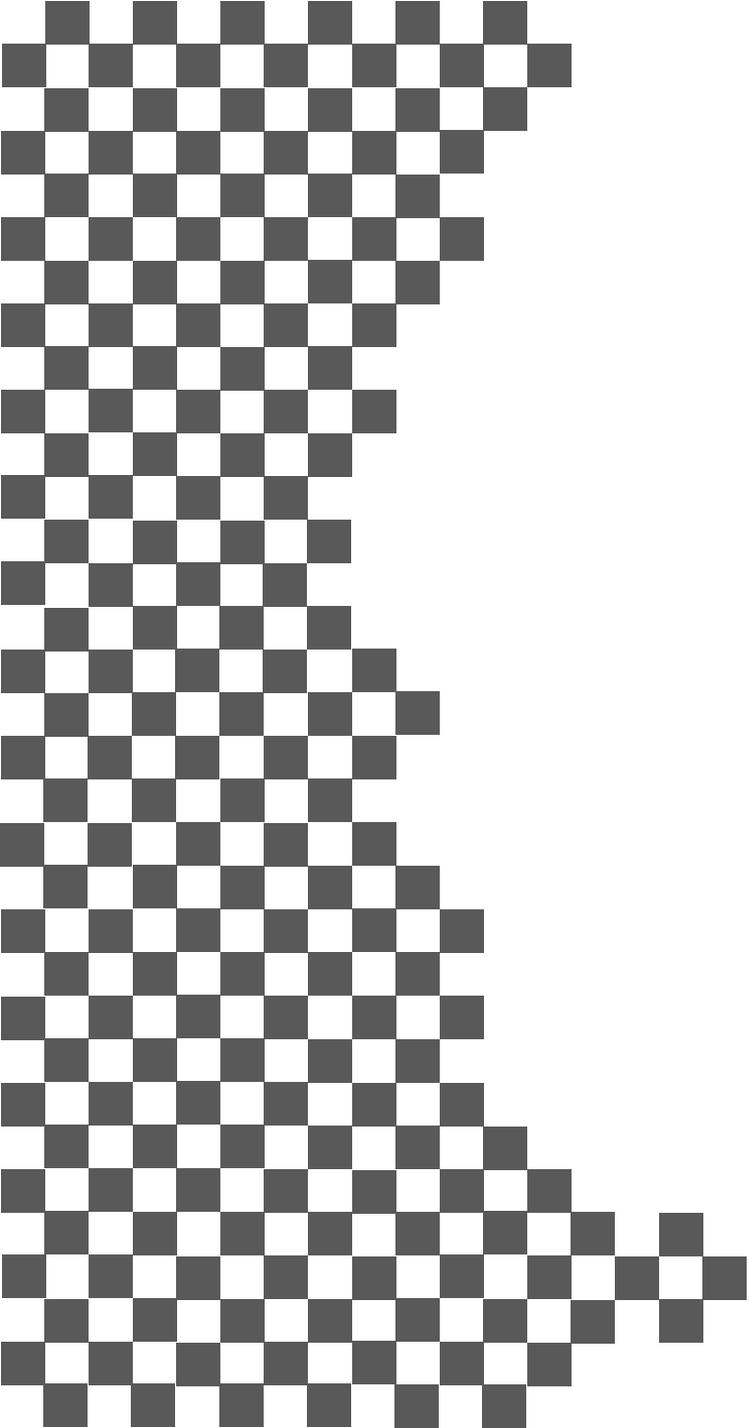
# IPMSM의 토크 특성과 전기자동차



Team : Ctrl M

2010003055 이동현

2014012760 한상원



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- AMEsim
  - EV motor 특성 분석
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# 팀명 선정 배경

모터 제어  
(MOTOR Control)



**C**ontrol **M**otor



Team : Ctrl M

포토샵

Ctrl + M

화면의 밝기를 나타냄

Word

Ctrl + M

앞으로 나아가는 기능



## 주제 선정 배경

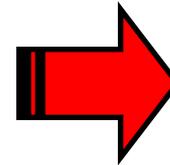
세계 자동차 판매 조건이 까다로워졌다.(유로6)

친환경 자동차 관심

전기자동차 수요가 해마다 증가

고도의 모터 제어 기술이 요구됨

IPMSM의 최대 토크 운전



IPMSM 최대 토크 제어로  
전기 자동차  
모터 모델링



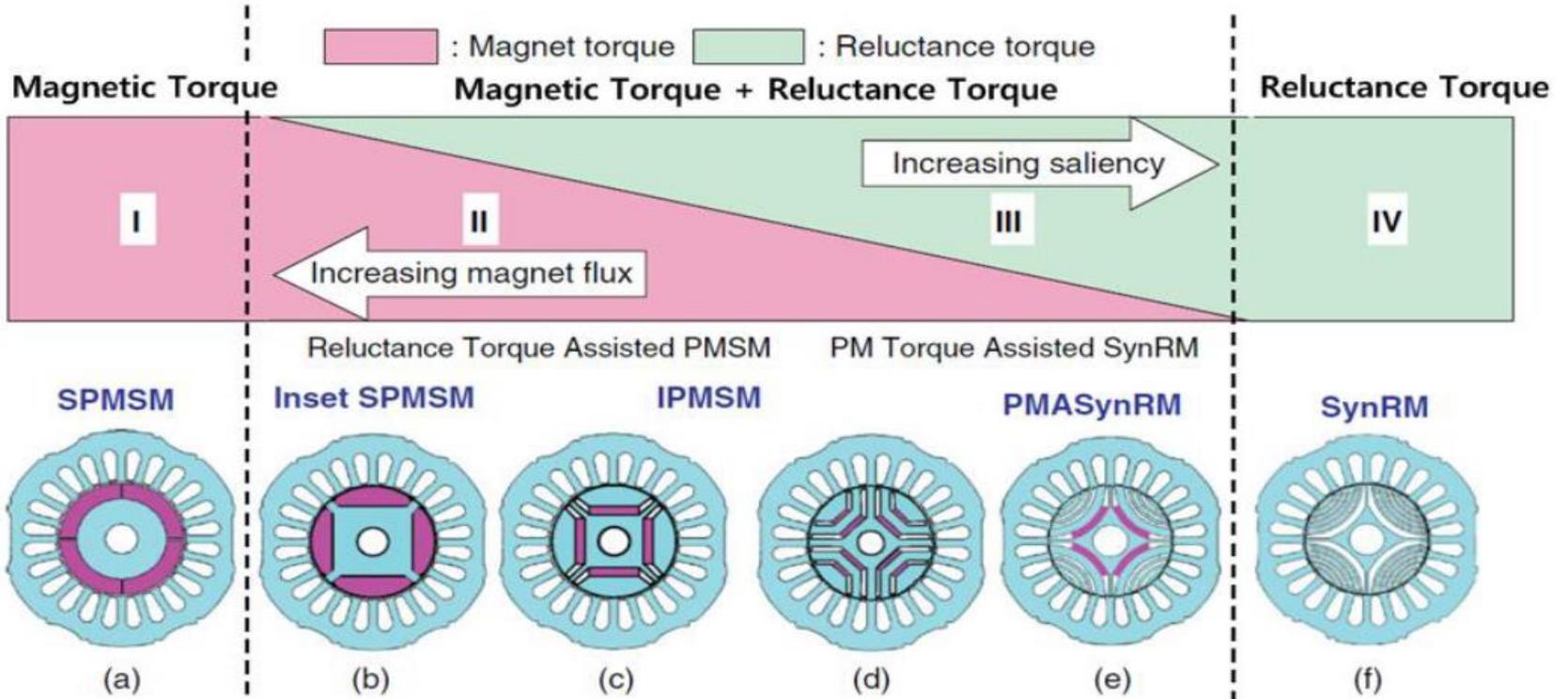
전기자동차 (테슬라 모델 S)



# 동기전동기 배경지식

영구자석 동기전동기 종류

종류에 따라 토크 발생 차이



원통형



동구형

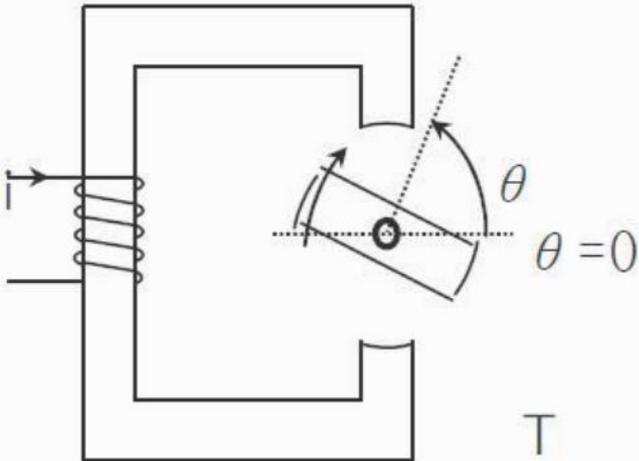


# 동기전동기 배경지식

릴럭턴스 토크란?

$$T_e = \frac{\partial W_m}{\partial \theta} = \frac{1}{2} i^2 \frac{dL}{d\theta} \Rightarrow \frac{dL}{d\theta}$$

릴럭턴스 토크  
:인덕턴스의 기울기에 비례

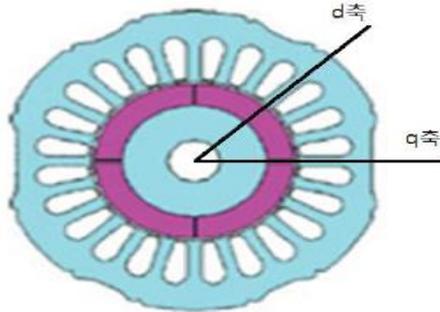


릴럭턴스 토크  
: 인덕턴스(릴럭턴스) 변화로 인한 토크



# 동기전동기 배경지식

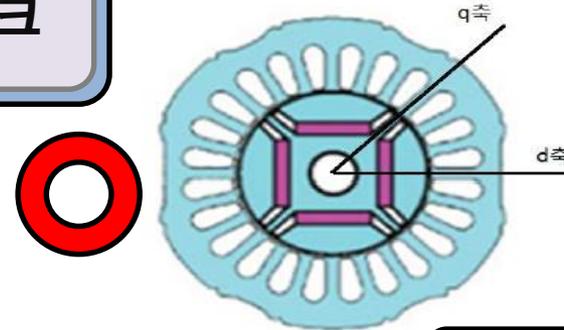
SPM (회전자 표면 자석)



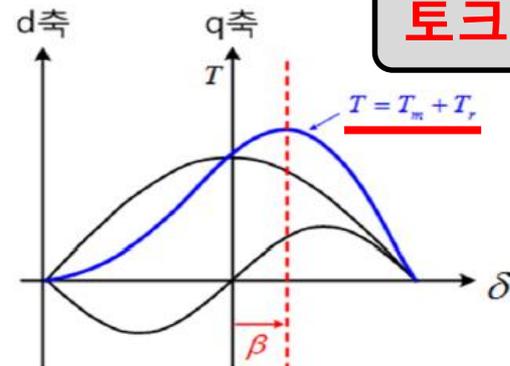
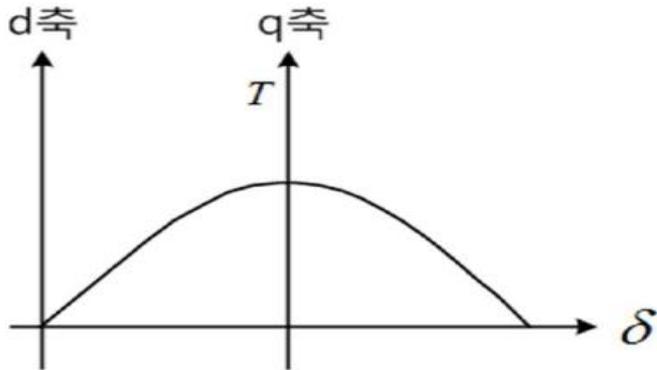
릴렉턴스 토크



IPM (회전자 내부 자석)



토크 증가



고출력  
고효율  
속도 향상

- 토크식 :  $T = P_n (\psi_a i_q)$

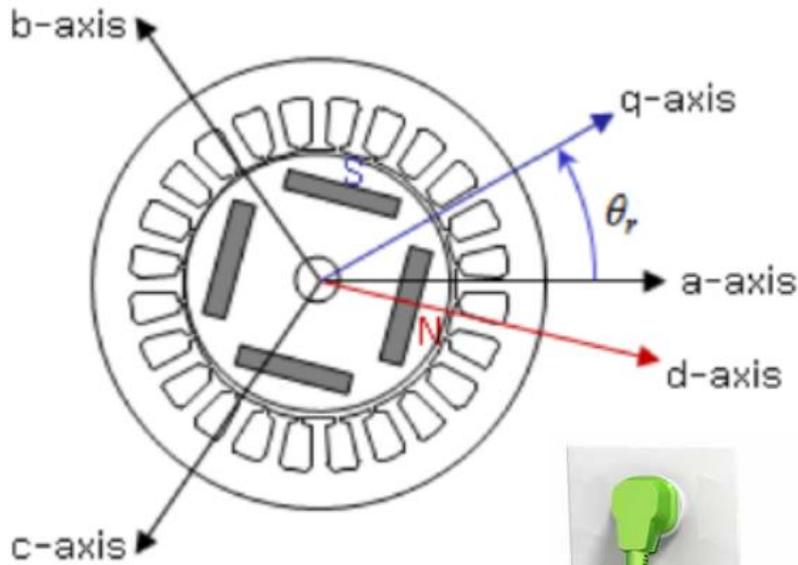
- 토크식 :  $T = P_n (\psi_a i_q + (L_d - L_q) i_d i_q)$



# IPMSM 벡터 제어

Interior Permanent Magnet Synchronous Motor

매입형 영구자석 동기 전동기



전기자동차는 넓은 운전 영역과 기저속도 이하의 큰 토크를 요구하는 분야이기에 약자속 제어가 필요

일정 토크 영역부터 일정출력 영역까지 최대 토크를 발생하는 **최적의 운전점**

**최대 토크 제어**

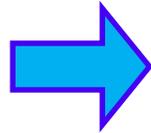
- ◆ 큰 출력 밀도
- ◆ 높은 효율
- ◆ 고속운전의 유리





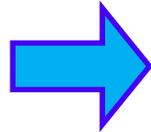
# 프로젝트 진행 순서

COMSOL



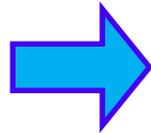
원통형 전동기 vs 돌극형 전동기  
모터 설계와 토크 곡선 구하기

Simulink



IPMSM 최대 토크 제어를 통해  
토크&RPM 곡선 구한다.

AMEsim



위에서 얻어진 토크&RPM 곡선을 통해  
전기자동차 동적 특성과 성능을 비교



# COMSOL : MOTOR

## 2D : Specification of Motor

Table 5.1 Specifications of stator and rotor

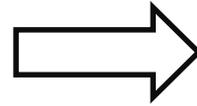
parameters	value	parameters	value
Number of stator slots	48	Air-gap length	0.74 mm
Outer stator diameter	269.24 mm	Outer rotor diameter	160.45 mm
Inner stator diameter	161.93 mm	Inner rotor diameter	26.67 mm
Stator tooth width	8.86 mm	Bearing distance	189.23 mm
Slot opening width	1.93 mm	PM thickness	5.08/6.1 mm
Stator core length	47.75 mm	Side-PM thickness	2.54 mm

Development and Analysis of Interior Permanent Magnet Synchronous Motor with Field Excitation Structure (Seong Taek Lee University of Tennessee – Knoxville)

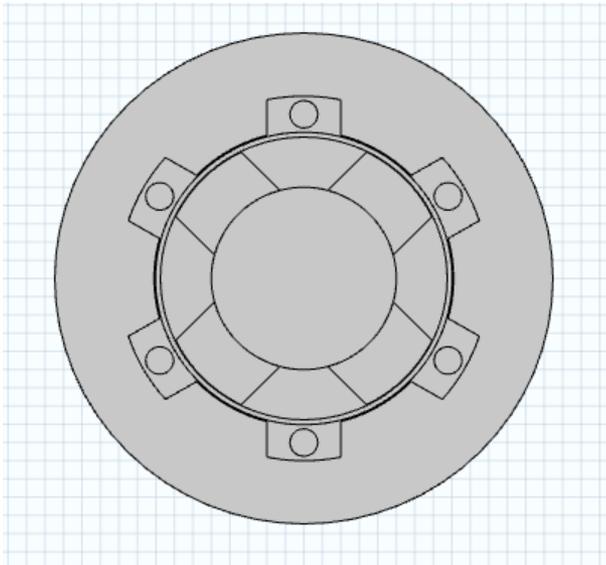


# COMSOL : MOTOR

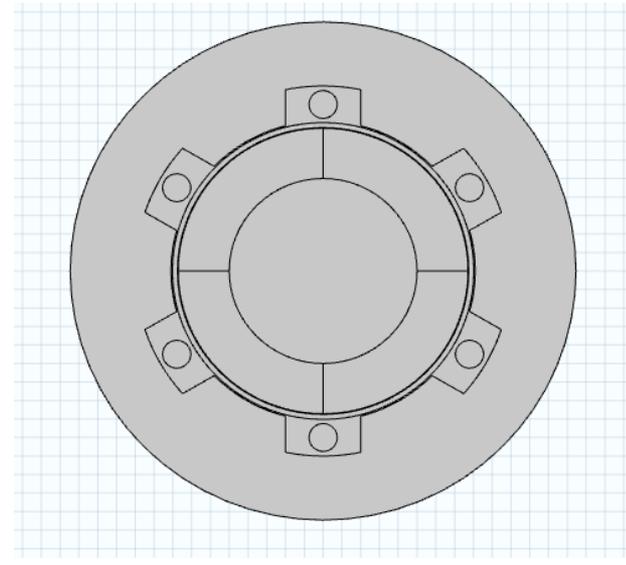
2D: 3상 4극 6슬롯 동기전동기



동일한 조건에서 분석



돌극형



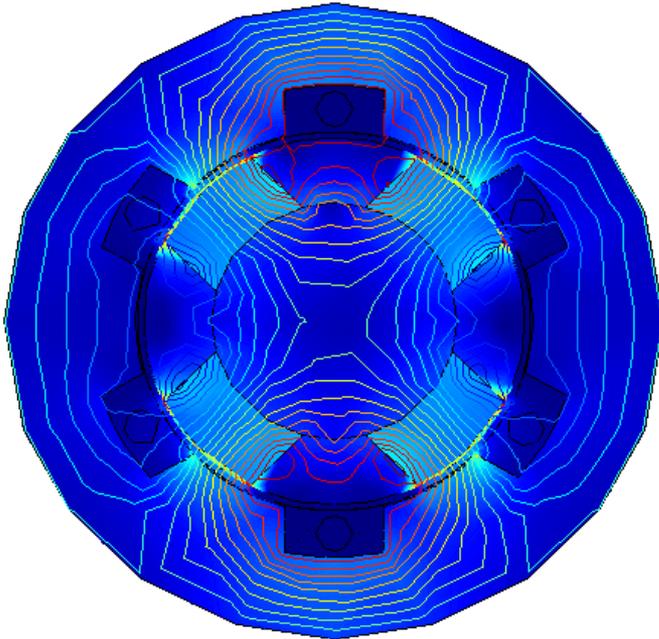
원통형



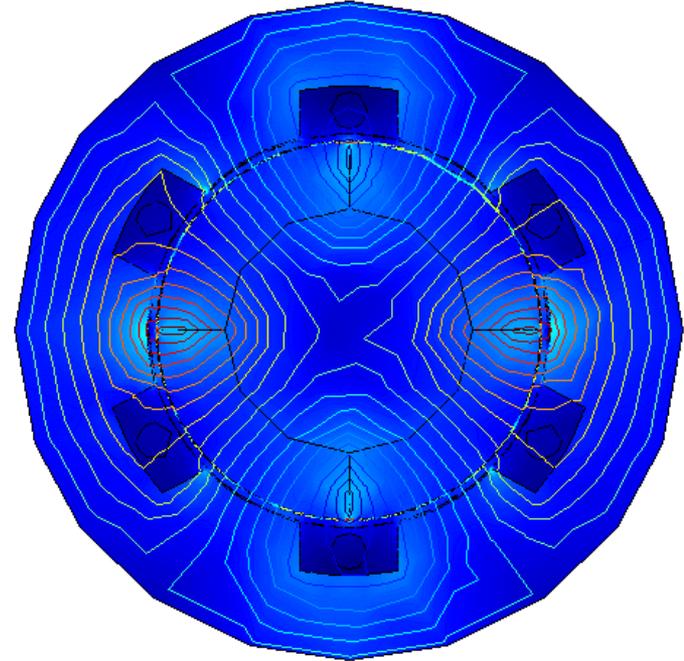
# COMSOL : MOTOR

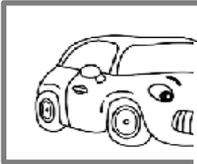
Compute 결과 : Animation

돌극형



원통형





1 개의 등급모델이 있습니다.

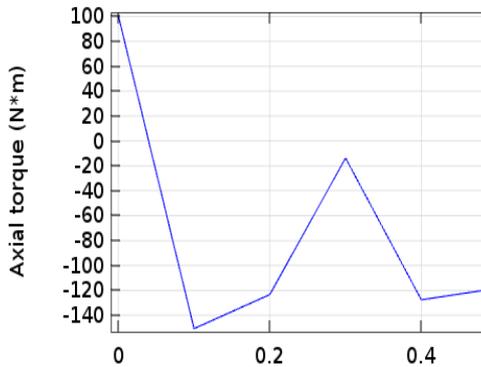


RR

## 모터의 토크 곡선

### 돌극

Global: Axial torque

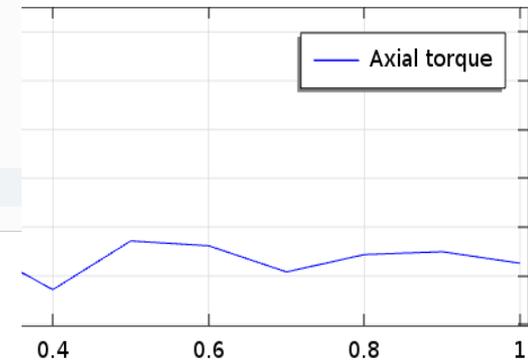


평균: 100Nm

모델명 가격	i3 가격정보없음 상세모델 별 가격 및 옵션
주요제원	엔진형식 과급방식 배기량 연료 연비(등급) 승차인원 구동방식 ? 변속기
엔진	엔진형식 배기량 연료 1회 충전 주행가능거리 에너지용량 모터최대출력 ? 모터최대토크 ?
	정보없음 정보없음 전기 정보없음 * 4인승 후륜구동(RR) 자동 1단 정보없음 전기 정보없음 33.2kWh 125.0kW 250.0Nm

### 통형

Global: Axial torque (N\*m)



평균: 250Nm

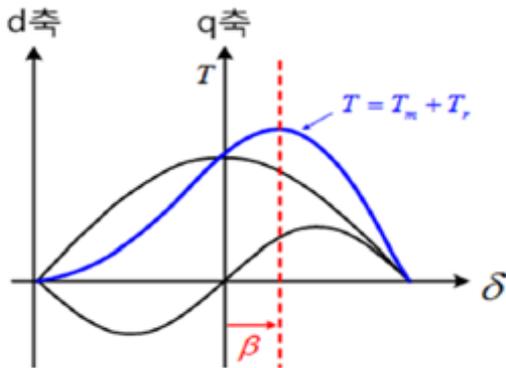
BMW i3의 모터 최대 토크는 250Nm



# COMSOL : MOTOR

## Comsol 분석

Q) 돌극형이 아까 더 크다고 하셨는데...?



돌극형

<원통형>

최대 rpm 제한 조건이 있다

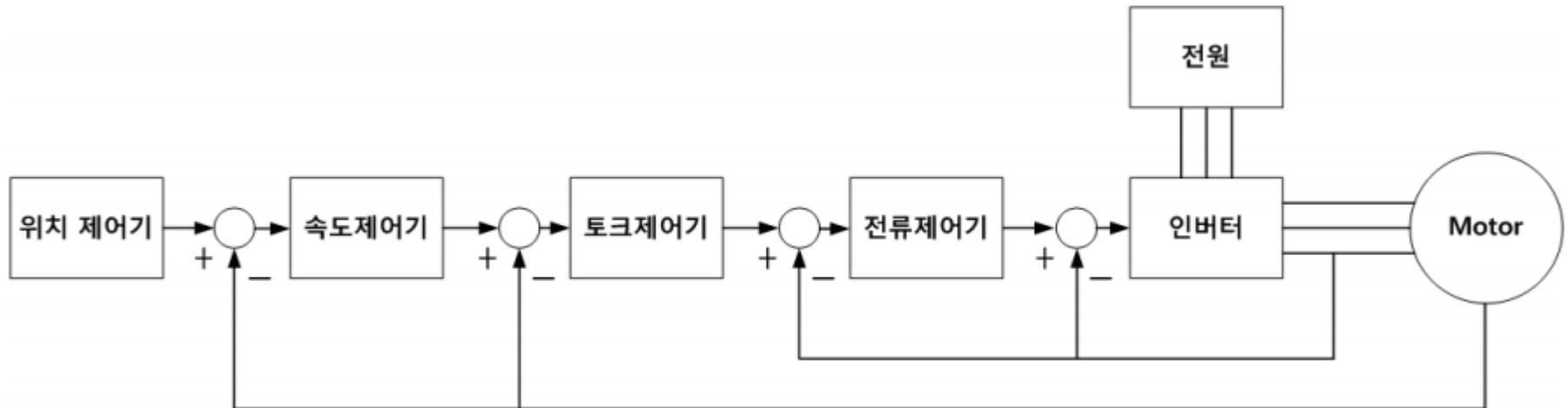
<돌극형>

RPM 조건이 비교적 자유로워 높은 RPM사용이 가능

같은 운전 조건(동일 rpm)이면 원통형 전동기가 더 성능이 좋지만, 돌극형 전동기는 릴럭턴스 토크로 높은 rpm에서 보상을 받을 수 있어 운전 영역이 넓은 자동차와 같은 경우에는 돌극형인 IPMSM이 더 좋다.



# Simulink Modeling

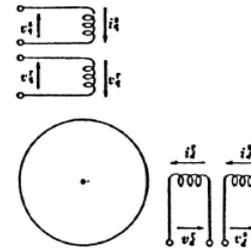
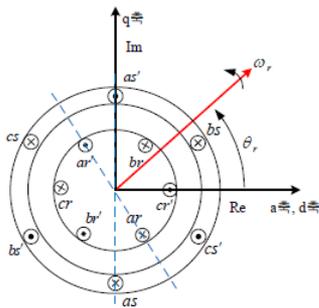




# 벡터 제어란?

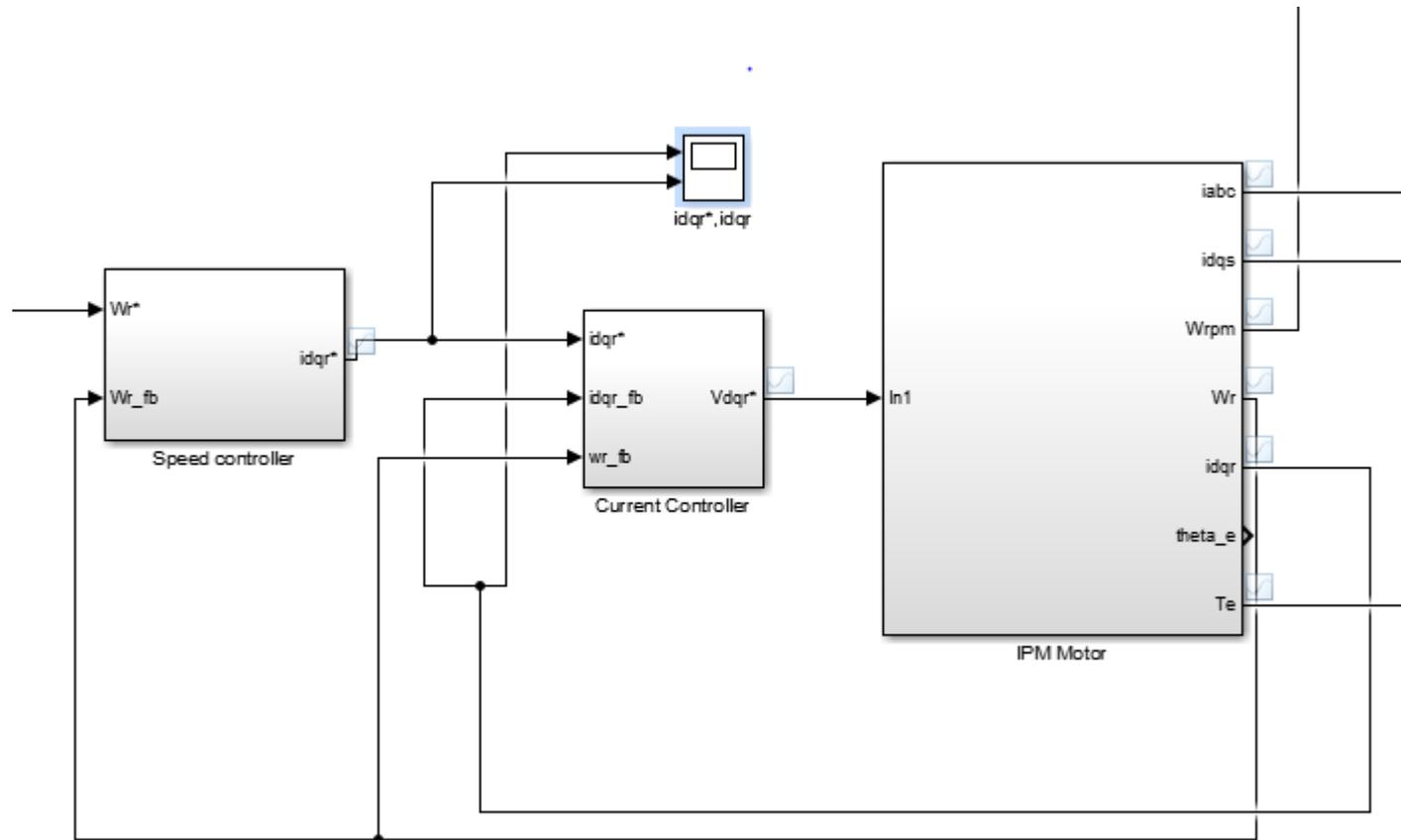
$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = \begin{bmatrix} R_s + PL_s & PM_s & PM_s & PM_{sr} \cos \theta & PM_{sr} \cos \theta_1 & PM_{sr} \cos \theta_2 \\ PM_s & R_s + PL_s & PM_s & PM_{sr} \cos \theta_2 & PM_{sr} \cos \theta & PM_{sr} \cos \theta_1 \\ PM_s & PM_s & R_s + PL_s & PM_{sr} \cos \theta_1 & PM_{sr} \cos \theta_2 & PM_{sr} \cos \theta \\ PM_{sr} \cos \theta & PM_{sr} \cos \theta_2 & PM_{sr} \cos \theta_1 & R_r + PL_r & PM_r & PM_r \\ PM_{sr} \cos \theta_1 & PM_{sr} \cos \theta & PM_{sr} \cos \theta_2 & PM_r & R_r + PL_r & PM_r \\ PM_{sr} \cos \theta_2 & PM_{sr} \cos \theta_1 & PM_{sr} \cos \theta & PM_r & PM_r & R_r + PL_r \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix}$$

**교류를 이용하는 전동기를 좌표변환을 통해 직류전동기처럼 해석하는 방법**





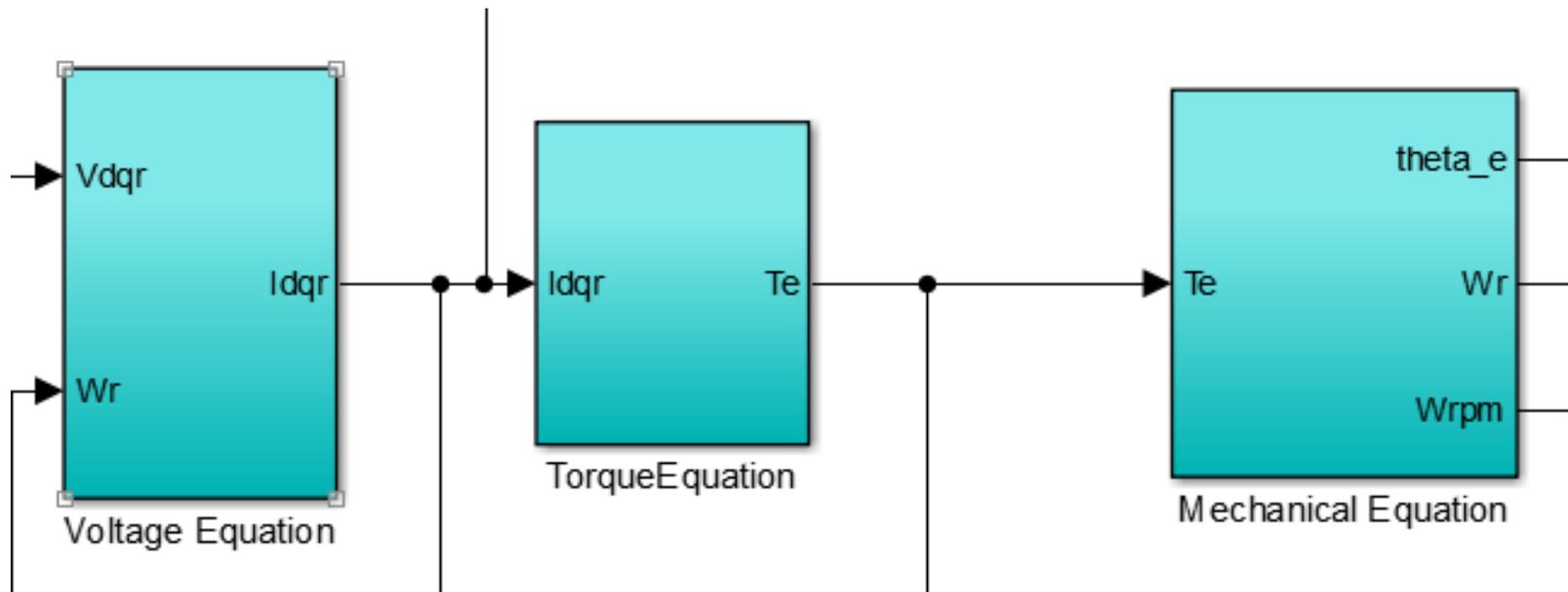
# Simulink





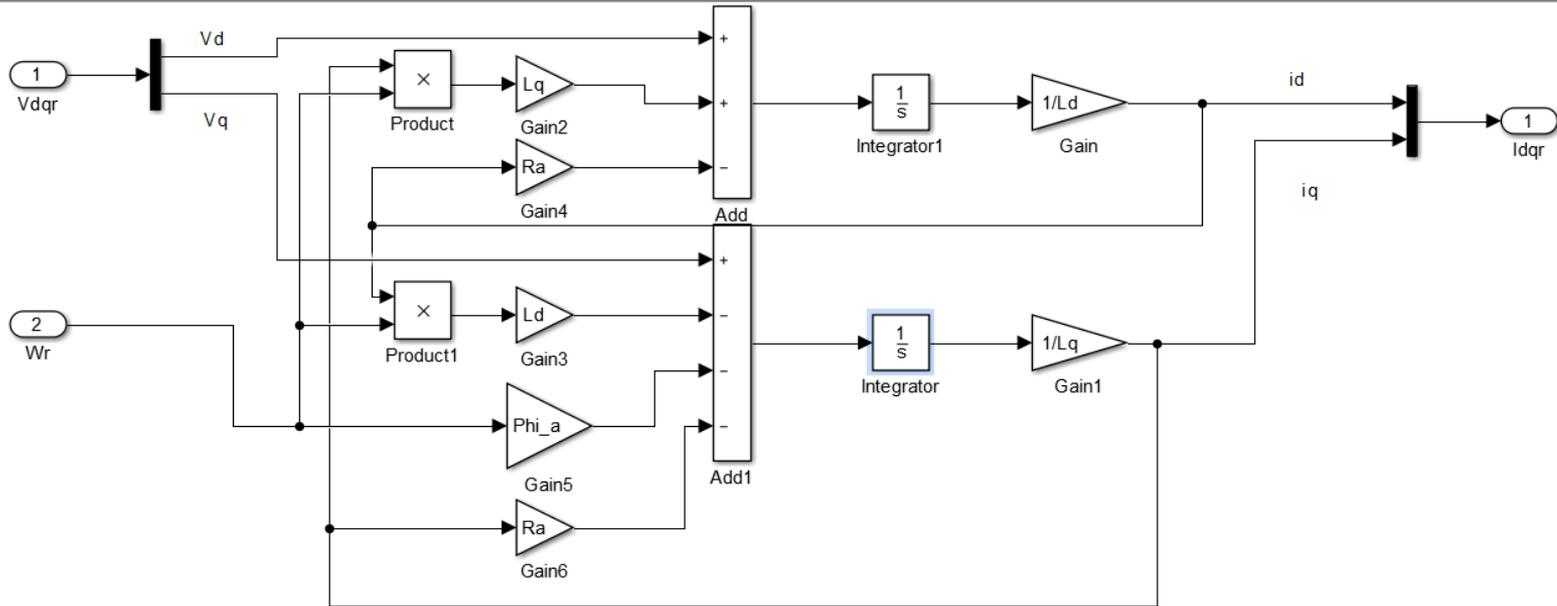


# IPMSM





# 전압방정식



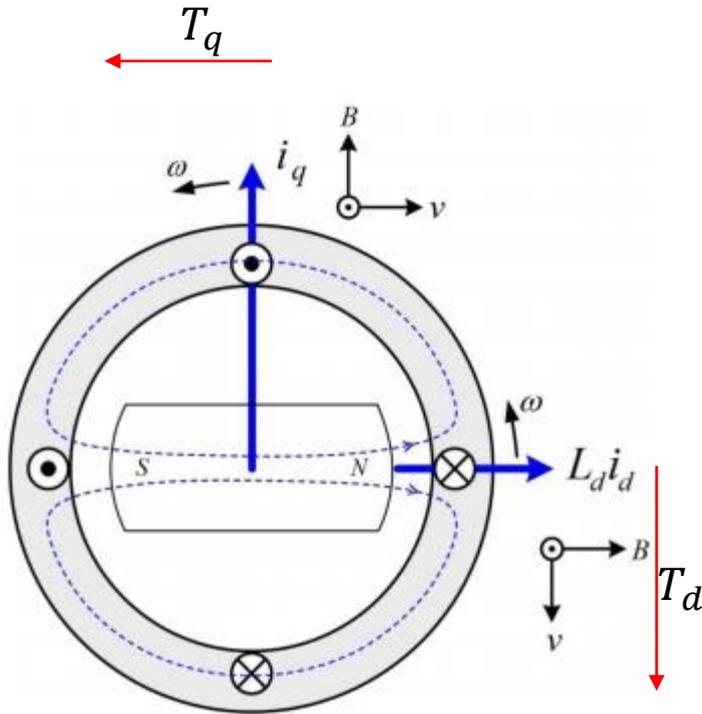
$$v = iR + \frac{d\phi}{dt} \rightarrow \text{역기전력}$$

$$v_d = i_d R_a + \frac{d\phi_d}{dt} = i_d R_a - \omega L_q i_q + L_d \frac{di_d}{dt}$$

$$v_q = i_q R_a + \frac{d\phi_q}{dt} = i_q R_a + \omega L_d i_d + L_q \frac{di_q}{dt} + \omega \phi_a$$



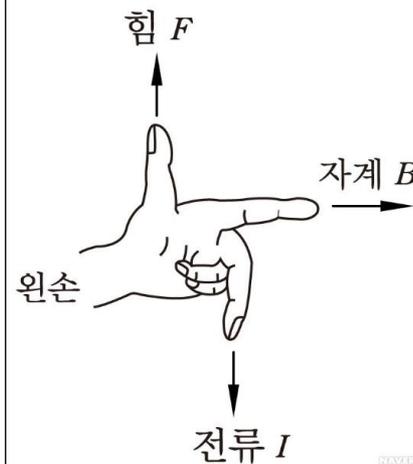
# 토크방정식



$$T = T_q + T_d = \varphi i = -\varphi_q i_d + \varphi_d i_q + \varphi_q i_d$$

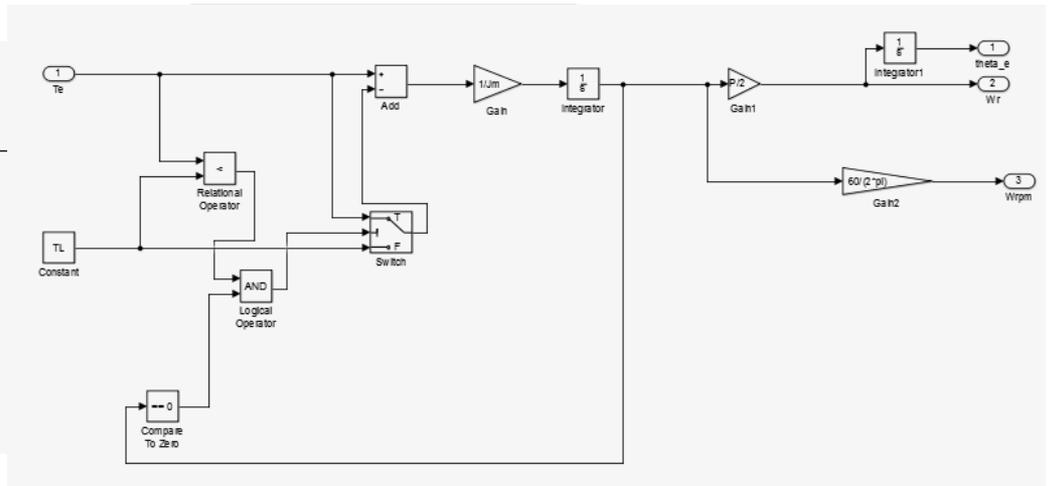
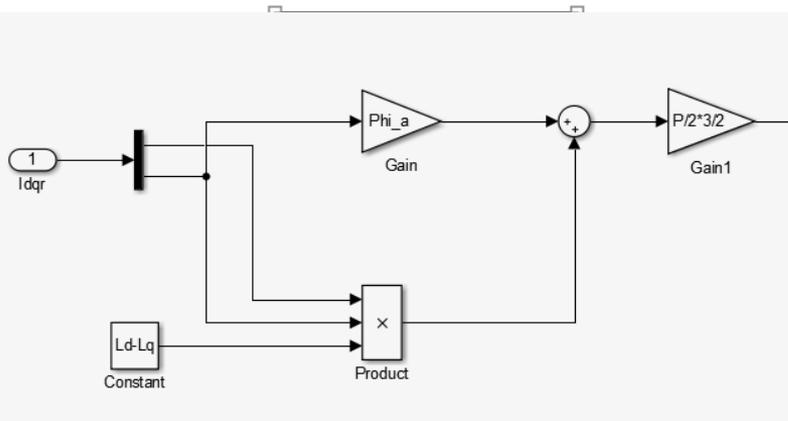
$$(\varphi_q = L_q i_q, \varphi_d = L_d i_d)$$

$$T = P_n(\varphi_a i_q + (L_d - L_q) i_d i_q)$$





# 토크&기계방정식



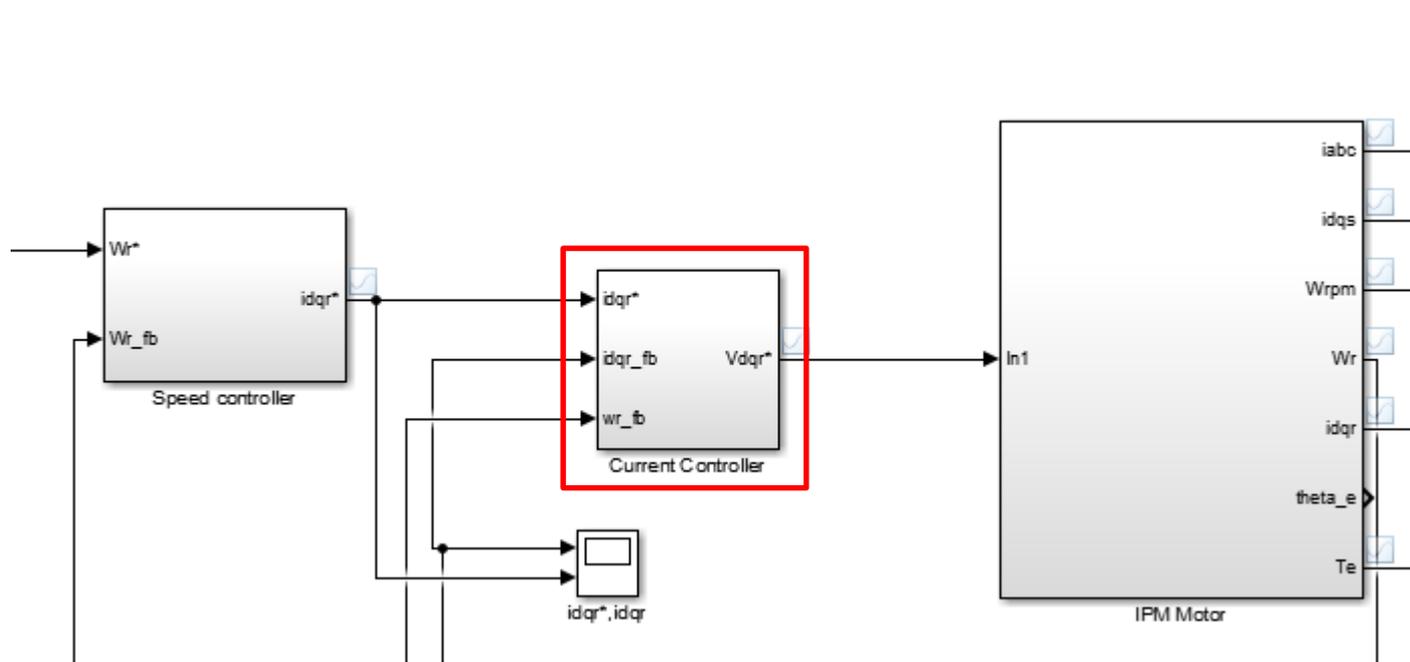
$$T_e = \frac{P}{2} \frac{3}{2} \{ \varphi_a i_q + (L_d - L_q) i_d i_q \}$$

$$T_e = J_m \frac{d\omega}{dt} + B\omega + T_L$$

$$\omega = \int \{ (T_e - T_L) / J_m \} dt$$



# 전류제어



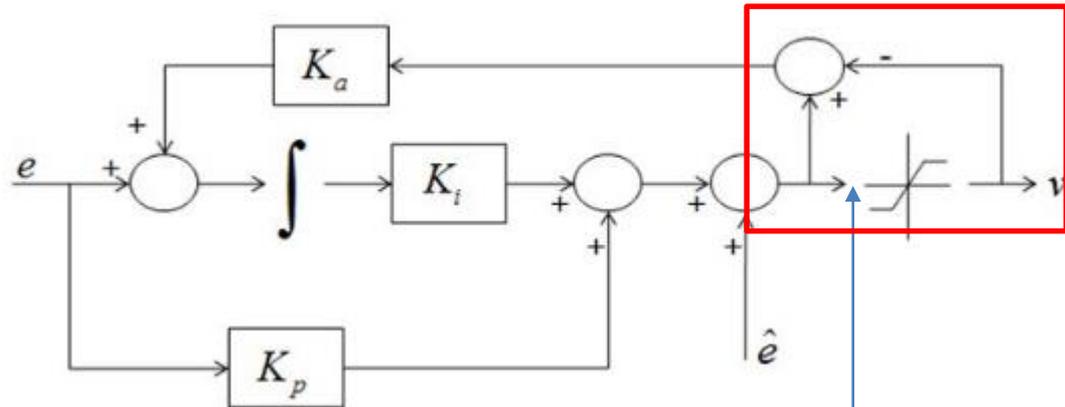


# Anti-Wind up & FeedForward Compensation

PI 제어

Anti-Wind up : 적분제어기에 쌓인 에러를 보정

FeedForward Compensation(전향보상) : 속도기전력 성분 보상



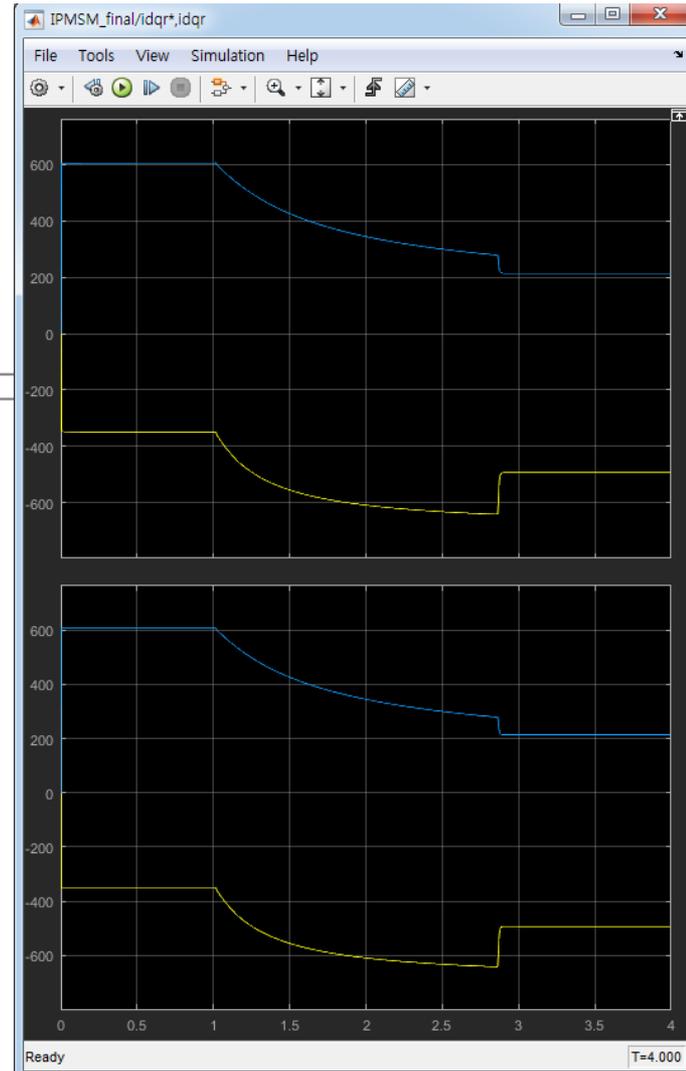
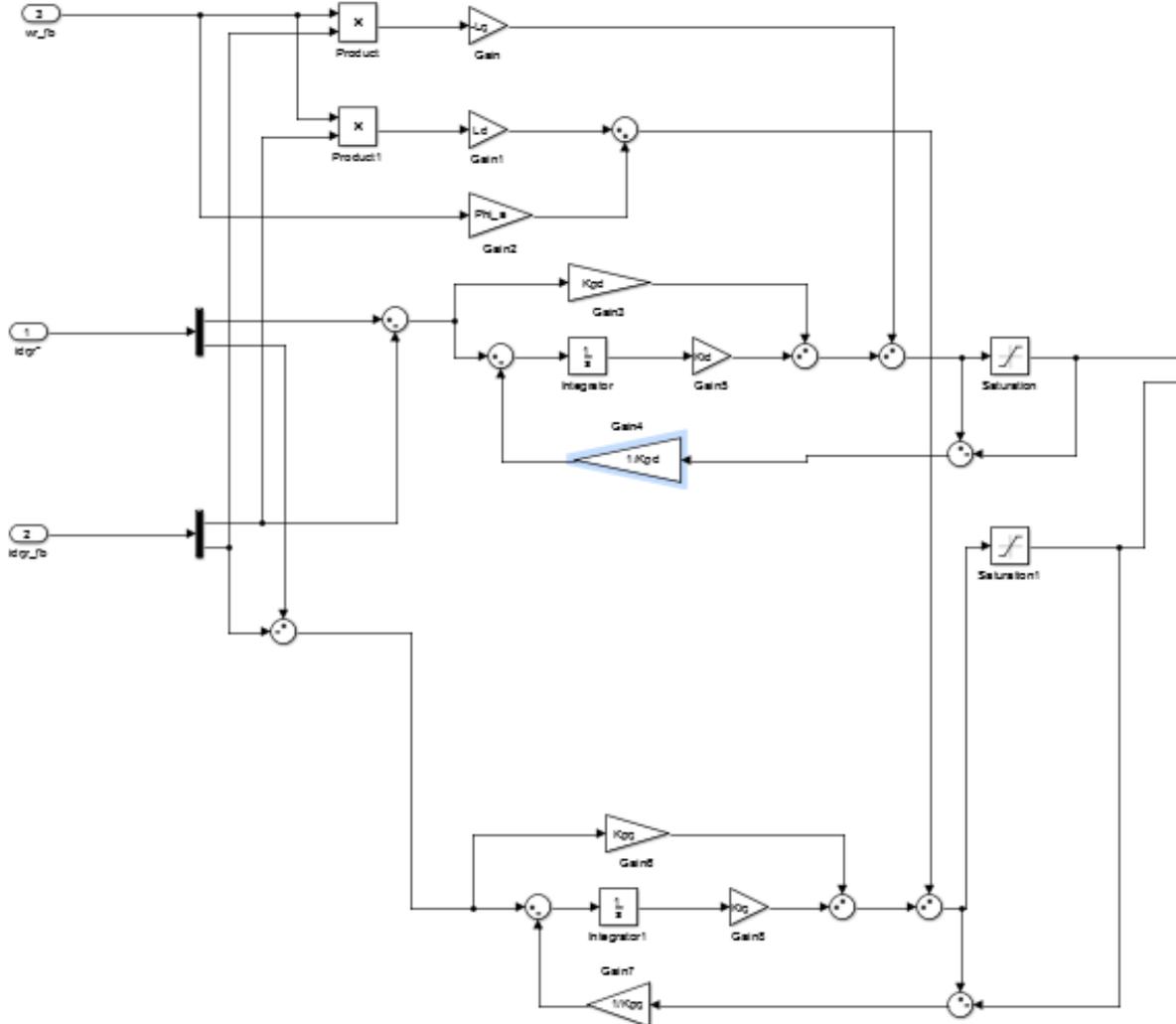
$$v_d = i_d R_a + \frac{d\phi_d}{dt} = i_d R_a - \omega L_q i_q + L_d \frac{di_d}{dt}$$

$$v_q = i_q R_a + \frac{d\phi_q}{dt} = i_q R_a + \omega L_d i_d + \omega \phi_a + L_q \frac{di_q}{dt}$$

전향보상

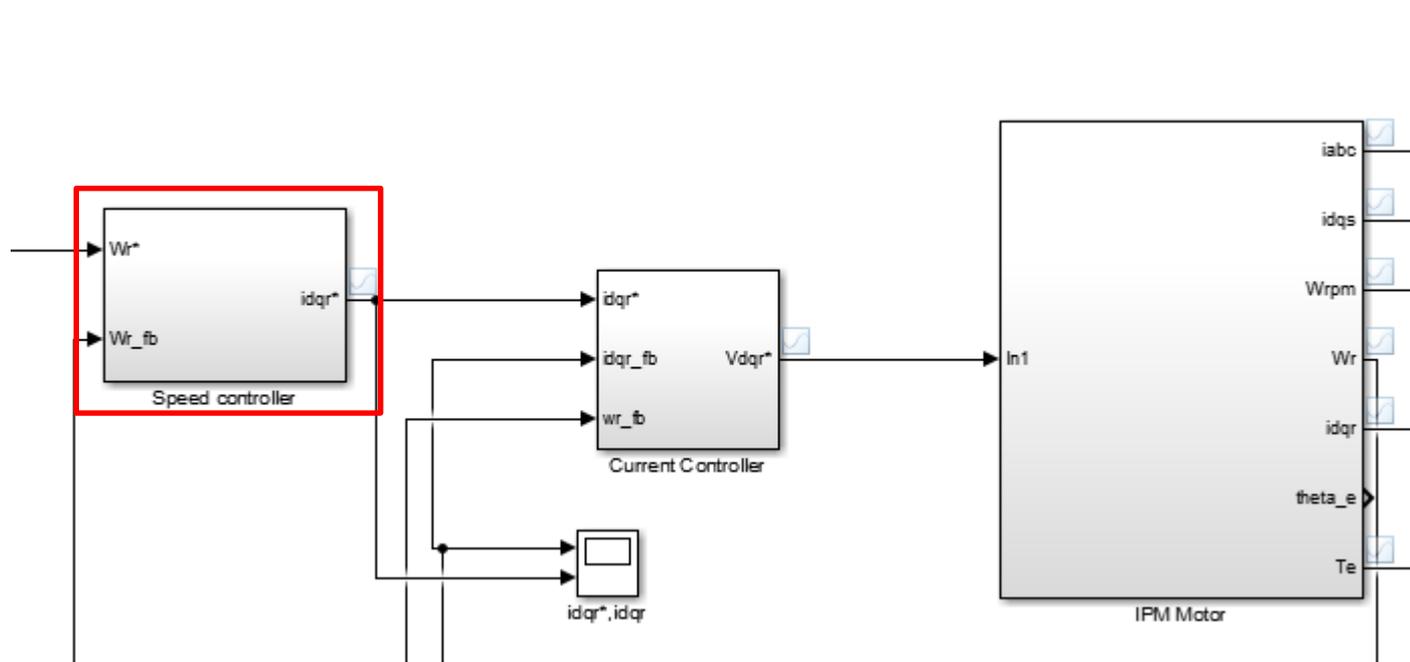


# 전류제어





# 속도제어





# 속도제어

MTPA제어 (최대토크제어)

$$T = P_n \left\{ \Psi_a I_a \cos \beta + \frac{1}{2} (L_q - L_d) I_a^2 \sin 2\beta \right\}$$

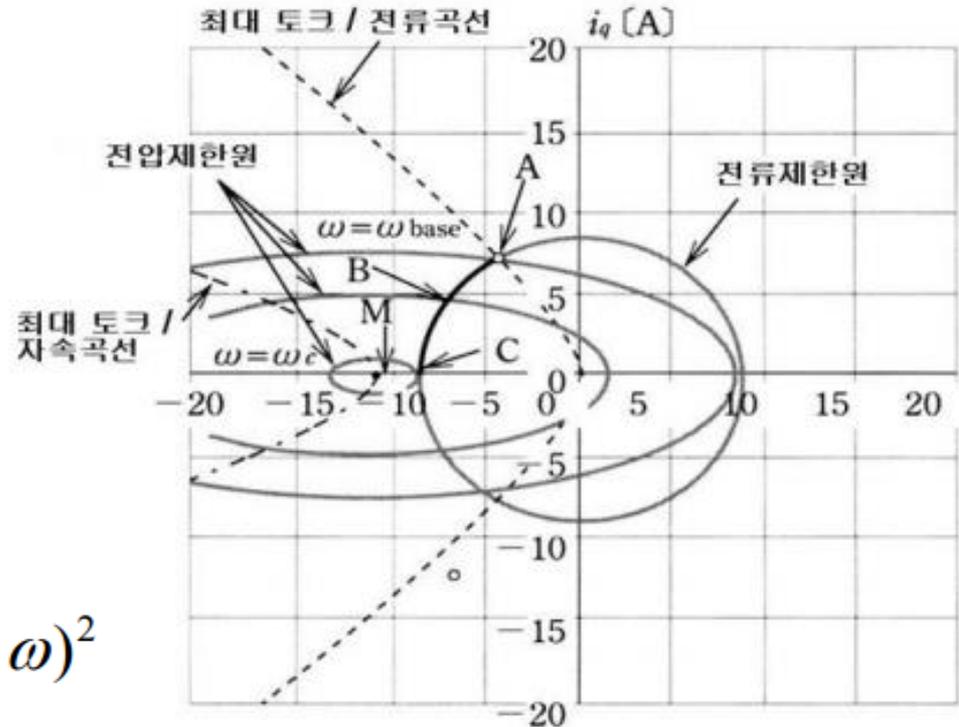
$$\therefore i_d = \frac{\Psi_a}{2(L_q - L_d)} - \sqrt{\frac{\Psi_a^2}{4(L_q - L_d)^2} + i_q}$$

약계자 제어  
전압제한

$$(L_q i_q)^2 + (L_d i_d + \Psi_a)^2 = (V_{om} / \omega)^2$$

전류제한

$$I_a = \sqrt{i_d^2 + i_q^2} \leq I_{am}$$





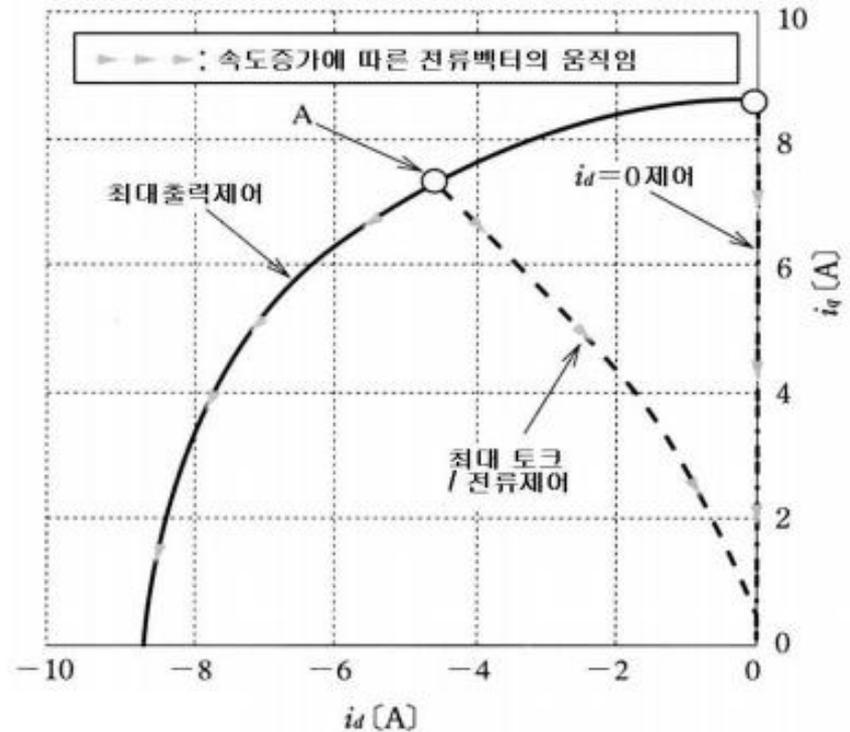
# 속도제어

$i_d=0$  제어

$$T_e = \frac{P}{2} \frac{3}{2} \{ \varphi_a i_q + (L_d - L_q) i_d i_q \}$$

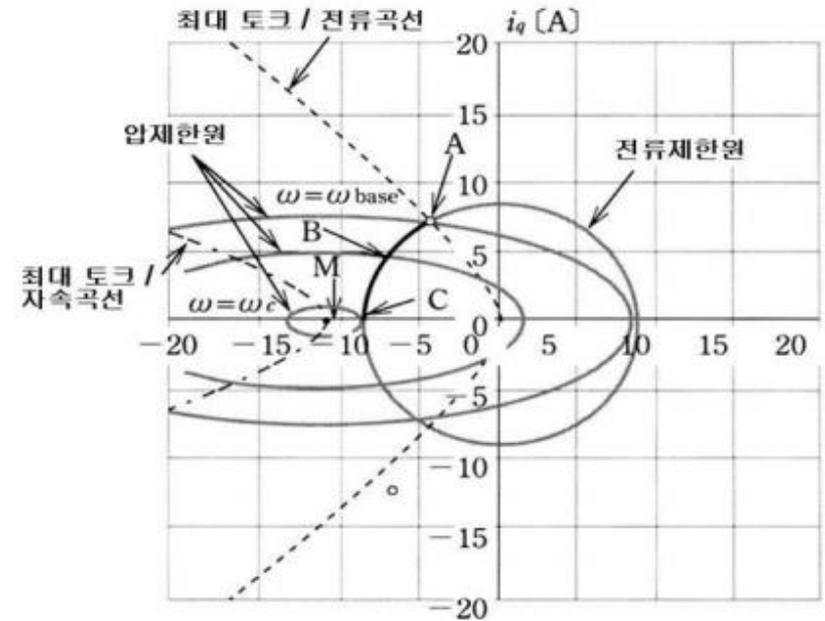
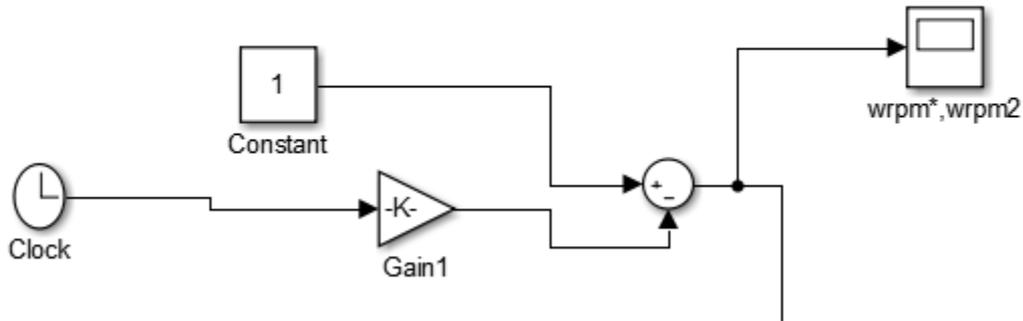
$$T = P_n \Psi_a i_q = P_n \Psi_a I_a$$

$$I_q = \frac{-R_a \omega \Psi_a + \sqrt{(R_a \omega \Psi_a)^2 - (\omega^2 L_q^2 + R_a^2)(\omega^2 \Psi_a^2 - V_{a,max}^2)}}{\omega^2 L_q^2 + R_a^2}$$





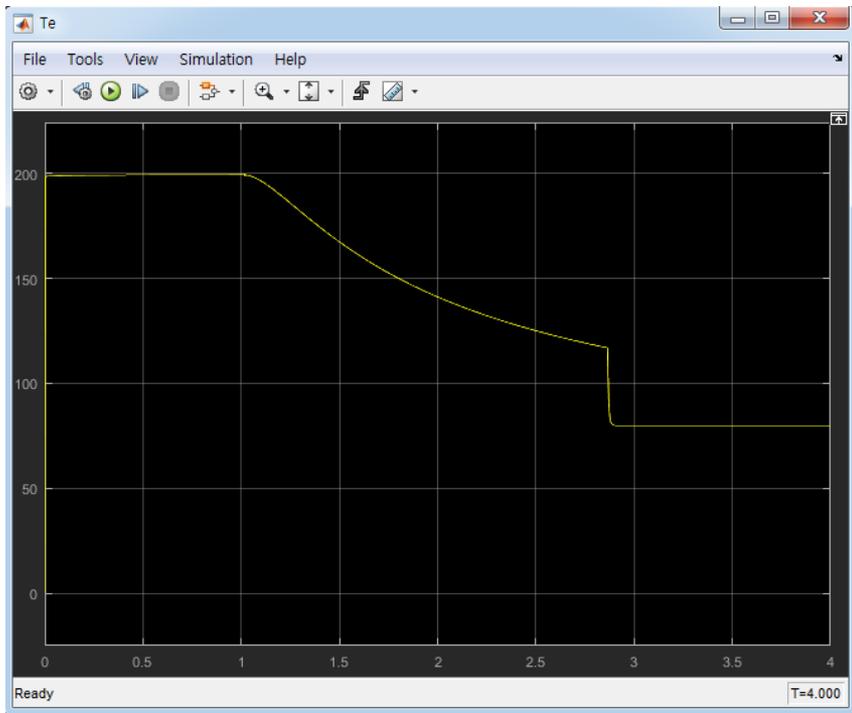
# 임의 제어



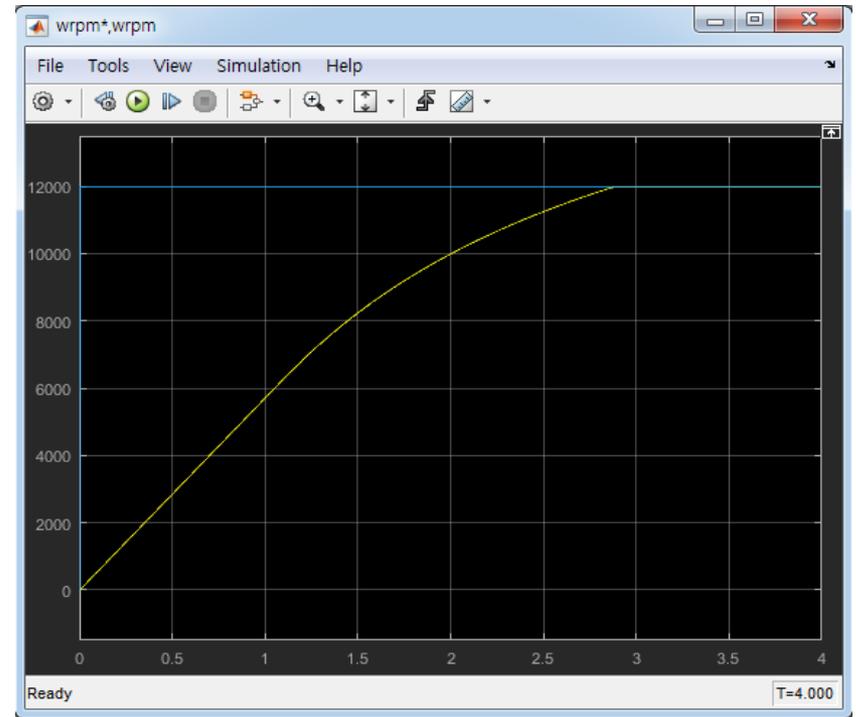


# 최대출력제어

토크



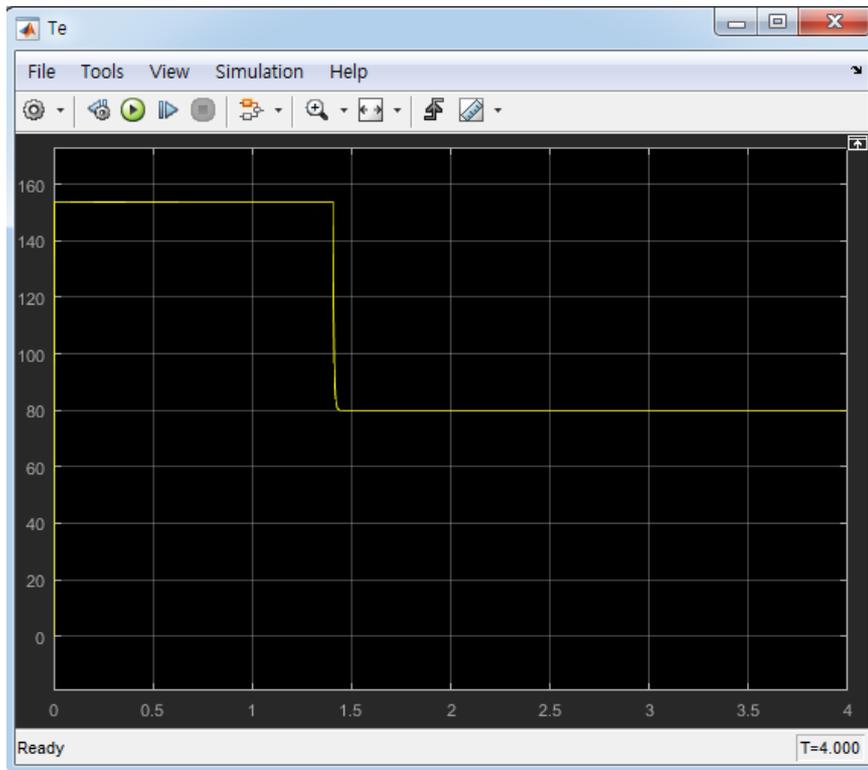
rpm



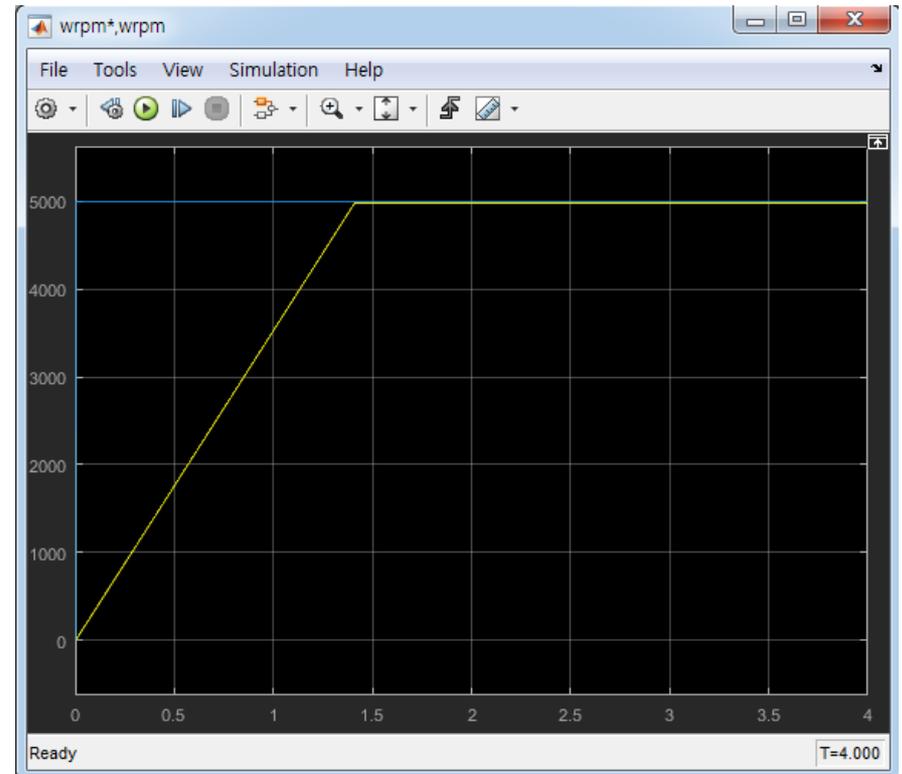


# $i_d = 0$ 제어

토크



rpm

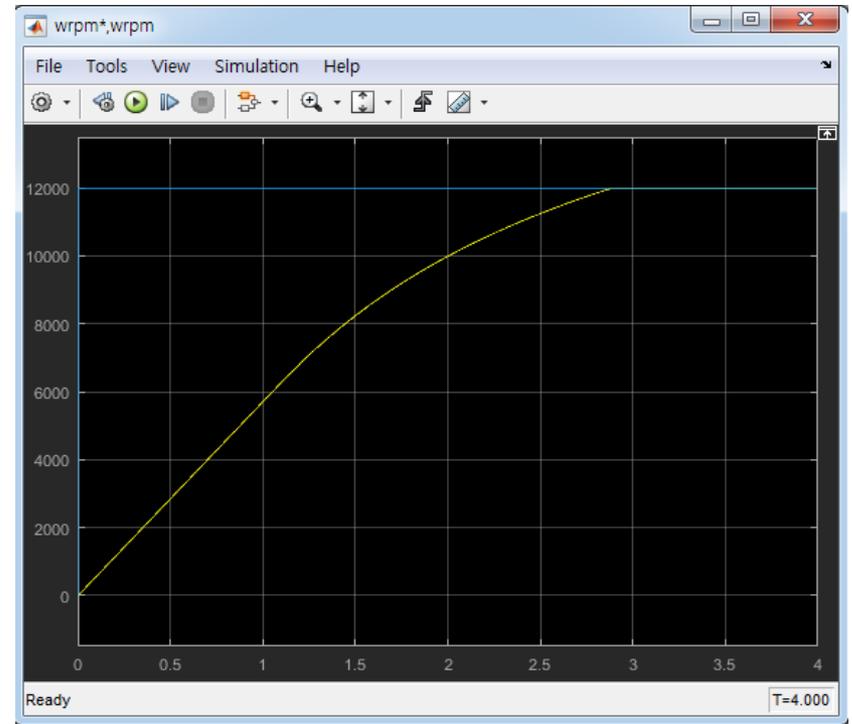
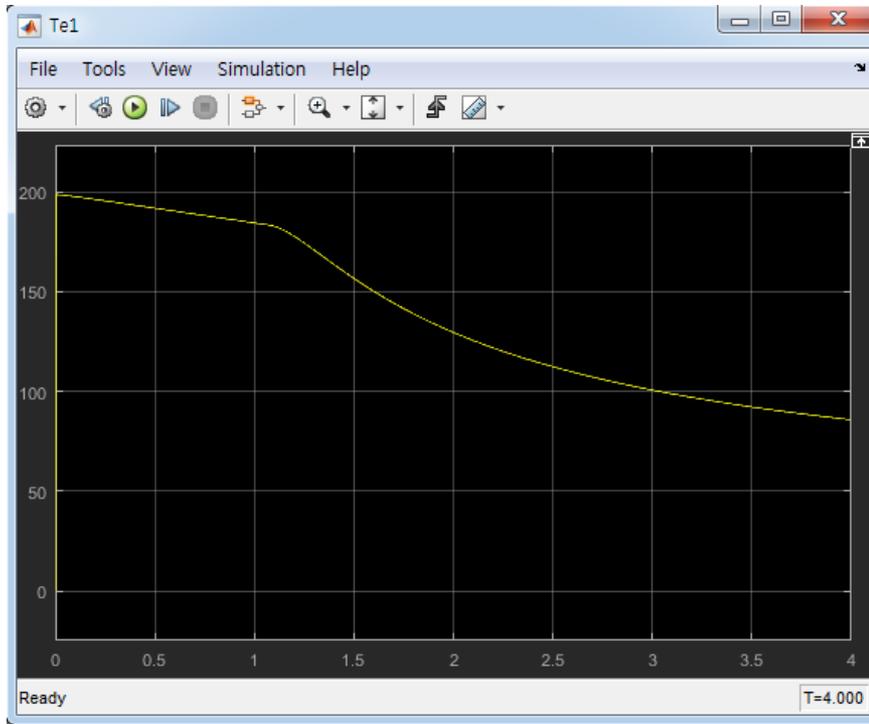




# 임의 제어

토크

rpm





# AMEsim

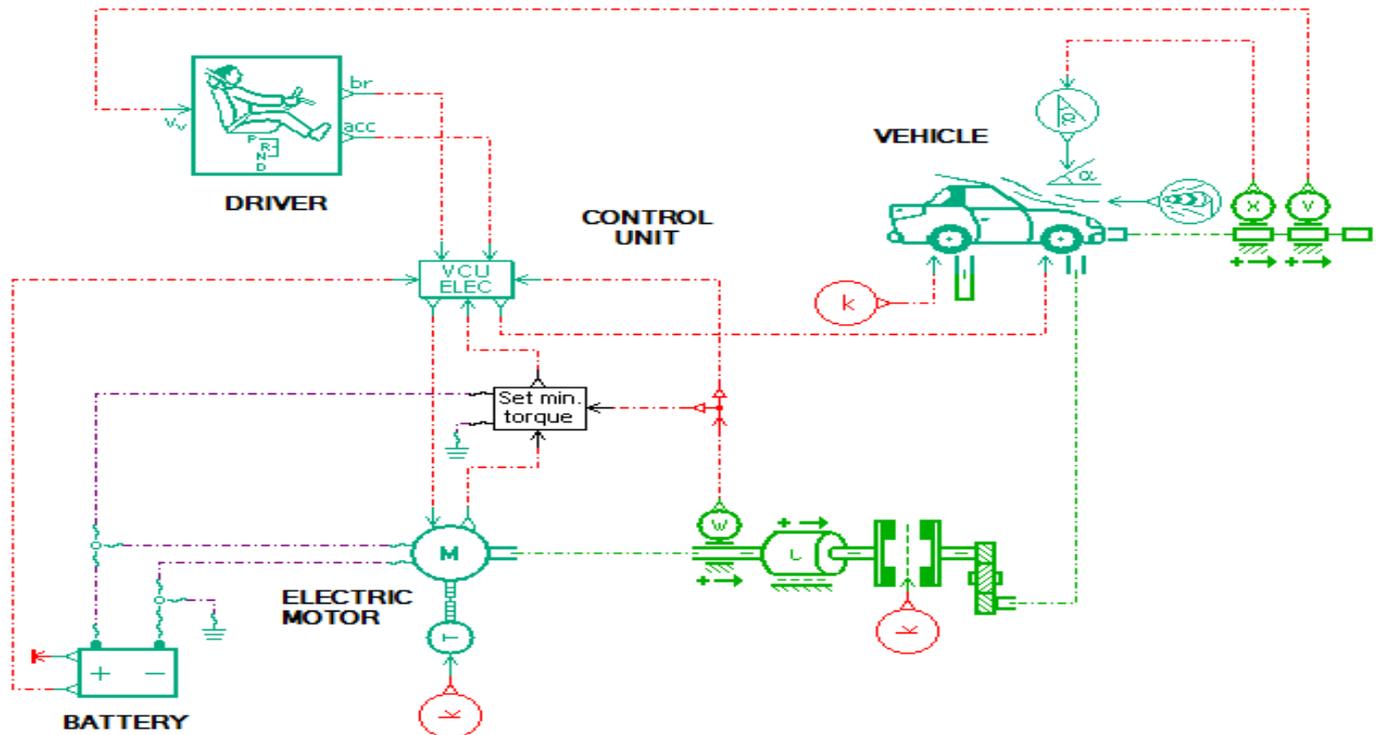
AMEsim : EV 동적 성능 파악

run stats



Electric vehicle

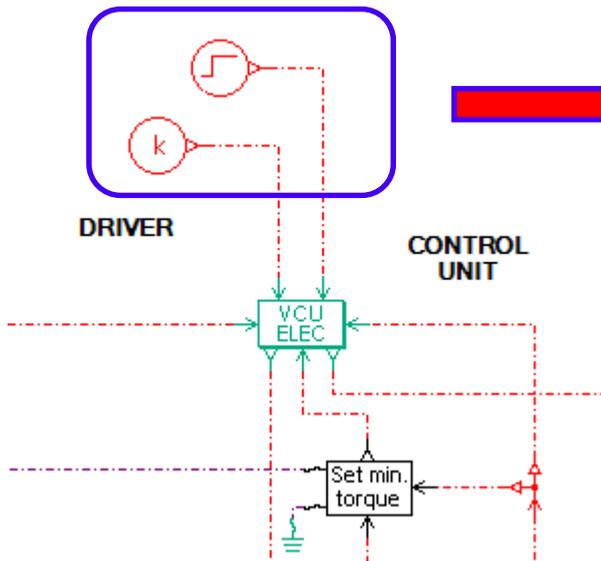
AMEsim  
Demo  
전기자동차 모델





# AMEsim

EV 동적 성능 : 0-100(제로백) & 최고 속도



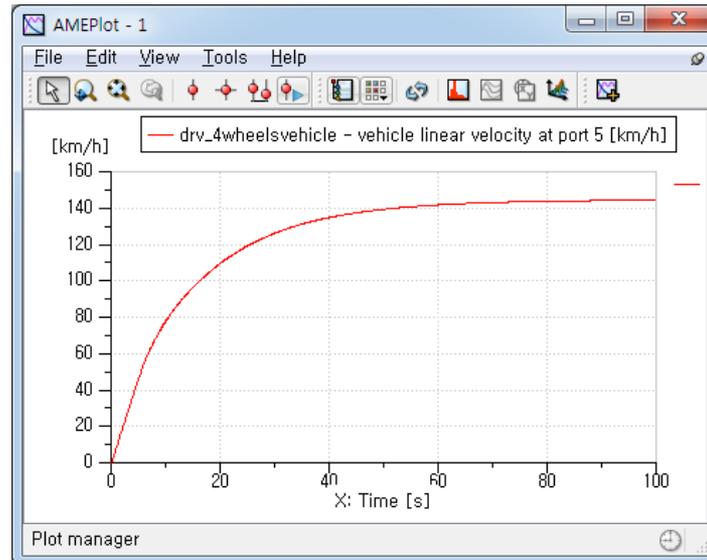
=1

Full Acceleration



=0

No Brake



0-100 : 16.250s

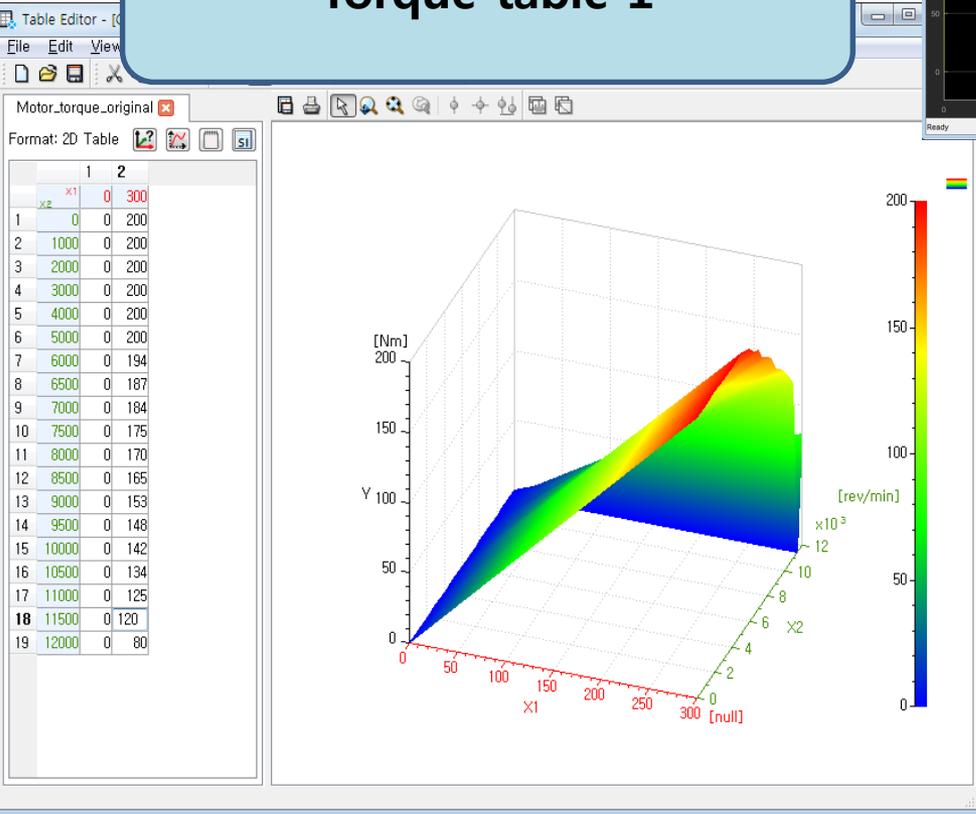
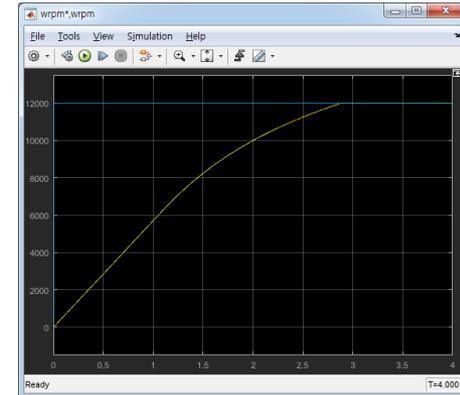
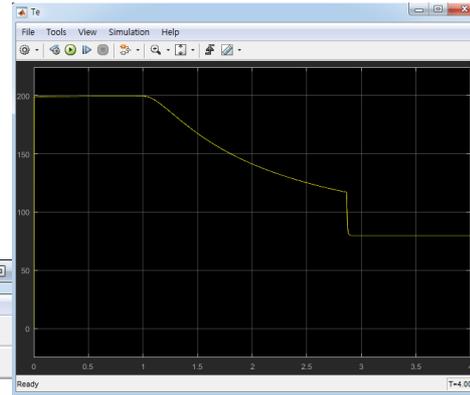
최고 속도  
144.34km/h



# AMEsim

## EV 동적 성능 1 [최대출력제어]

### Torque table 1



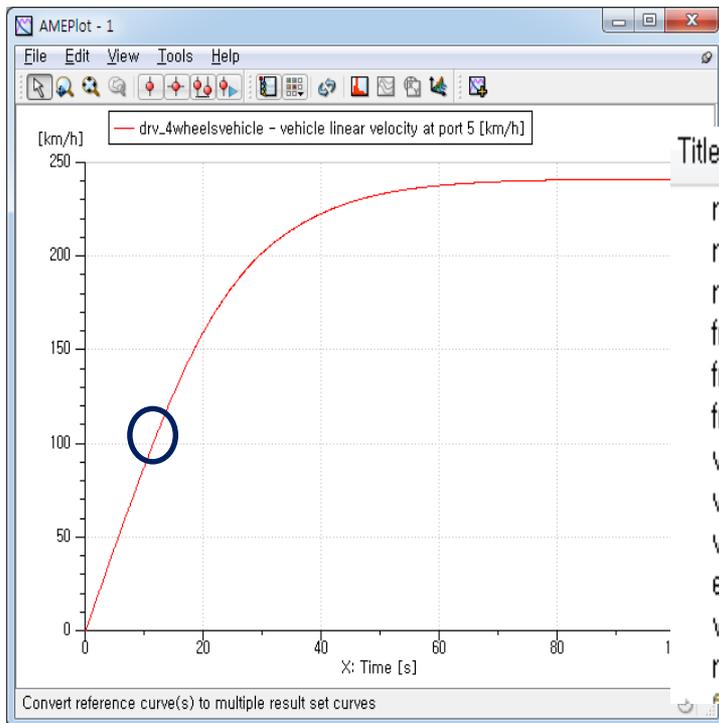
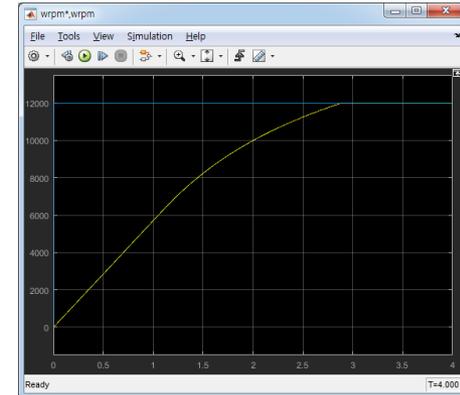
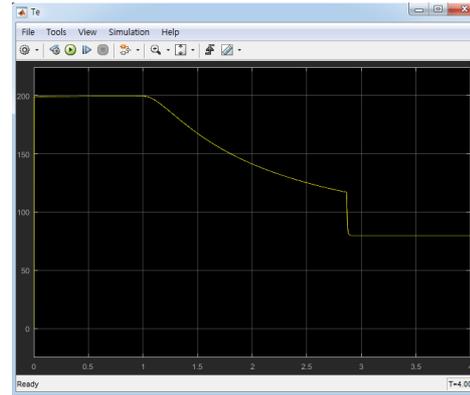
Simulink 토크&rpm 그래프로  
Motor Torque table 1 작성



# AMEsim

## EV 동적 성능 1 [최대출력제어]

### 차량 속도 그래프1



Title	Value	Unit
rear axle braking signal at port 1	0	null
rear wheel rotary velocity at port 2	-2121,81	rev/min
rear axle torque at port 2	0	Nm
front axle braking signal at port 3	0	null
front wheel rotary velocity at port 4	-2121,81	rev/min
front axle torque at port 4	660,159	Nm
vehicle linear velocity at port 5	241,171	km/h
vehicle linear displacement at port 5	5528,37	m
vehicle linear acceleration at port 5	0,00277496	m/s/s
external force at port 5	0	N
wind speed at port 6	0	m/s
road slope at port 7	0	null

0-100 : 11.574s

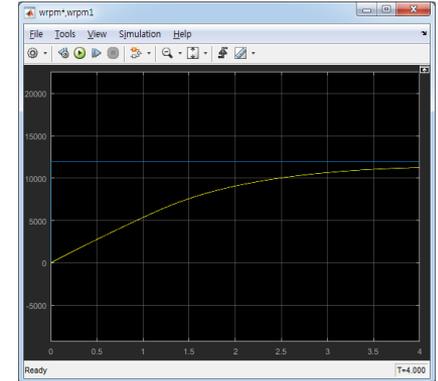
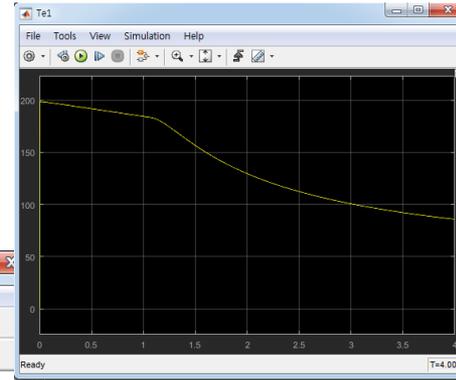
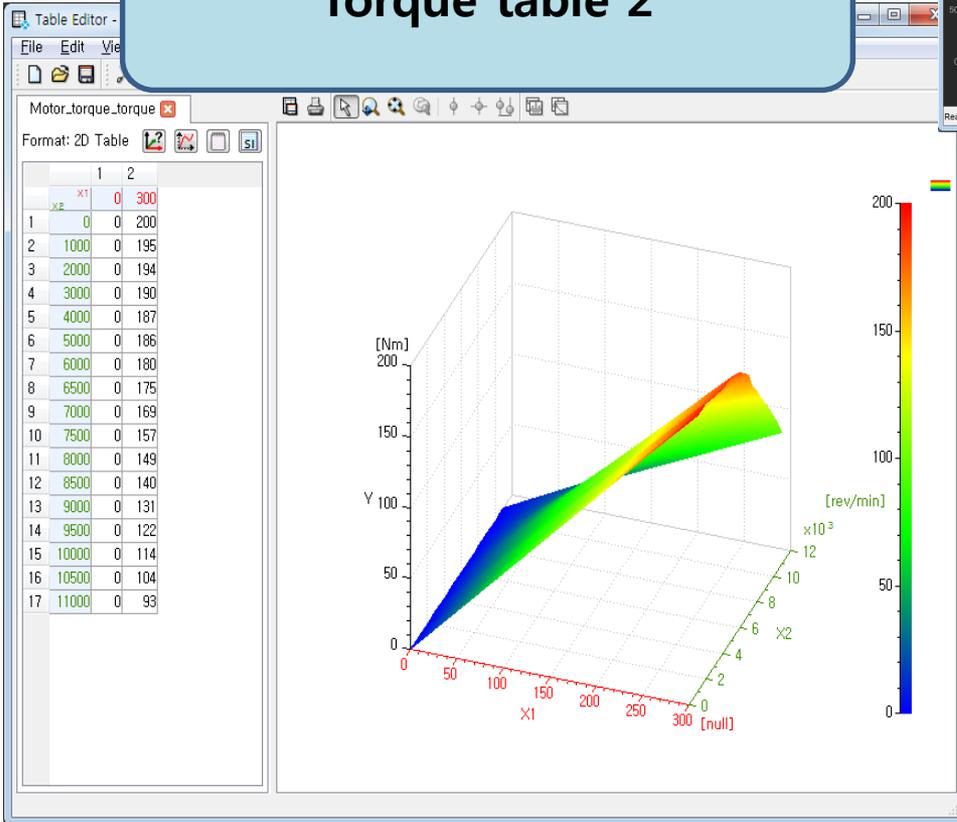
최고 속도  
241.171km/h



# AMEsim

## EV 동적 성능 2 [임의 제어]

### Torque table 2



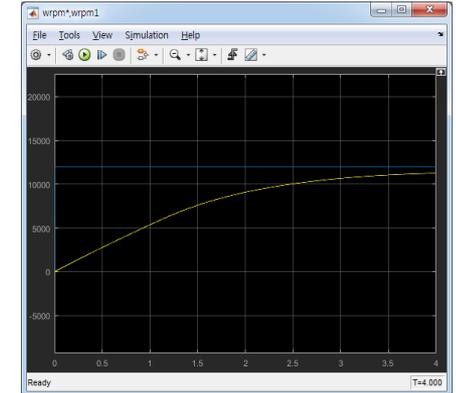
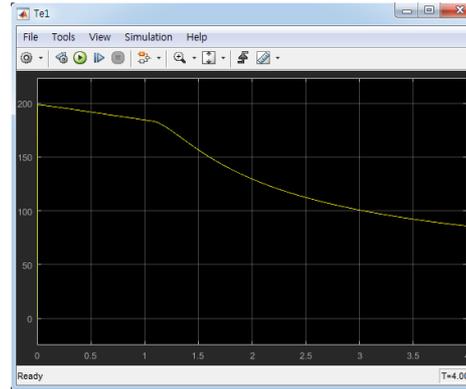
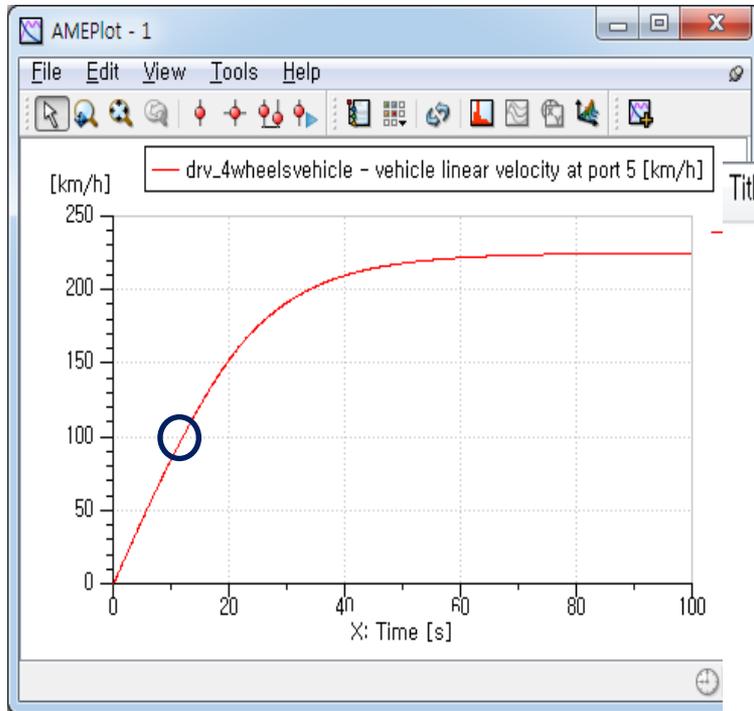
Simulink 토크&rpm 그래프로  
Motor Torque table 2 작성



# AMEsim

## EV 동적 성능 2 [임의 제어]

### 차량 속도 그래프2



Title	Value	Unit
rear axle braking signal at port 1	0	null
rear wheel rotary velocity at port 2	-1977,86	rev/min
rear axle torque at port 2	0	Nm
front axle braking signal at port 3	0	null
front wheel rotary velocity at port 4	-1977,86	rev/min
front axle torque at port 4	578,83	Nm
vehicle linear velocity at port 5	224,809	km/h
vehicle linear displacement at port 5	5190,08	m
vehicle linear acceleration at port 5	0,00302108	m/s/s
external force at port 5	0	N
wind speed at port 6	0	m/s
road slope at port 7	0	null

0-100 : 12.072s

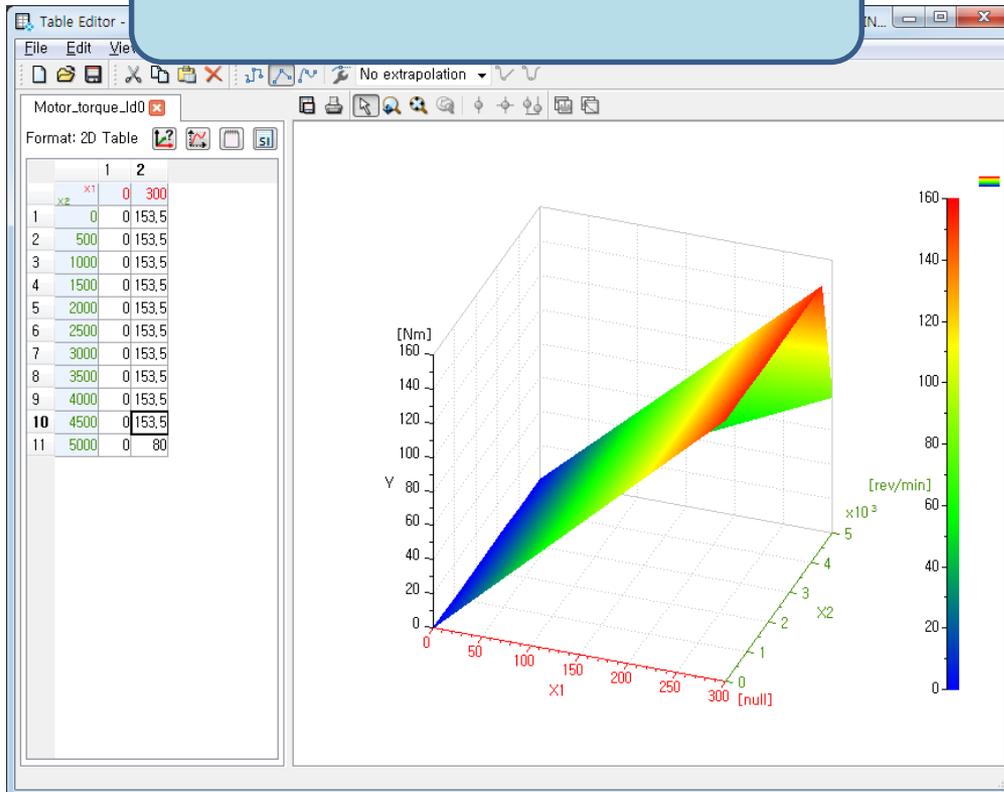
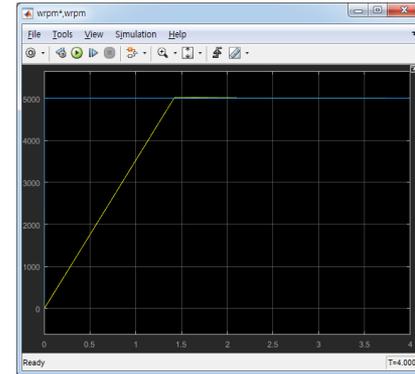
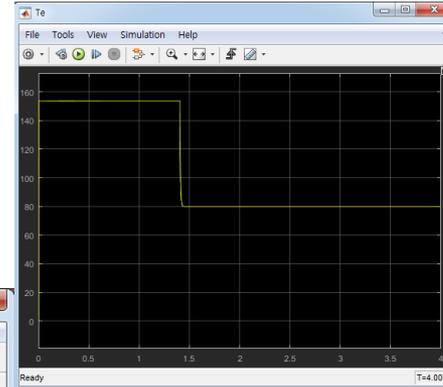
최고 속도  
224.809km/h



# AMEsim

EV 동적 성능 3 [ $i_d = 0$ ]

Torque table 3



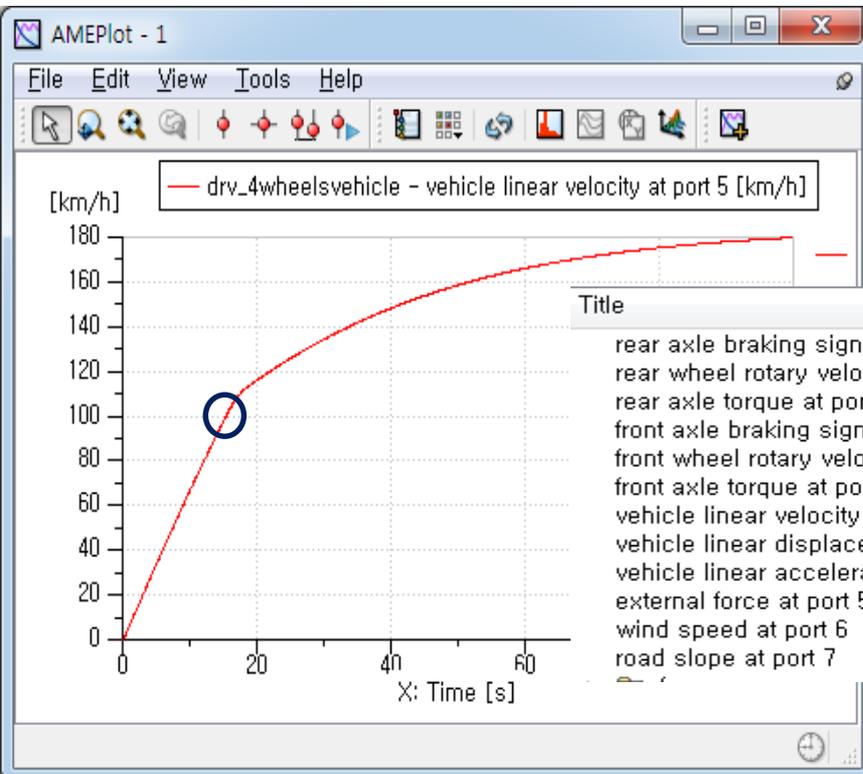
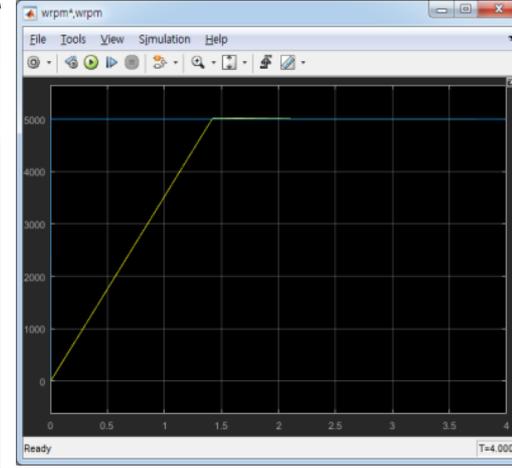
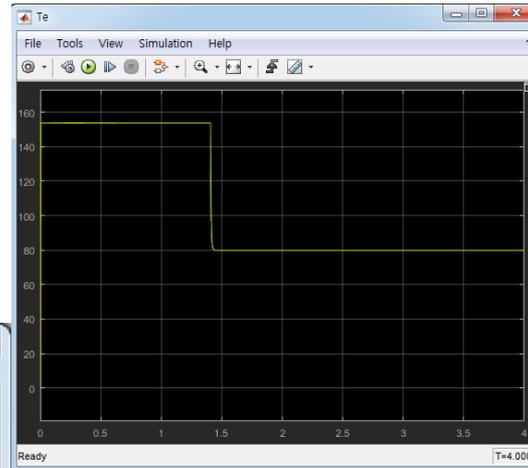
Simulink 토크&rpm 그래프로  
Motor Torque table 3 작성



# AMEsim

EV 동적 성능 3 [ $i_d = 0$ ]

차량 속도 그래프 3



0-100 : 15.433s

최고 속도  
179.861km/h



# Conclusion

AMEsim  
Demo  
전기자동차 모델

0-100 : 16.250s

최고 속도  
144.34km/h



1번  
[최대출력제어]

0-100 : 11.574s

최고 속도  
241.171km/h

2번  
[임의 제어]

0-100 : 12.072s

최고 속도  
224.809km/h

3번  
[ $i_d = 0$ ]

0-100 : 15.433s

최고 속도  
179.861km/h

IPMSM의 **최대 출력 제어**로 얻은 토크&rpm  
그래프에서의 자동차 성능이 제일 우수함.

**IPMSM 최대 출력 제어**로  
운전하는 것이 **옳다.**

# Reference

- [논문자료] A Study on the Optimal Design and Control Performance of Interior Permanent Magnet Synchronous Motor for EV/HEV
  - [논문자료] Development and Analysis of Interior Permanent Magnet Synchronous Motor with Field Excitation Structure  
Seong Taek Lee(*University of Tennessee - Knoxville*)
- [논문자료] "An Analysis Package Comparing PID Anti-Windup Strategies"
- 네오디뮴 자속: <http://www.magnetsales.com/neo/neoprops.htm#magnetic>
  - 모터 전류 : <http://www.seminartoday.net/news/articleView.html?idxno=3835>

**감사합니다.**





# 부록

Project  
보충자료



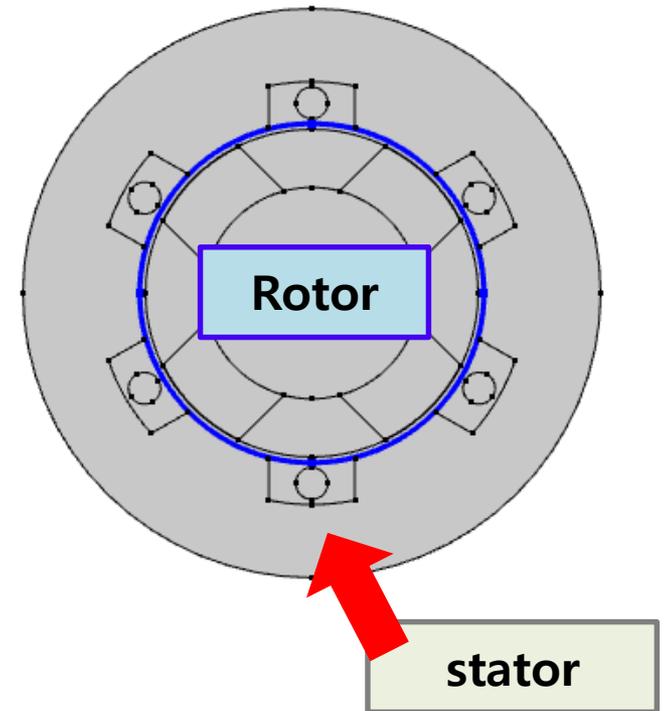
# COMSOL : MOTOR

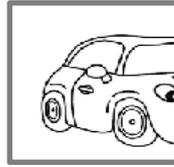
- Component 1 (comp1)
  - Definitions
    - Integration 3 (intop3)
    - Integration 2 (intop2)
    - Integration 1 (intop1)
    - Identity Pair 1 (ap1)**
    - Boundary System 1 (bs1)
    - Cylindrical System 1 (cs1)
  - View 1
  - Geometry 1
    - Import 1 (imp1)
    - Import 2 (imp2)
    - Form Assembly (imp)
  - Materials
  - Rotating Machinery, Magnetic
  - Mesh 1
- Study 1
  - Step 1: Stationary**
  - Step 2: Time Dependent
- Solver Configurations
  - Solution 1 (sol1)

Rotor 와 Stator 사이에서 슬립이 일어나면서 회전을 진행

Rotor 와 Stator는 따로 돌아야 되기 때문에 각각 Import

시간에 따라 Rotor의 회전을 표현  
[Study : Time dependent 추가]





**Magnetic Properties**

Grade	Br (Gauss)	Hc (Oersteds)	Hci (Oersteds)	BHmax (MGOe)	Temp. Coefficient of Br (%/°C)	Max. Op. Temp. (°C)	Density (lbs/in <sup>3</sup> )
4SB	3,460	3,460	9,600	3	-0.10	150	0.217
B10N	6,800	5,780	10,300	10	-0.10	150	0.217
24	9,800	7,500	8,000	24	-0.12	80	0.275
24UH	10,000	9,600	41,000	24	-0.10	210	0.271
27	10,850	9,650	13,500	27	-0.12	80	0.267
27H	10,600	10,100	17,000	27	-0.11	150	0.271
28	10,800	10,100	17,000	28	-0.11	150	0.271
28UH	10,900	10,400	25,000	28	-0.09	190	0.271
30	11,400	10,400	13,500	30	-0.12	150	0.267
30H	11,200	10,700	17,000	30	-0.11	150	0.271
32SH	11,600	11,100	31,000	32	-0.10	180	0.271
35	12,300	11,300	14,000	35	-0.11	150	0.271
35SH	12,200	11,700	26,000	36	-0.10	160	0.271
38H	12,550	11,700	17,000	39	-0.10	130	0.271
39H	12,800	12,300	21,000	40	-0.10	150	0.271
40	12,900	12,400	12,000	40	-0.11	130	0.271
42	13,050	12,500	14,000	41	-0.11	120	0.271
42H	13,300	12,700	17,000	43	-0.10	120	0.271
45	13,550	11,750	11,000	44	-0.12	100	0.271
45H	13,500	12,900	15,000	45	-0.11	100	0.271
48	14,100	12,900	13,500	48	-0.12	80	0.271

- Rotating Machinery, Ma
- Electric Field Transf
- Ampère's Law 1
- Mixed Formulation 1
- Magnetic Insulation
- Initial Values 1
- Prescribed Rotation
- Permanent Magnets
- Permanent Magnets
- iron
- Continuity 1
- iron 1
- External Current Der
- External Current Der
- External Current Der

A상  
250000cos(wt)

B상  
250000cos(wt-2/3π)

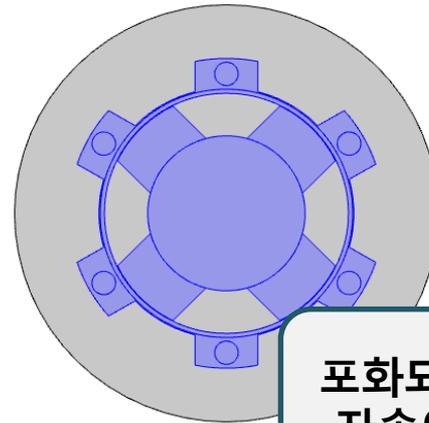
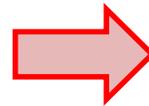
The permanent magnet material used in this motor is NdFeB type of which remanence flux density ( $B_r$ ) is 1.1 T, coercive field ( $H_c$ ) is -750000 A/m, and relative



# COMSOL : MOTOR

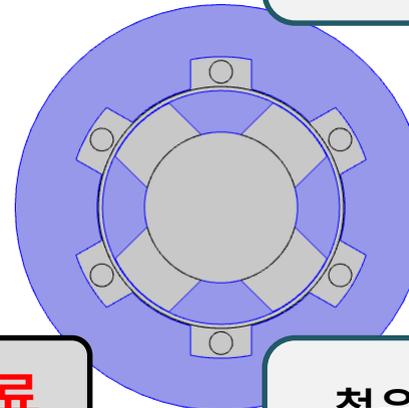
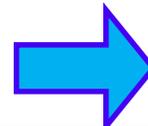
- Materials
  - Air (mat1)
    - Basic (def)
      - Piecewise (eta)
      - Piecewise 2 (Cp)
      - Analytic (rho)
      - Piecewise 3 (k)
      - Analytic 2 (cs)

- Refractive index (rfi)
  - Silicon Steel NGO 35JN200 (mat3)
    - Basic (def)
    - HB curve (HBCurve)
      - Interpolation 1 (HBCurve1)
    - BH curve (BHCurve)
      - Interpolation 1 (BHCurve1)



공기

포화되는 특성이 없는 재료  
자속이 잘 흐르지 않는다.



Silicon steel  
(nonlinear)

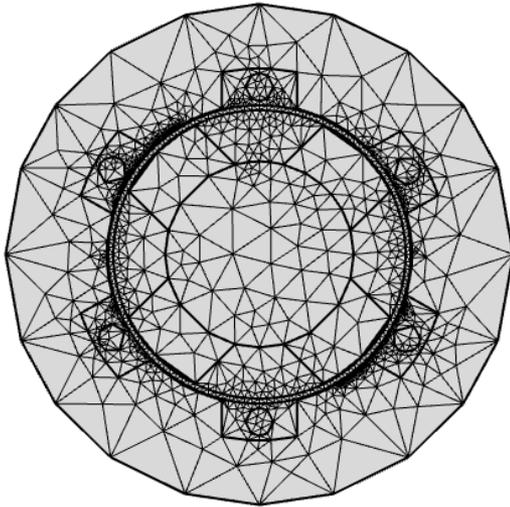
Nonlinear 재료

철은 철 내부 자속이 포화  
되는 특성을 가지고 있다.

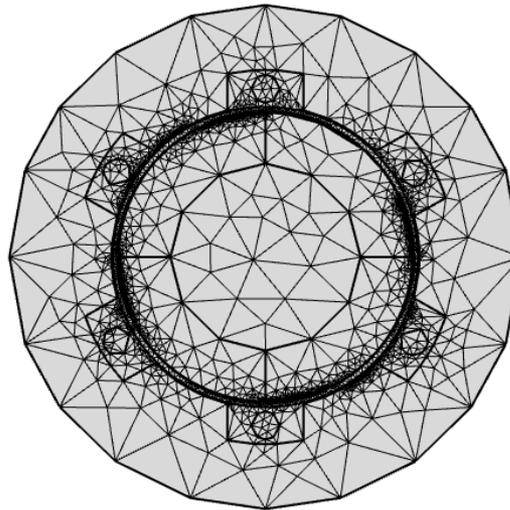


# COMSOL : MOTOR

Mesh : Extremely coarse



돌극형



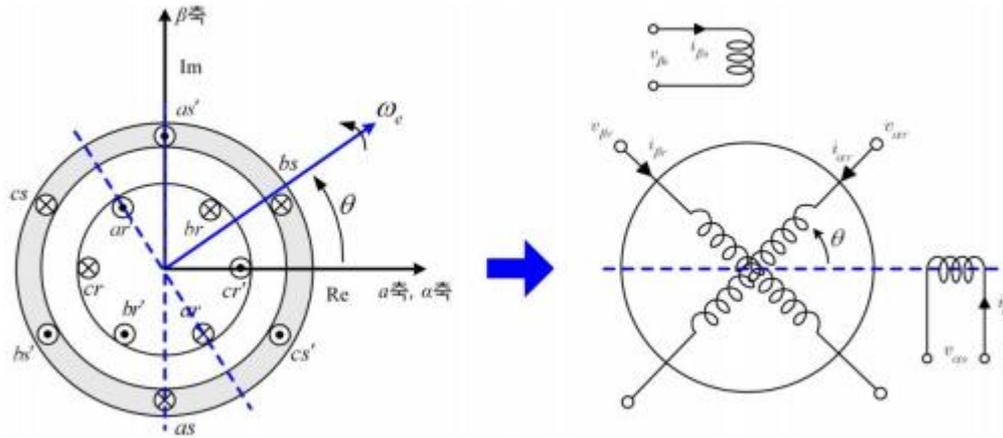
원통형

Mesh를 증가 시키면  
결과값은 큰 차이가 없다  
계산량을 줄이기 위해  
**Extremely coarse 사용**

Rotor 와 Stator의 경계에  
많은 매쉬가 형성 됨.



## 좌표 변환



3상

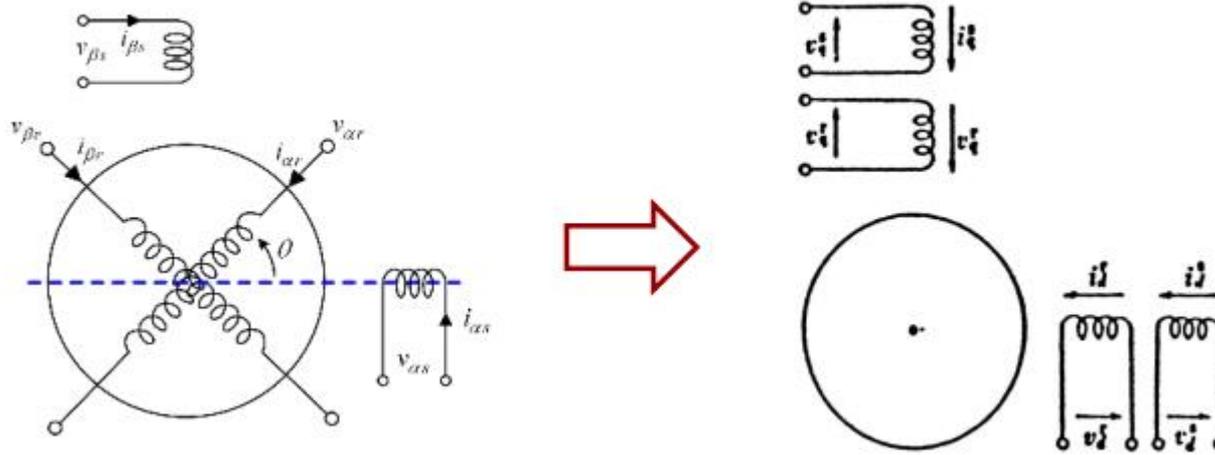


2상

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos 0^\circ & \cos 120^\circ & \cos 240^\circ \\ \sin 0^\circ & \sin 120^\circ & \sin 240^\circ \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$



# 좌표 변환



회전좌표

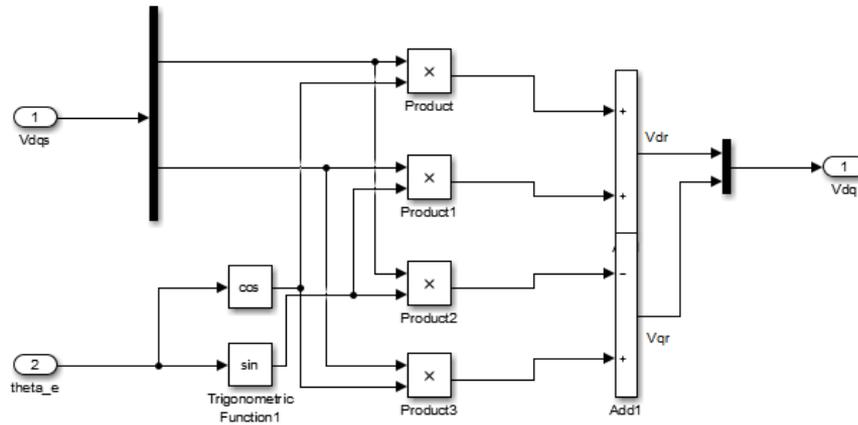
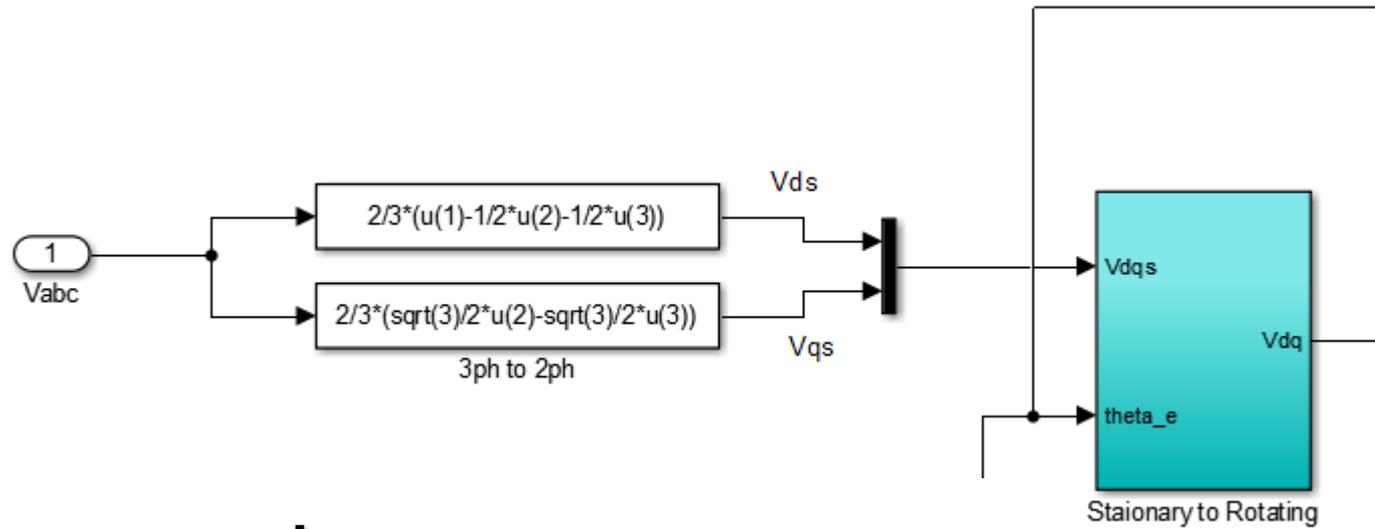


고정좌표

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$



## 좌표 변환



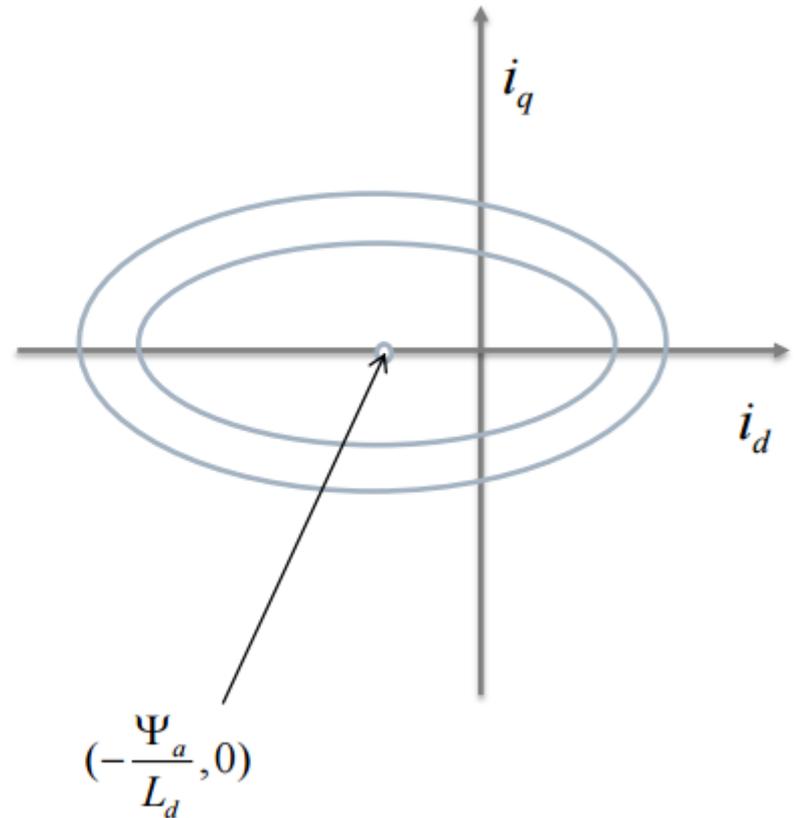
## 전압제한

$$\sqrt{v_{od}^2 + v_{oq}^2} = V_o = V_a - R_a I_a \leq V_{am} - R_a I_{am} = V_{om}$$

$$v_{od} = -\omega L_q i_q \quad v_{oq} = \omega L_d i_d + \omega \Psi_a$$

$$(\omega L_q i_q)^2 + (\omega L_d i_d + \omega \Psi_a)^2 = (V_{om})^2$$

$$(L_q i_q)^2 + (L_d i_d + \Psi_a)^2 = (V_{om} / \omega)^2$$



## (1) MTRA제어

$$T = P_n \left\{ \Psi_a I_a \cos \beta + \frac{1}{2} (L_q - L_d) I_a^2 \sin 2\beta \right\}$$

$$\begin{aligned} \frac{\partial T}{\partial \beta} &= P_n \left\{ -\Psi_a I_a \sin \beta + (L_q - L_d) I_a^2 \cos 2\beta \right\} \\ &= P_n \left\{ -\Psi_a I_a \sin \beta + (L_q - L_d) I_a^2 (1 - 2 \sin^2 \beta) \right\} \end{aligned}$$

$$\frac{\partial T}{\partial \beta} = 0 \text{ 일 때, Maximum Torque}$$



$$\sin \beta = \frac{-\Psi_a \pm \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a}$$

$$\therefore \beta = \sin^{-1} \left( \frac{-\Psi_a + \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a} \right)$$

$$T = P_n \left\{ \Psi_a I_a \cos \beta + \frac{1}{2} (L_q - L_d) I_a^2 \sin 2\beta \right\}$$

$$\begin{aligned} \frac{\partial T}{\partial \beta} &= P_n \left\{ -\Psi_a I_a \sin \beta + (L_q - L_d) I_a^2 \cos 2\beta \right\} && \text{토크식을 beta에 대해 미분} \\ &= P_n \left\{ -\Psi_a I_a \sin \beta + (L_q - L_d) I_a^2 (1 - 2 \sin^2 \beta) \right\} \end{aligned}$$

$$\frac{\partial T}{\partial \beta} = 0 \text{ 일 때, } \textit{Maximum Torque}$$

$$\frac{\partial T}{\partial \beta} = P_n \left\{ -\Psi_a I_a \sin \beta + (L_q - L_d) I_a^2 (1 - 2 \sin^2 \beta) \right\} = 0$$

$$\Rightarrow 2(L_q - L_d) I_a \sin^2 \beta + \Psi_a \sin \beta - (L_q - L_d) I_a = 0 \quad \text{근의 공식}$$

$$\sin \beta = \frac{-\Psi_a \pm \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a}$$

$$\therefore \beta = \sin^{-1} \left( \frac{-\Psi_a + \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a} \right)$$

$$i_d = -I_a \sin \beta, \quad i_q = I_a \cos \beta, \quad I_a = \sqrt{i_d^2 + i_q^2} \quad d, q \text{ 축 전류 관계식}$$

$$i_d = -I_a \left( \frac{-\Psi_a + \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a} \right)$$

$$= \frac{\Psi_a - \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 (i_d^2 + i_q^2)}}{4(L_q - L_d)}$$

$$\Rightarrow \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 (i_d^2 + i_q^2)} = \Psi_a - 4(L_q - L_d) i_d \quad \text{좌, 우변 정리하여 근의 공식}$$

$$\Rightarrow \Psi_a^2 + 8(L_q - L_d)^2 (i_d^2 + i_q^2) = \Psi_a^2 - 8(L_q - L_d) \Psi_a i_d + 16(L_q - L_d)^2 i_d^2$$

$$\Rightarrow 8(L_q - L_d)^2 i_d^2 - 8(L_q - L_d) \Psi_a i_d - 8(L_q - L_d)^2 i_q^2 = 0$$

$$\Rightarrow (L_q - L_d) i_d^2 - \Psi_a i_d - (L_q - L_d) i_q^2 = 0$$

$$\Rightarrow i_d = \frac{\Psi_a \pm \sqrt{\Psi_a^2 + 4(L_q - L_d)^2 i_q^2}}{2(L_q - L_d)}$$

$$\therefore i_d = \frac{\Psi_a}{2(L_q - L_d)} - \sqrt{\frac{\Psi_a^2}{4(L_q - L_d)^2} + i_q^2}$$

## 약계자제어

$$i_{d2} = \frac{\Psi_a L_d - \sqrt{(\Psi_a L_q)^2 + (L_q^2 - L_d^2) \left\{ (L_q I_{am})^2 - \left( \frac{V_{om}}{\omega} \right)^2 \right\}}}{L_q^2 - L_d^2}$$

$$i_{q2} = \sqrt{I_{am}^2 - i_{d2}^2}$$

# ST, 전기 자동차 개발 가속화 실리콘-카바이드 전력 디바이스 발표

완벽한 디바이스 세트르 자동차의 파워 모듈을 SiC(Silicon Carbide)로 전환

최광민 기자 | 승인 2016.05.19 11:04

댓글 0 | 트위터 | 페이스북



다양한 전자 애플리케이션에 걸쳐 고객들에게 기여하는 세계적인 반도체 회사 ST마이크로일렉트로닉스(STMicroelectronics, 이하 ST)가 하이브리드 및 전기 자동차(EV)를 위한 첨단 고효율 전력 반도체를 발표하고, 이와 관련된 자동차 품질 표준 AEC-Q101 인증 일정도 예고했다.

STPSC20065WY는 현재 TO-247 패키지로 양산 중이다. 이 제품은 저전류 등급의 소형 폼팩터 TO-220 패키지 옵션도 포함하고 있다. 1200V SiC 다이오드STPSC10H12DY는 현재 주요 고객 대상으로 폼팩터 TO-220AC 패키지 기반 샘플이 공급되고 있고 양산은 이번 달부터 시작 된다. 자동차 등급 제품은 2016년 4분기에 양산 시작 예정이다. **6A에서 20A에 이르는 다양한 전류 등급과 패키징 옵션도 제공될 예정이다.**

**모터 전류 6~20A**

<http://www.seminartoday.net/news/articleView.html?idxno=3835>

# 네오디뮴 Br 출처

네오디뮴 Br 평균값  
1.2 Tesla

<http://www.magnetsales.com/neo/neoprops.htm#magnetic>

## Magnetic Properties

Grade	Br (Gauss)	Hc (Oersteds)	Hci (Oersteds)	BHmax (MGOe)	Temp. Coefficient of Br (%/켈)	Max. Op. Temp. (켈)	Density (lbs/in <sup>3</sup> )
4SB	3,460	3,460	9,600	3	-0.10	150	0.217
B10N	6,800	5,780	10,300	10	-0.10	150	0.217
24	9,800	7,500	8,000	24	-0.12	80	0.275
24UH	10,000	9,600	41,000	24	-0.10	210	0.271
27	10,850	9,650	13,500	27	-0.12	80	0.267
27H	10,600	10,100	17,000	27	-0.11	150	0.271
28	10,800	10,100	17,000	28	-0.11	150	0.271
28UH	10,900	10,400	25,000	28	-0.09	190	0.271
30	11,400	10,400	13,500	30	-0.12	150	0.267
30H	11,200	10,700	17,000	30	-0.11	150	0.271
32SH	11,600	11,100	31,000	32	-0.10	180	0.271
35	12,300	11,300	14,000	35	-0.11	150	0.271
35SH	12,200	11,700	26,000	36	-0.10	160	0.271
38H	12,550	11,700	17,000	39	-0.10	130	0.271
39H	12,800	12,300	21,000	40	-0.10	150	0.271
40	12,900	12,400	12,000	40	-0.11	130	0.271
42	13,050	12,500	14,000	41	-0.11	120	0.271
42H	13,300	12,700	17,000	43	-0.10	120	0.271
45	13,550	11,750	11,000	44	-0.12	100	0.271
45H	13,500	12,900	15,000	45	-0.11	100	0.271
48	14,100	12,900	13,500	48	-0.12	80	0.271