

5kW IPM Motor Drive System for a Golf Cart

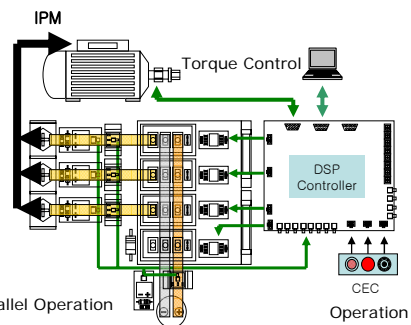
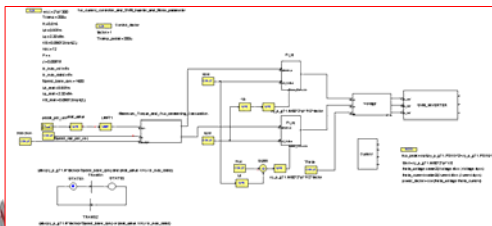
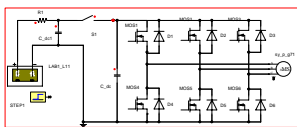
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5kW IPM Motor Drive System for a golf cart



목적: Simplorer를 이용하여 IPM 전
동기 구동시스템의 설계를 위한 시뮬
레이션 모델 개발 및 특성 해석



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Contents

1. IPM Motor Model
2. SVM Inverter
3. Transformation
4. Current Controller
5. Maximum Torque & Field Weakening Algorithm
6. Simulation and Experiment
7. Conclusion



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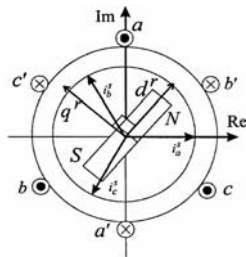
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1. IPM Motor Model

모델링시의 가정

- 1) 고정자의 3상 권선 : 대칭분포
- 2) 철손 무시
- 3) 공극에 채교하는 자속이 공간적으로 정현파 분포
- 4) 철심의 투자율: 무한대 → 포화현상 무시

IPM Motor (Interior Permanent Magnet Motor)



트크 $T_e = \frac{3}{2} \frac{P}{2} (\phi_r i'_{qt} + (L_{dt} - L_{qt}) i'_{ds} i'_{qs})$

정지좌표계 as-bs-cs

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix}$$

$$\begin{aligned} L_{aa} &= L_0 - L_2 \cos 2\theta_r \\ L_{bb} &= L_0 - L_2 \cos(2\theta_r + 2\pi/3) \\ L_{cc} &= L_0 - L_2 \cos(2\theta_r - 2\pi/3) \end{aligned}$$

$$\begin{aligned} L_{ab} &= L_{ba} = -0.5L_0 - L_2 \cos(2\theta_r - 2\pi/3) \\ L_{bc} &= L_{cb} = -0.5L_0 - L_2 \cos 2\theta_r \\ L_{ca} &= L_{ac} = -0.5L_0 - L_2 \cos(2\theta_r + 2\pi/3) \end{aligned}$$

3상/2상 변환

$$\begin{bmatrix} V_{ds}^s \\ V_{qs}^s \end{bmatrix} = R_s \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + p \begin{bmatrix} a + b \cos 2\theta_r & -b \sin 2\theta_r \\ -b \sin 2\theta_r & a - b \cos 2\theta_r \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \phi_f \begin{bmatrix} \cos \theta_r \\ \sin \theta_r \end{bmatrix}$$

$$L_{ds}^s = \frac{3}{2}(L_0 - L_2), L_{qs}^s = \frac{3}{2}(L_0 + L_2), \quad a = \frac{L_{ds}^s + L_{qs}^s}{2}, b = \frac{L_{ds}^s - L_{qs}^s}{2}$$

정지좌표계 dq (회전자자속 기준)

정지/동기좌표 변환

$$\begin{bmatrix} V_{ds}^r \\ V_{qs}^r \end{bmatrix} = \begin{bmatrix} R_s + L_{ds} \frac{d}{dt} & -\omega_r L_{qs} \\ \omega_r L_{ds} & R_s + L_{qs} \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix}$$

IPM형 동기전동기 모델



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1. IPM Motor Model

Voltage Equation

$$\begin{bmatrix} V_{1d} \\ V_{1q} \end{bmatrix} = R_1 \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + p \cdot \begin{bmatrix} \lambda_{1d} \\ \lambda_{1q} \end{bmatrix} + p \cdot \begin{bmatrix} -\omega \cdot \lambda_{1q} \\ \omega \cdot \lambda_{1d} \end{bmatrix}$$

Subscript 1: stator

Flux Linkage Equation

$$\lambda_{1d} = L_{1d} \cdot i_{1d} + k_e$$

$$\lambda_{1q} = L_{1q} \cdot i_{1q}$$

Rotor Flux Linkage [Vs] → $k_e = L_m \cdot i_{fr}$

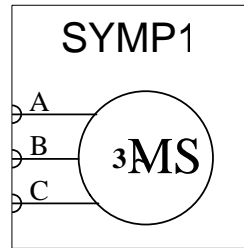
Torque Equation (electromagnetic developed "internal" torque)

$$m_i = \frac{3}{2} \cdot p \cdot (\lambda_{1d} \cdot i_{1q} - \lambda_{1q} \cdot i_{1d})$$

where p: number of pole pairs

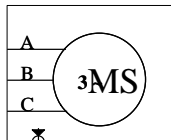
Motion Equation

$$\frac{d\omega}{dt} = \frac{1}{J} (m_i - m_w)$$



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1. IPM Motor Model



SVM_inverter_and_Motor_parameter1

ICA:

R:=0.016
Ld:=0.937m
Lq:=2.3245m
KE:=0.09072/sqrt(2.)
Vdc:=72
P:=4
J:=0.00575
Is_max_set:=54
Is_max_rated:=54
Speed_base_rpm:=1600
Ld_real:=0.937m
Lq_real:=2.3245m
KE_real:=0.09072/sqrt(2.)

Properties - sy_p_g71 - PM Synchronous without Damper

Parameters | Output / Display | Tolerances | Library

Name: sy_p_g71 | Show Name:

| Description | Name | Value |
|--------------------------|------|---------|
| Stator Resistance | R1 | R |
| Stator Inductance d-Axis | L1D | Ld_real |
| Stator Inductance q-Axis | L1Q | Lq_real |
| Rotor Flux [Vs] | KE | KE_real |
| Number Of Pole Pairs | P | 2 |
| Rotor Moment of Inertia | J | J |

Initial Values (Value, Variable)

| Description | N... | V... | Unit |
|--------------------------------|------|------|------|
| Initial Current Stator Phase a | I1A0 | 0 | A |
| Initial Current Stator Phase b | I1B0 | 0 | A |
| Initial Current Stator Phase c | I1C0 | 0 | A |
| Initial Rotor Speed | N0 | 0 | rpm |
| Initial Rotor Position | PHI0 | 0 | de |

Default Outputs

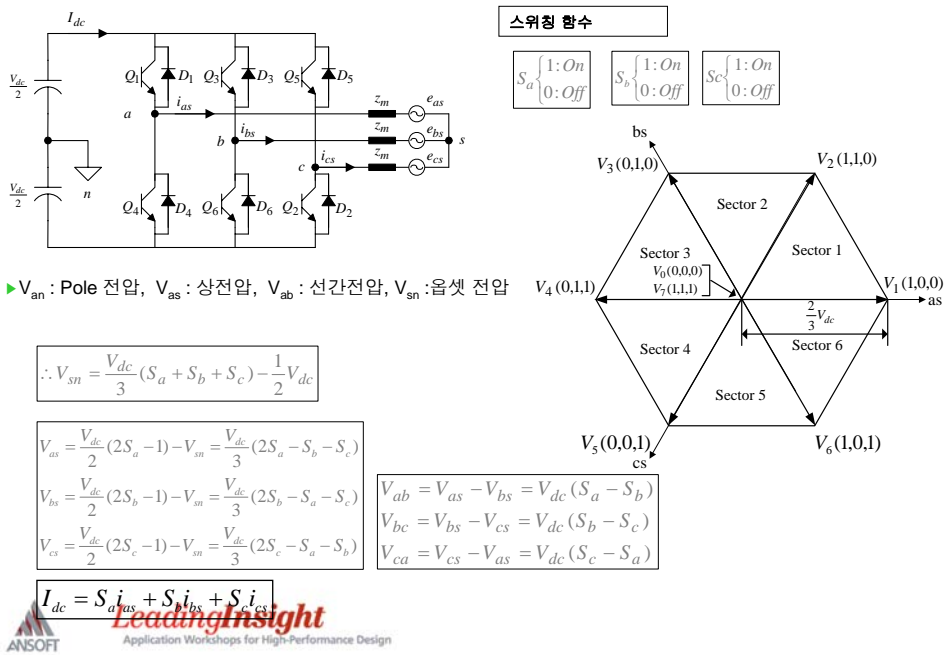
- Rotor Speed [rpm]
- Rotor Torque [Nm]
- Load Torque [Nm]
- Rotor Position [rad]
- Current Stator Phase a [A]
- Current Stator Phase b [A]
- Current Stator Phase c [A]

Buttons: 확인, 취소, 적용(Δ), 도움말

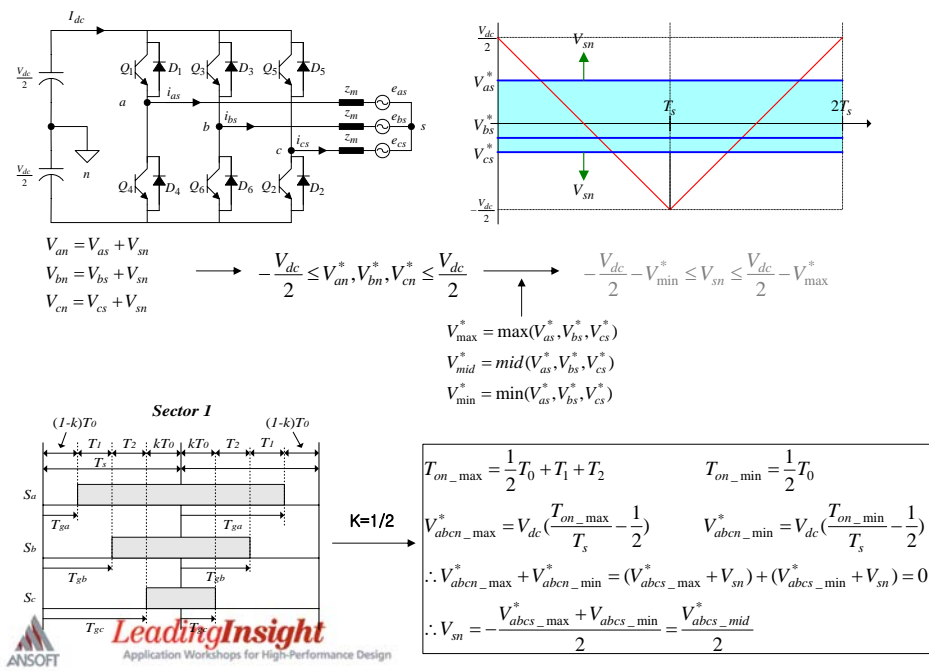


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2. SVM INVERTER

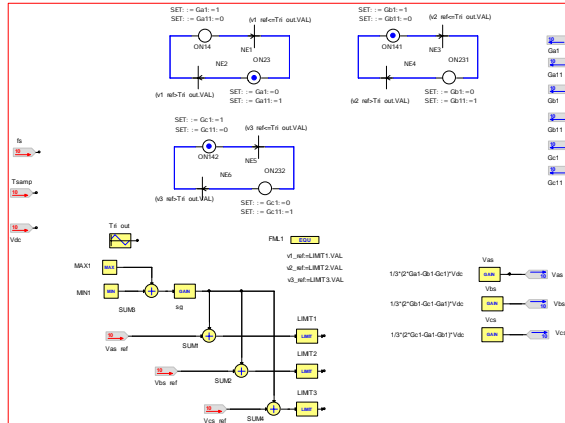


2. SVM INVERTER



2. SVM INVERTER-Subsheet

SVM INVERTER

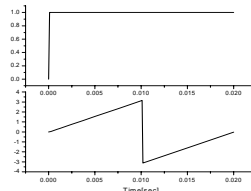


3. Transformation

공간벡터

$$\vec{f}_{dq} = |\vec{f}| e^{j\theta_s}$$

$$\theta_s = \int \omega \cdot dt$$



정지좌표계 as-bs-cs
: 3상 교류

$$\begin{aligned} f_{as}^s &= |\vec{f}_{dq}| \cos(\theta_s) \\ f_{bs}^s &= |\vec{f}_{dq}| \cos(\theta_s - \frac{2\pi}{3}) \\ f_{cs}^s &= |\vec{f}_{dq}| \cos(\theta_s + \frac{2\pi}{3}) \\ \theta_s &= \int \omega \cdot dt \end{aligned}$$

3상/2상 좌표변환

2상/3상 좌표변환

정지좌표계 ds-qs
: 2상 교류

$$\begin{aligned} f_{ds}^s &= |\vec{f}_{dq}| \cos(\theta_s) \\ f_{qs}^s &= |\vec{f}_{dq}| \sin(\theta_s) \\ \theta_s &= \int \omega \cdot dt = \tan^{-1} \left(\frac{f_{qs}^s}{f_{ds}^s} \right) \end{aligned}$$

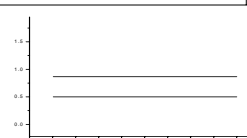
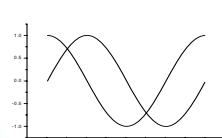
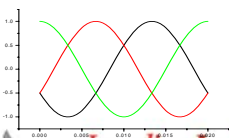
동기좌표계 de-qe
: 직류

$$\begin{aligned} f_{de}^s &= |\vec{f}_{dq}| \cos(\theta_s - \theta) \\ f_{qe}^s &= |\vec{f}_{dq}| \sin(\theta_s - \theta) \\ \theta_s &= \int \omega \cdot dt \quad \theta = \int \omega \cdot dt + \theta(0) \\ \theta_s - \theta &= \tan^{-1} \left(\frac{f_{qe}^s}{f_{de}^s} \right) \end{aligned}$$

동기/정지좌표변환

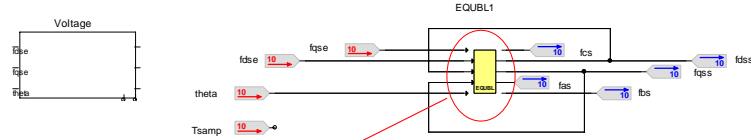
정지/동기좌표변환

항상 θ 정보 필요



3. Transformation

3상 a-b-c stationary reference frame → 2상 dq stationary reference frame
2상 dq rotating reference frame



Properties - EQUBL1 - Equation Block

Name: EQUBL1 Show Name

Display Error Messages

| Name | Use Pin | Input Signal |
|----------|-------------------------------------|---------------|
| INPUT[0] | <input checked="" type="checkbox"/> | fdse |
| INPUT[1] | <input checked="" type="checkbox"/> | EQUBL1.VAL[0] |
| INPUT[2] | <input checked="" type="checkbox"/> | EQUBL1.VAL[1] |
| INPUT[3] | <input checked="" type="checkbox"/> | fqse |
| INPUT[4] | <input checked="" type="checkbox"/> | theta |

Equation

```

VAL[0] := INPUT[0] * cos(INPUT[4] * ...
VAL[1] := INPUT[0] * sin(INPUT[4] * ...
VAL[2] := INPUT[1]
VAL[3] := -1/2 * INPUT[1] + sqrt(3) * ...
VAL[4] := -1/2 * INPUT[1] - sqrt(3) * ...
    
```

| Name | Use Pin | Output |
|--------|-------------------------------------|--------------------------|
| VAL[0] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[1] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[2] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[3] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[4] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |

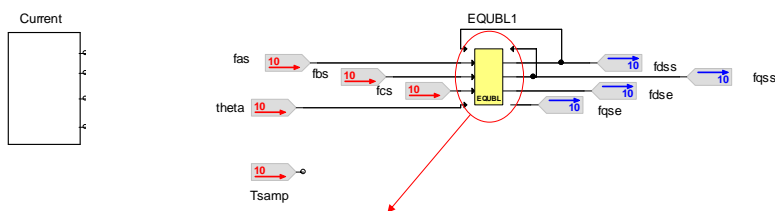
Sample Time: Tsamp s

Use Pin

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3. Transformation

2상 dq rotating reference frame → 2상 dq stationary reference frame
3상 a-b-c stationary reference frame



Properties - EQUBL1 - Equation Block

Name: EQUBL1 Show Name

Display Error Messages

| Name | Use Pin | Input Signal |
|----------|-------------------------------------|---------------|
| INPUT[0] | <input checked="" type="checkbox"/> | fqs |
| INPUT[1] | <input checked="" type="checkbox"/> | fbs |
| INPUT[2] | <input checked="" type="checkbox"/> | fcs |
| INPUT[3] | <input checked="" type="checkbox"/> | theta |
| INPUT[4] | <input checked="" type="checkbox"/> | EQUBL1.VAL[0] |
| INPUT[5] | <input checked="" type="checkbox"/> | EQUBL1.VAL[1] |

Equation

```

VAL[0] := 1/3 * (2 * INPUT[0] - INPUT[1] - INPUT[2])
VAL[1] := 1/sqrt(3) * (INPUT[1] - INPUT[2])
VAL[2] := INPUT[4] * cos(INPUT[3] * ...
VAL[3] := INPUT[4] * sin(INPUT[3] * ...
    
```

| Name | Use Pin | Output |
|--------|-------------------------------------|--------------------------|
| VAL[0] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[1] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[2] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |
| VAL[3] | <input checked="" type="checkbox"/> | <input type="checkbox"/> |

Sample Time: Tsamp s

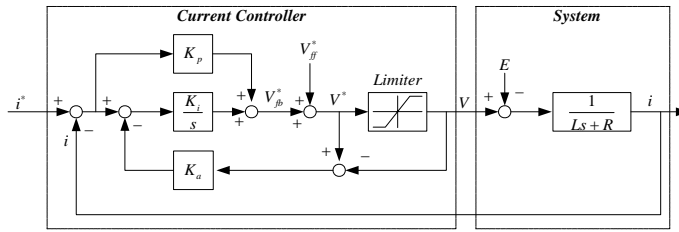
Use Pin

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4. Current Controller

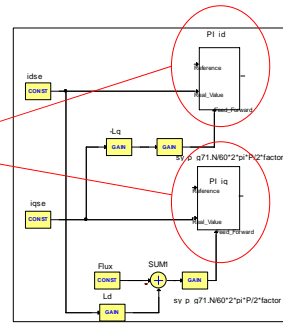
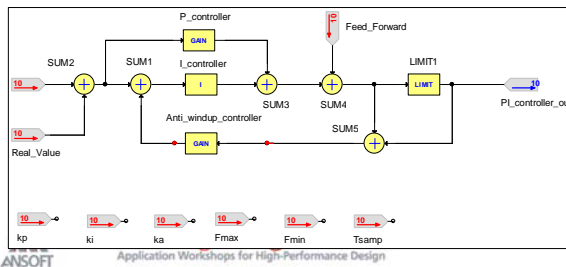
PI 전류 제어기(리미터, Anti-Windup 포함)



PI 전류제어기 출력 (전압지령) $\Rightarrow V^* = V_{fb}^* + V_{ff}^*$

Feedforward(역기전력 추정) $V_{ff}^* = \bar{E}$

Feedback 계한성분 $V_{fb}^* = K_p(i^* - i) + K_i \int (i^* - i) + K_a(V^* - V) dt$



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5. Maximum Torque & Field Weakening Algorithm

IPM SM의 Torque

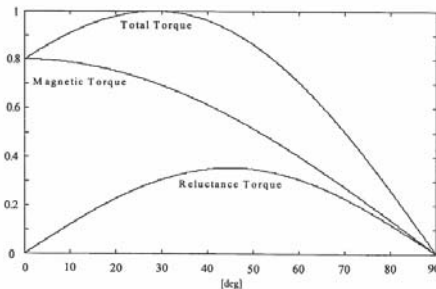
$$T_e = \frac{3P}{2} (L_{ds} - L_{qs}) i_{qs}^r \left(\frac{\phi_f}{L_{ds} - L_{qs}} + i_{ds}^r \right)$$

Maximum Torque \rightarrow

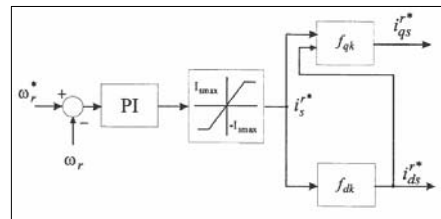
$$i_{qs}^r = \text{sign}(i_s^r) \cdot \sqrt{i_s^{r2} - i_{ds}^{r2}}$$

$$\propto |\gamma| \text{시, } \begin{cases} \text{if } i_s^r \geq 0, & \text{sign}(i_s^r) = 1 \\ i_s^r < 0, & \text{sign}(i_s^r) = -1 \end{cases}$$

$$i_{ds}^r = \frac{\phi_f - \sqrt{\phi_f^2 + 8(L_{qs} - L_{ds})^2 i_s^{r2}}}{4(L_{qs} - L_{ds})}$$



토크 성분의 비교.
Comparison of the torque component.

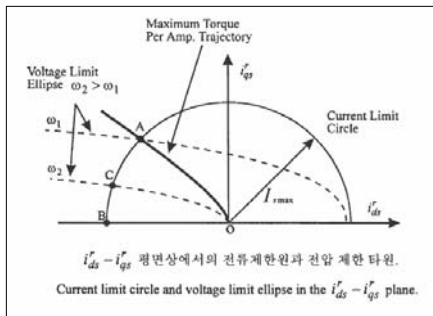


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5. Maximum Torque & Field Weakening Algorithm

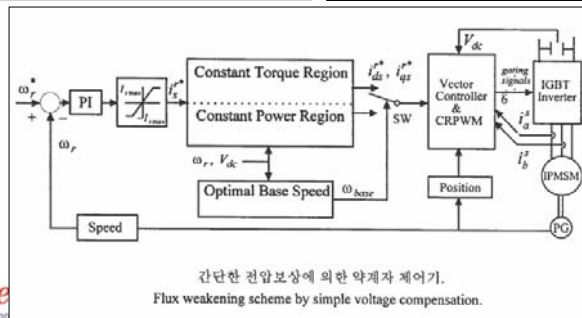


$$i_{qs}^* = \text{sign}(i_{df}^*) \cdot \sqrt{i_{df}^{*2} - i_{ds}^{*2}}$$

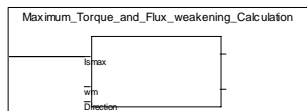
$$\text{여기서 } \begin{cases} i_{df}^* \geq 0, & \text{sign}(i_{df}^*) = 1 \\ i_{df}^* < 0, & \text{sign}(i_{df}^*) = -1 \end{cases}$$

$$i_{ds}^* = \frac{L_{d1}\phi_f - \left((L_{d1}\phi_f)^2 + (L_{q1}^2 - L_{d1}^2)(\phi_f^2 + (L_{d1}i_f^*)^2 - (V_f / \omega_r)^2) \right)^{1/2}}{L_{q1}^2 - L_{d1}^2}$$

여기서, $V_f = V_{s\max} - R_s I_s^{\max}$

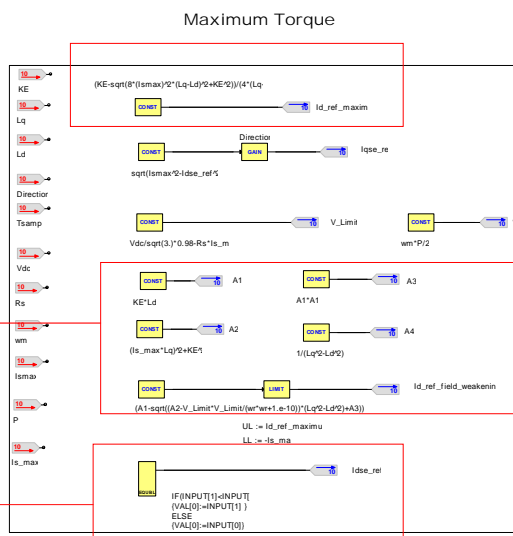


5. Maximum Torque & Field Weakening Algorithm

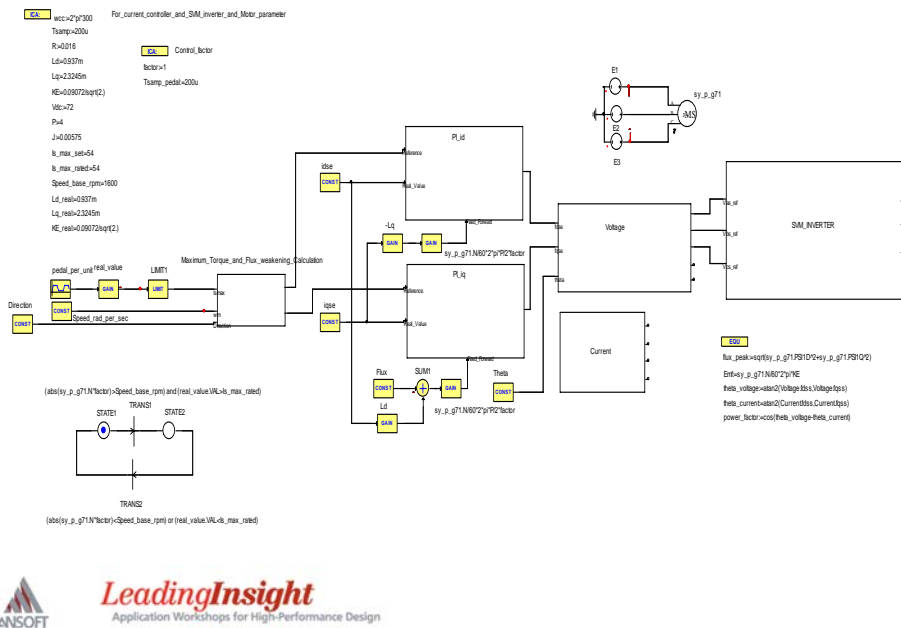


Field Weakening

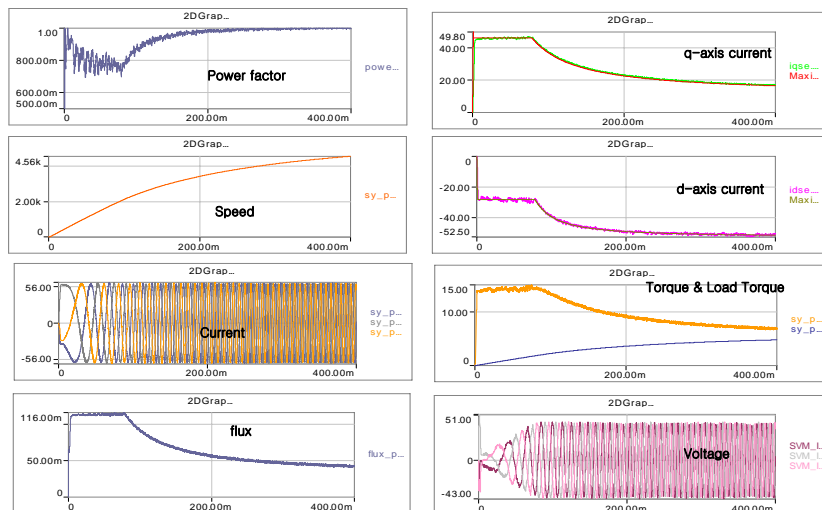
Selection of D-axis Current reference



6. Simulation and Experiment

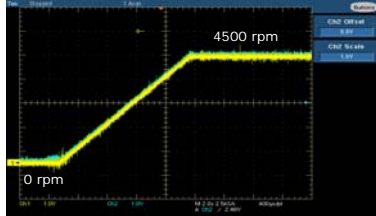


6. Simulation and Experiment

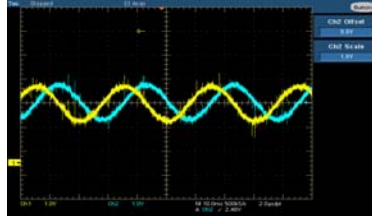


6. Simulation and Experiment

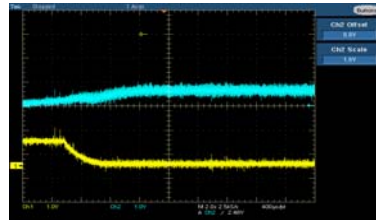
Speed Reference, Speed



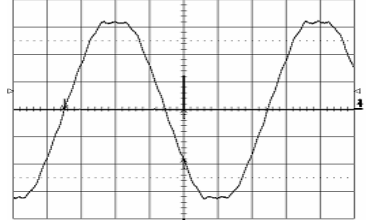
I_{dss}, I_{qss}



I_{dse}, I_{qse}



역기전력, Z pulse



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7. Conclusion

- 1) 골프카용 IPM Motor Drive System 의 시뮬레이션 모델 개발
 - SVM Inverter
 - Transformation
 - Current Controller
 - Maximum Torque & Field Weakening Algorithm
- 2) 시뮬레이션 모델을 이용한 구동시스템의 특성 파악
 - 자속각의 오차에 대한 영향
 - Maximum Torque 및 Field Weakening Algorithm의 동작 특성 확인
 - Parameter 오차에 대한 영향 분석
 - 전동기의 기계적 출력 확인
- 3) 차후 개발 모델
 - EPLD 및 DSP 프로그램, 센서 등을 탑재한 구동시스템의 모든 부분이 포함된 시뮬레이션 모델 개발



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