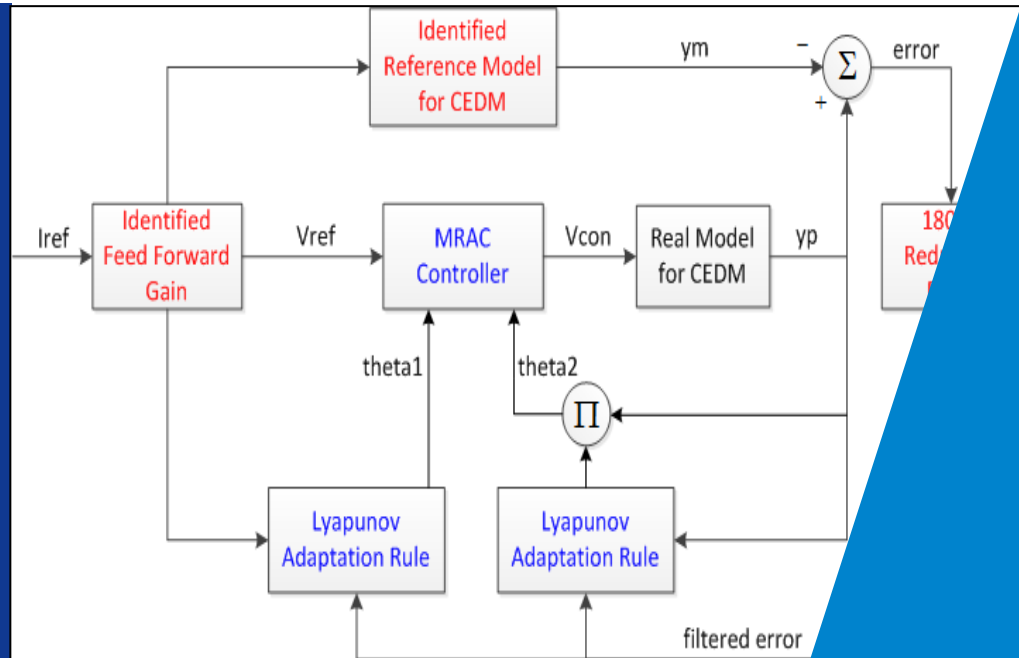


A Modified MRAC for a Single Motor of Latch Type CEDM



2016. 10. 27.
박배정

[발표순서]

1 CEDM and Control System Description

2 Why MRAC?

3 Control Algorithm (Structure)

4 System Identification (Modeling)

5 Stability Analysis and Proof

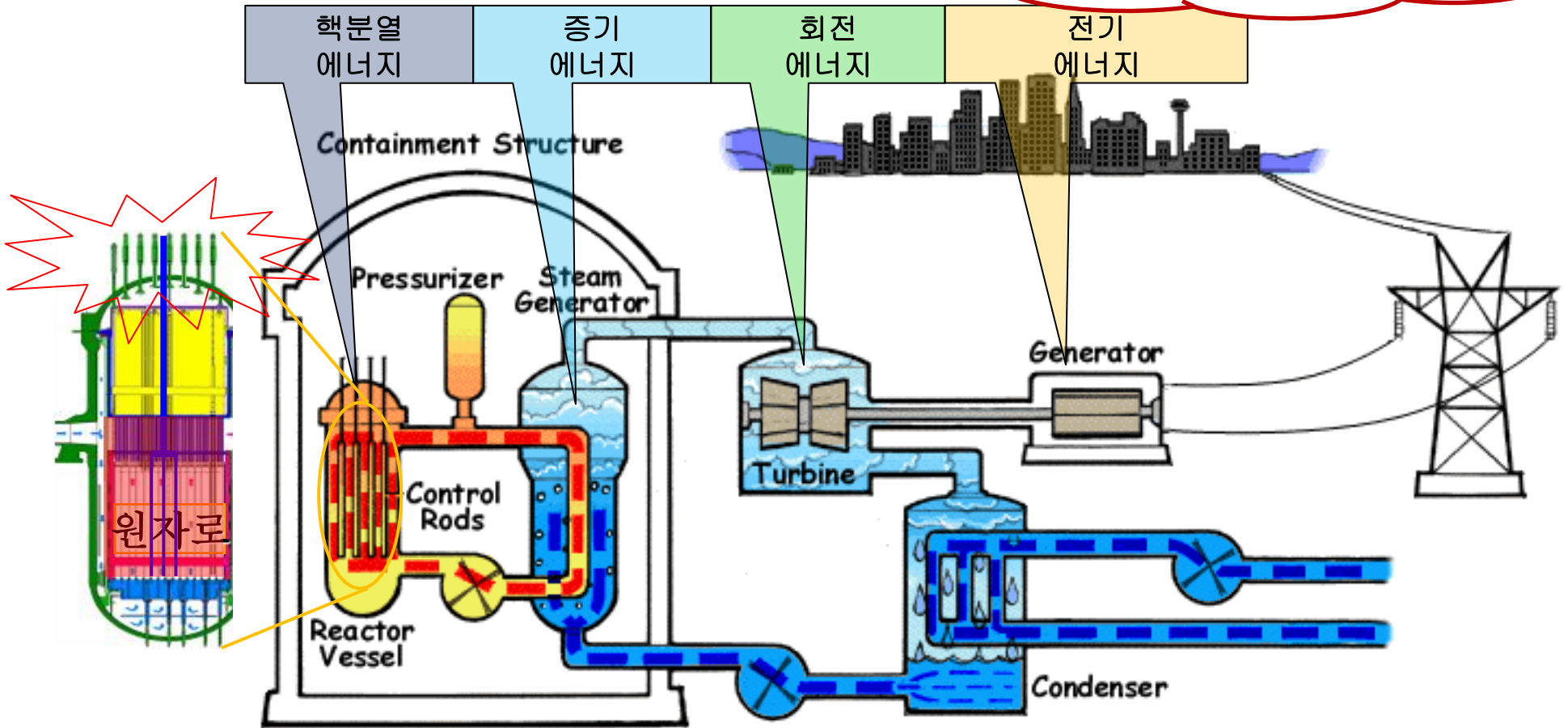
6 Simulation Results using MATLAB®

7 Experimental Results

8 Contribution and Conclusion

제어봉구동장치 제어계통은?

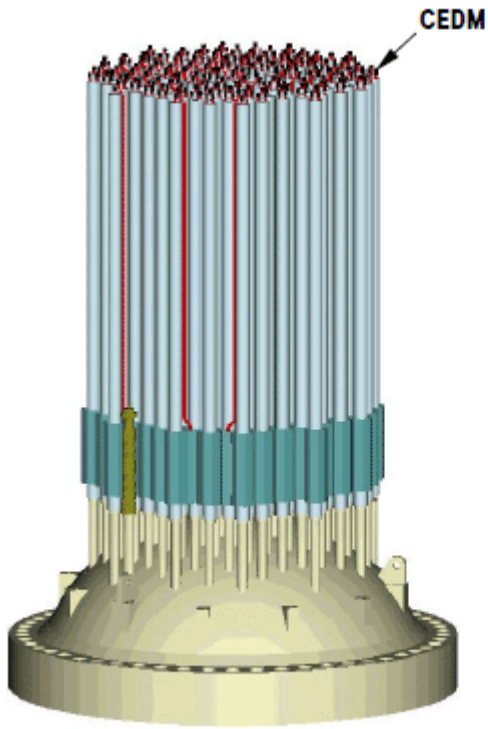
‘원전정지’와 직접 관련되는 매우 민감한 계통



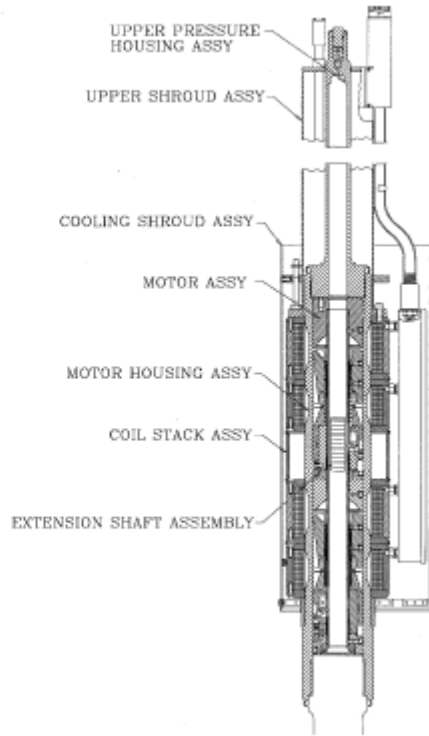
<설명>

제어봉구동장치 제어계통: 원자로 핵분열 반응도 조절을 위해 제어봉 집합체를 제어하는 계통
제어봉 구동장치: 4개의 모터장치로 구성, Latch(Magnetic Jack)를 갖는 특수한 Linear Motor
전력변환회로: APR1400 기준 제어봉 93개 X 4개의 모터장치 에 전원을 공급하는 3상 반파정류회로로 구성
 OPR1000 기준 제어봉 73개 , APR+ 기준 제어봉 101개

제어봉 구동장치(CEDM)는?



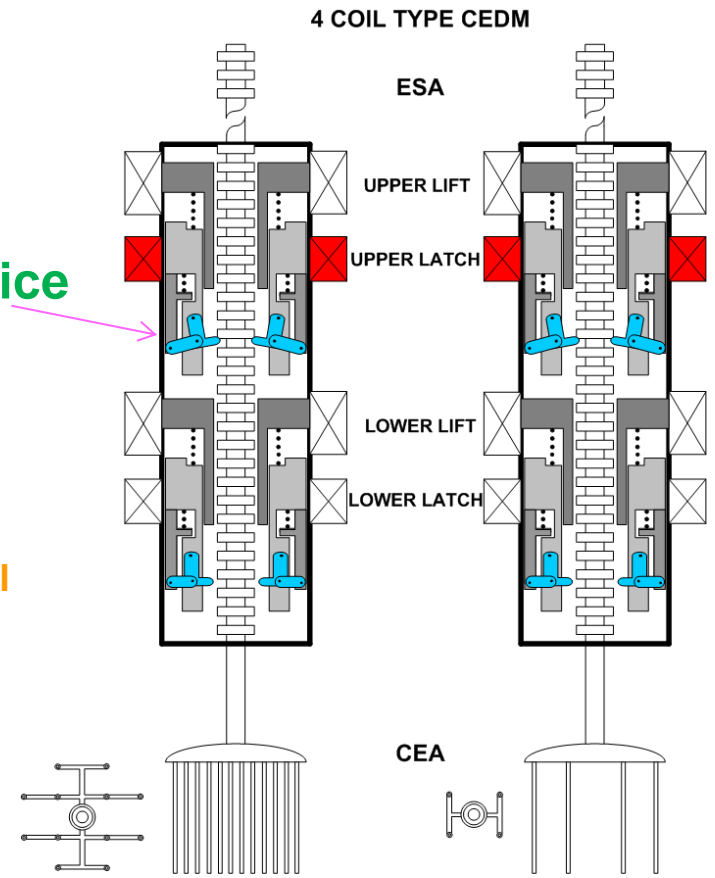
Reactor Head and CEDM



CEDM Assembly

Latch Device

Simplified Model



12 Finger Model

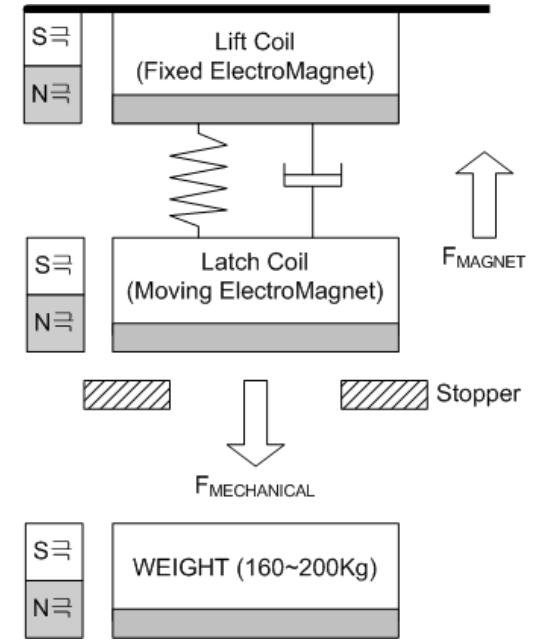
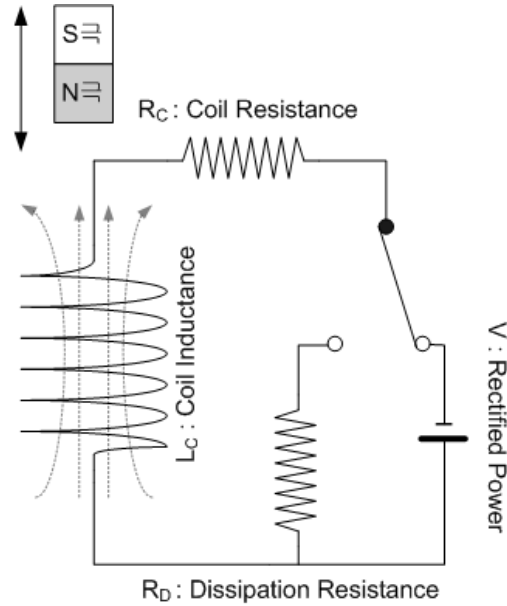
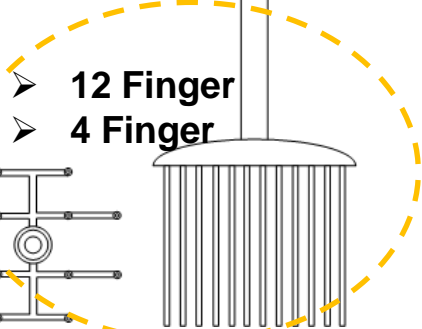
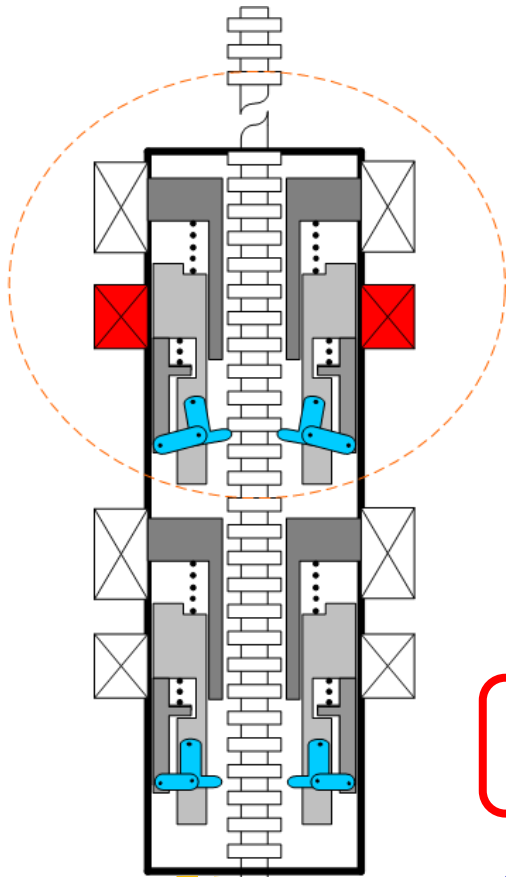
4 Finger Model

<용어설명>

- ESA(Extension Shaft Assembly): 제어봉 연결축 집합체
- CEDM(Control Element Driving Mechanism): 제어봉 구동장치
- CEA(Control Element Assembly): 제어봉 집합체
- 12 Finger CEA: 12발 제어봉 집합체
- 4 Finger: 4발 제어봉 집합체

“CEDM은 Latch구조의 특수한 Linear Motor”

Why MRAC? PID 제어기의 성능한계 <Re-tuning 및 M/H 손실> 발생



Non-linear Time-varying System

- ✓ 3 Phase Half Rectifier
- ✓ Resistance Variation
- ✓ Inductance Variation

⇒ 전기적 시정수 4배 변화

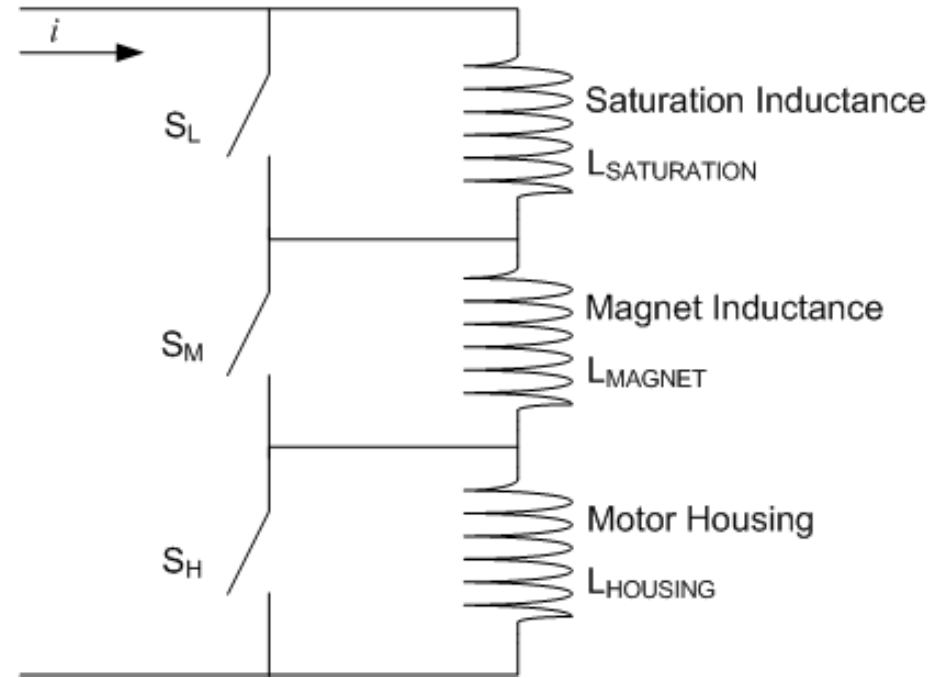
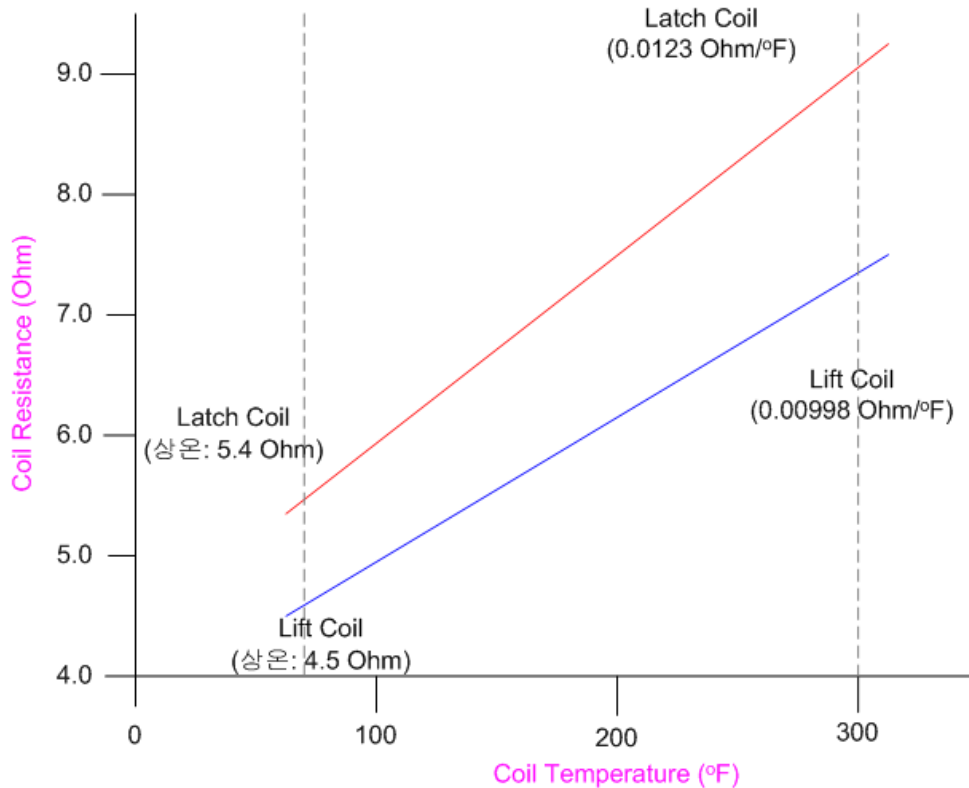


Unmodeled Dynamics
Unmodeled Disturbance

- ✓ Weight Variation
- ✓ Reactor Temperature/Pressure
- ✓ Mechanical Friction
- ✓ Magnetic Force etc...

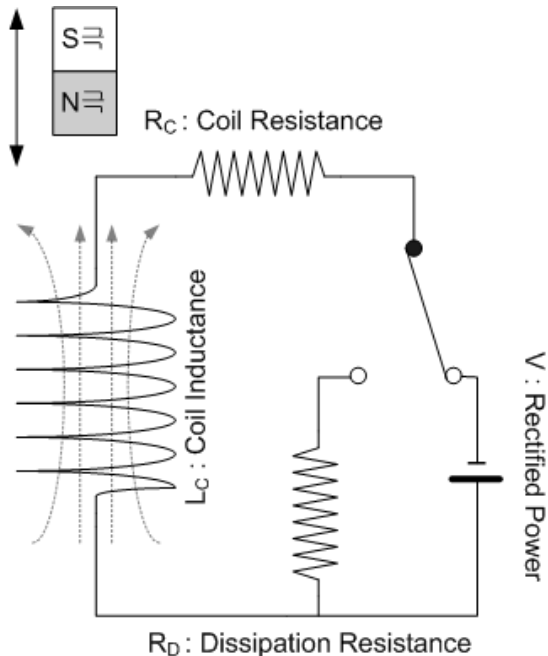
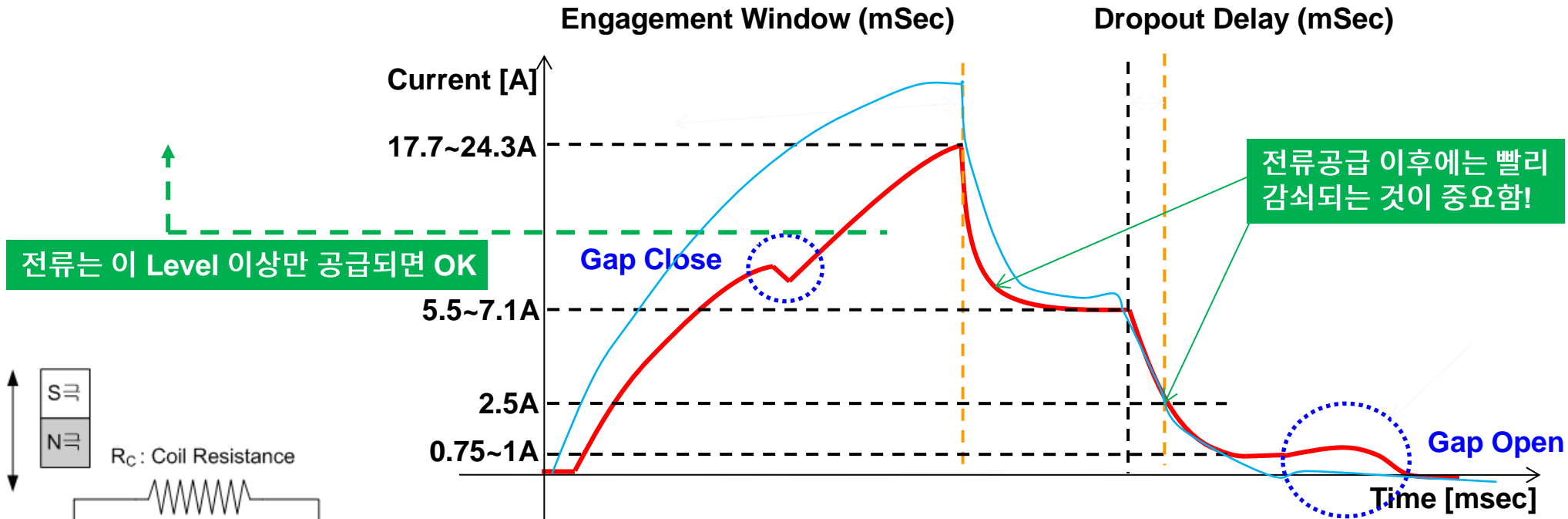
⇒ 제어봉무게 2배 차이 + 압력 변화

[참조] CEDM 비선형성 : Resistance 및 Inductance의 변화--Time varying



- Coil Temperature에 따른 Coil Resistance 변화**
- ✓ Lift Coil : 4.5~7.4 Ohm
 - ✓ Latch Coil : 5.4 ~ 9.1 Ohm
- Magnetic Flux 및 Latch 위치에 따른 Inductance 변화**
- ✓ Coil Assembly (130mH)
 - ✓ Motor Assembly (250mH)
 - ✓ Latch Motor Saturation (500mH 이상)

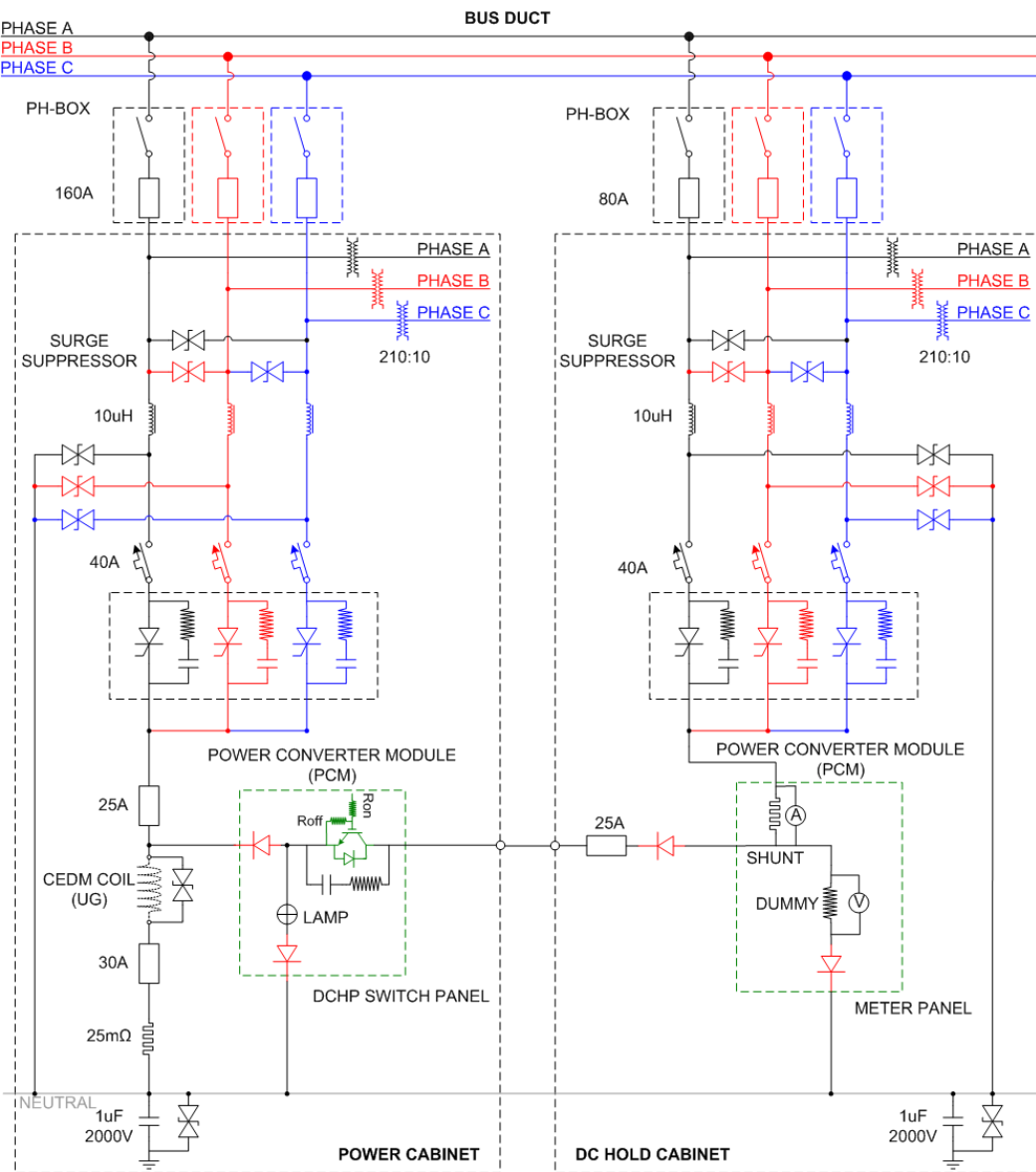
[참조] CEDM 비선형성 : 코일 전류 파형의 형태 (Typical)



‘렌츠의 법칙’에 의한 전류변화 <Glitch 발생>

- ✓ Gap Close: N극을 코일에 넣을 때
- ✓ Gap Open: N극을 코일에서 뺄 때

[참조] 제어봉 구동장치는 어떤 H/W를 통해서 제어되는가?



<전력변환회로>

(성능)

- 3상 전원 > 반파 정류 > DC 전원 (전류제어)
- Closed-loop Control

(안정성)

- 3상 전원 > 반파 정류 > DC 전원 (전압제어)
- Open-loop Control

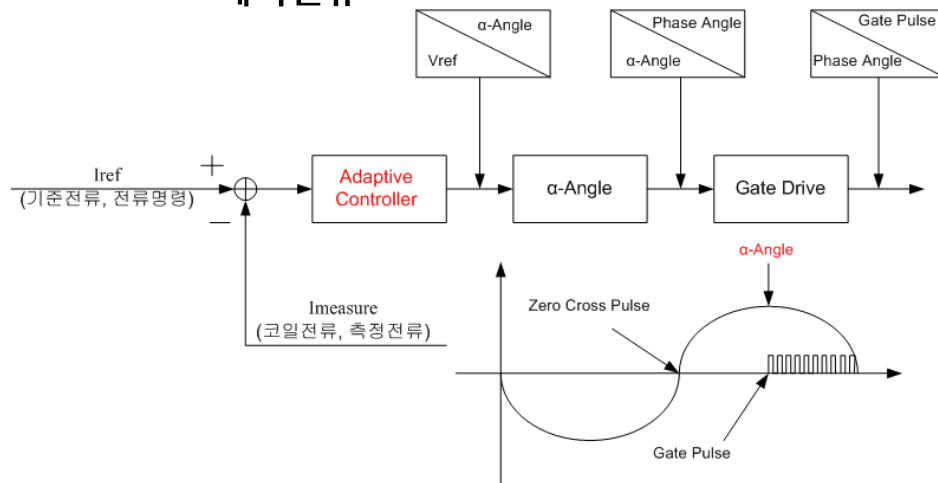
<전력함 제어기>

(입력)

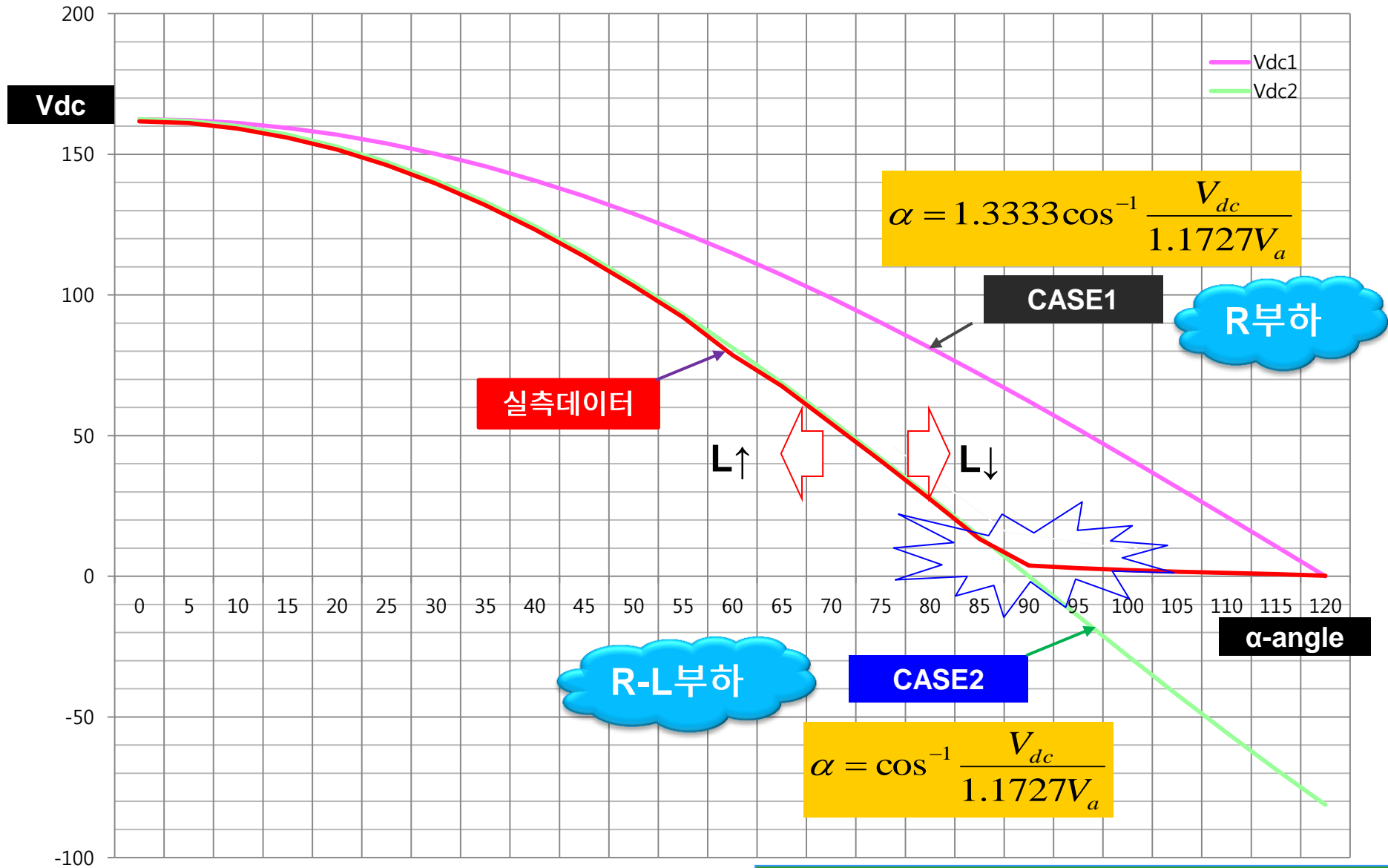
- 3상 전원 영점 검출
- 코일전류

(출력)

- 싸이리스터(SCR) 점호각 -비선형 관계형성
- 제어전류



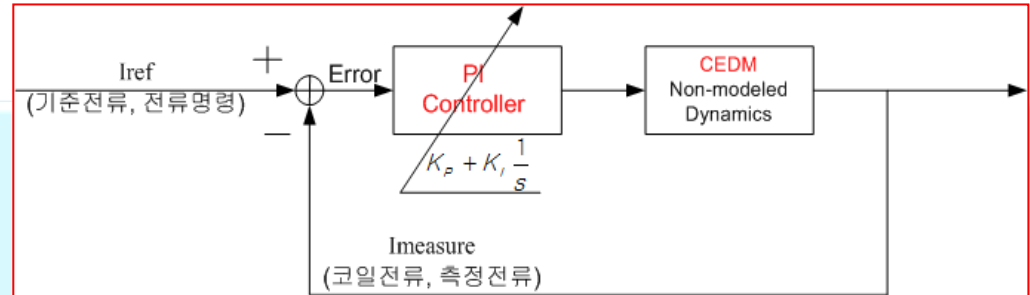
[참조] 위상각 vs. 출력전압의 비선형성?



[참조] **PID 제어기로 납품했더니... <제품 공급사의 위치에서의...>**

기존 PID 방식 제어기 한계?

- 경험이 풍부한 개발자 필요
- 경험에 의존한 **93개** 제어봉 Tuning 작업
- 93개 제어봉 적용 후 가장 적절한 제어이득 선정
- 시험조건/환경조건 변화에 따른 **Re-Tuning** 작업



1개에 10분 소요되어도 2일은 족히...

왜 Re-Tuning이 필요한가? 매 시험 공정마다 부하 및 시험 조건이 계속 변화한다면?

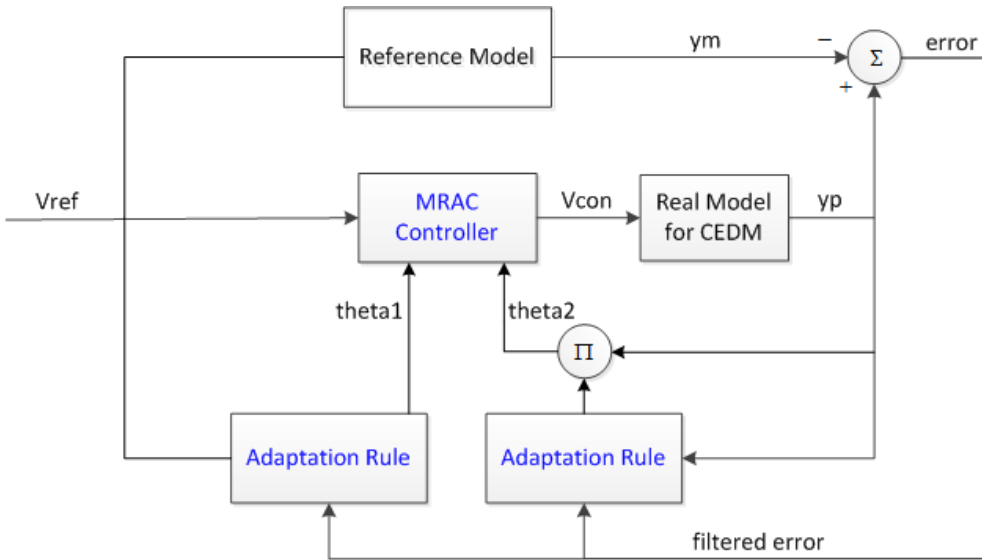
- FAT(공장시험): **R/L 부하** 사용 <FAT 시는 93개 제어봉 CEDM 구축 불가능>
- SAT(현장시험) CEDM <**상온조건**>
- Start-Up(기동시험): CEDM <Reactor Coolant System 온도반영: 코일온도 약 **150°C**까지 상승>

원전 계통 병입 직전 10시간 안에 가장 급하게 진행되는 업무인데, 이것이 지연된다면?

- 공급자 지체상금(**LD: Liquidated Damages**) 유발
- O/H 공사기간 **1일 지연** 시 **10억/일** 손실 유발
- **엄청난 경제적 손실**

경험이 많이 축적되었지만, **Tuning**만 안 해도 경제적 효과는 엄청난데...

[Control Algorithm(Structure)] Basic MRAC vs. Modified MRAC?

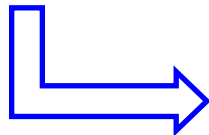


Basic MRAC Structure

Control Law
 $V_{con} = V_{ref} \times \theta_{1} - y_p \times \theta_{2}$

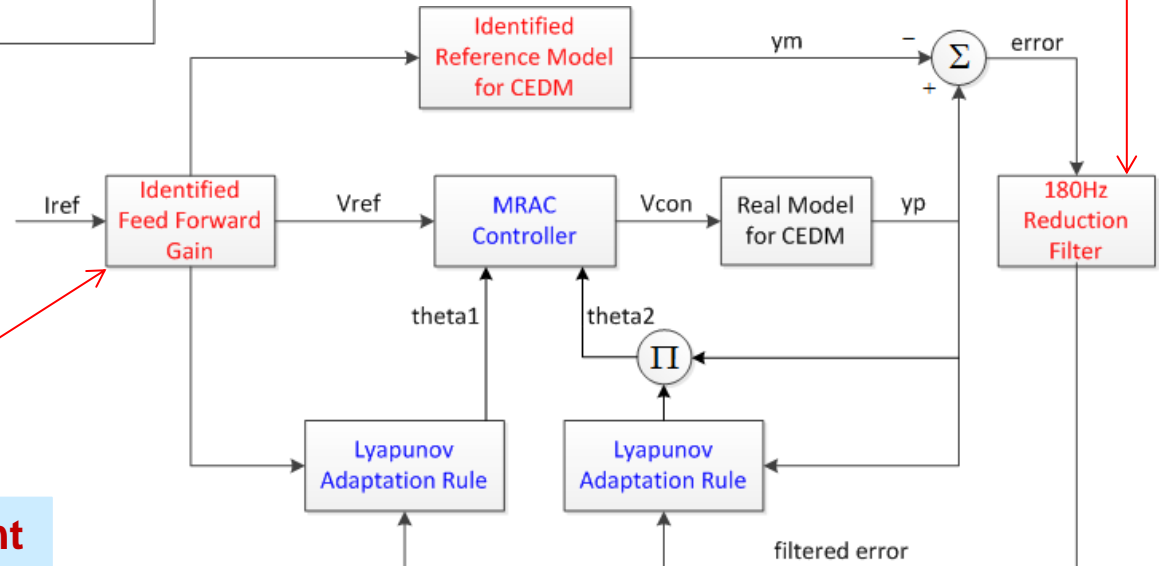
Lyapunov Adaptation Rule

Error Convergence Improvement



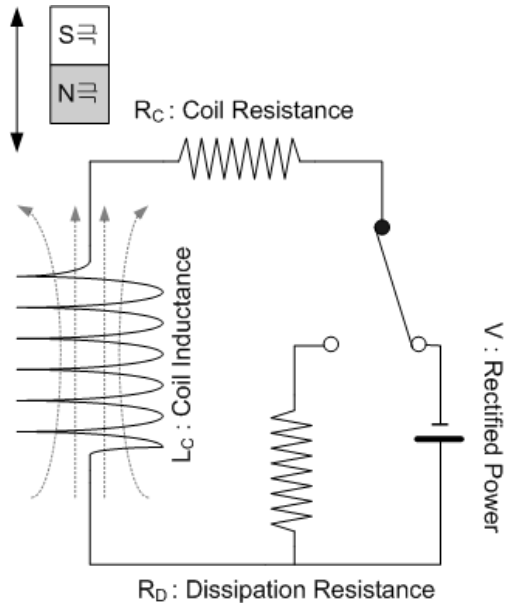
For better implementation

Transient Response Improvement



Modified MRAC Structure

[System ID for MRAC] 전기적 등가모델을 어떻게 얻을 수 있나?



By Kirchhoff Voltage Law

$$L_C \frac{di}{dt} + R_C i = v(t)$$

By Laplace Transform

$$\frac{I(s)}{V(s)} = \frac{1}{L_C s + R_C} = \frac{1/L_C}{s + R_C/L_C}$$

Known Model Structure

By Equivalent ID Model (1st Order System)

$$\frac{I_{exp}(s)}{V_{exp}(s)} \approx \frac{b}{s + a} \quad a \approx \frac{R_C}{L_C} \quad b \approx \frac{1}{L_C}$$

White-Box Model

Unmodeled Dynamics

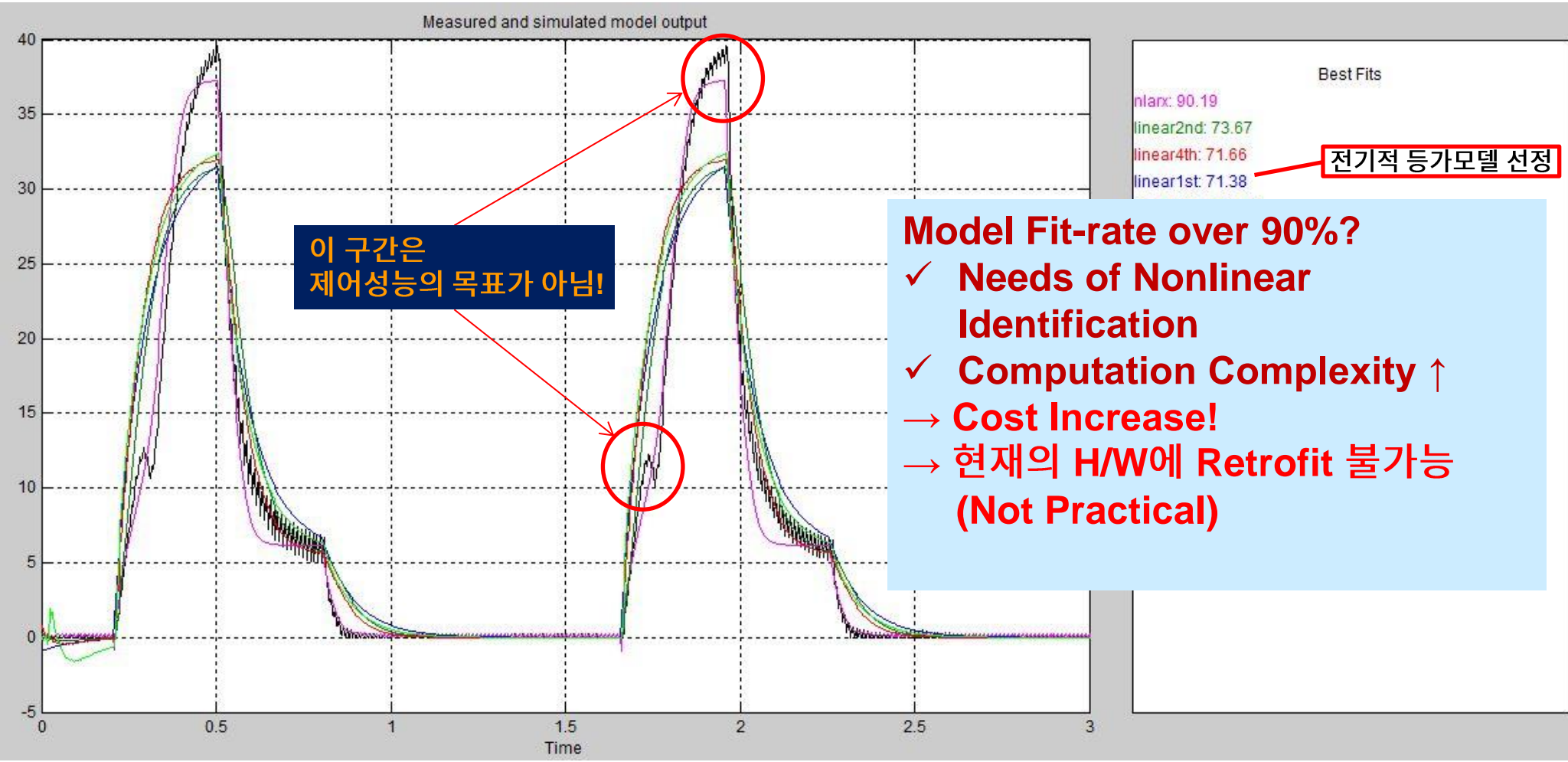
Then, Reference Model Dynamics?

$$\dot{y} + a_m y = b_m u$$

Unknown Model Parameter

Error는 '0'으로 보내야? Reduced Model이 적용가능?

[Identified Reference Model] 전기적 등가모델 결과는?



Convergence 및 Computational Complexity를 고려하여, Linear 1st Order Model 선정

[Stability Analysis & Proof] Control Law and Error Dynamics

$\dot{y}_m + a_m y_m = b_m r,$ *Reference Model : via System Identification*

$\dot{y}_p + a y_p = b u,$ *Assumption: Real Plant Model Dynamics*

제어기설계를 위해...

$e = y_p - y_m,$ *Definition: Error*

$u = r\theta_1 - y_p\theta_2,$ *Control Law: via MRAC Structure*

$\dot{e} = -a_m e - (b\theta_2 + a - a_m)y_p + (b\theta_1 - b_m)r,$ *Error Dynamics → Zero*

Control Purpose?
Is it Simple?

Stability
Error Convergence

~~*Parameter Estimation*
Tracking~~

$\theta_1 = \frac{b_m}{b}, \theta_2 = \frac{a_m - a}{b},$ *Perfect Parameter Estimation Possible? Don't Care*
=> Future Work! <제어/감시/진단을 동시 수행>

[Stability Analysis & Proof] Lyapunov Adaptation Rule

Lyapunov Function Candidate:

Positive Definite

$$V = \frac{1}{2} \gamma e^2 + \frac{1}{2b} (b\theta_1 - b_m)^2 + \frac{1}{2b} (b\theta_2 + a - a_m)^2, \gamma = \text{adaptation gain}$$

$$\dot{V} = \gamma e \dot{e} + \dot{\theta}_1 (b\theta_1 - b_m) + \dot{\theta}_2 (b\theta_2 + a - a_m)$$

Negative Semi-Definite

$$= -\gamma a_m e^2 + (\gamma e r + \dot{\theta}_1) (b\theta_1 - b_m) + (\dot{\theta}_2 - \gamma e y_p) (b\theta_2 + a - a_m) \leq 0$$

$$\dot{\theta}_1 = -\gamma e r$$

$$\dot{\theta}_2 = \gamma e y_p$$

Gamma Tuning?

- 1) $\gamma \rightarrow 0$ Convergence
- 2) $\gamma \rightarrow 1$ Tracking

How Implementation?

- 1) Error \rightarrow Filtered Error
- 2) Reference Input \rightarrow Feedforward Gain

Lyapunov Function Candidate에 의한 Adaptation Rule은

Closed-Loop Stability 및 *Error Convergence*는 보장됨!

단, 보다 우수한 성능을 위한 Lyapunov Function Candidate의 선정은 향후 과제로 한다.

[참조] Lyapunov Stability Theorem

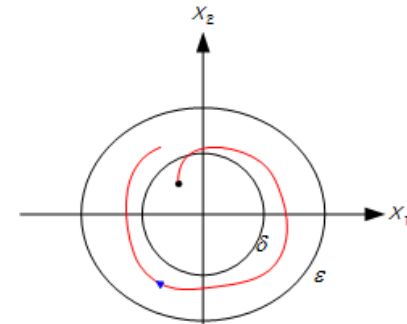
$V(x)$: Lyapunov Function Candidate

- 1. $V(x) > 0, x > 0$: Positive Definite
- 2. $V(0) = 0$

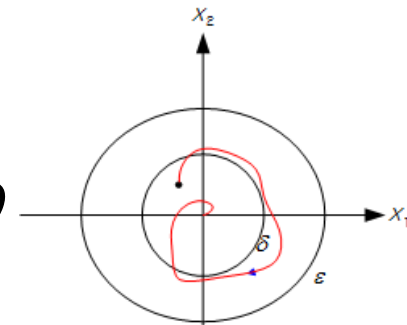
Stability Check!

- 1. $\dot{V}(x) \leq 0$: Negative Semi – definite
 - ➔ Stable at the origin (equilibrium point)
- 2. $\dot{V}(x) < 0$: Negative Definite
 - ➔ Asymptotically Stable
- 3. $\|x\| \rightarrow \infty \Rightarrow V(x) \rightarrow \infty$
 - ➔ Globally Asymptotically Stable

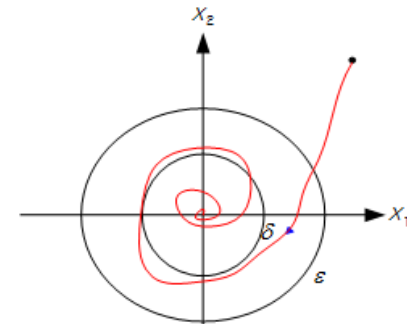
Lyapunov Stability Theorem은 Adaptive Controller 설계에 매우 유용함



Stable at the origin



Asymptotically Stable



Globally Asymptotically Stable

[**MATLAB® Simulation**] (**PID vs. MRAC**) Simulink® File

MRAC 제어기

Feed-forward Gain

Reference Model

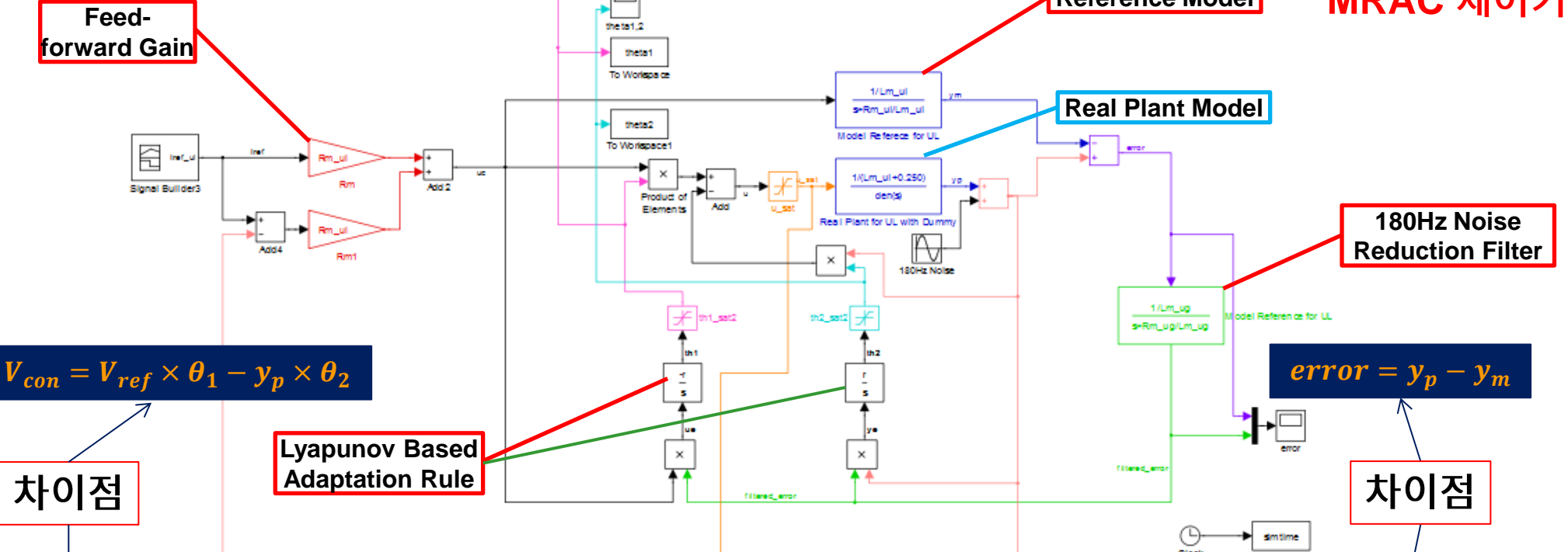
Real Plant Model

180Hz Noise Reduction Filter

$error = y_p - y_m$

Lyapunov Based Adaptation Rule

차이점



$V_{con} = V_{ref} \times \theta_1 - y_p \times \theta_2$

차이점

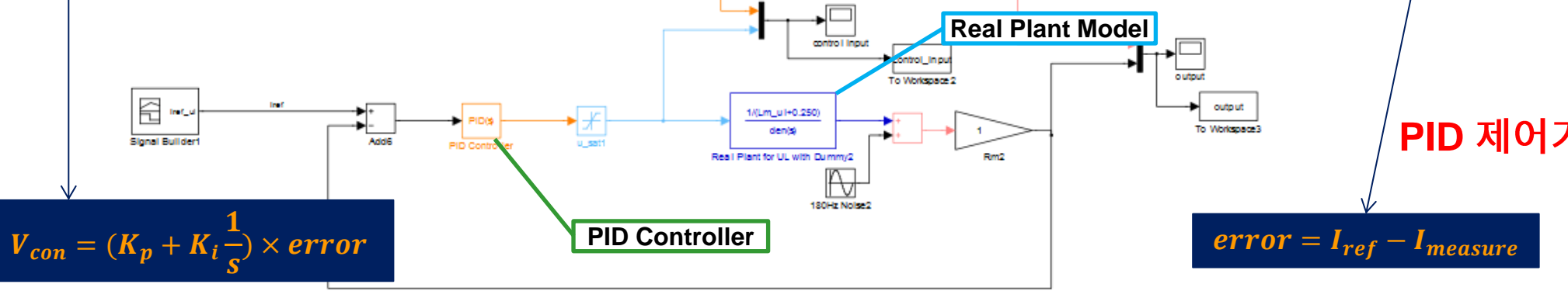
$V_{con} = (K_p + K_i \frac{1}{s}) \times error$

PID Controller

Real Plant Model

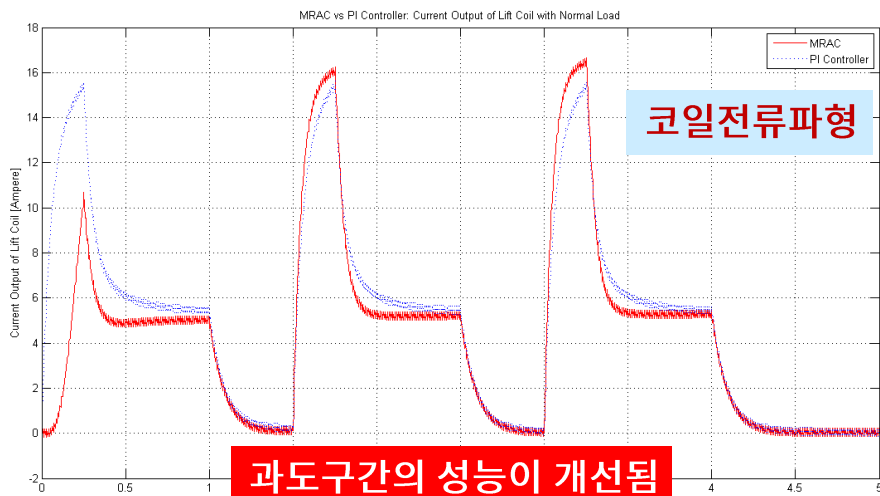
PID 제어기

$error = I_{ref} - I_{measure}$



[MATLAB® Simulation] 결과 비교 (PID vs. MRAC)

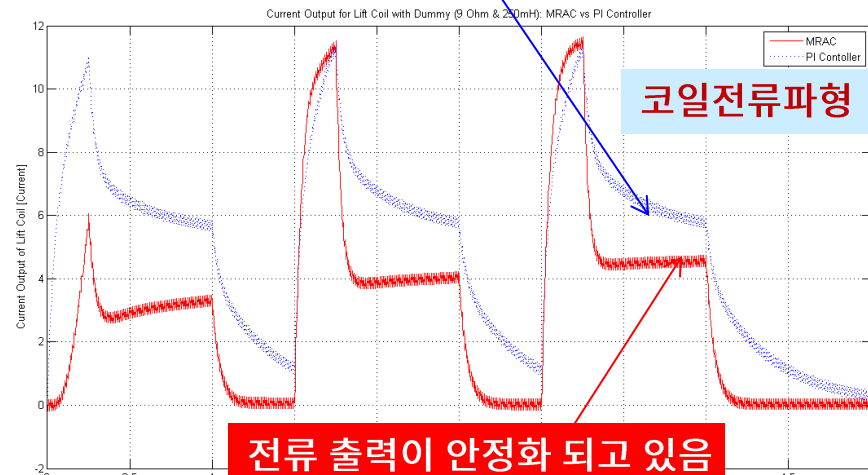
전류출력이 안정화 되지 못함



코일전류파형

과도구간의 성능이 개선됨

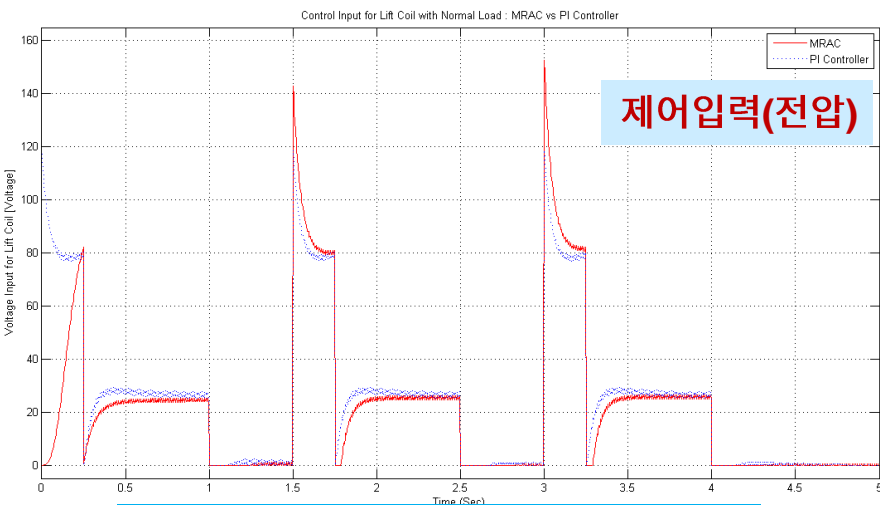
정상부하



코일전류파형

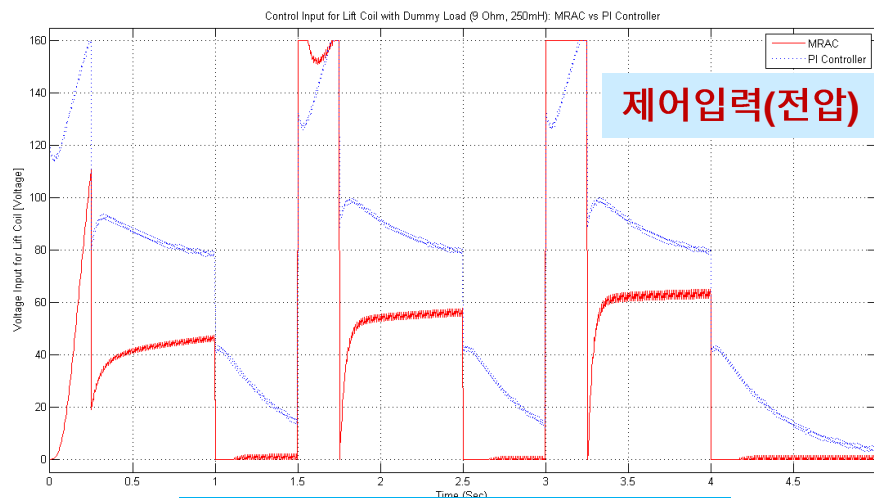
전류 출력이 안정화 되고 있음

비정상부하 (9Ω, 250mH추가)



제어입력(전압)

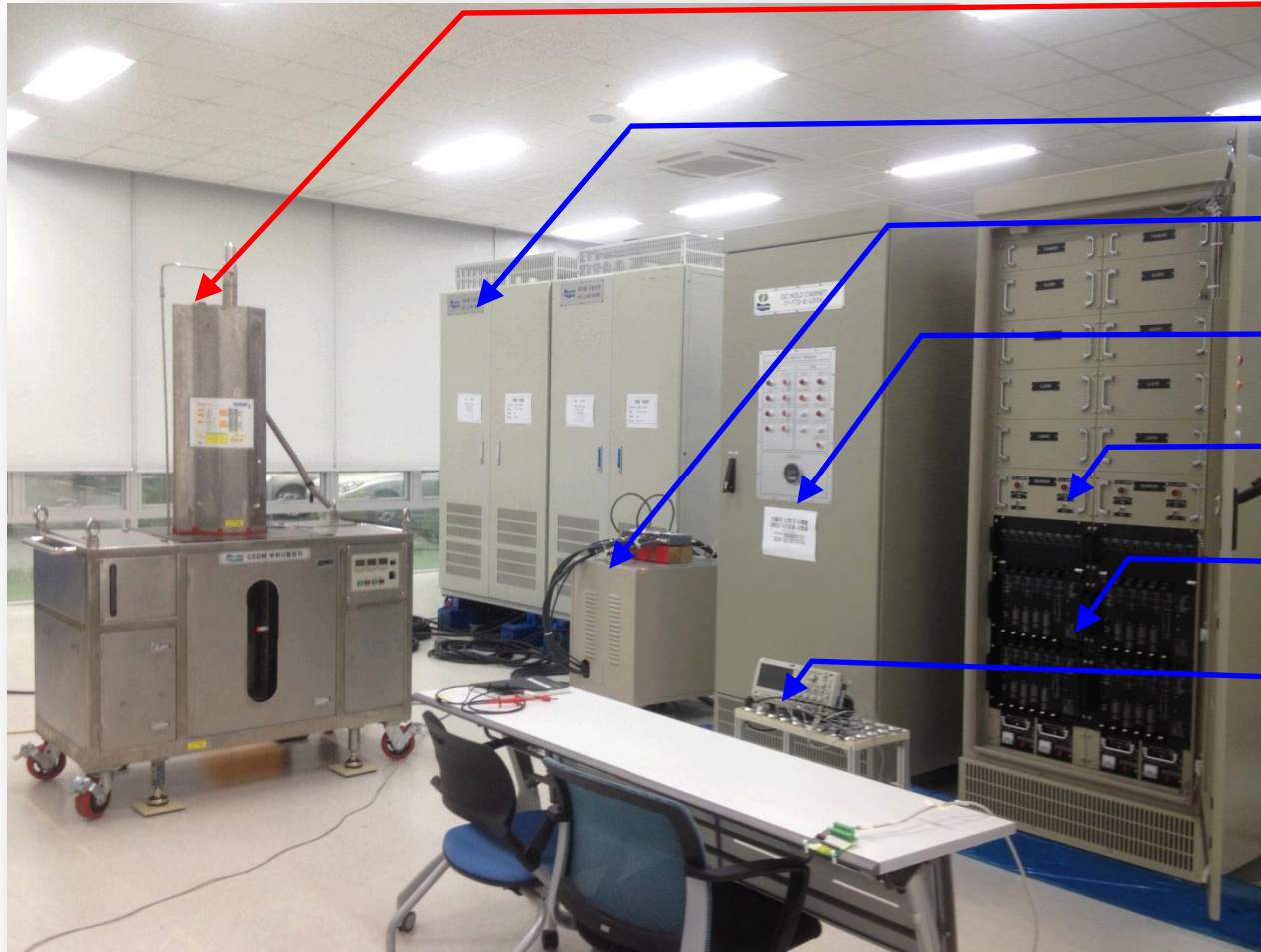
제어입력의 큰 차이를 보이지 않음



제어입력(전압)

제어입력의 큰 차이가 발생함

[Experimental Result] Test Bed 구축 <CEDM Mock-up 사용>



CEDM Mock-up

R/L Load Bank

3 Phase Power

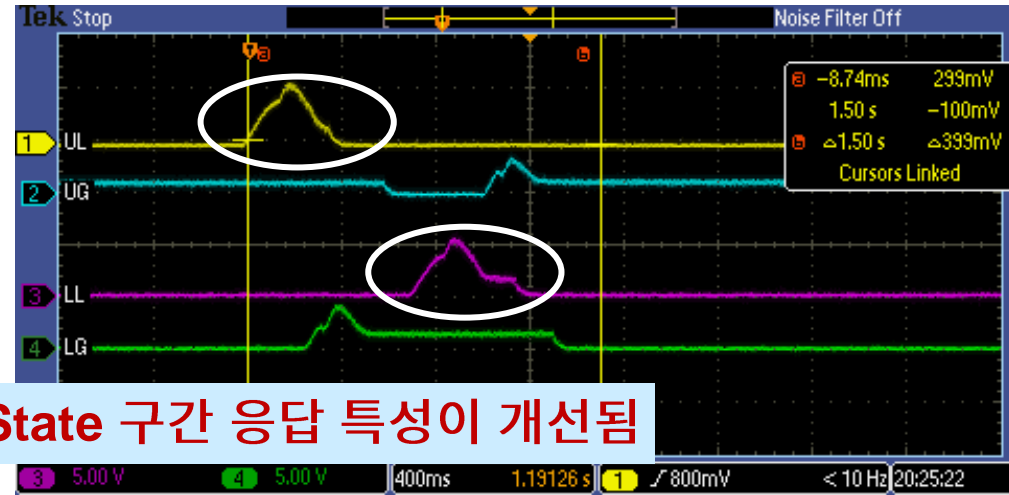
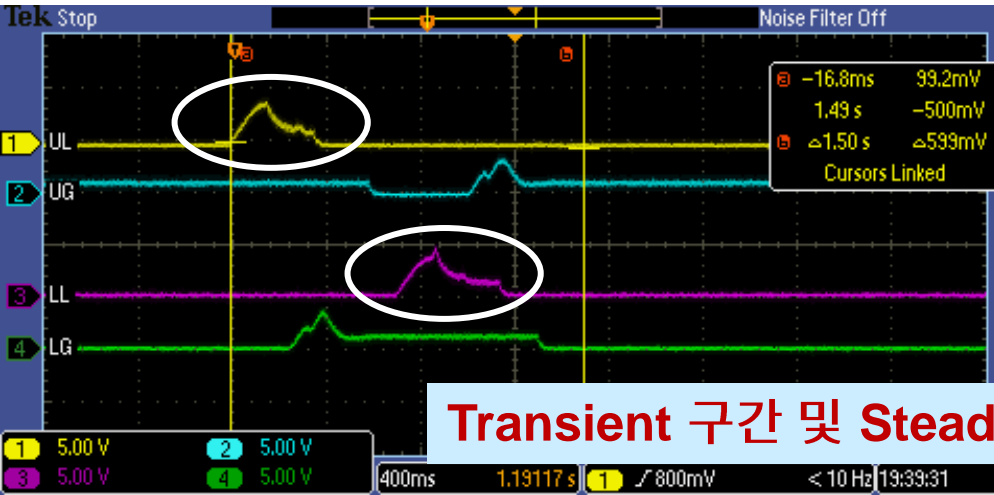
DC Hold Cabinet

Power Cabinet

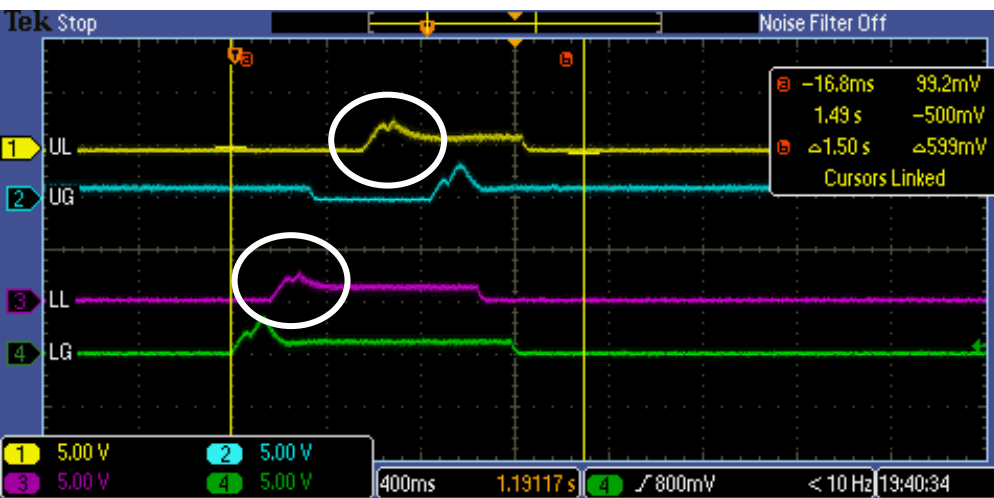
Power Control Unit

Oscilloscope

[Experimental Result] (PID vs. MRAC): 정상 부하

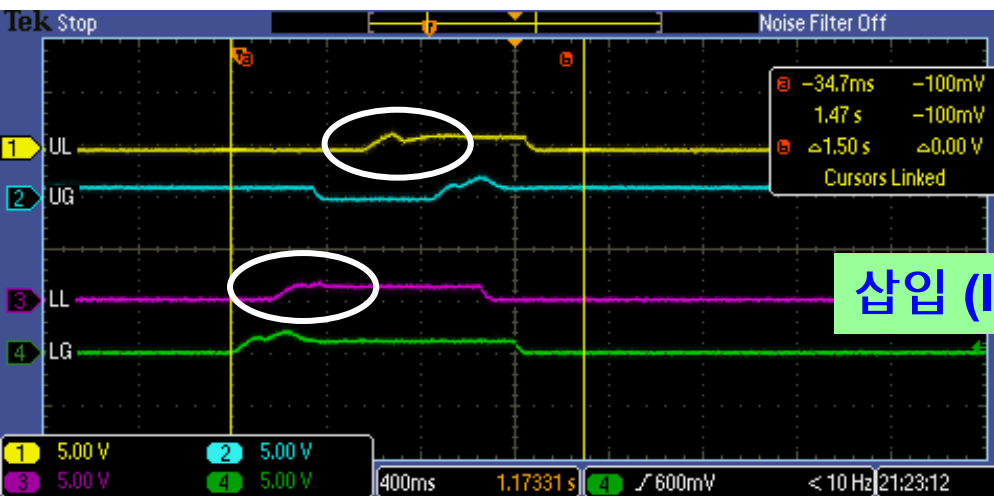
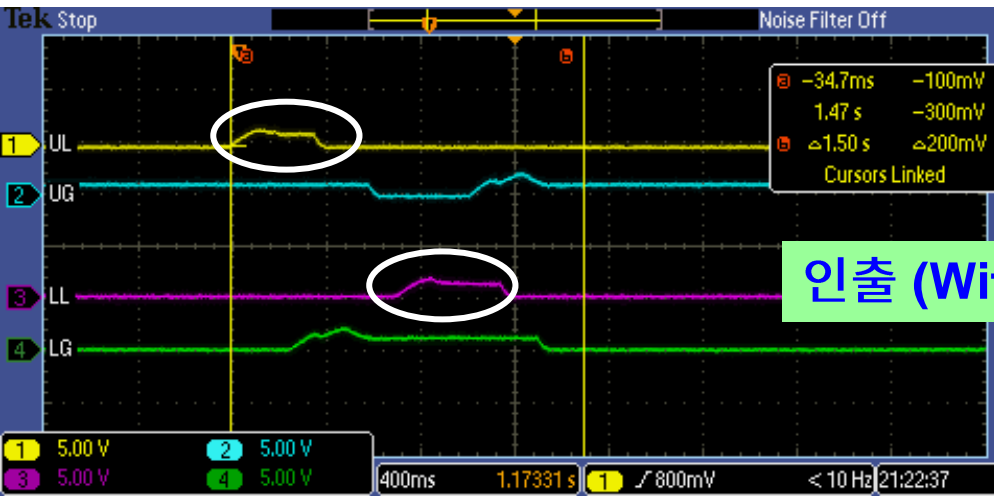


Transient 구간 및 Steady-State 구간 응답 특성이 개선됨



Lift Coil의 인가전류는 PID 및 MRAC 충분히 공급하여 인출/삽입 이 정상적으로 이루어짐

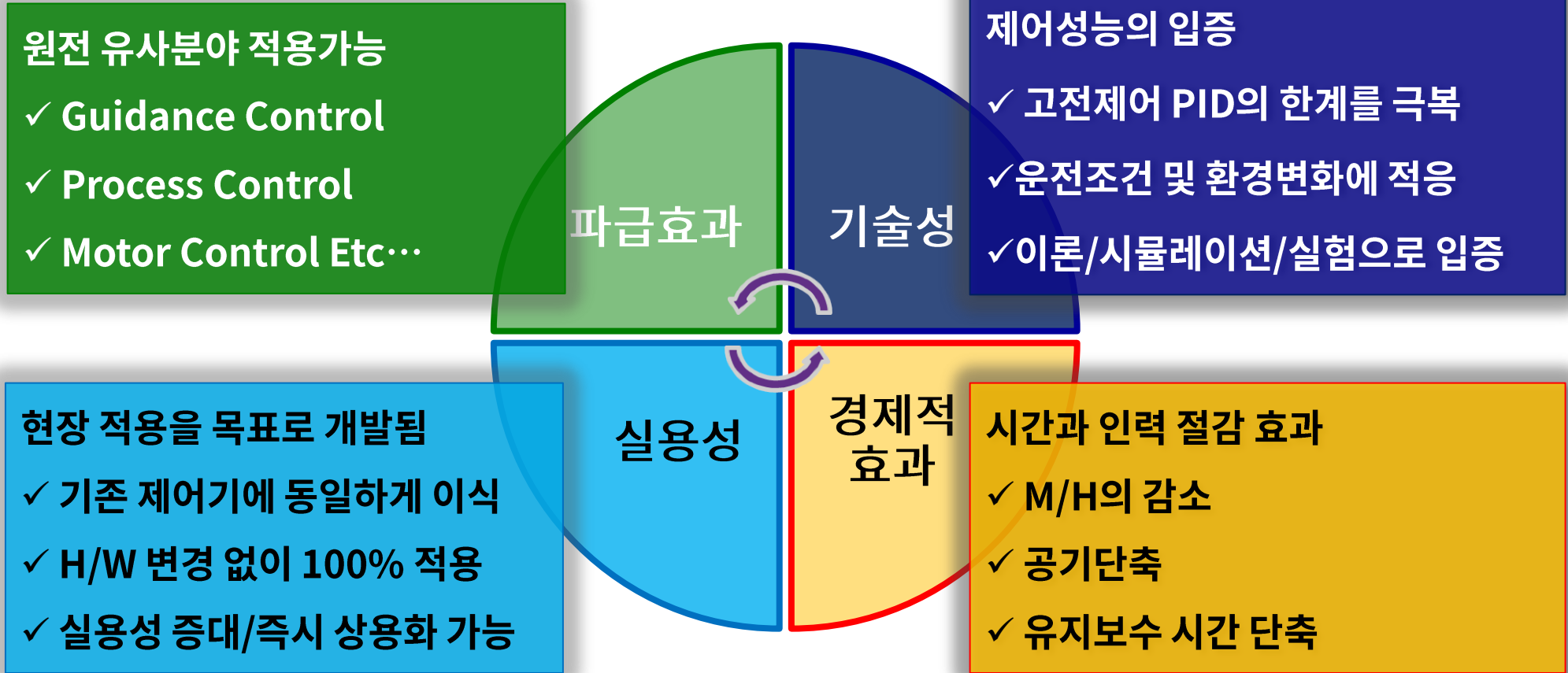
[Experimental Result] (PID vs. MRAC): 비정상 부하 (9Ω, 250mH추가)



Lift Coil의 인가전류가 부족하여 인출/삽입 실패

Lift Coil의 인가전류가 충분하여 인출/삽입 가능

[Project Contribution & Conclusion] 기술성과 실용성을 바탕으로 신규 건설원전에 적용을 목표로 함



[참조] 소프트웨어 구현 결과 Sample

MATLAB®

```

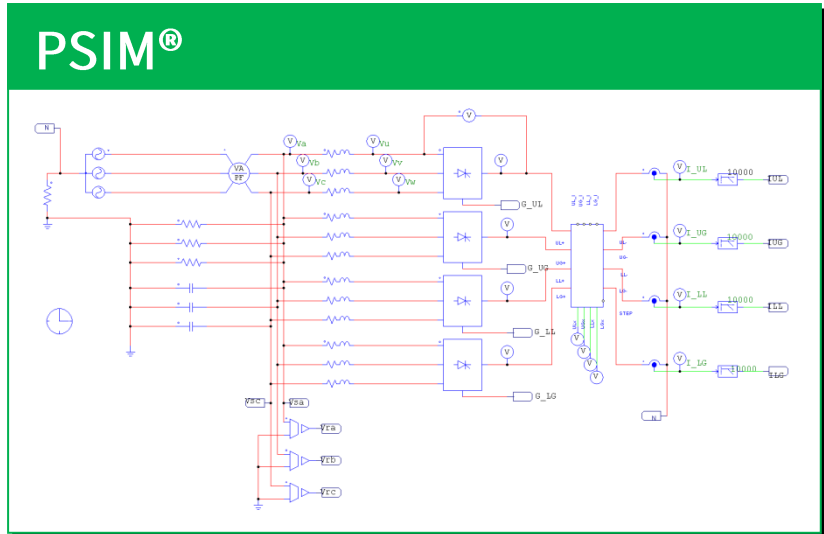
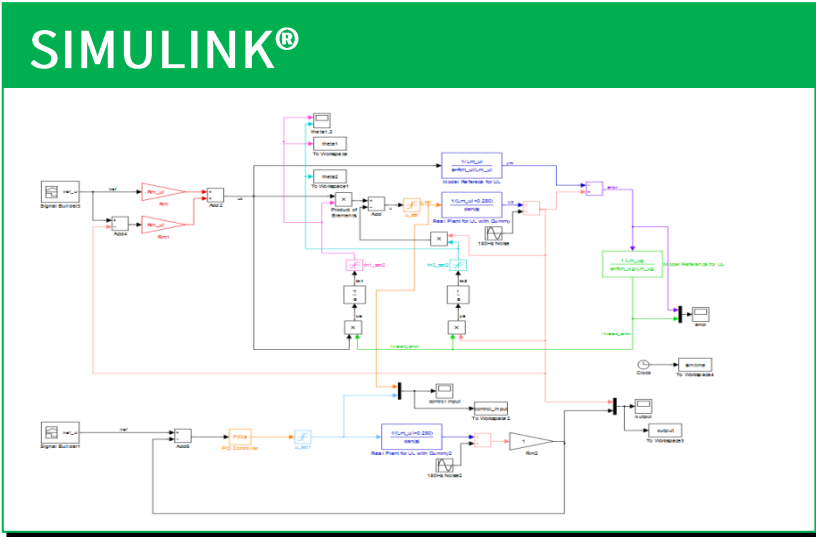
%time=idup111(1,:);           % time
u=idup10(2,:);               % input vector : 10001x1
y=idup10(3,:);               % output vector : 10001x1

N=length(y);
t=[0: 0.001: N/1000-0.001];

figure(1)
subplot(311);
plot(t, u); grid on;
subplot(312);
plot(t, y); grid on;

P=10000*eye(5);
theta=zeros(5,N);
lambda=1.00001;             %forgetting rate

for k=3:N,
    ph=[-y(k-1) -y(k-2) u(k) u(k-1) u(k-2)]';
    P=1/lambda+(P-P*ph*ph'+P/(lambda+ph'*P*ph));
    theta(:,k)=theta(:,k-1)+P*ph*(y(k)-ph'*theta(:,k-1));
end
    
```



Code Composer® C-code

```

void PC_Regulator_UL(int *reset){
    int i=0; // UL Coil Current Regulator
    float Vr=0.0; // for loop
    float Ucr=0.0; // voltage
    float tVr=0.0; // voltage
    float alpha=0.0; // voltage temp
    float angle=0.0; // alpha
    float zero=1.0; // algle
    float deg2rad=3.141592/180.0; // zero

    for(i=0;i<du_Motor;i++){
        if(reset[i]==1) zero=0.0; // V1,V2,V3,V4
        else if(reset[i]==0)zero=1.0; // check reset flag
        // else set

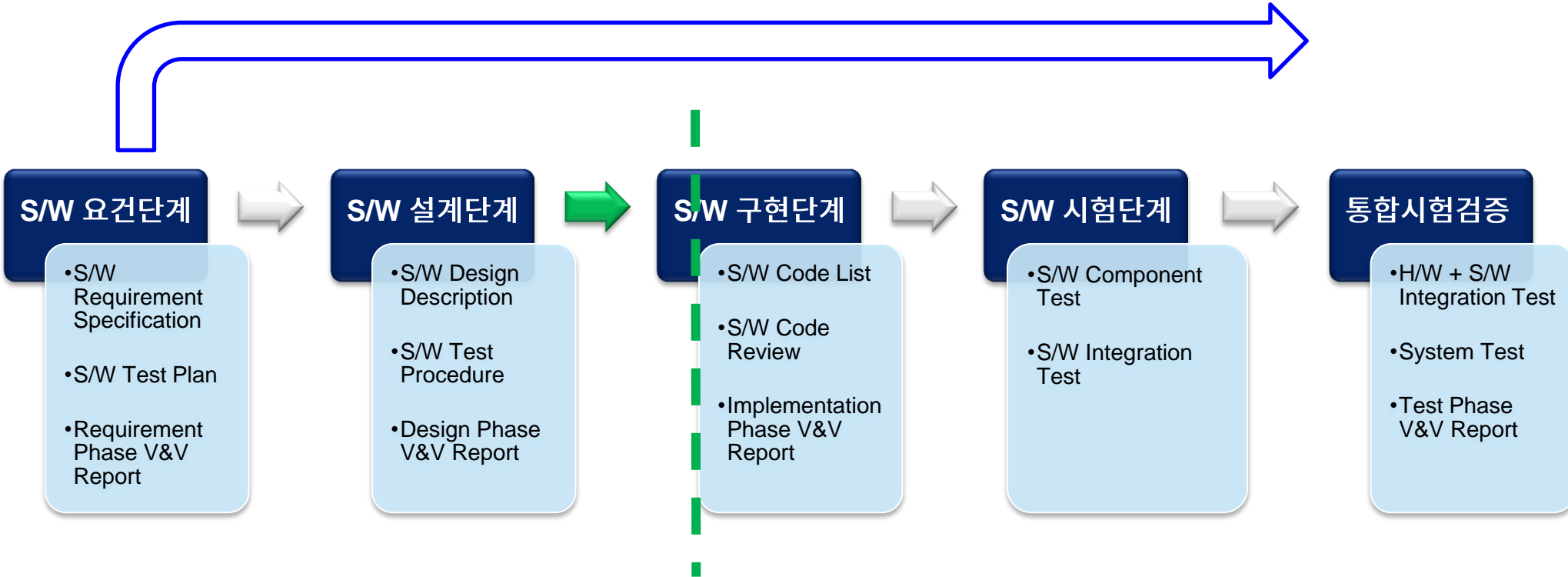
        if(du_MS_my==1){ // if Master
            Vr=P_Reg_UL(i, zero)+f_SP_R_UL+f_l_UL_r[i]; // get P control value
            Ucr=MRAC_UL(Vr, i); // get MRAC compensation
        }
        // else (Slave)
        // updated by 485com
    }

    if(Ucr>165.0) Ucr=165.0; // Max voltage 165 set
    else if(Ucr<0.0) Ucr=0.0; // Min voltage 0 set

    angle=deg2rad*VoltToAng(Ucr);

    ok_UL=SCGD_UL_Set_Alpha(i, angle); // Set Gate Angle
}
    
```

[향후 업무 계획] 신규원전으로부터 단계적으로 설비 적용 <S/W V&V>



신고리 5,6호기 현재 개발단계

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