



전기차 구동모터

PMSM

CAE TEAM PROJECT

2022025087 안선재

2023066008 양승연



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01 팀 소개

FOCUS PMSM

안선재

Simulink 기반 PMSM 모델 구현
COMSOL을 활용한 2D 모델링

양승연

Simulink 기반 PMSM FOC 제어 시스템 구축
COMSOL 2D 기반 해석

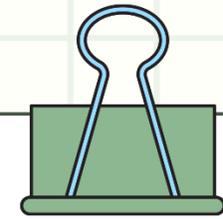


02 주제 선정 배경

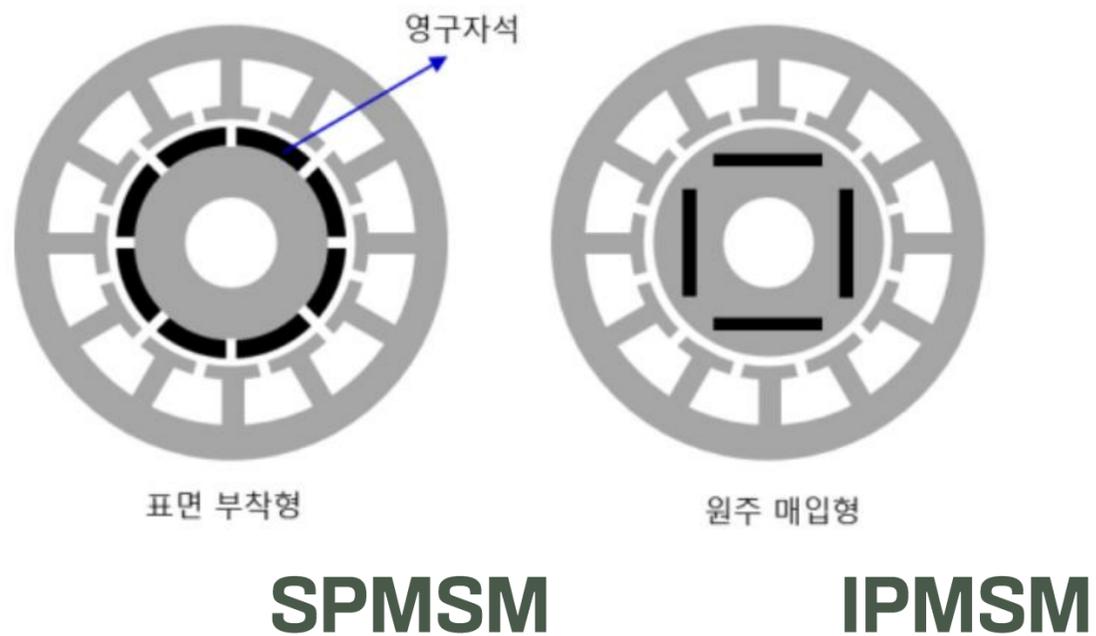


PMSM(영구자석 동기 모터)은 기존 모터에 비해 상당한 에너지 절감 효과를 제공하는 고효율 모터입니다. 전 세계 산업과 정부가 에너지 효율성과 지속 가능성을 우선시함에 따라 PMSM에 대한 수요는 앞으로 급증할 것으로 예상됩니다. PMSM은 에너지 소비가 주요 관심사인 전기 자동차, 산업 기계, 가전 제품과 같은 응용 분야에 특히 적합합니다. 제조업체는 PMSM을 채택함으로써 운영 비용을 절감하고 보다 친환경적인 환경에 기여할 수 있습니다.

글로벌 영구 자석 동기 모터 Pmsm 시장 조사 보고서



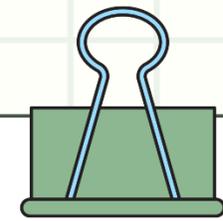
02 주제 선정 배경



PMSM 모터 수학적 모델링 일반화

FOC (Field Oriented Control) 모델링

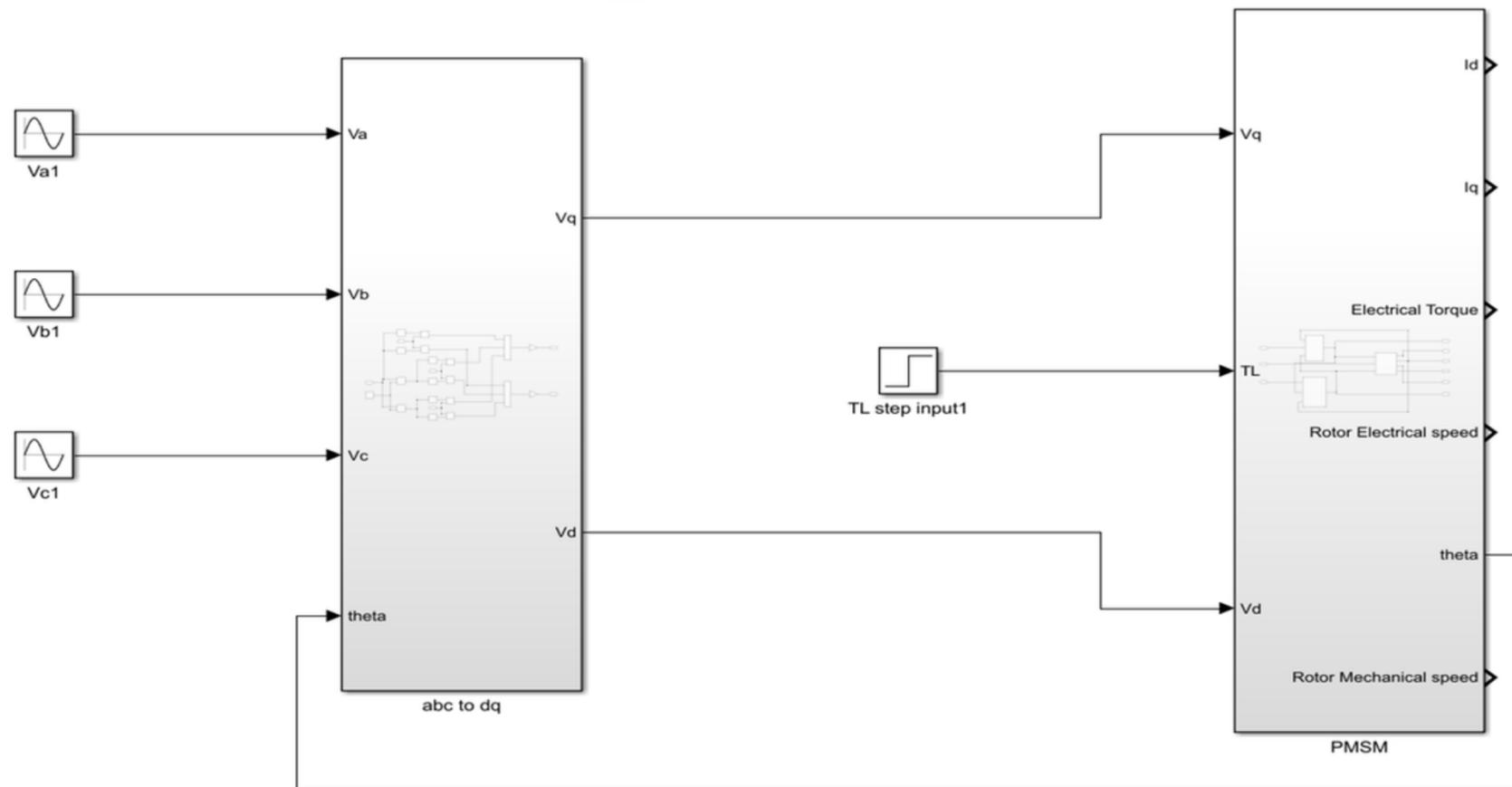
Comsol 동손(copper loss) 해석



04 Simulink

PMSM

(Permanent Magnet Synchronous Motor)



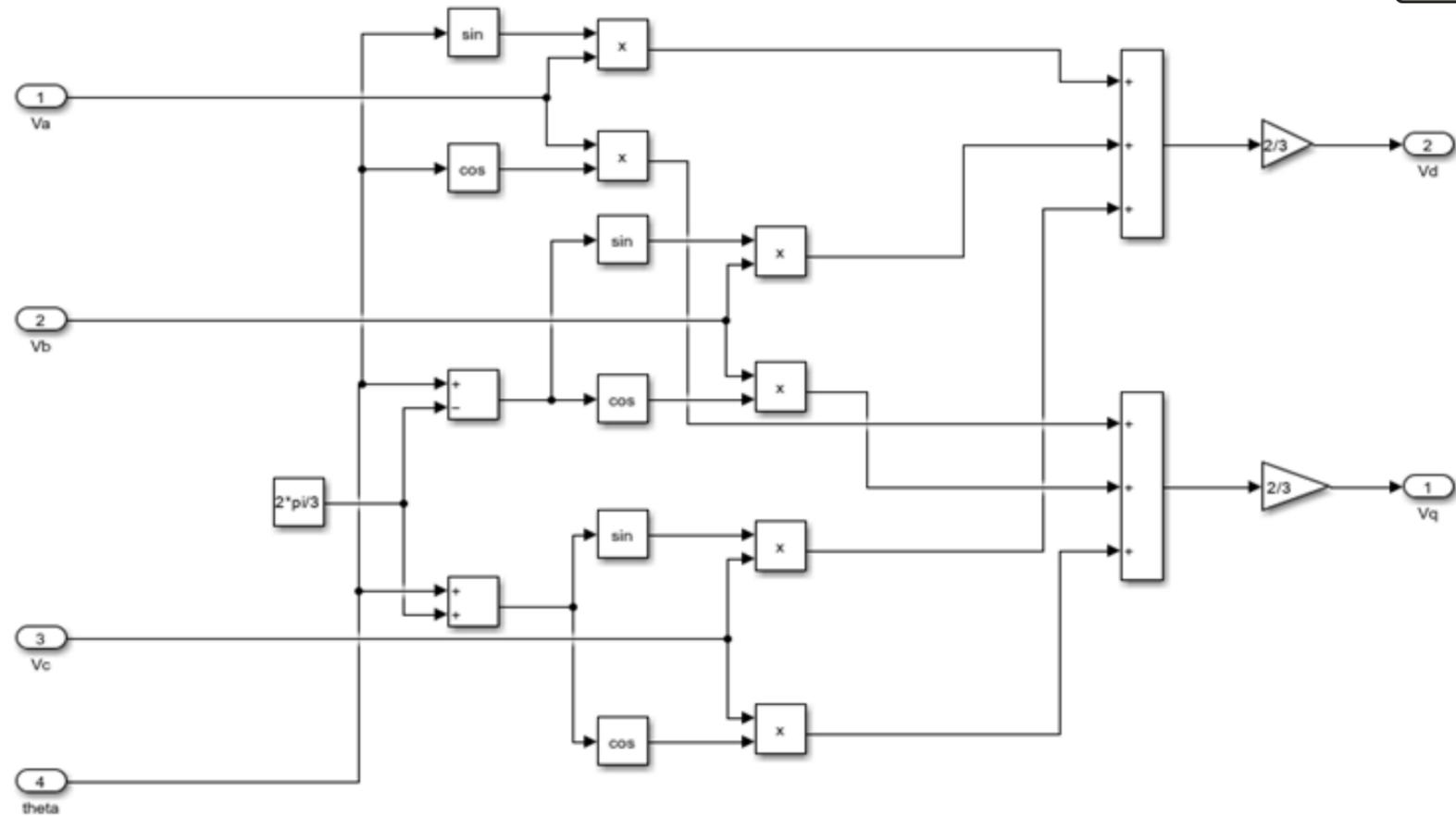
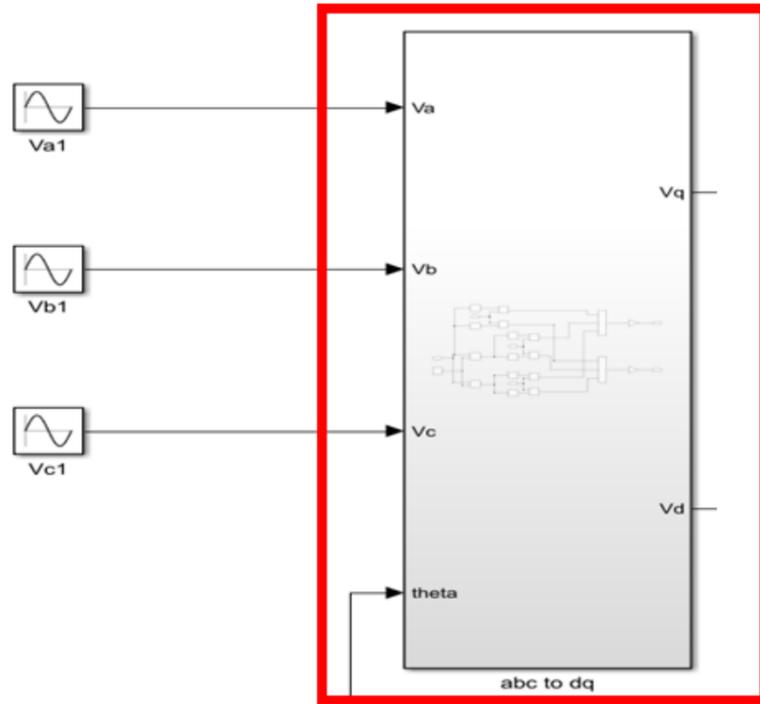
Parameter	Value	Units	Scale	Real/Imaginary
B	1.4161E-6	double (auto)	[1 1]	real
J	0.00119	double (auto)	[1 1]	real
Ld	0.00401	double (auto)	[1 1]	real
Lq	0.00401	double (auto)	[1 1]	real
P	5	double (auto)	[1 1]	real
Rs	0.26	double (auto)	[1 1]	real
lambda	0.154	double (auto)	[1 1]	real

PARAMETERS OF THE PMSM

Parameters	Values
Nominal Power (P_n)	1.5 kW
Nominal Speed (n)	2000 rpm
Stator Resistance (R_s)	0.26 Ω
Stator inductance ($L_d = L_q$)	4.01 mH
Inertia Moment (J)	0.00119 kg.m ²
Friction Coefficient (B)	0.0000014161 Nm.s
Magnet Flux (ψ_M)	0.0946 Wb
Number of Poles ($2p$)	10

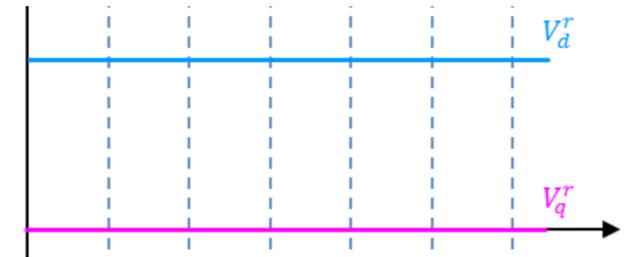
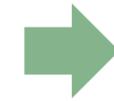
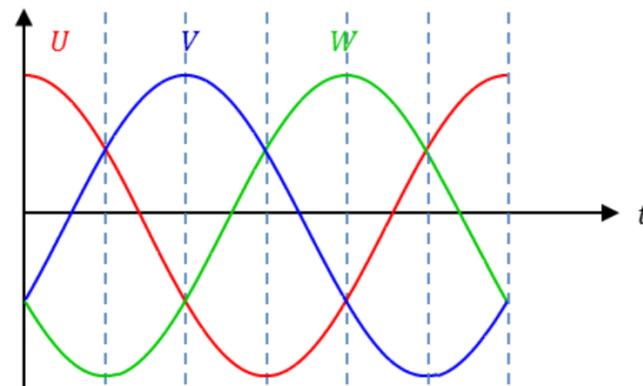
Field-Oriented Control of the PMSM with 2-DOF PI Controller Tuned by Using PSO

dq Transformation



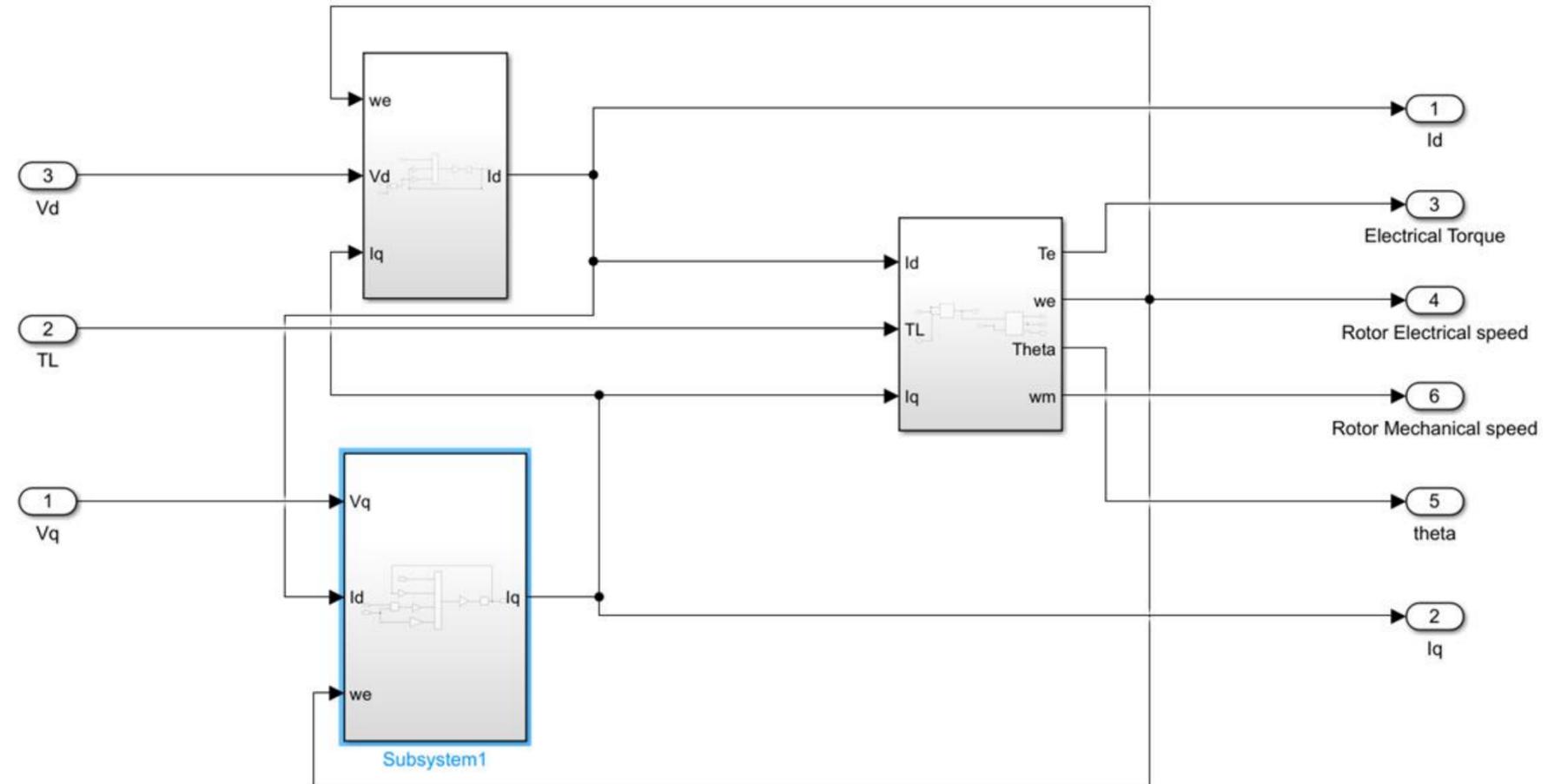
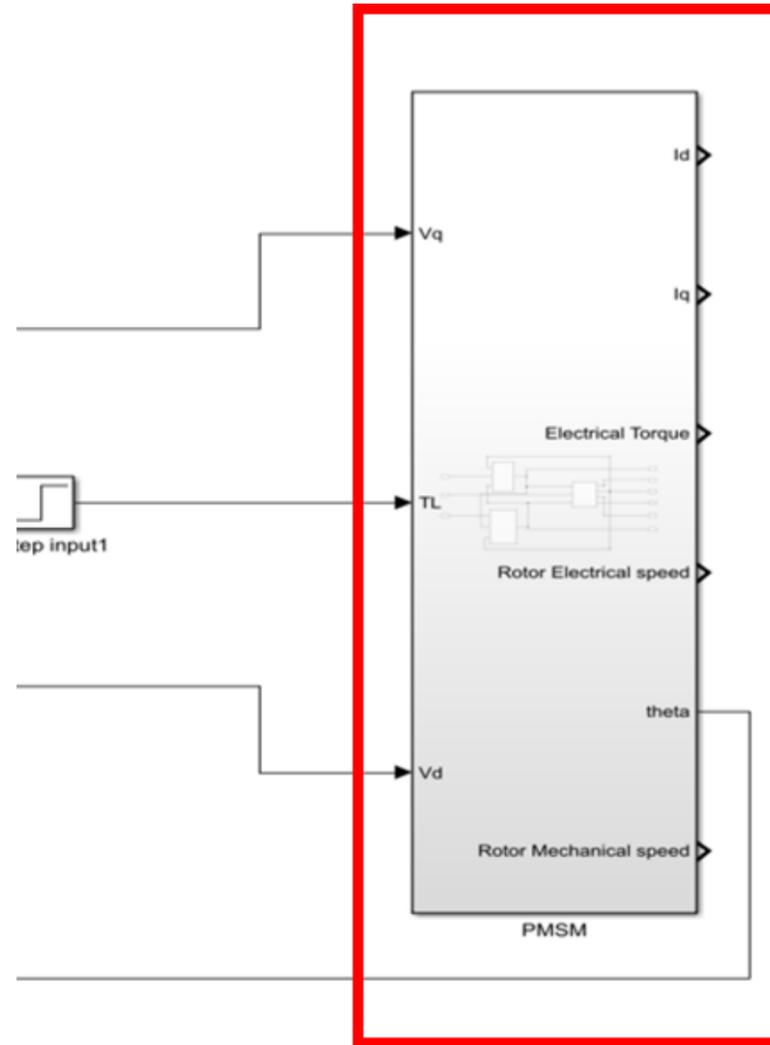
$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin \theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$V_d = \frac{2}{3} \left(V_a \cos \theta + V_b \cos(\theta - 2\pi/3) + V_c \cos(\theta + 2\pi/3) \right)$$

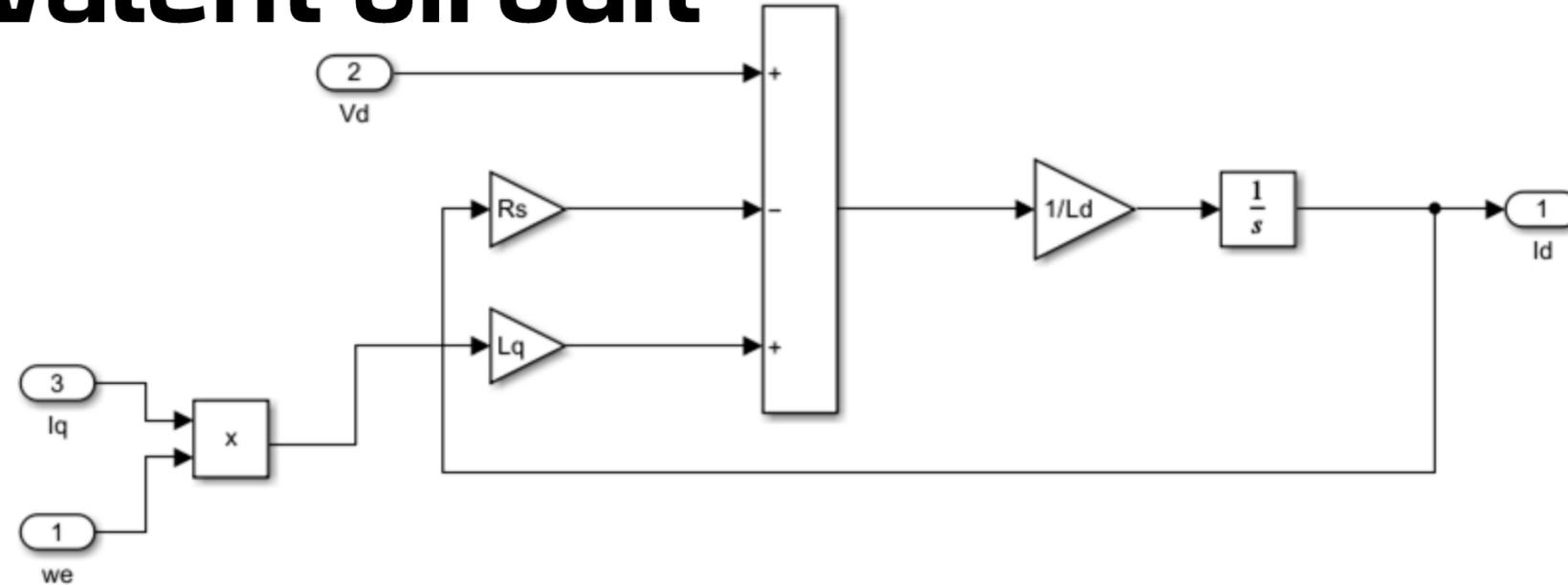
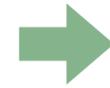
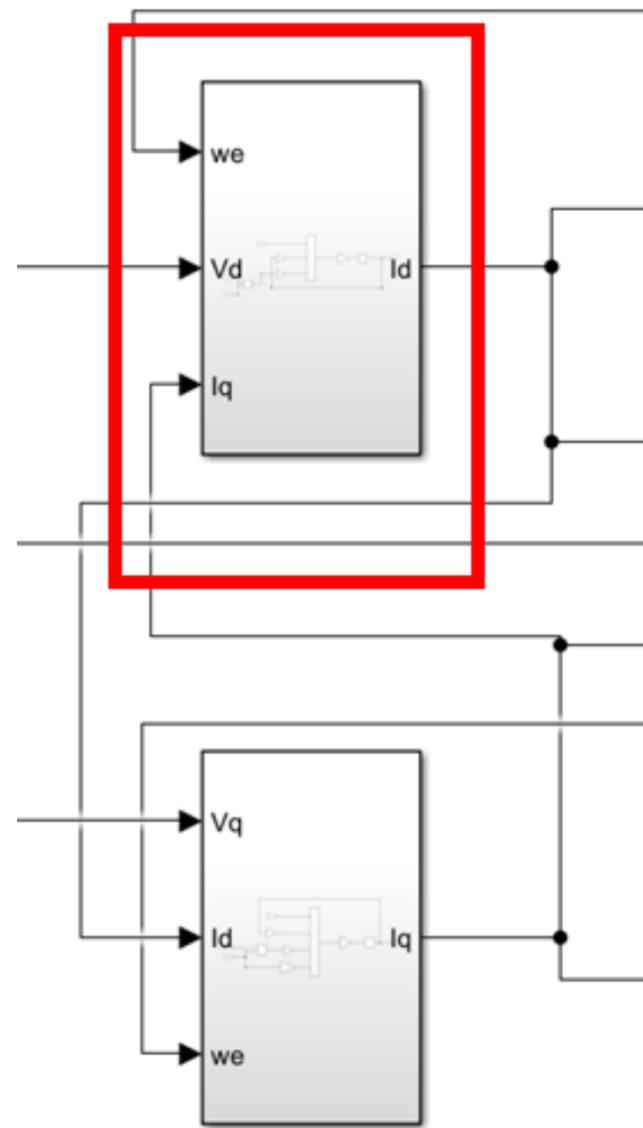


$$V_q = \frac{2}{3} \left(V_a \sin \theta + V_b \sin(\theta - 2\pi/3) + V_c \sin(\theta + 2\pi/3) \right)$$

PMSM Subsystem



The d-axis equivalent circuit

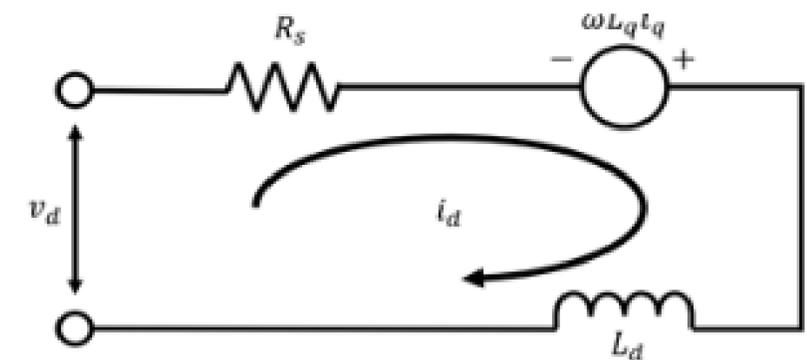


d축 등가회로 KVL 적용

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

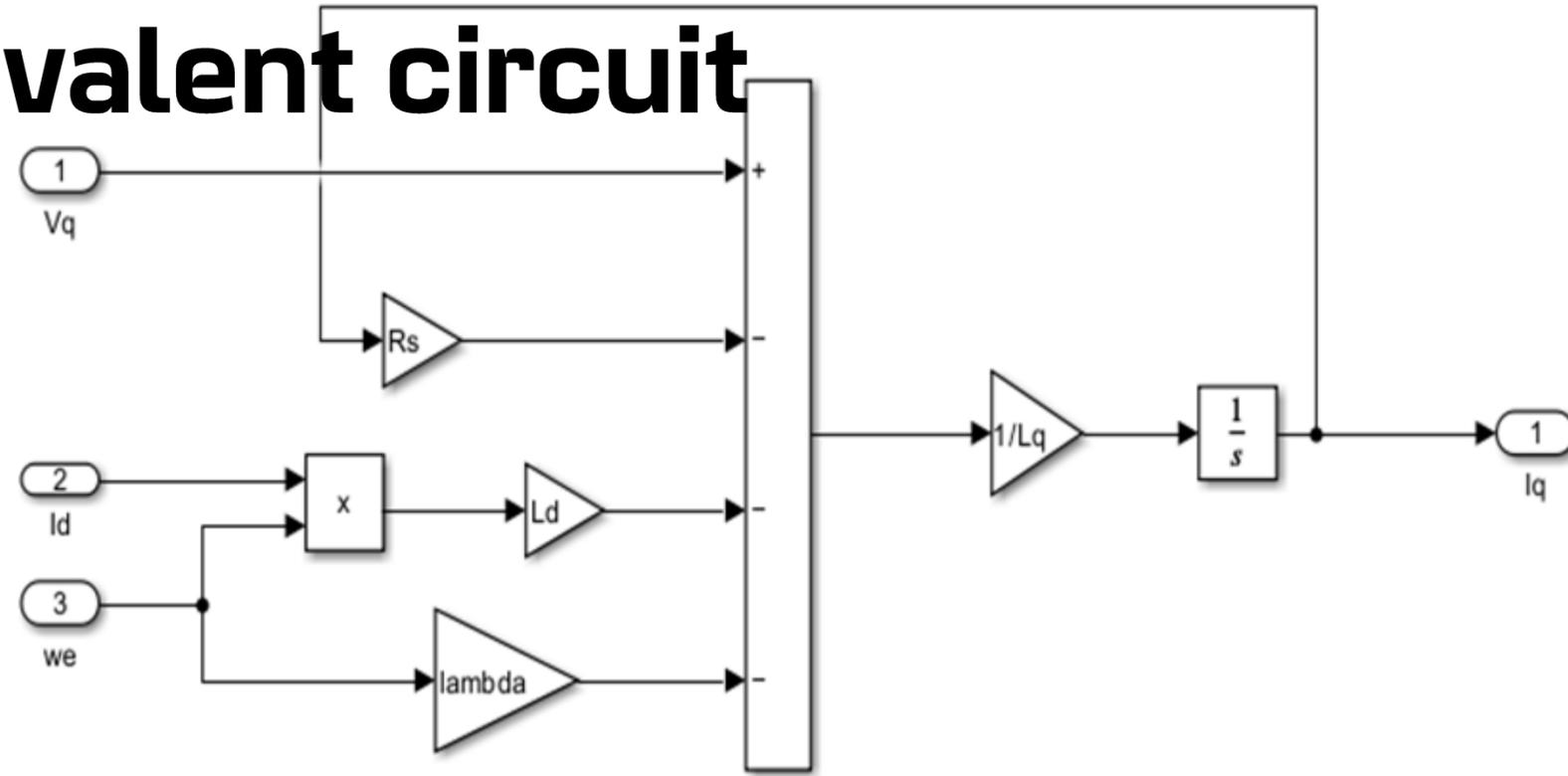
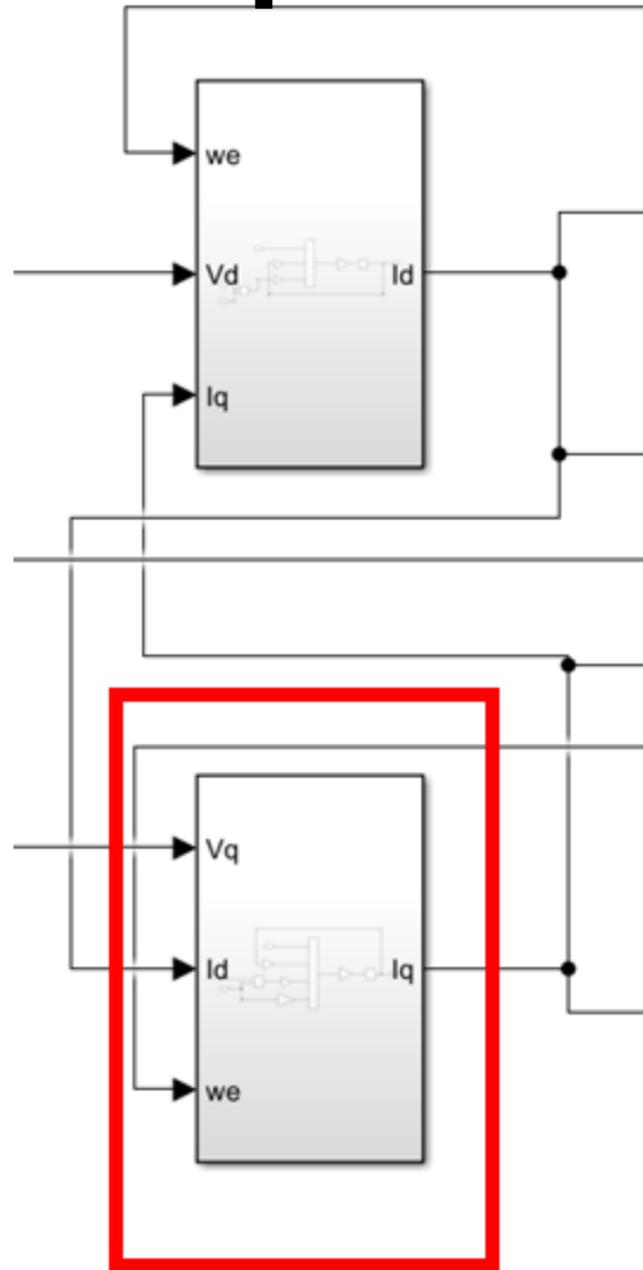


$$\frac{di_d}{dt} = \frac{1}{L_d} (V_d - R_s i_d + \omega_e L_q i_q)$$



참고 논문-Time-series based System Stability Estimation for Railroad Vehicle PMSM Using Real-time Simulator
Hwan-hee Cho, Jae-won Kim, Hyung-chul Kim

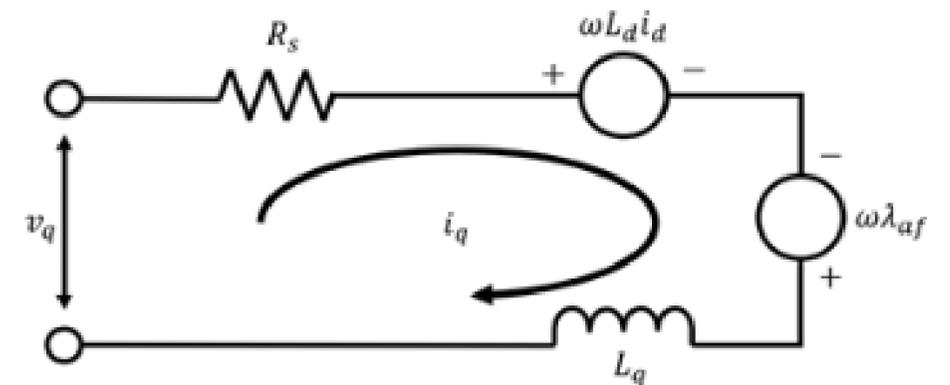
The q-axis equivalent circuit



q축 등가회로 KVL 적용

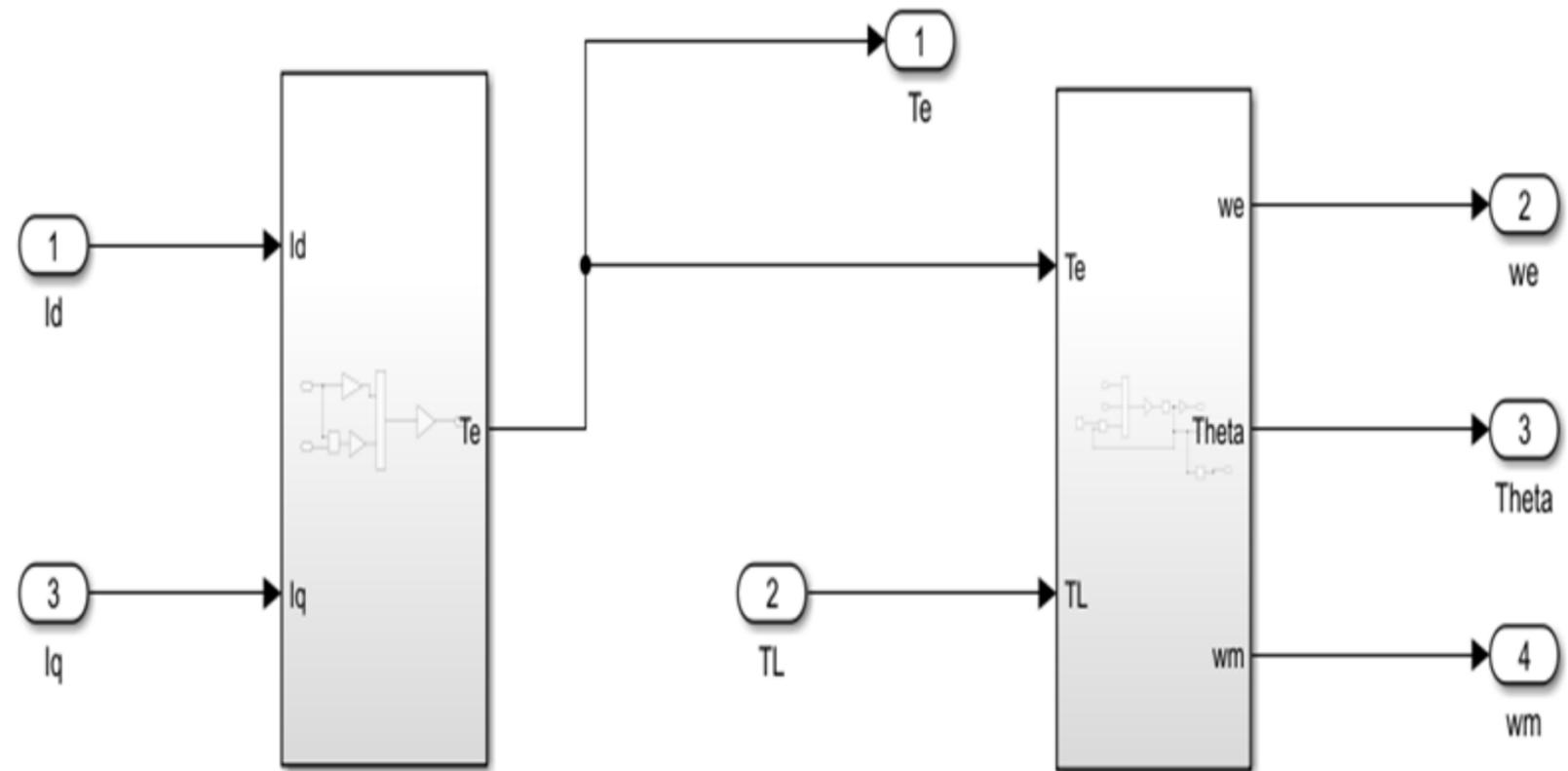
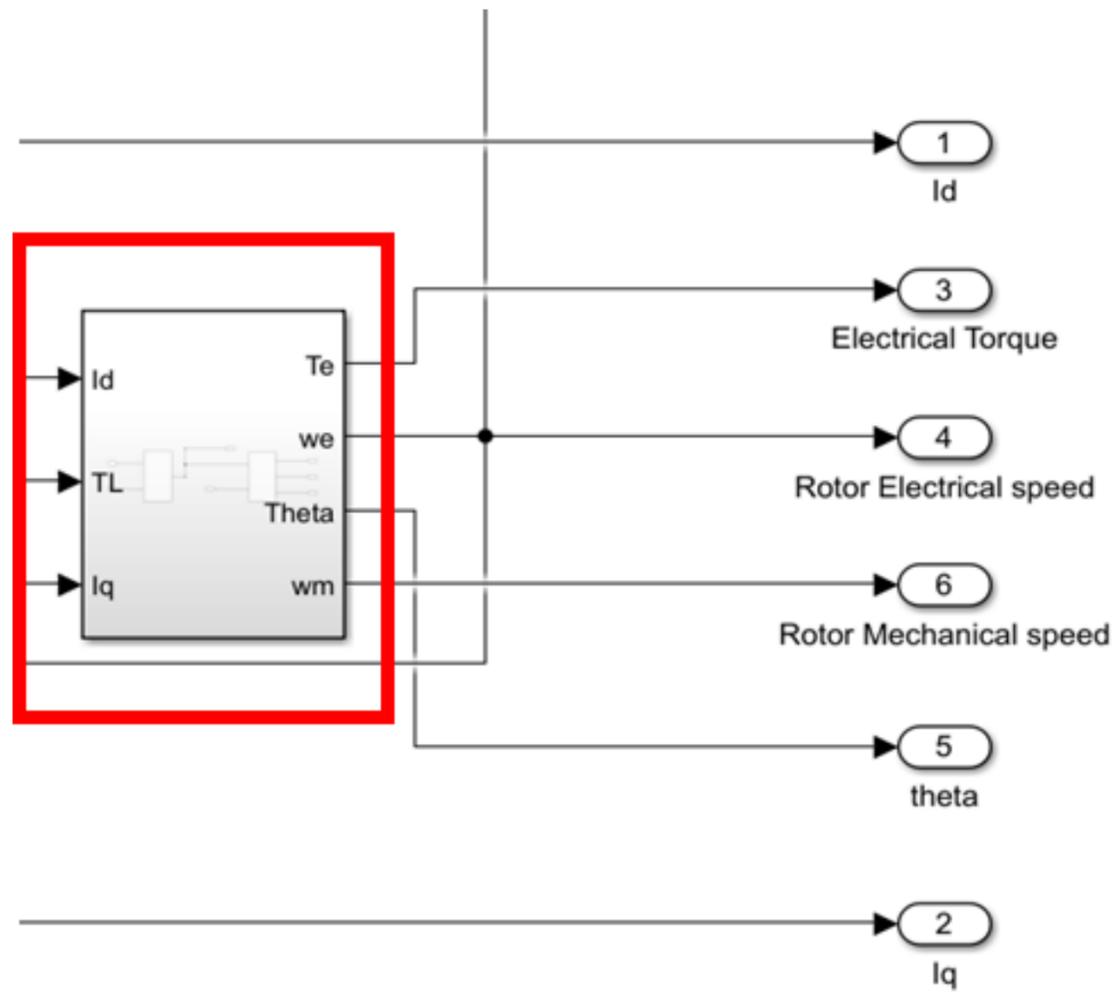
$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_m$$

$$\frac{di_q}{dt} = \frac{1}{L_q} \left(V_q - R_s i_q - \omega_e L_d i_d - \omega_e \lambda_m \right)$$



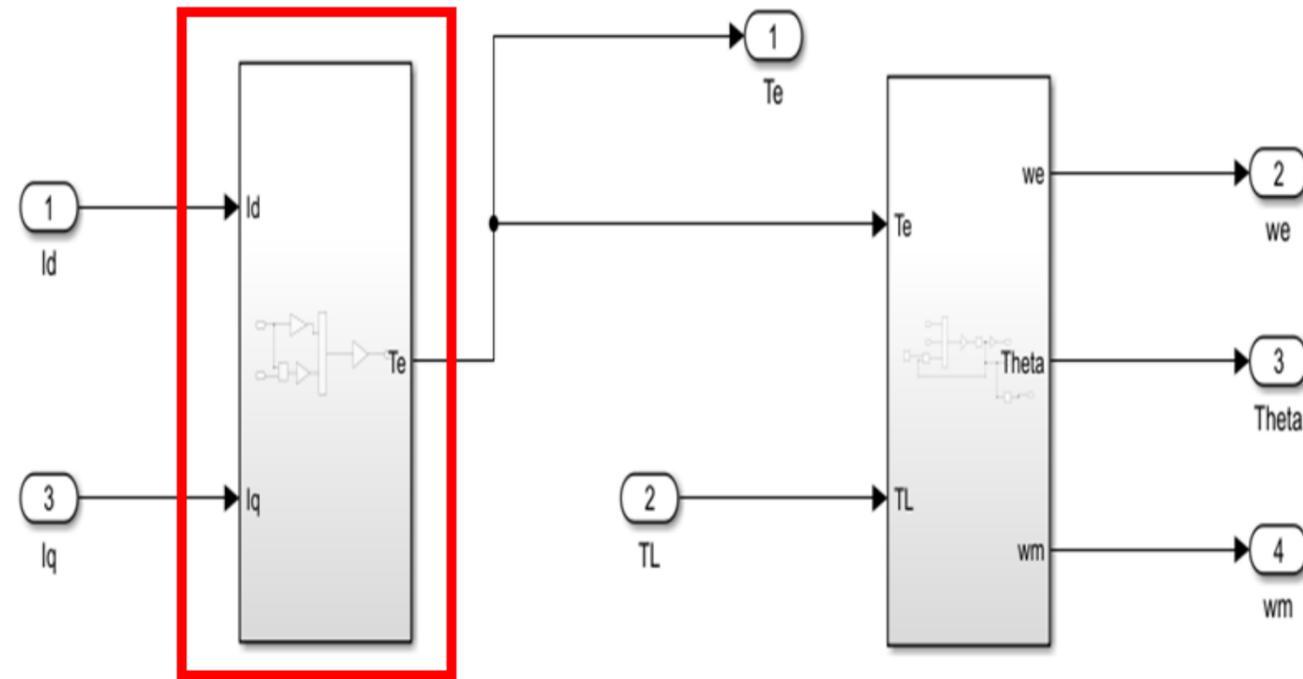
참고 논문-Time-series based System Stability Estimation for Railroad Vehicle PMSM Using Real-time Simulator
Hwan-hee Cho, Jae-won Kim, Hyung-chul Kim

Subsystem





Electromagnetic Torque Equation

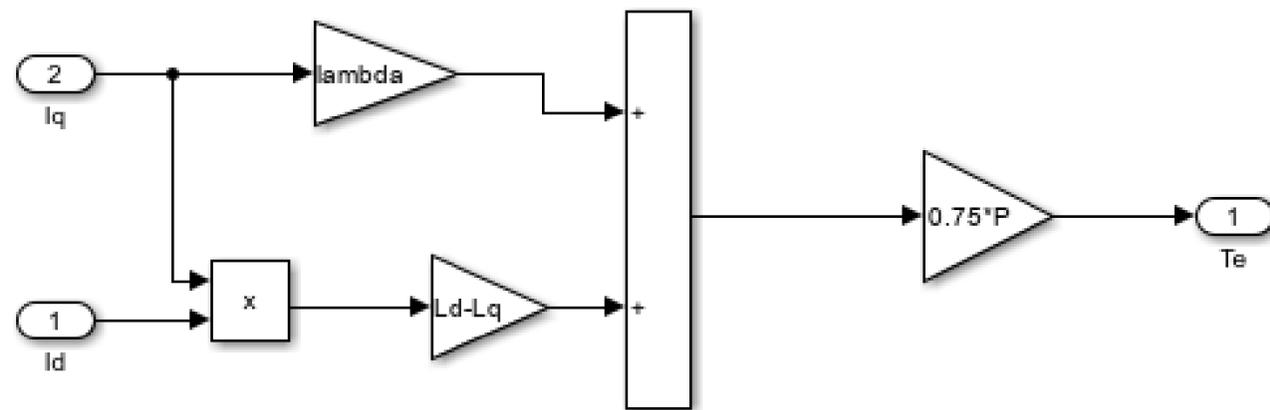


The electromagnetic torque produced by the motor is given by:

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_m i_q + (L_{ds} - L_{qs}) i_q i_d), \quad (2)$$

where P is the number of rotor magnetic poles. If the rotor is perfectly round, the quadrature and direct impedances are equal, and in this case the electromagnetic torque only depends on the quadrature stator current.

참고 문서-MODELLING OF PMSM
Dr. Bibhu Prasad Ganthia

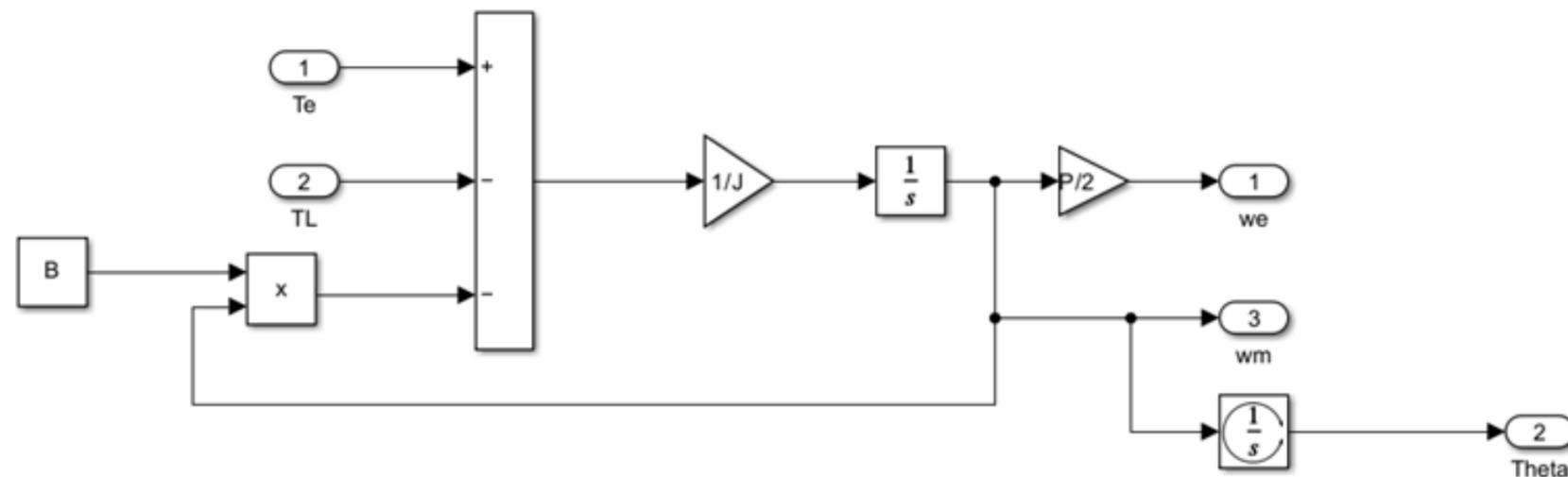
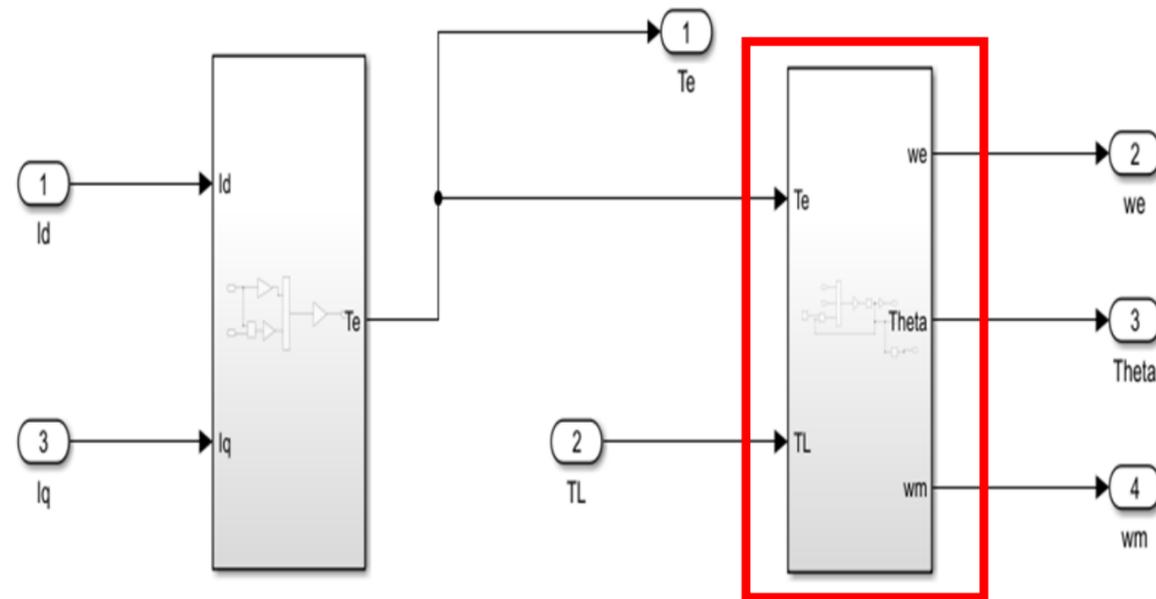


$$T_e = 0.75 P (\lambda i_q + (L_d - L_q) i_d i_q)$$

Te: electromagnetic torque
P: pole pairs
λ: flux linkage



Mechanical Angular Speed Equation



The equation that represents the mechanical torque is given as [15]:

$$\omega_m = \int \frac{(T_e - T_L - B\omega_m)}{J} dt \quad (10)$$

참고 논문 -Mathematical Model of Permanent Magnet Synchronous Motor
Fatimah F. Jaber† , Abdulhasan F. Abdulhasan ‡

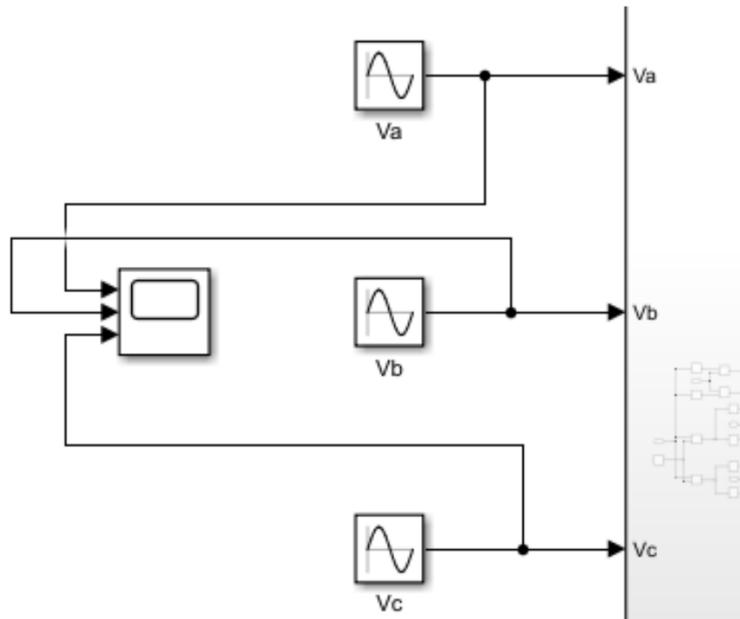
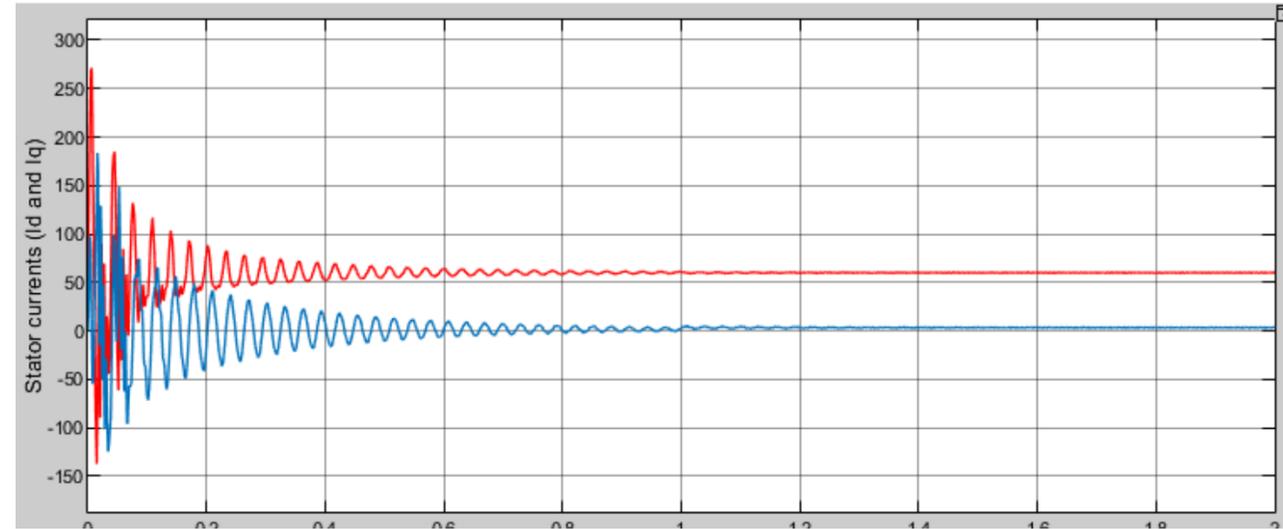
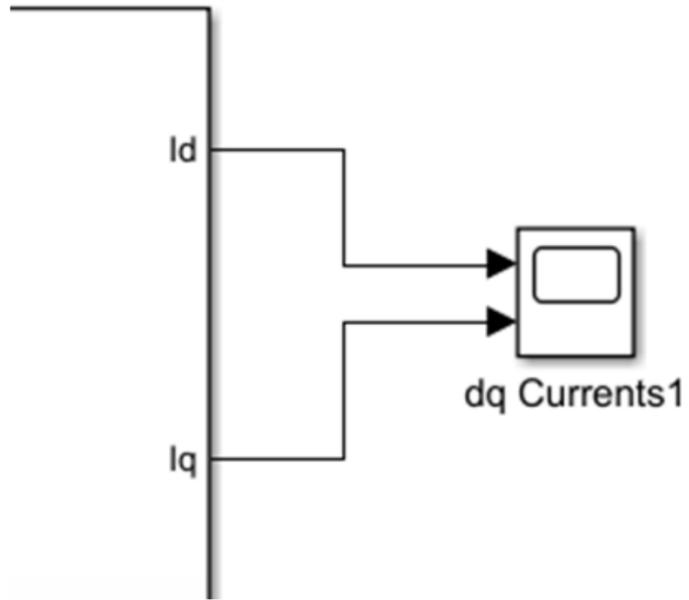
$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m$$

J: moment of inertia

Bwm: Viscous friction torque

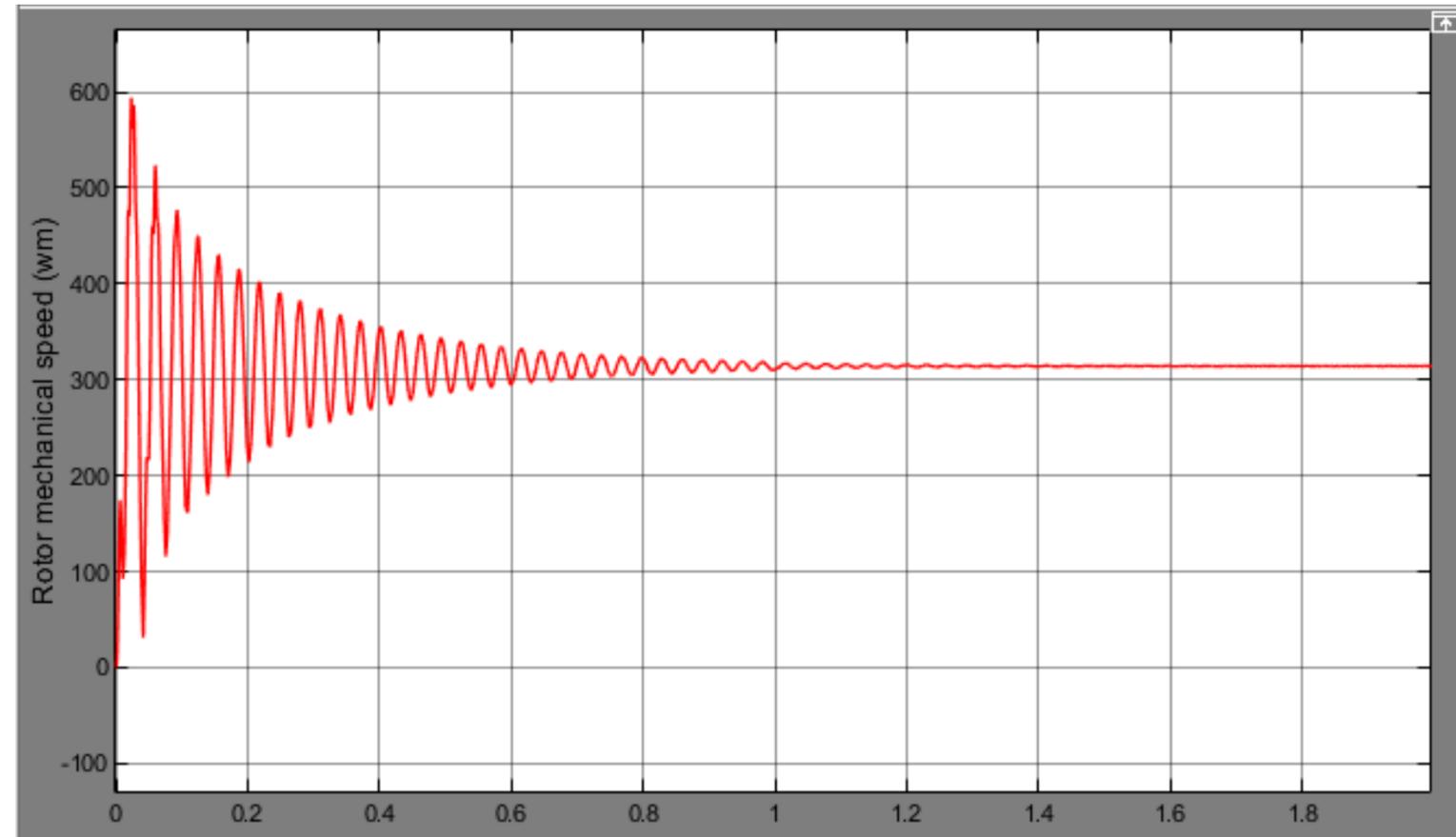
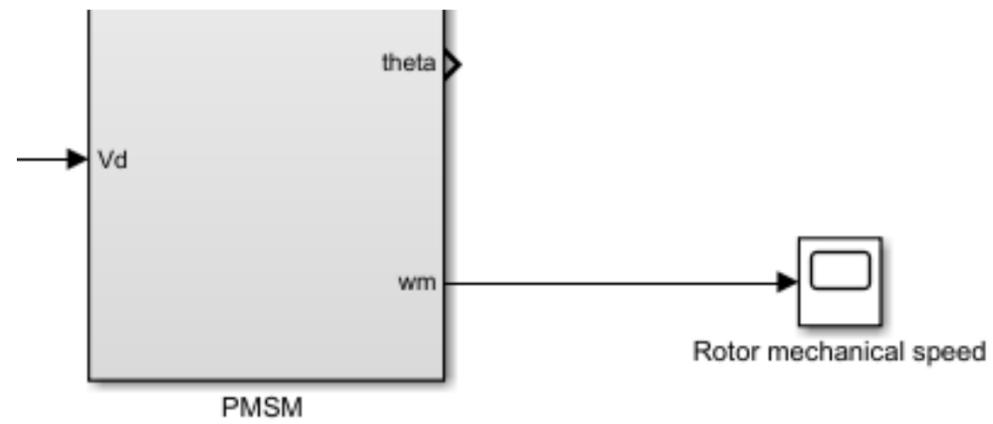
Wm: Mechanical angular speed (rad/s)

dq Current

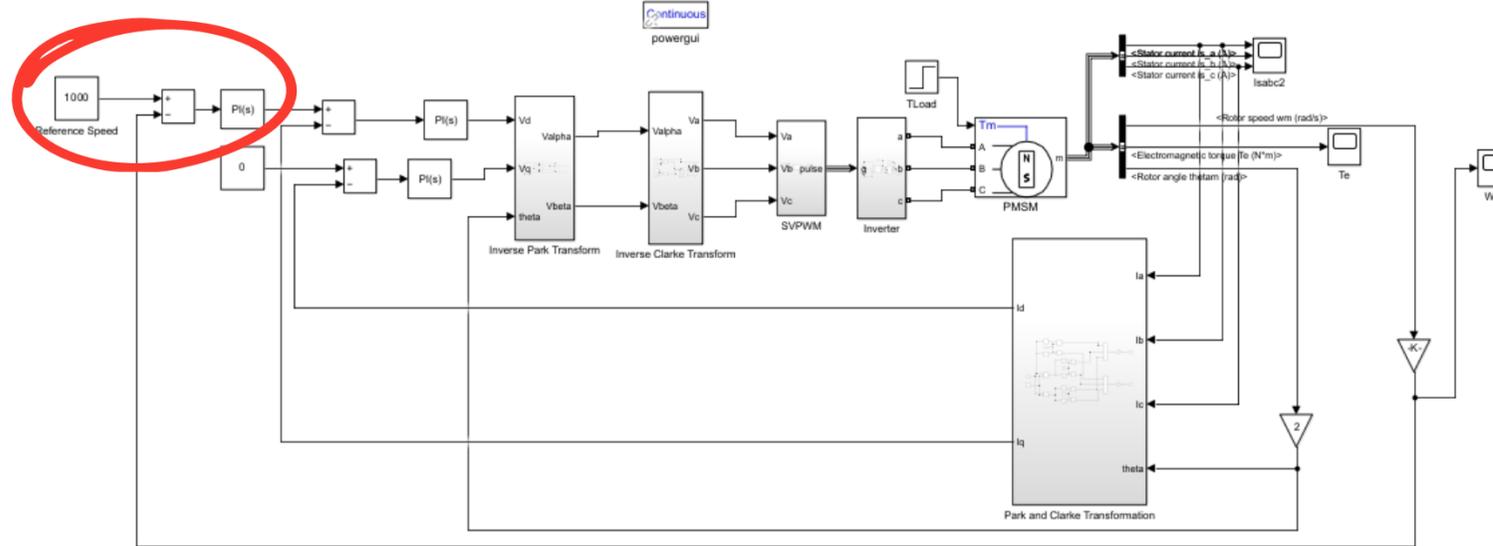


3상 AC 전압을 두 개의 DC 전압으로 변환

Rotor Mechanical Speed

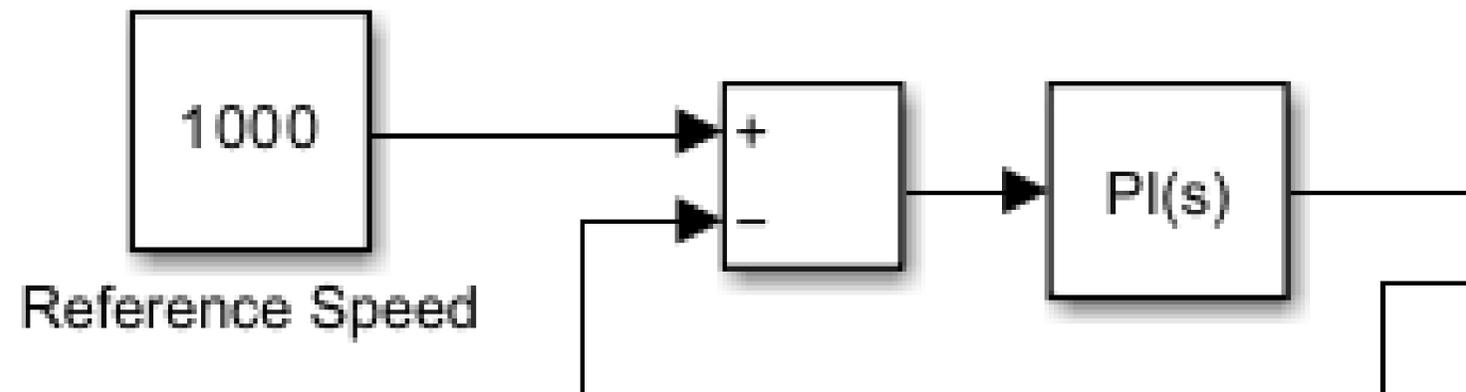


RPM Insert

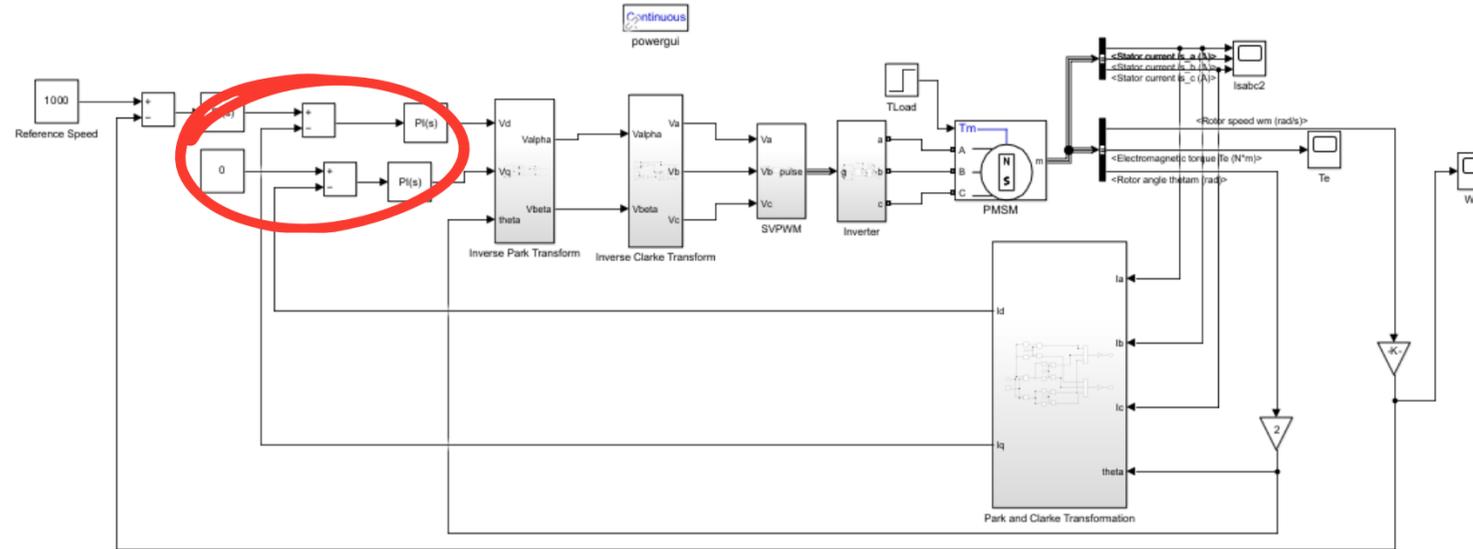


모터 회전수 : 1000rpm

Sum block : (목표 속도 - 현재 속도) 오차 구하기
 PI 제어기 : 속도 오차를 전류 명령으로 바꿔줌.

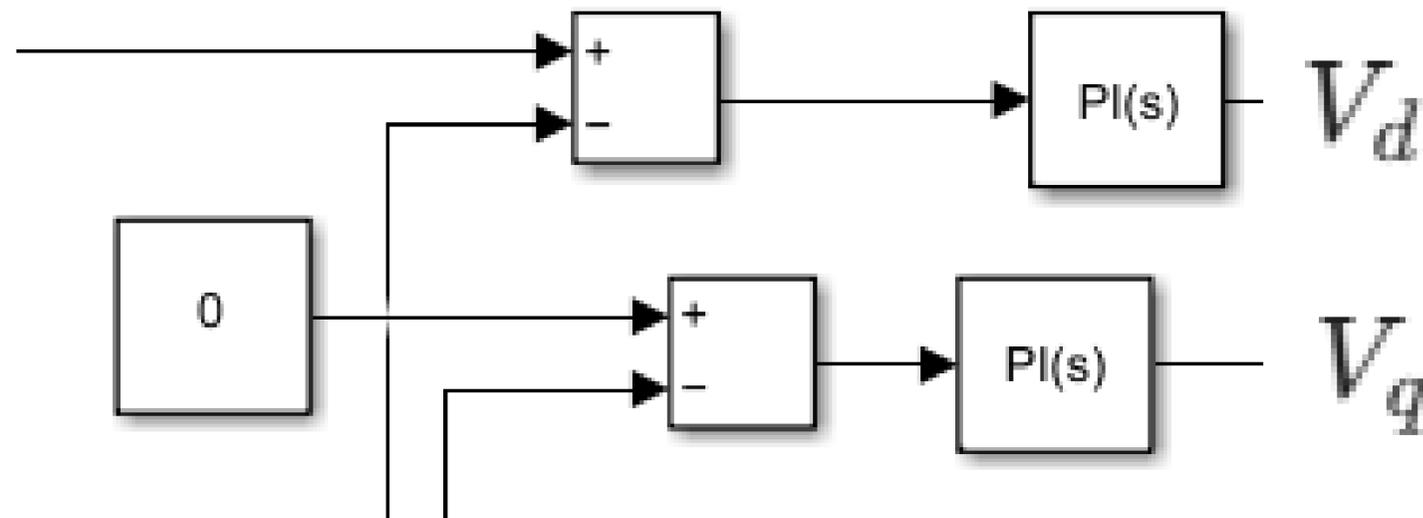


PI Controller

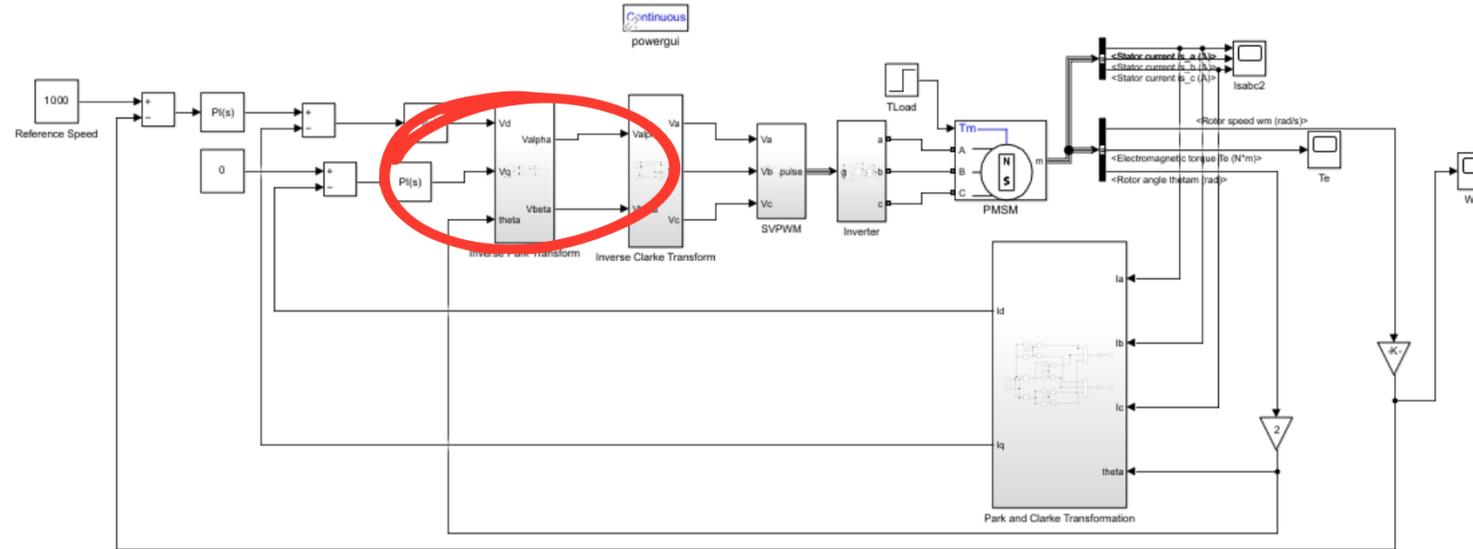


Constant 전류 지령치 $I_d = 0$
 자속을 만드는 d축 전류 0으로 유지.

위쪽 PI : 실제 I_d 전류가 0이 되도록 전압(V_d) 조절.
 아래쪽 PI : 실제 I_q 전류가 위의 속도 제어기가
 시킨 만큼 흐르도록 전압(V_q) 조절.

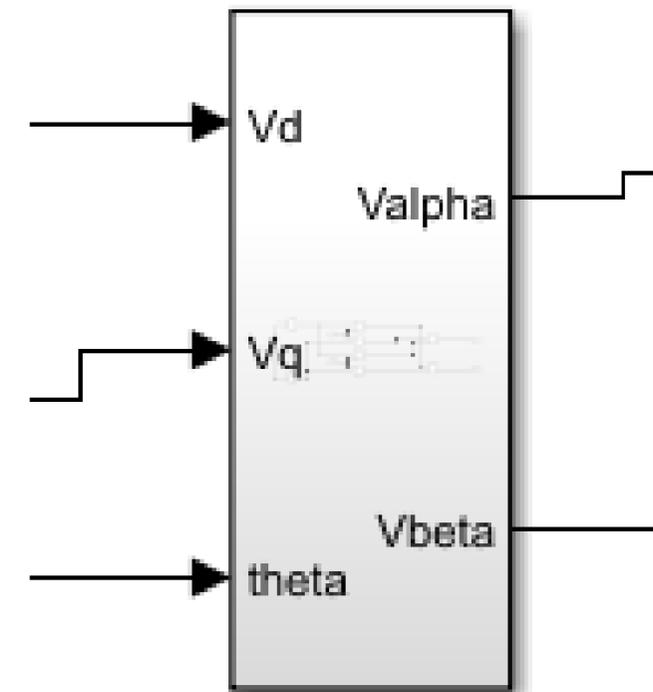


Inverse Park Transform



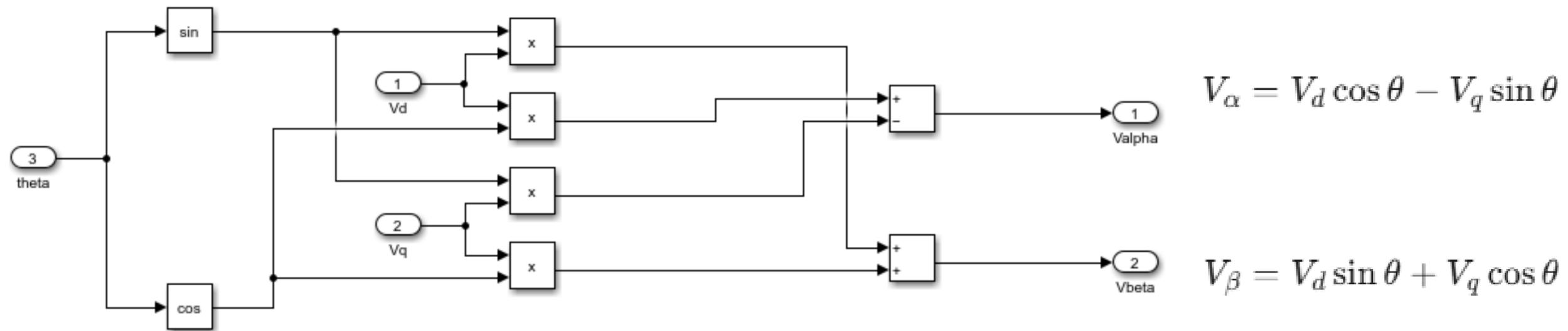
회전 좌표계(d, q) → 정지 좌표계(alpha, beta) 변환

제어기는 모터랑 같이 돌면서 (d와 q)를 출력하지만,
실제 전압은 alpha, beta의 언어로 바뀌어야함.



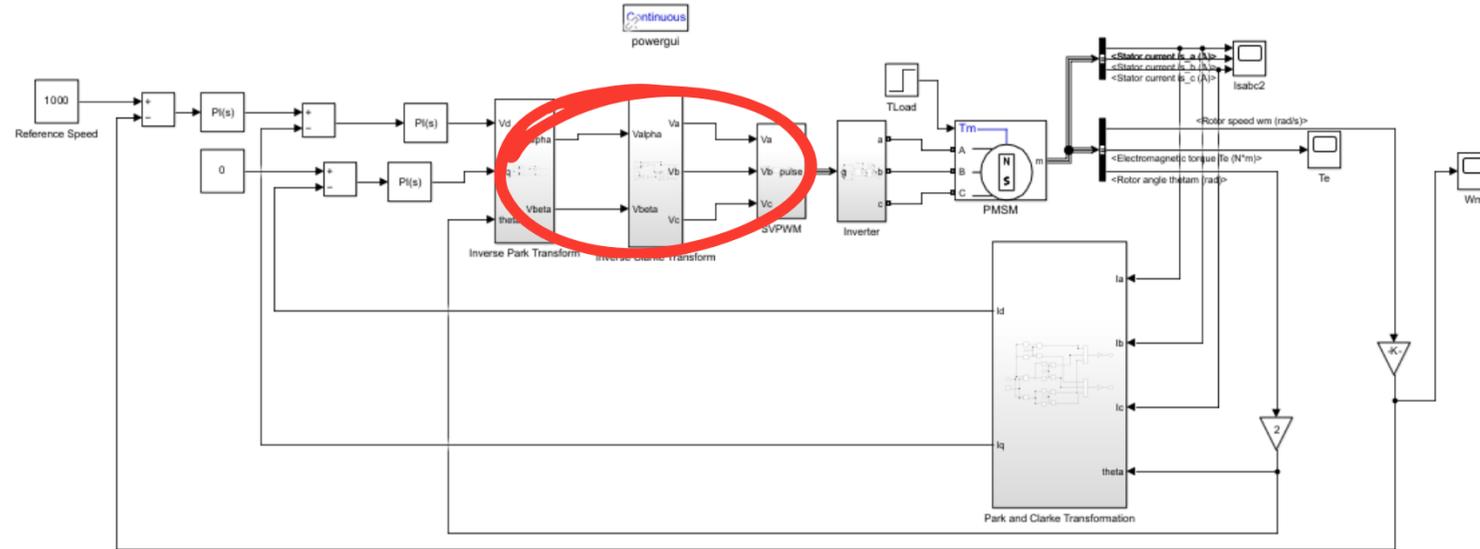
Inverse Park Transform

Inverse Park Transform



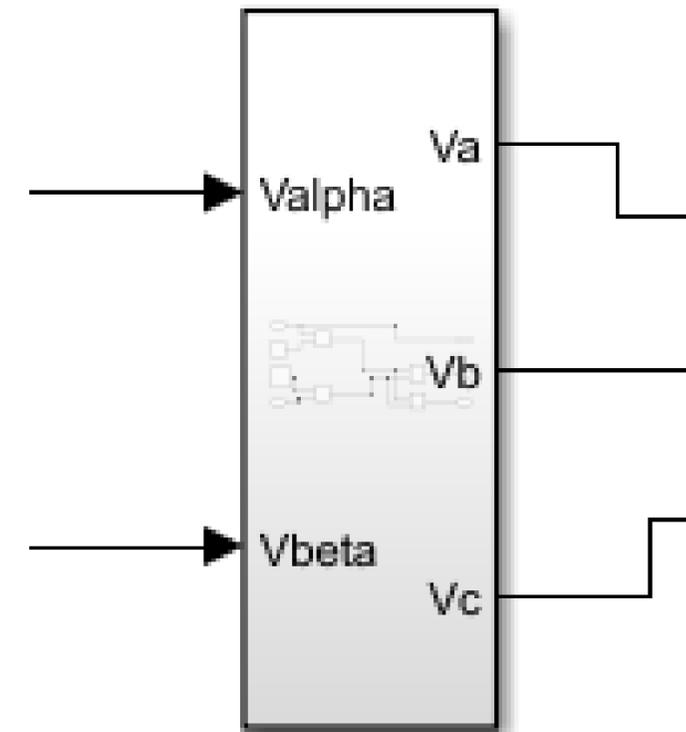
현재 모터의 회전 각도를 실시간으로 반영해서
직류였던 신호를 회전하는 성분인 교류 전압으로 변환.

Inverse Clarke Transform

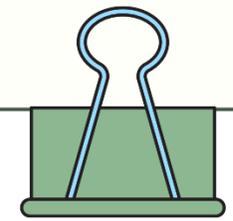


2상(alpha, beta) → 3상(a, b, c) 변환

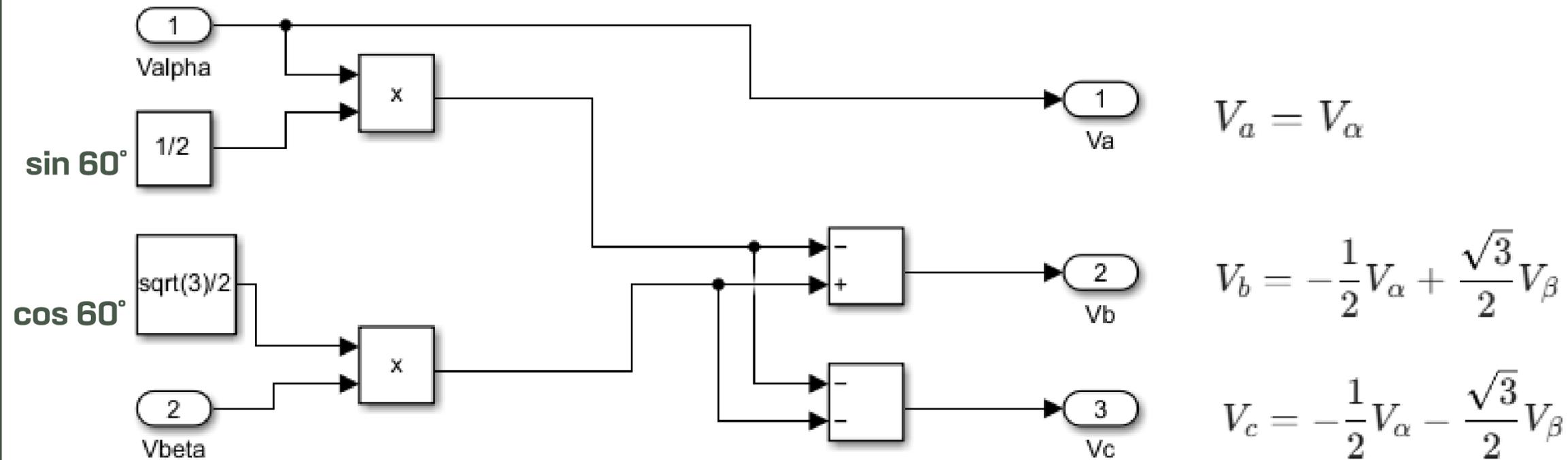
수학적으로 계산된 2개의 신호를 실제 모터에 연결된 3개의 전선(a, b, c)에 맞는 신호로 바꾸어 전선 분배.



Inverse Clarke Transform

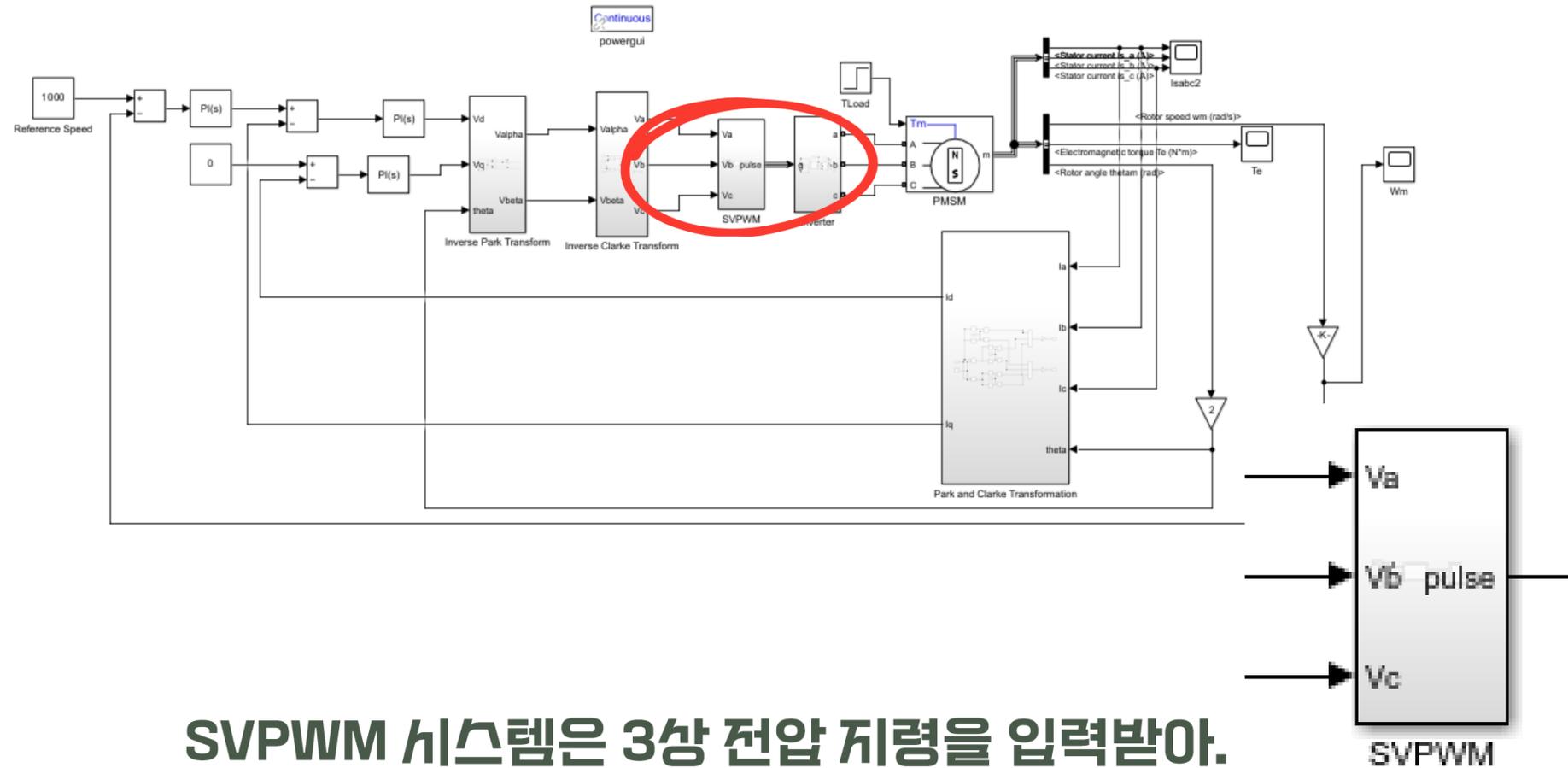


Inverse Clarke Transform



블록 내부에 보이는 1/2과 sqrt(3)/2은 모터의 3상 권선이 기계적으로 120°씩 벌어져 있기 때문에 생기는 기하학적인 투영 계수임.
위의 과정은 수학적인 2축(alpha, beta) 좌표를 물리적인 3축(a, b, c) 좌표로 맵핑(Mapping)하는 과정임.

SVPWM



SVPWM 시스템은 3상 전압 지령을 입력받아.

현재 전압 벡터의 위치를 파악하고,

각 위치에 맞는 스위칭 시간(T1, T2)을 수학적으로 계산한 뒤,

이를 삼각파와 비교하여 인버터를 구동할

최적의 펄스 신호를 생성하는 과정.

(iii). Generation of SVPWM Waveform

The relation between N and switch operation times is realized in Fig. 6, where $T_a = (T - T_1 - T_n) / 4$, $T_b = T_a + T_1 / 2$, and $T_c = T_b + T_n / 2$, T_{on1} , T_{on2} and T_{on3} are the operation times of three phases respectively.

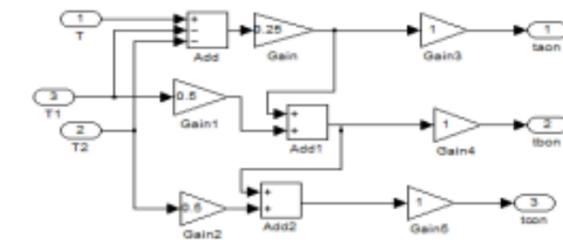


Fig. 6. Model of switch operation time

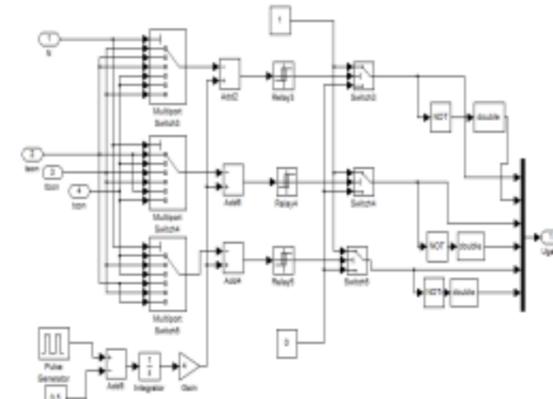
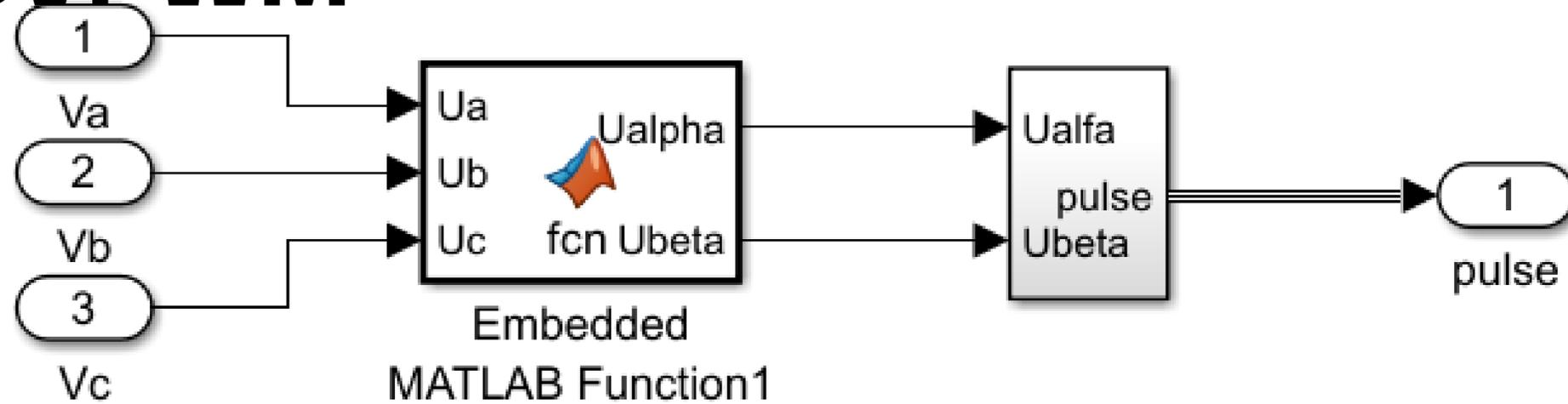


Fig. 7. Model of relation between N , T_{on} , T_a , T_b and T_c and generation of SVPWM waveform.

SVPWM



focfinal ▶ SVPWM ▶ Embedded MATLAB Function1

```
1 function [Ualpha,Ubeta]= fcn(Ua,Ub,Uc)  
2 Ualpha=2/3*(Ua-0.5*Ub-0.5*Uc);  
3 Ubeta=2/3*(sqrt(3)/2*Ub-sqrt(3)/2*Uc);
```

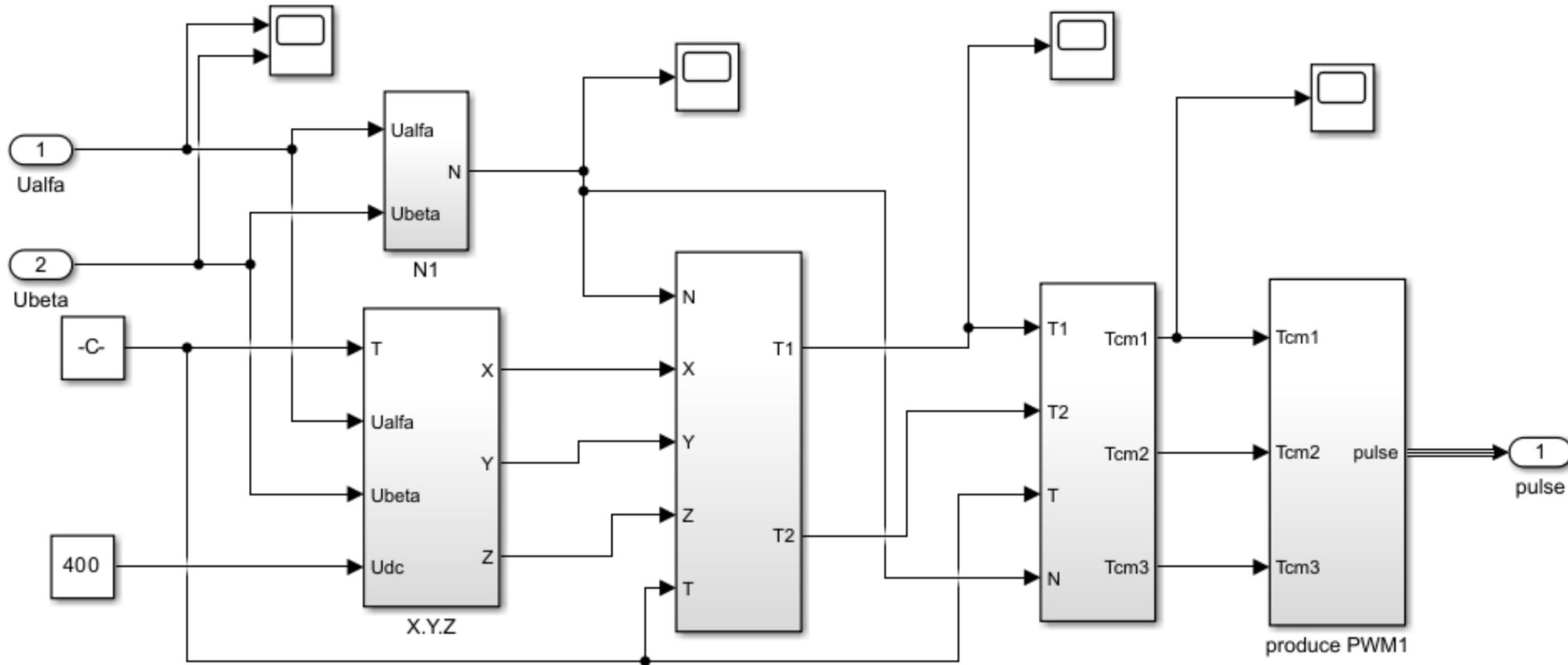
$$U_{alpha} = \frac{2}{3}(V_a - 0.5V_b - 0.5V_c)$$

$$U_{beta} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}V_b - \frac{\sqrt{3}}{2}V_c\right)$$

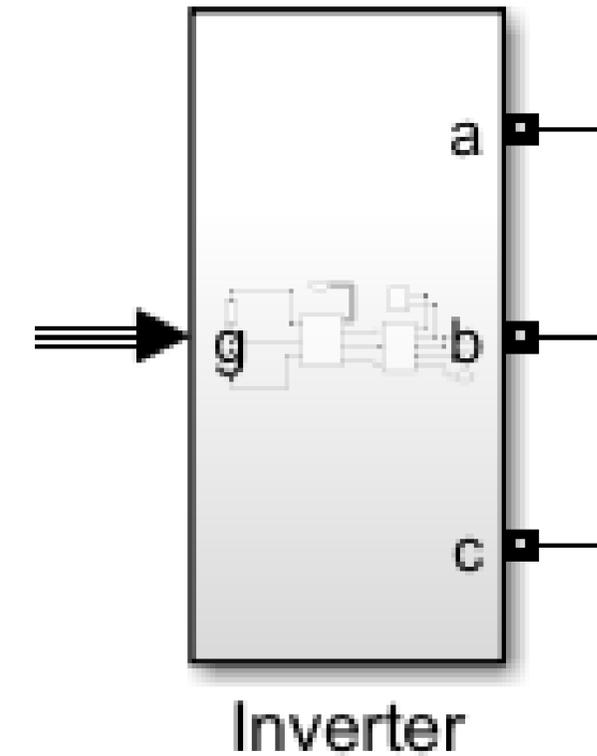
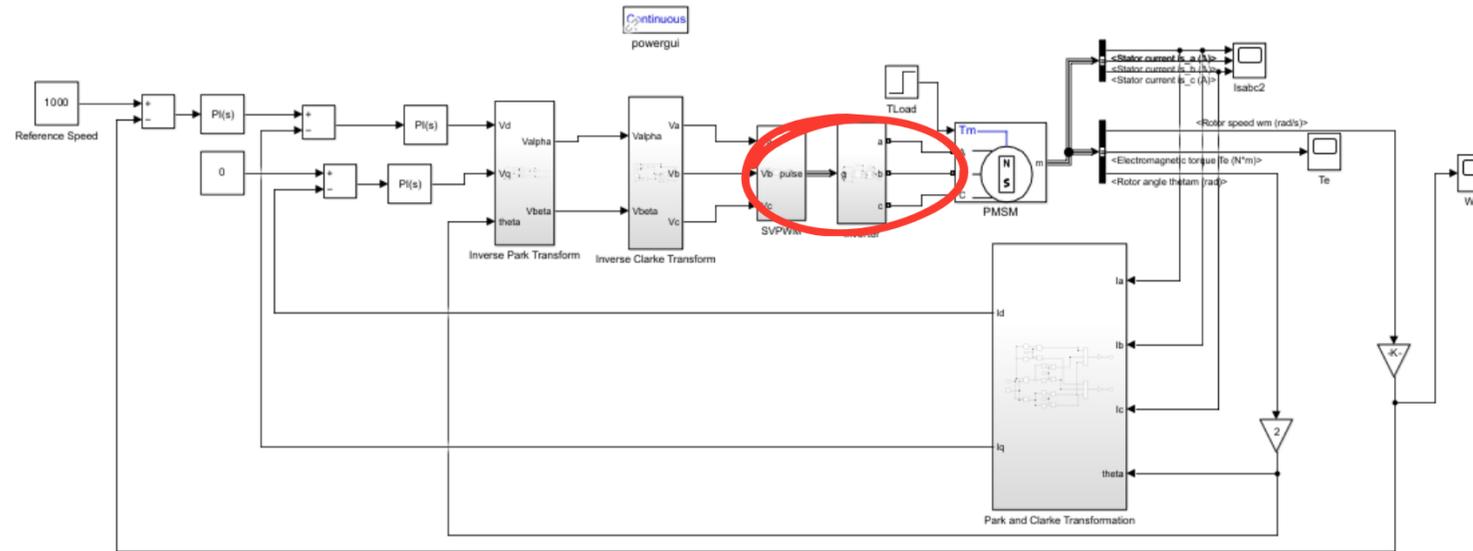
→ 클라크 변환

3상 신호를 SVPWM 계산에
필요한 2상 성분으로 변환.
pulse : 변환된 신호를 가지고
실제로 펄스를 만드는 핵심 블록
으로 들어감.

SVPWM

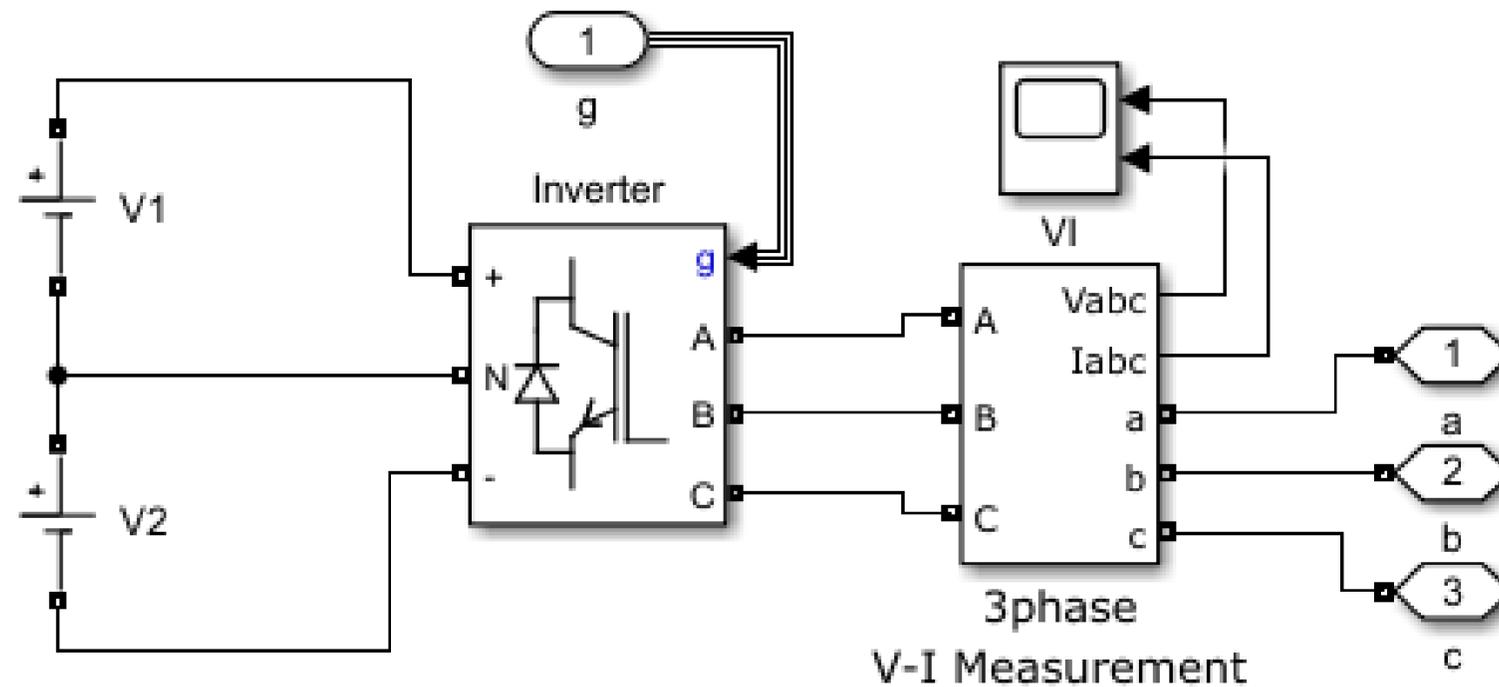


Inverter



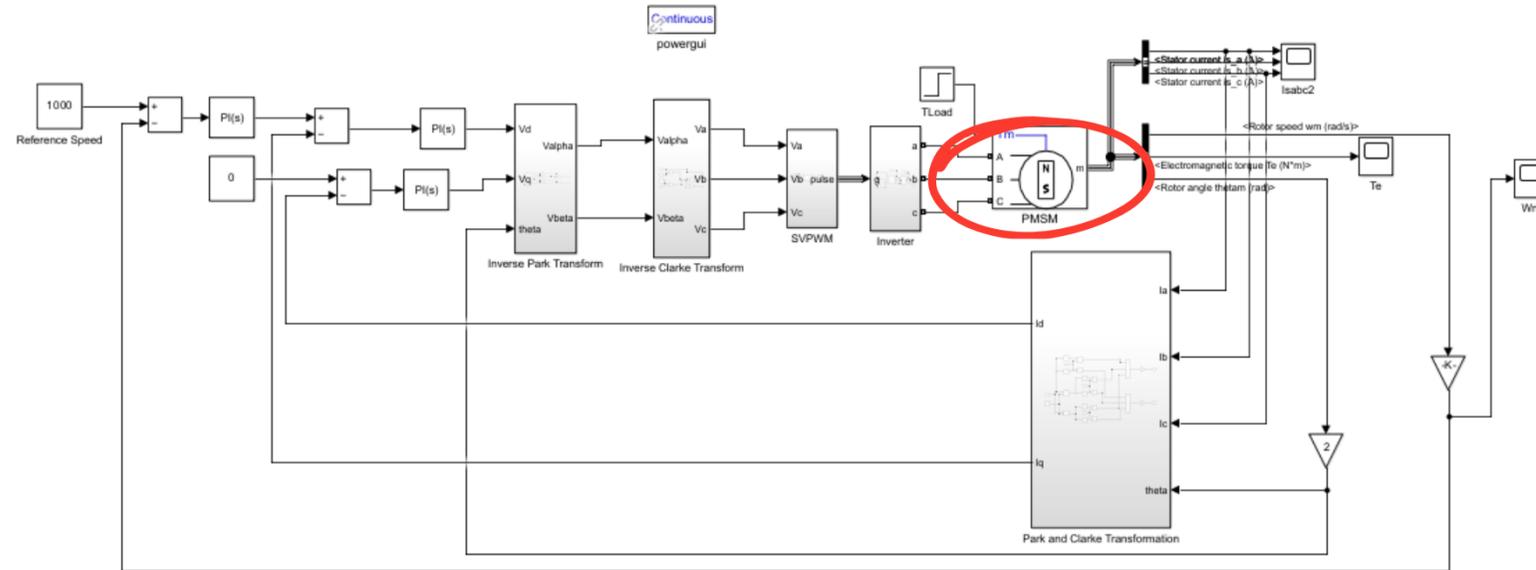
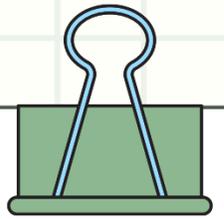
인버터는 배터리의 직류(DC) 전원을 받아서, 모터가 회전하는데 필요한 3상 교류(AC) 전원으로 변환하여 공급.
제어기의 명령에 따라 전압의 크기와 주파수를 자유자재로 조절하여 모터의 속도와 토크를 정밀하게 제어.

3phase V-I Measurement

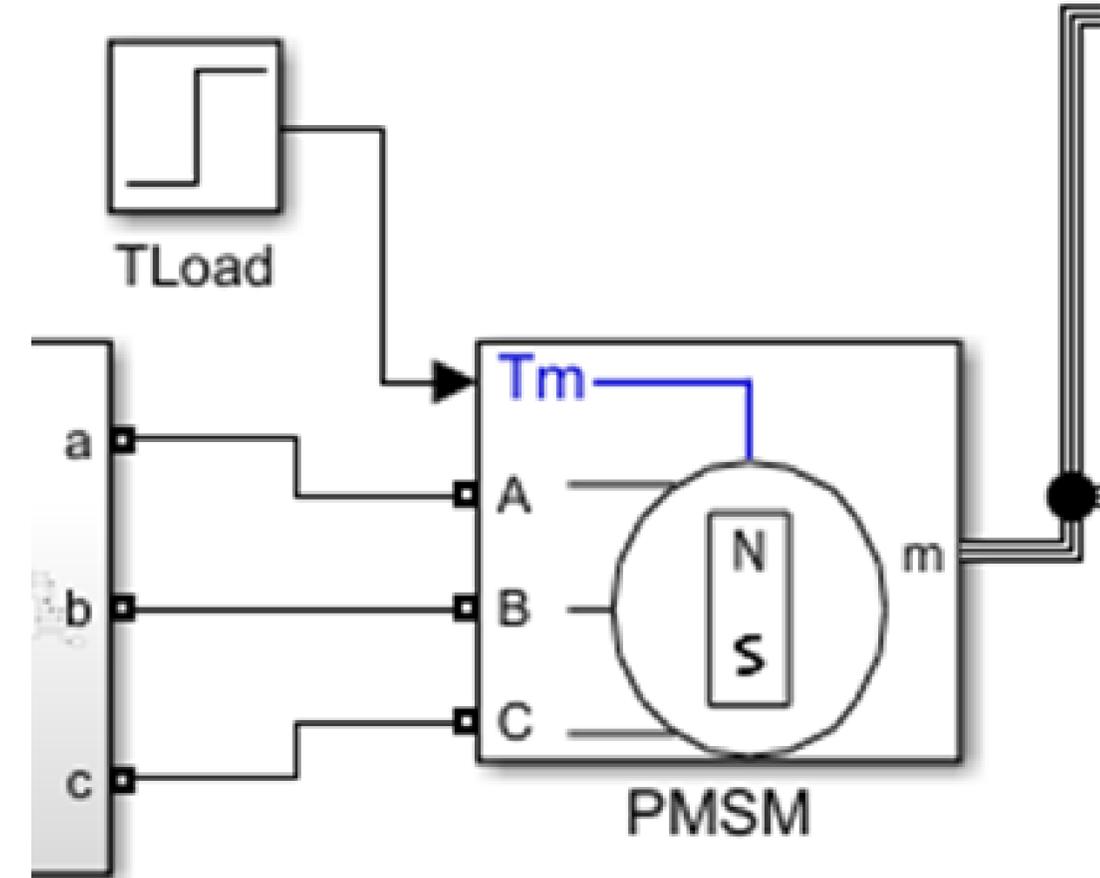


배터리의 직류(DC) 전원을 모터 구동에 필요한 3상 교류(AC) 전원으로 변환하고, 그 출력값을 계측하는 시스템.
출력된 값은 뒤에 모터와 연결됨.

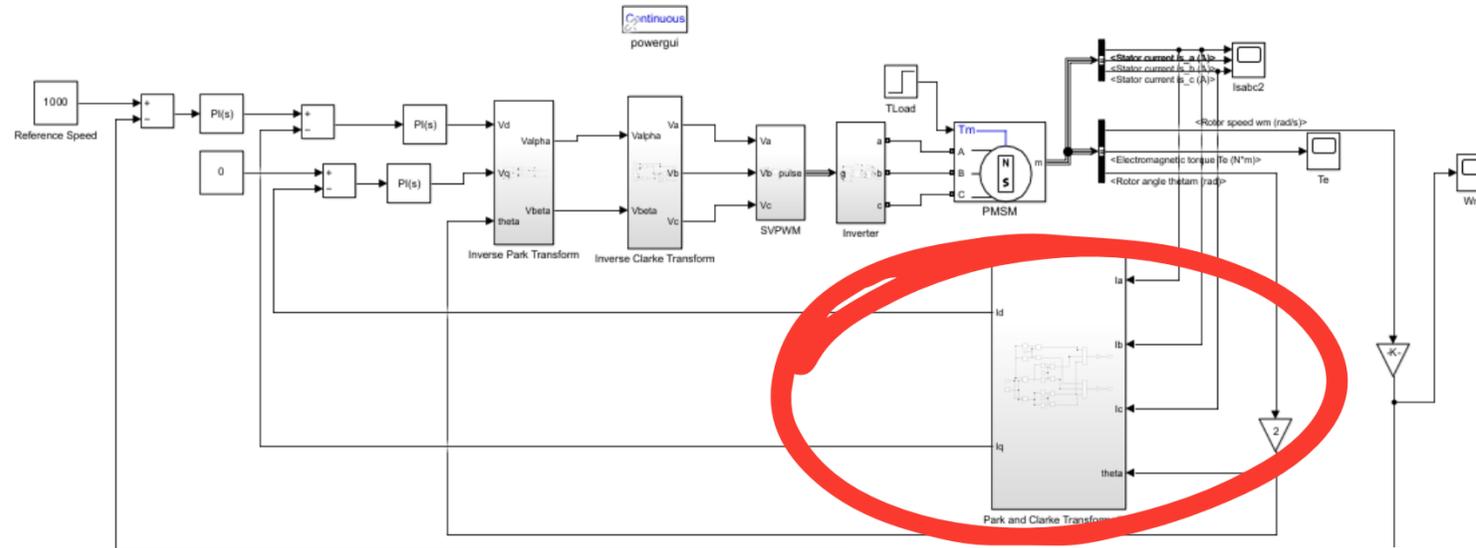
PMSM



**PMSM : 영구자석 동기 전동기의 수학적 모델.
동그라미 안에 들어있는 N/S 자석이 영구자석.
전기 에너지를 받아서 회전 에너지로 바꾸는 역할을 함.**



Park and Clarke Transformation

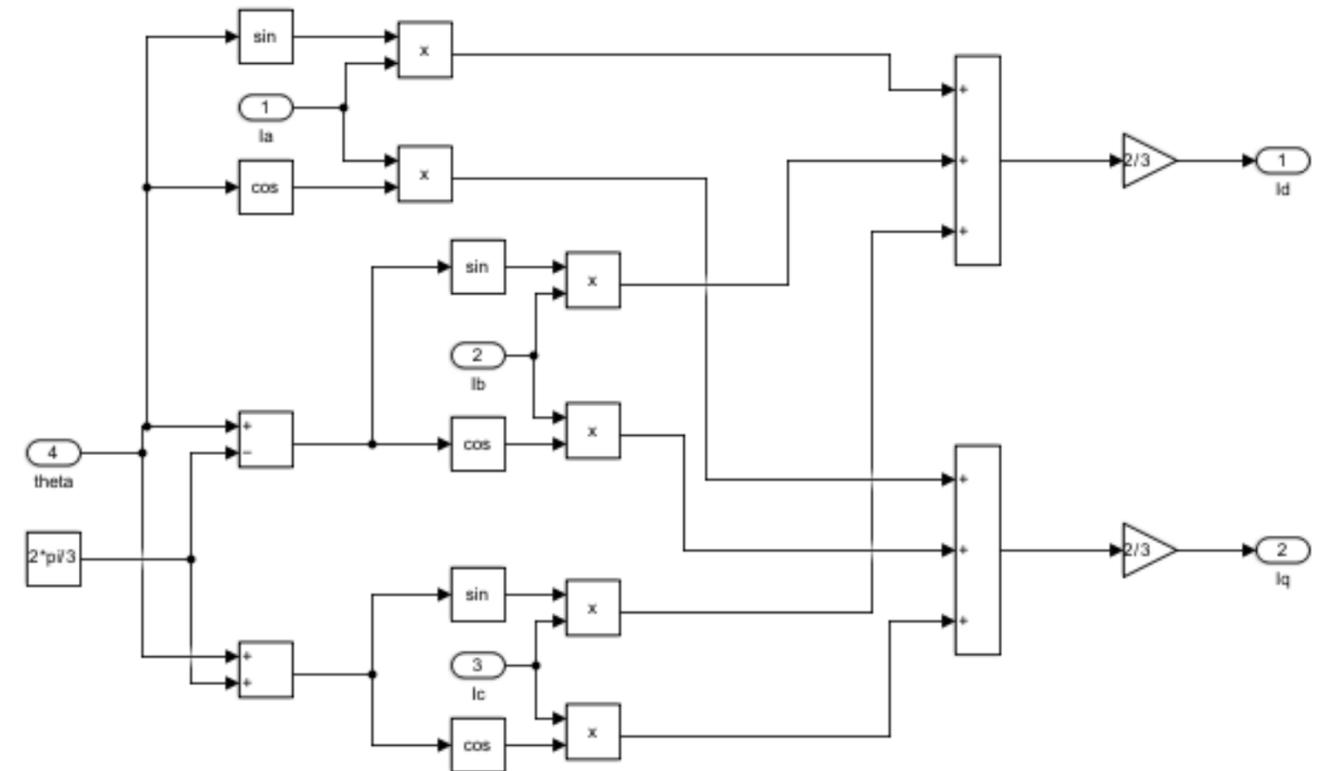
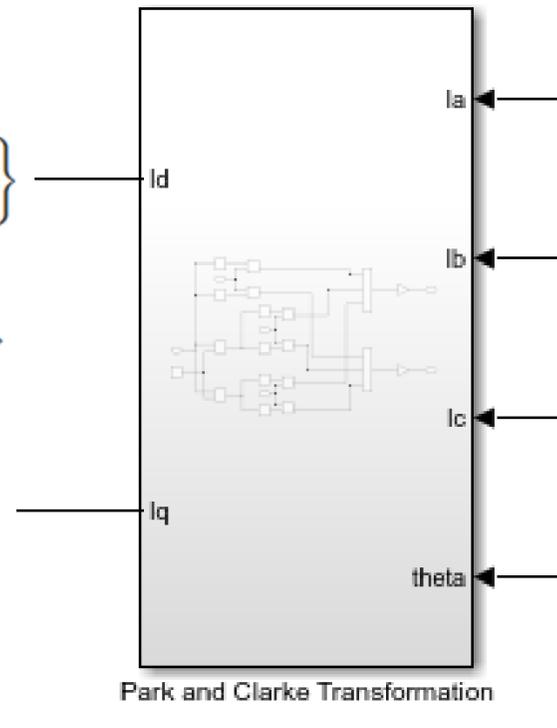


모터에서 측정된 3상 교류전류와 회전자 각도를 제어기가 이해할 수 있는 직류 전류로 변환.

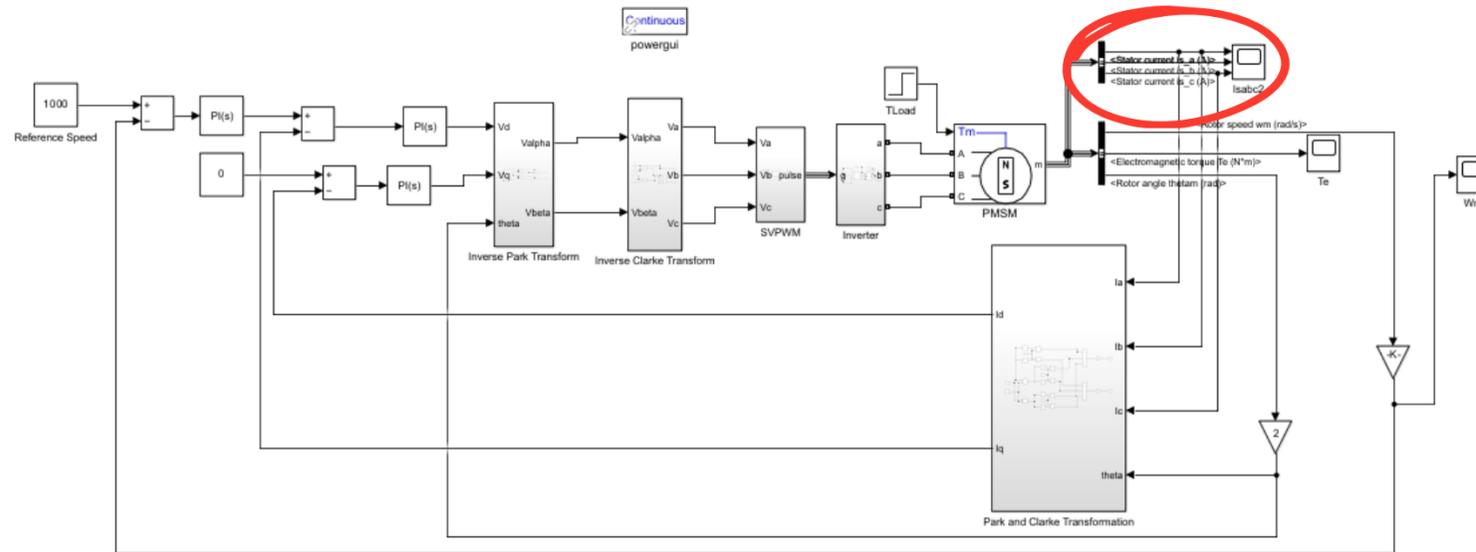
I_d : 자속을 만드는 전류 성분 (0으로 제어)
 I_q : 토크를 만드는 전류 성분 (속도 제어기가 명령)

$$I_d = \frac{2}{3} \left\{ I_a \sin(\theta) + I_b \sin\left(\theta - \frac{2\pi}{3}\right) + I_c \sin\left(\theta + \frac{2\pi}{3}\right) \right\}$$

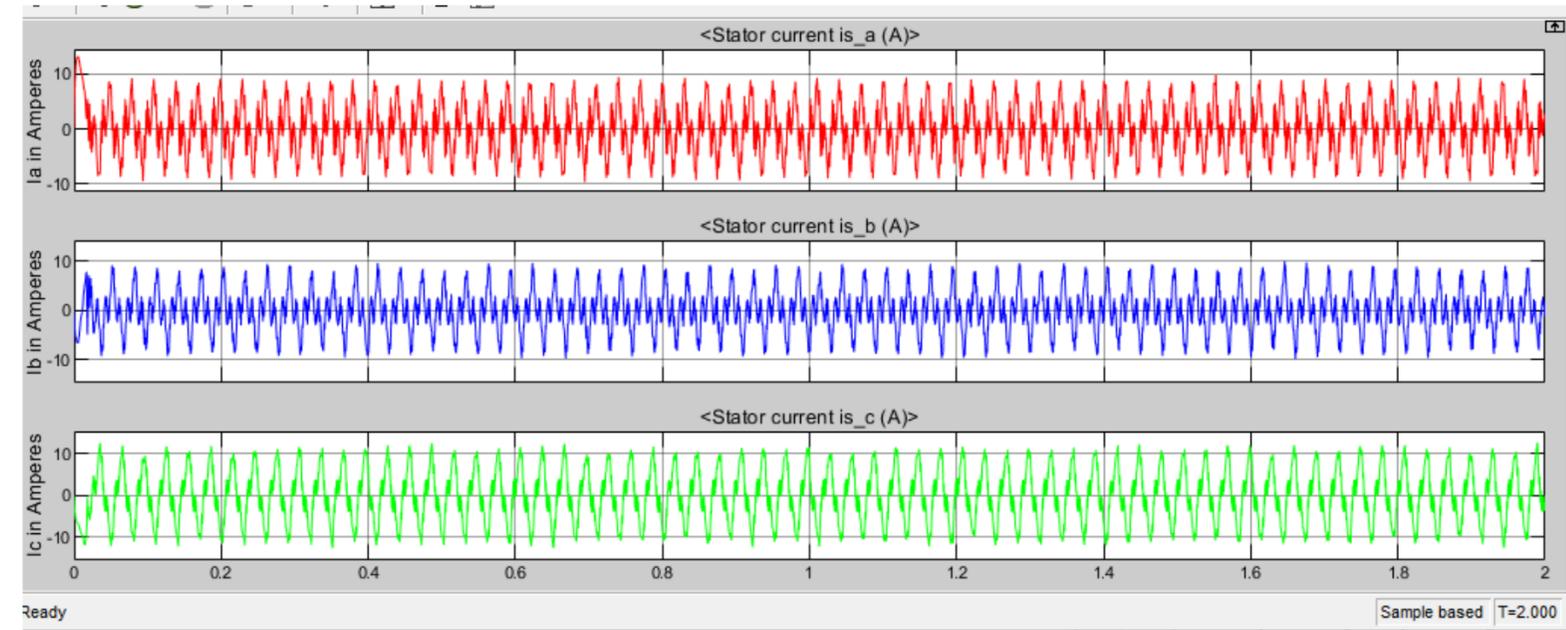
$$I_q = \frac{2}{3} \left\{ I_a \cos(\theta) + I_b \cos\left(\theta - \frac{2\pi}{3}\right) + I_c \cos\left(\theta + \frac{2\pi}{3}\right) \right\}$$



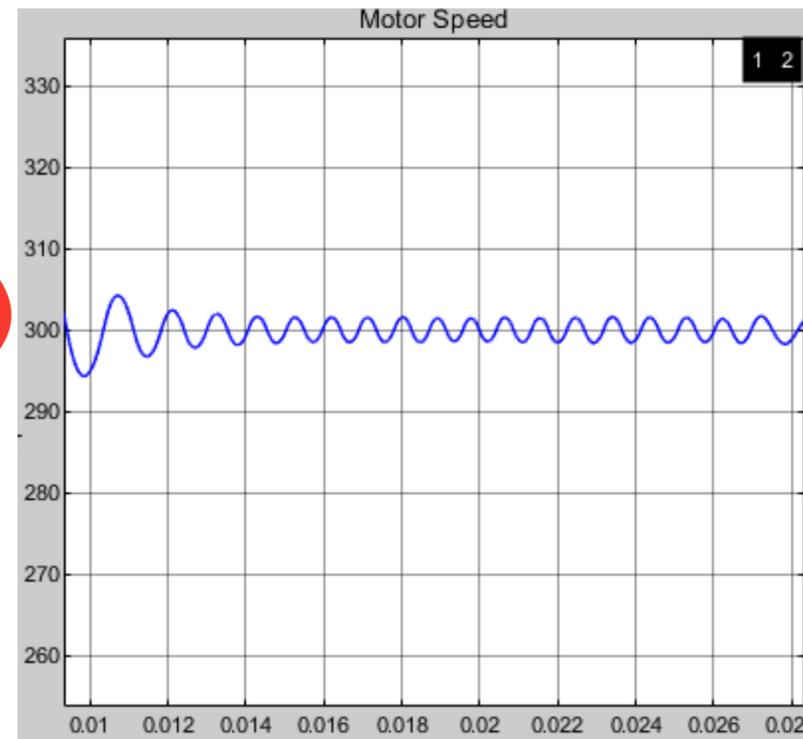
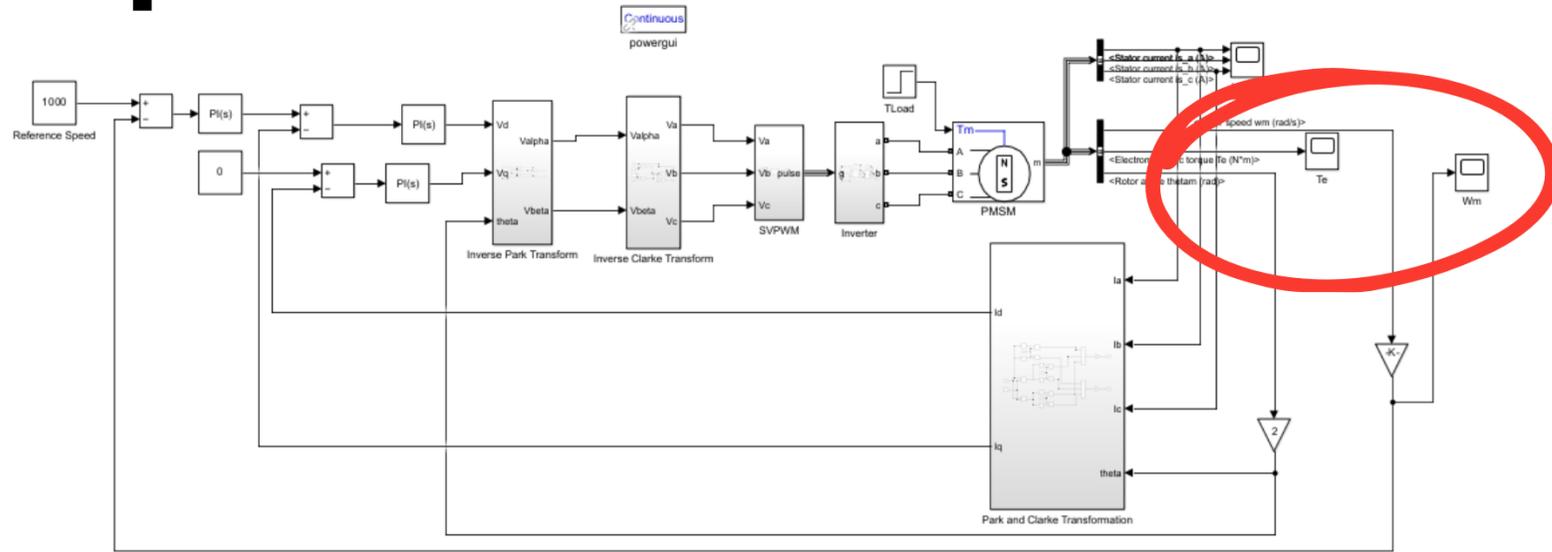
Sinusoidal



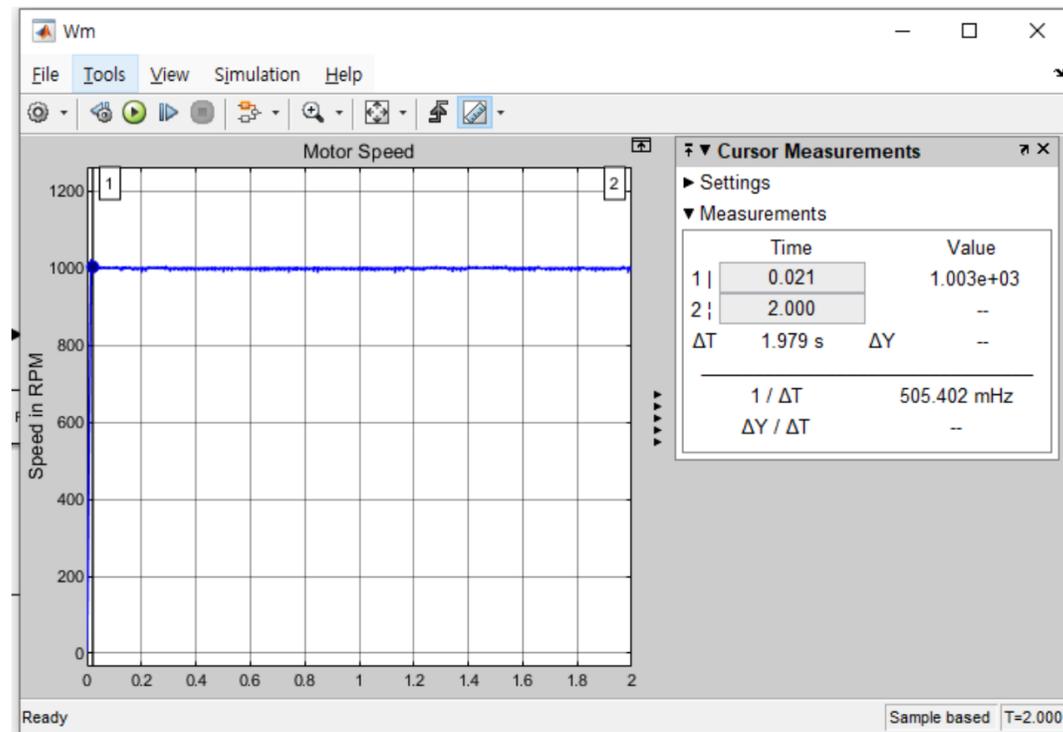
3상 : 120도의 위상차
정현파(Sinusoidal) 형태



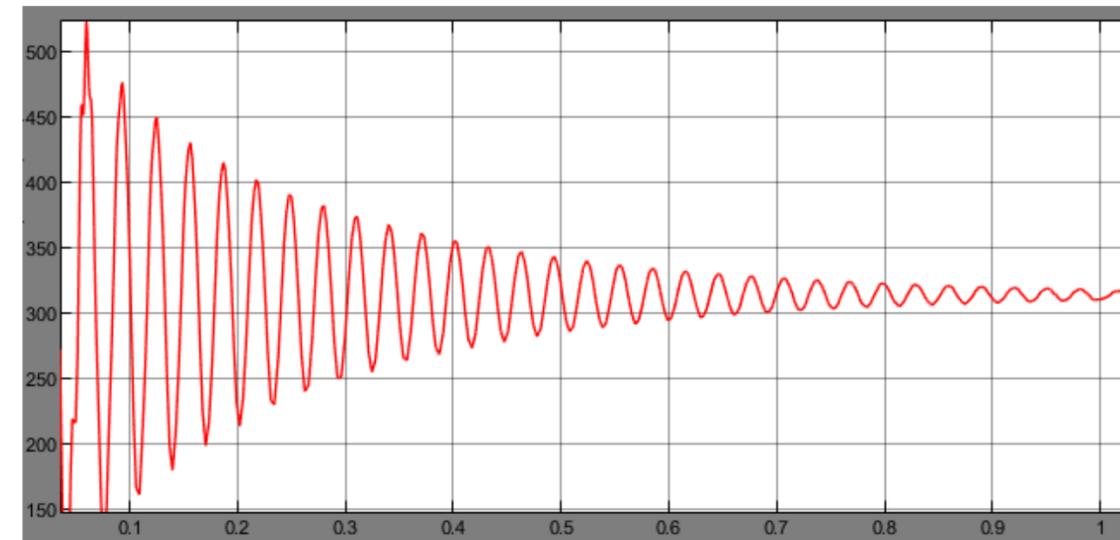
Graph



FOC 제어

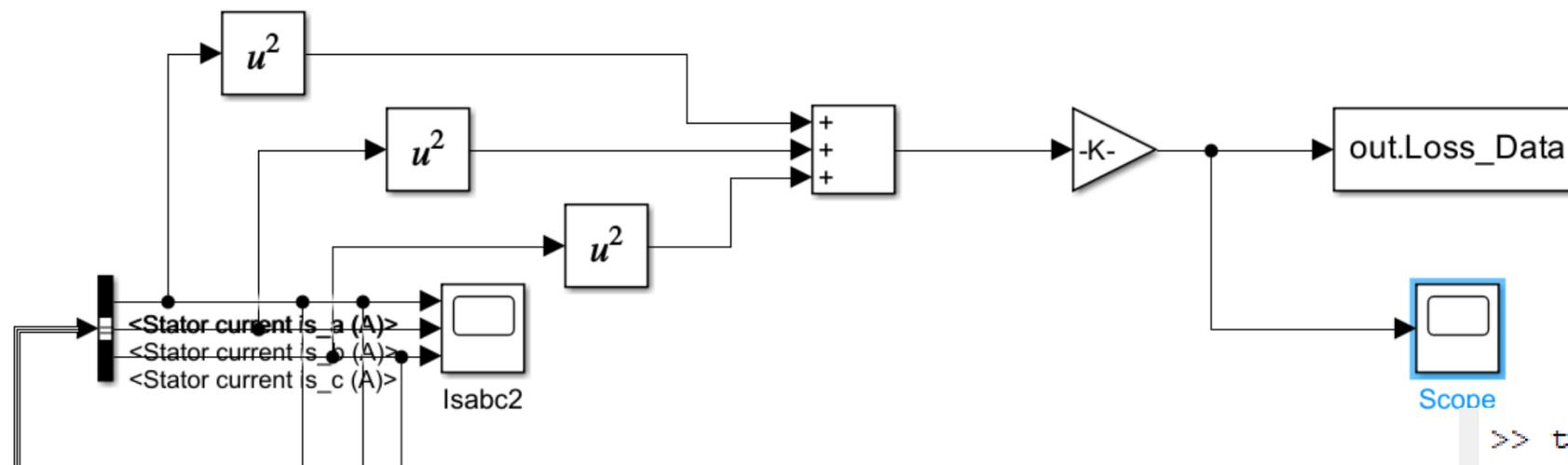
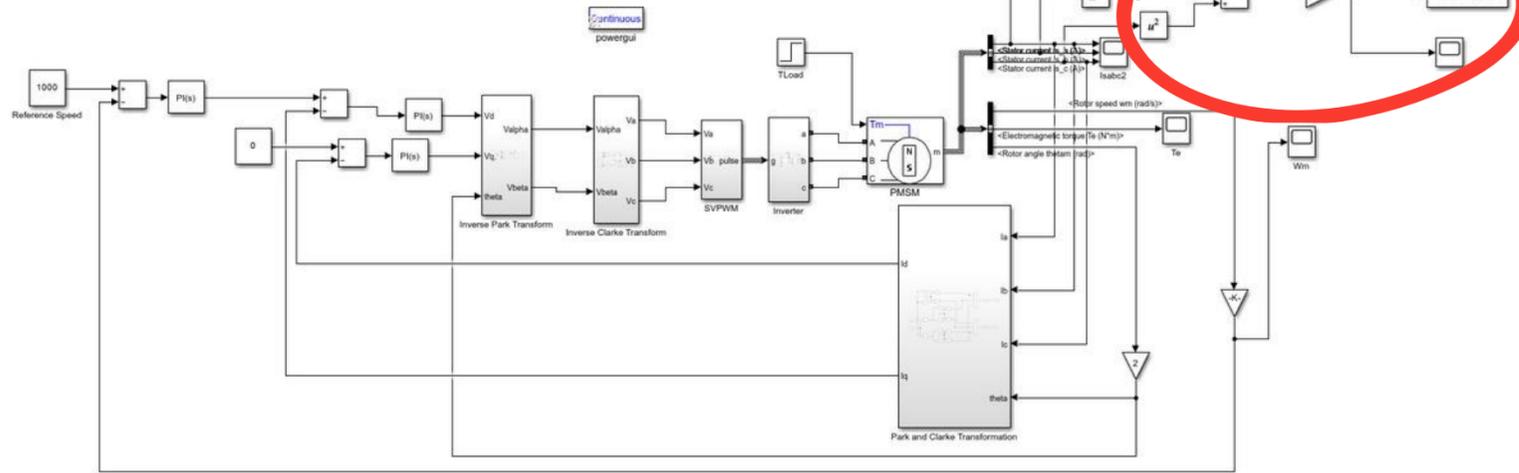


목표 회전수 : 1000rpm



기존 PMSM 모델

Out_Loss_Data



열손실량 구하는 블록 생성.
command 창을 통해 손실량 txt파일 생성.

motor_loss - Windows 메모장

파일(F) 편집(E) 서식(O) 보기(V) 도움말(H)

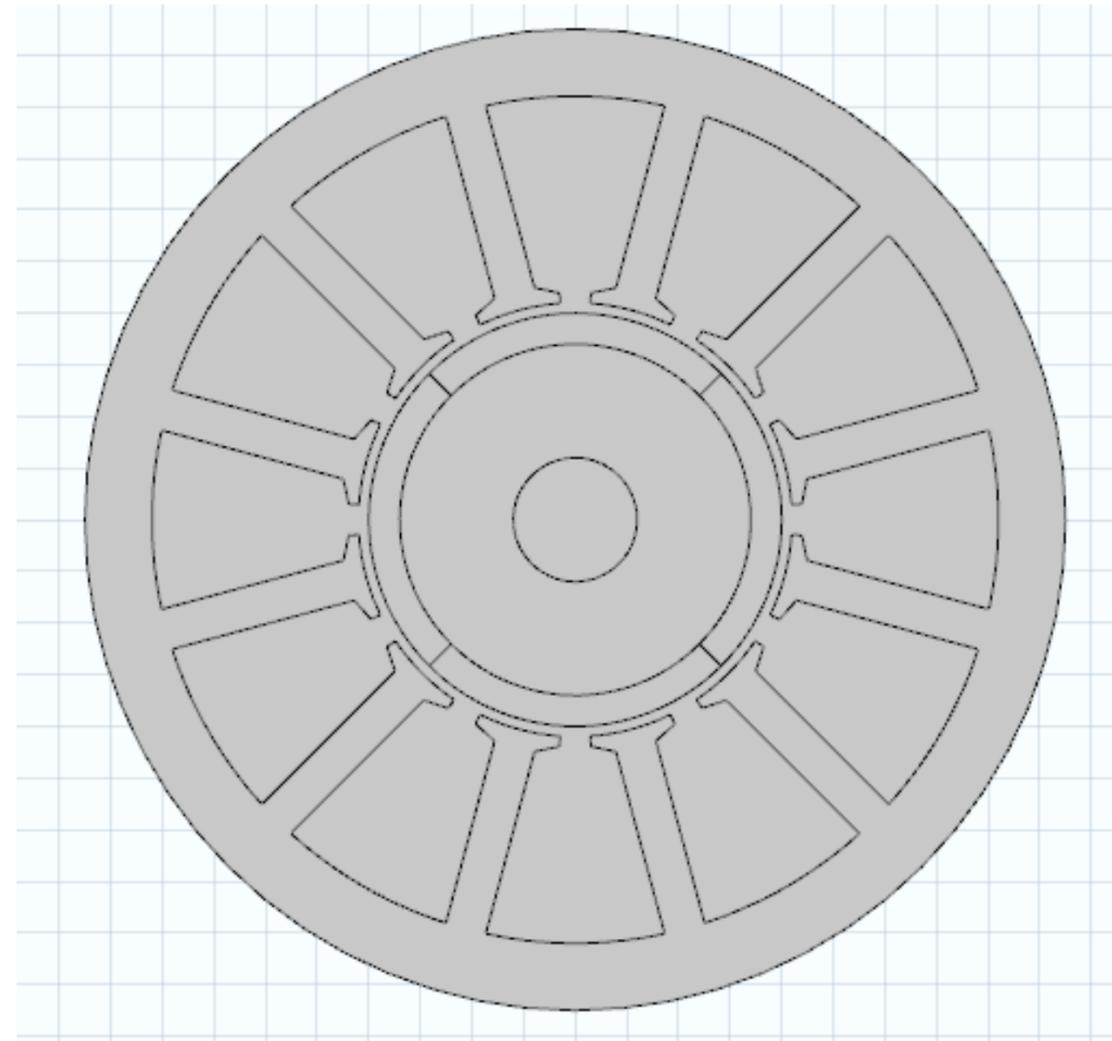
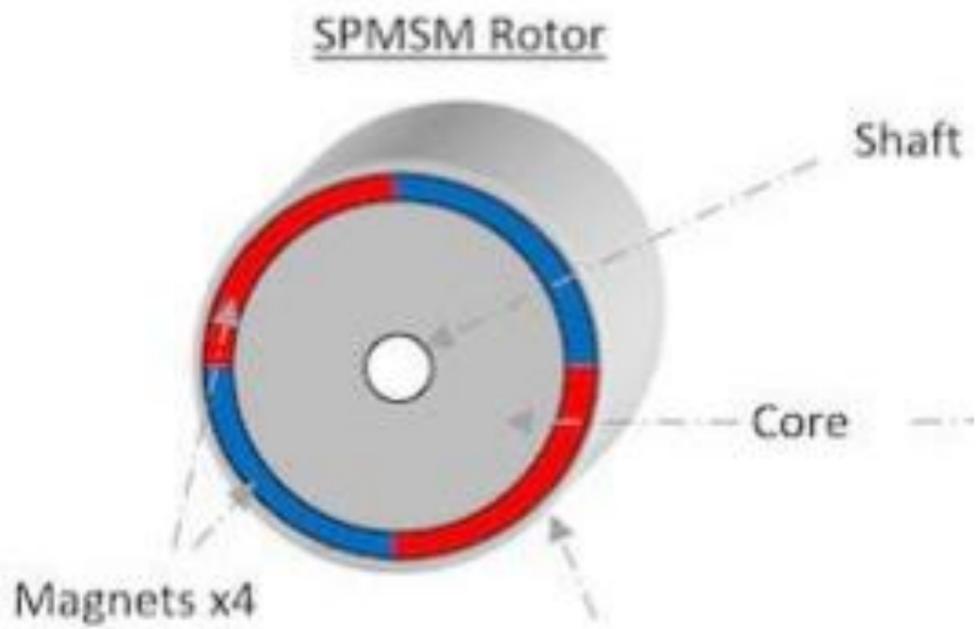
```
0,0
3.15544362088405e-30,1.91499417171764e-82
1.9320847562087e-17,2.64009197714716e-25
1.93208475620921e-17,2.64009197714855e-25
1.10940425553111e-05,0.0810048471515931
1.28285956905638e-05,0.108118542553716
1.40460859305199e-05,0.153521517319547
2.01335371303007e-05,0.495109761659981
2.85385013557091e-05,1.28143581532741
3.69434655811174e-05,2.42694923099786
4.76850479985605e-05,4.40369974790971
5.84266304160036e-05,6.94373289452401
7.18951370360454e-05,10.904926065862
8.53636436560872e-05,15.7068300557343
0.000101762269215281,22.6533447769274
0.000118160894774475,30.7676199886066
0.000138506376195666,42.3957855784359
0.000158851857616857,55.6806207286
0.000185431361472944,75.4086901980101
0.000212010865329031,97.6776307276358
0.00024965620300014,133.269571600163
0.000295729249075933,182.750535242612
0.000341802295151727,238.089024920574
0.00038787534122752,298.633424186176
0.000433948387303313,363.781226256369
0.000480021433379107,432.975739705757
```

Ln 1, Col 1 100% Windows (CF)

```
>> ts = out.Loss_Data;
time_data = ts.Time;
loss_data = ts.Data;
loss_data = real(loss_data);
writematrix([time_data, loss_data], 'motor_loss.txt');
>>
```



05 Comsol





05 Comsol

모터의 2D 단면 형상 모델링 고정자, 회전자, 코일, 영구자석

The screenshot shows the COMSOL Multiphysics software interface for a 2D motor model. The main window displays a 2D cross-section of a motor with a grid. The left sidebar shows the Selection List with a tree view of the model's components, including Global Definitions, Component 1 (comp1), Geometry 1, Materials, Mesh 1, and Study 1. The Settings panel in the center shows the Geometry 1 settings, including units (mm and Degrees) and advanced options like Automatic rebuild. The Graphics window on the right shows the 2D plot of the motor cross-section. A Parameters table is overlaid on the bottom right, listing various parameters and their values.

Name	Expression	Value	Description
R_s_out	40 [mm]	0.04 m	고정자 외경
R_s_in	22.5 [mm]	0.0225 m	고정자 내경
R_r_out	20[mm]	0.02 m	회전자 외경
R_shaft	6 [mm]	0.006 m	샤프트 반지름
Th_mag	3 [mm]	0.003 m	자석 두께
L_motor	50 [mm]	0.05 m	모터 길이

Material



Material: Copper

Property	Name	Value	Unit	Property group
Heat capacity at constant pressure	Cp	385 J/(kg·K)	J/(kg·K)	Basic
Density	rho	8960 kg/m³	kg/m³	Basic
Thermal conductivity	k	400 W/(m·K)	W/(m·K)	Basic
Relative permeability	mur	1	1	Basic
Electrical conductivity	sigma	5.998e7 S/m	S/m	Basic
Coefficient of thermal expansion	alpha	17e-6 1/K	1/K	Basic
Relative permittivity	epsilon	1	1	Basic
Young's modulus	E	110e9 Pa	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	0.35	1	Young's modulus and Poisson's ratio
Reference resistivity	rho0	1.72e-8 Ohm·m	Ohm·m	Linearized resistivity
Resistivity temperature coefficient	alpha	0.0039 1/K	1/K	Linearized resistivity
Reference temperature	Tref	298 K	K	Linearized resistivity

Material: Structural steel

Property	Name	Value	Unit	Property group
Heat capacity at constant pressure	Cp	475 J/(kg·K)	J/(kg·K)	Basic
Thermal conductivity	k	44.5 W/(m·K)	W/(m·K)	Basic
Density	rho	7850 kg/m³	kg/m³	Basic
Relative permeability	mur	1	1	Basic
Electrical conductivity	sigma	4.032e6 S/m	S/m	Basic
Relative permittivity	epsilon	1	1	Basic
Coefficient of thermal expansion	alpha	12.3e-6 1/K	1/K	Basic
Young's modulus	E	200e9 Pa	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	0.33	1	Young's modulus and Poisson's ratio
Murnaghan third-order elastic constant	l	-3.0e11 N/m²	N/m²	Murnaghan
Murnaghan third-order elastic constant	m	-6.2e11 N/m²	N/m²	Murnaghan

Material: My_magnet

Property	Name	Value	Unit	Property group
Density	rho	7500 kg/m³	kg/m³	Basic
Heat capacity at constant pressure	Cp	500 J/(kg·K)	J/(kg·K)	Basic
Thermal conductivity	k	8 W/(m·K)	W/(m·K)	Basic
Electrical conductivity	sigma	625000 S/m	S/m	Basic
Relative permittivity	epsilon	1	1	Basic
Relative permeability	mur	1.05	1	Basic

Material 부여
air, copper, steel, magnet

Heat



heat source, heat flux

The image displays four panels illustrating different heat source and heat flux settings in a CAD software environment. Each panel shows a 3D model of a circular gear-like component with a central hole and radial spokes, overlaid on a 2D coordinate system (x and y axes ranging from -120 to 120).

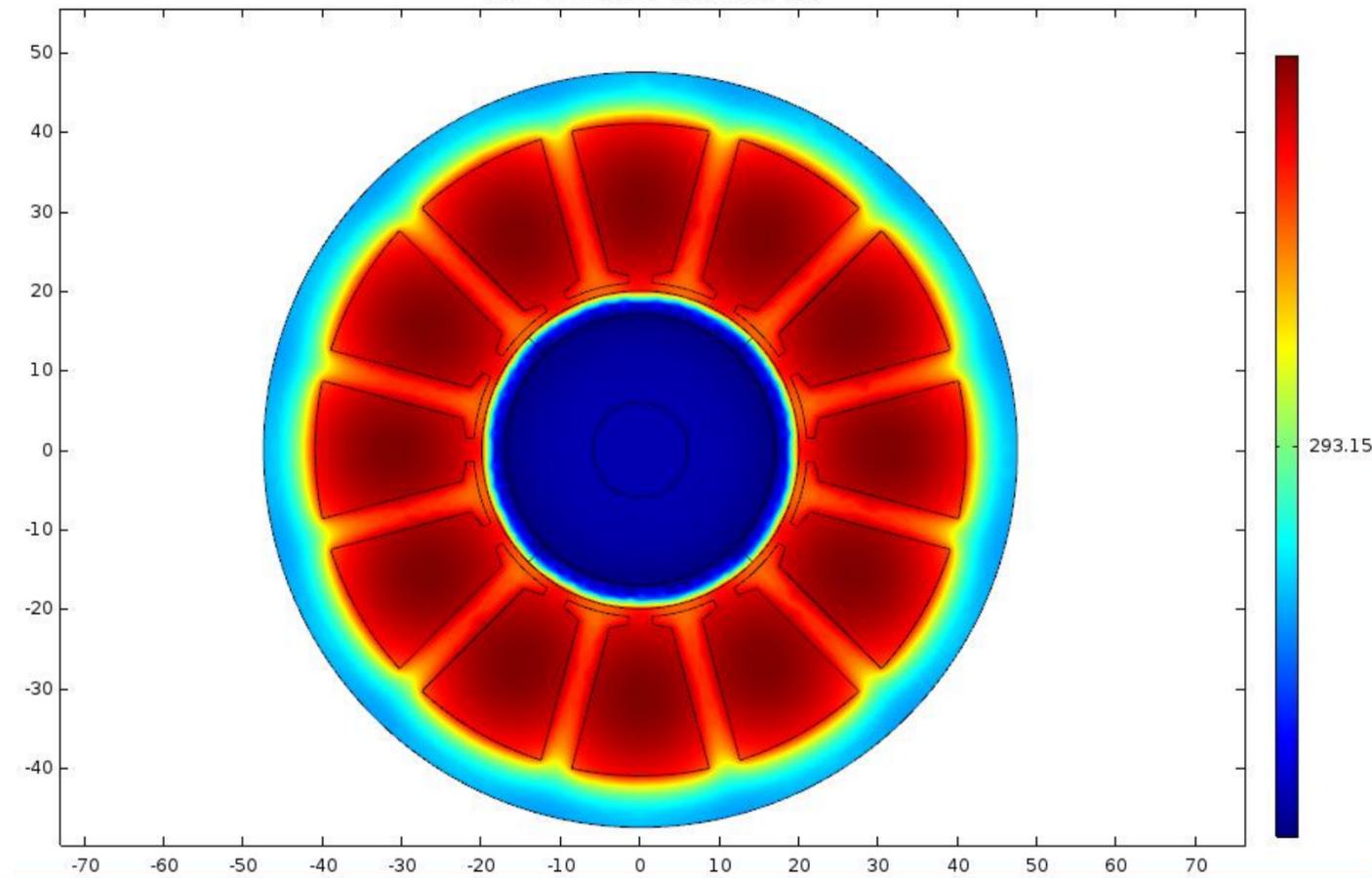
Panel 1 (Top Left): Heat Source 1
Settings: Heat Source, Domain Selection: Manual, Selection: 1. Equation: $Q_0 = \frac{P_0}{V}$. Convergence Plot: Shows a plot of Q_0 vs. iteration, converging to approximately 78.

Panel 2 (Top Right): Heat Source 2
Settings: Heat Source, Domain Selection: Manual, Selection: 2. Equation: $Q_0 = \frac{P_0}{V}$. Convergence Plot: Shows a plot of Q_0 vs. iteration, converging to approximately 126.

Panel 3 (Bottom Left): Heat Source 3
Settings: Heat Source, Domain Selection: Manual, Selection: 3, 4, 5, 6. Equation: $Q_0 = \frac{P_0}{V}$. Convergence Plot: Shows a plot of Q_0 vs. iteration, converging to approximately 133.

Panel 4 (Bottom Right): Heat Flux 1
Settings: Heat Flux, Boundary Selection: Manual, Selection: 77, 78, 126, 133. Equation: $Q_0 = h \cdot (T_{ext} - T)$. External temperature: $T_{ext} = 293.15 [K]$. Convergence Plot: Shows a plot of Q_0 vs. iteration, converging to approximately 133.

06 Result



1s

General source

λ_0 User defined

$P_{loss_func}(t)$ W/m

Linear source

$\lambda_0 = q_s \cdot T$

Overall heat transfer rate

$\lambda_0 = \frac{P_0}{V}$

```
>> ts = out.Loss_Data;  
time_data = ts.Time;  
loss_data = ts.Data;  
loss_data = real(loss_data);  
writematrix([time_data, loss_data], 'motor_loss.txt');  
>>
```

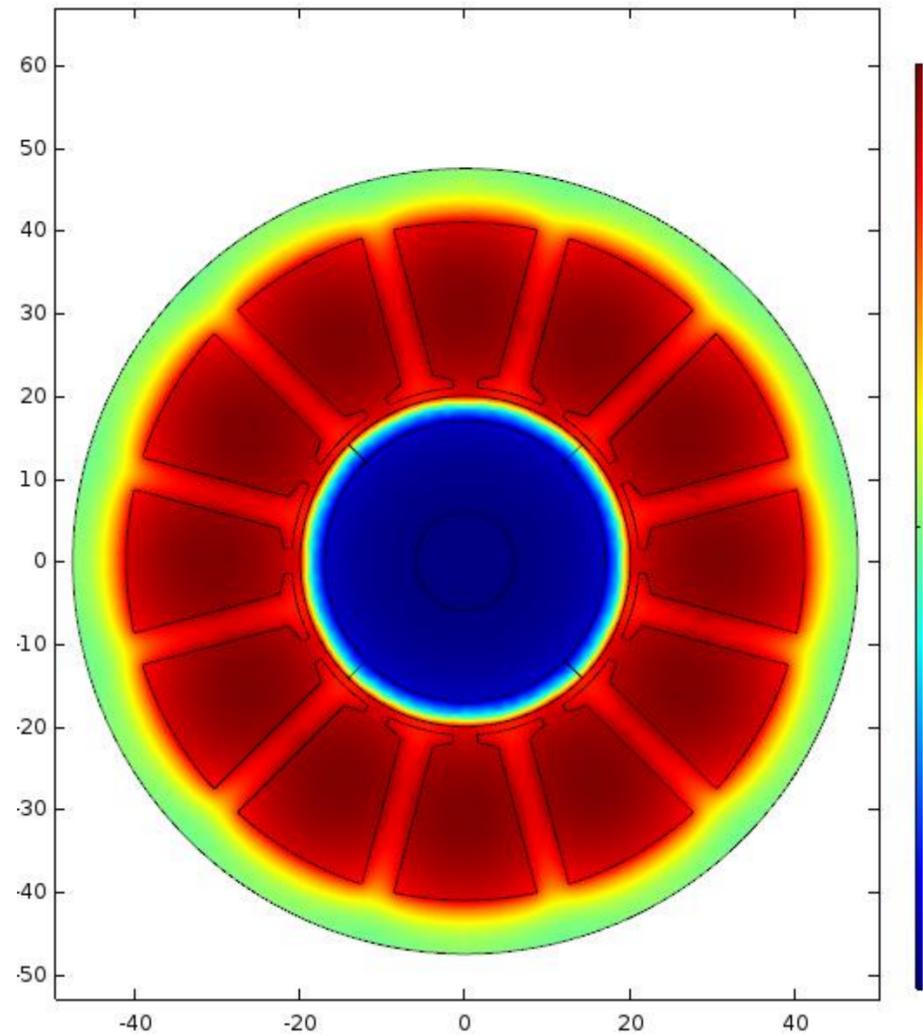
P_loss_data (1) - Windows 메모장

파일을	편집(E)	서식(O)	보기(V)	도움말(H)
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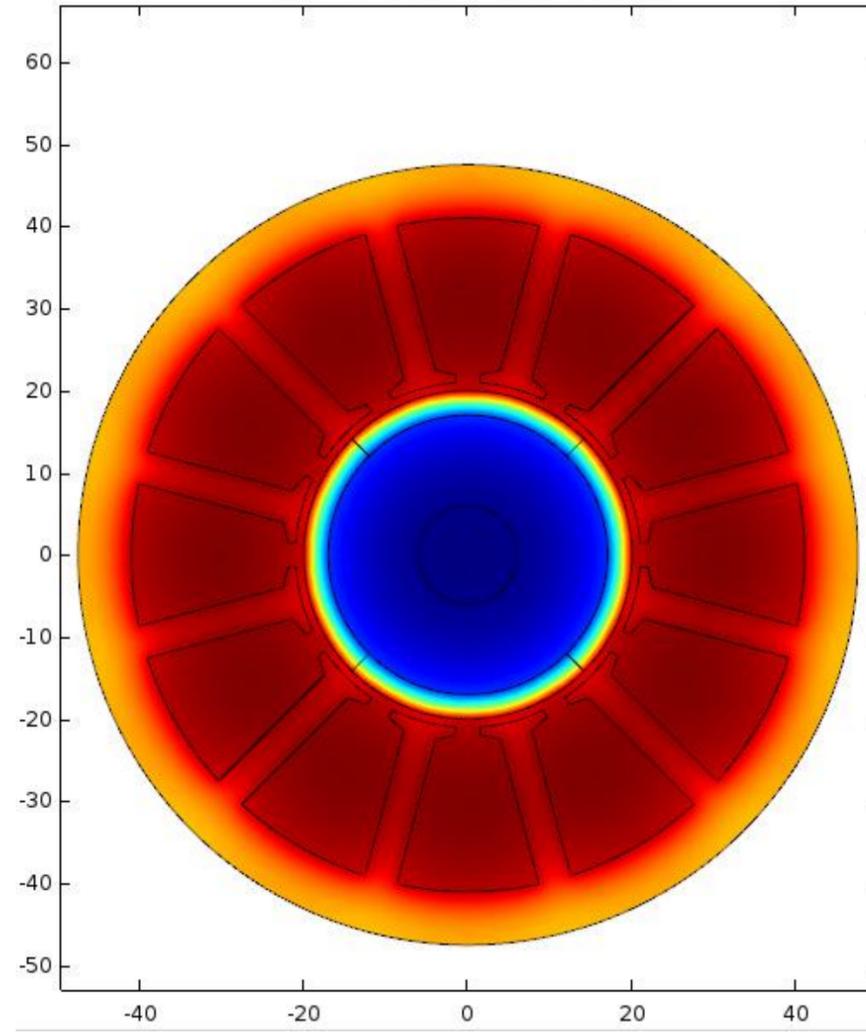
```
0.413167925241369,0.720252076265627  
0.413173005970412,0.71956307438151  
0.413173005970415,0.719563074382807  
0.413174096174721,0.7200771861931  
0.413174096174724,0.720077186195155  
0.413191538967078,0.759601778841603  
0.413212324268843,0.881523959435295  
0.413217430302585,0.866043347070996  
0.413230495546474,0.99417105673318  
0.413251475550093,1.25819628946657  
0.41327245553712,1.59549093918386  
0.413301115451168,2.16871765050434  
0.413301115451171,2.16871765058315  
0.413301551094738,2.17839575635971  
0.413301551094741,2.17839575643875  
0.413301986738308,2.18810255323201  
0.413304164956142,2.2370515918585  
0.413315056045312,2.49226909135758  
0.413327826097051,2.81272925231487  
0.413327826097054,2.81272925240717  
0.413334448958064,2.98775559806232  
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0.413374186124126,4.15912312563581  
0.413409326342659,5.35748714480761  
0.413409326342662,5.35748714493604
```

Time range(0, 1, 300)

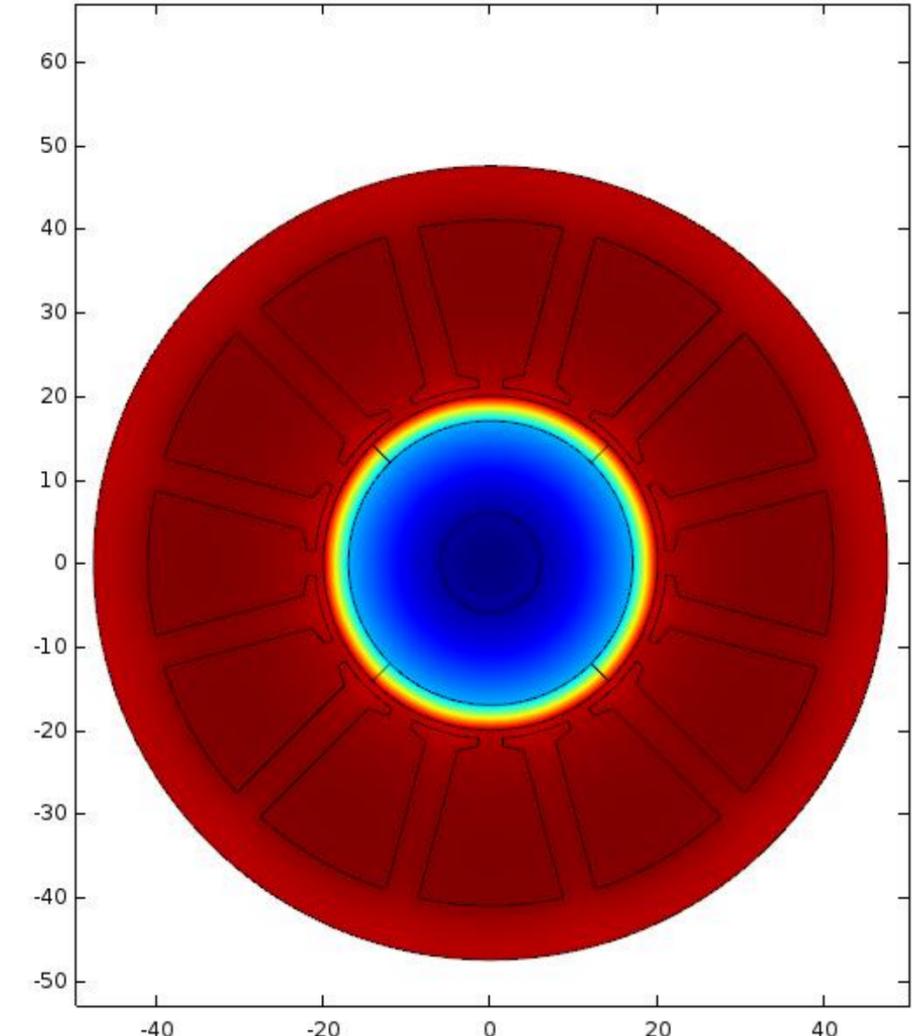
06 Result



2s



5s



10s



07 References

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<https://ieeexplore.ieee.org/document/10421371>

<https://community.nxp.com/t5/Model-Based-Design-Toolbox-MBDT/Module-2-PMSM-and-FOC-Theory/m-p/761926>

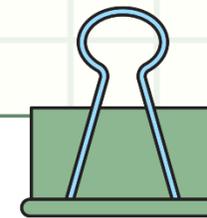
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감사합니다

THANK
YOU!