

The Multiphysics Analysis of the Perovskite Solar Cell and System

열 일하는 줄
Heat Work Joule

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Team 소개

김민우

Semiconductor
Module, Cell
Analysis

COMSOL

PV Solar System

이상훈

MPPT Boost
Controller

Simulink

1. Perovskite Module : Electrical Conductor Model

Perovskite Layer 내부 전위 분포 계산 목적
Semiconductor Module 부재

지배 방정식: 전하 보존식과 옴의 법칙을 사용하여 PDE로 정의

$$\nabla \cdot \mathbf{J} = Q_{gen}, \quad \mathbf{J} = -\sigma \nabla V$$

Weak Form: Test Function을 곱하고 적분을 통해 PDE를 FEM 형식으로 전환

$$\int_{\Omega} (\sigma \nabla V \cdot \nabla \tilde{V}) d\Omega = \int_{\Omega} Q_{gen} \tilde{V} d\Omega$$

COMSOL 입력 수식:

$$-\sigma * (Vx * test(Vx) + Vy * test(Vy) + Vz * test(Vz)) + Q_gen * test(V)$$

1. Perovskite Module : Electrical Conductor Model

Single Diode Model Equation을 사용

$$J(V) = J_{sc} - J_0 \left(\exp \left(\frac{qV_{app}}{nkT_{avg}} \right) - 1 \right)$$

T_{avg} : 3D 열해석으로 얻은 Perovskite 평균온도[K]

q : 전자 전하

k : 볼츠만 상수

n : 이상 계수

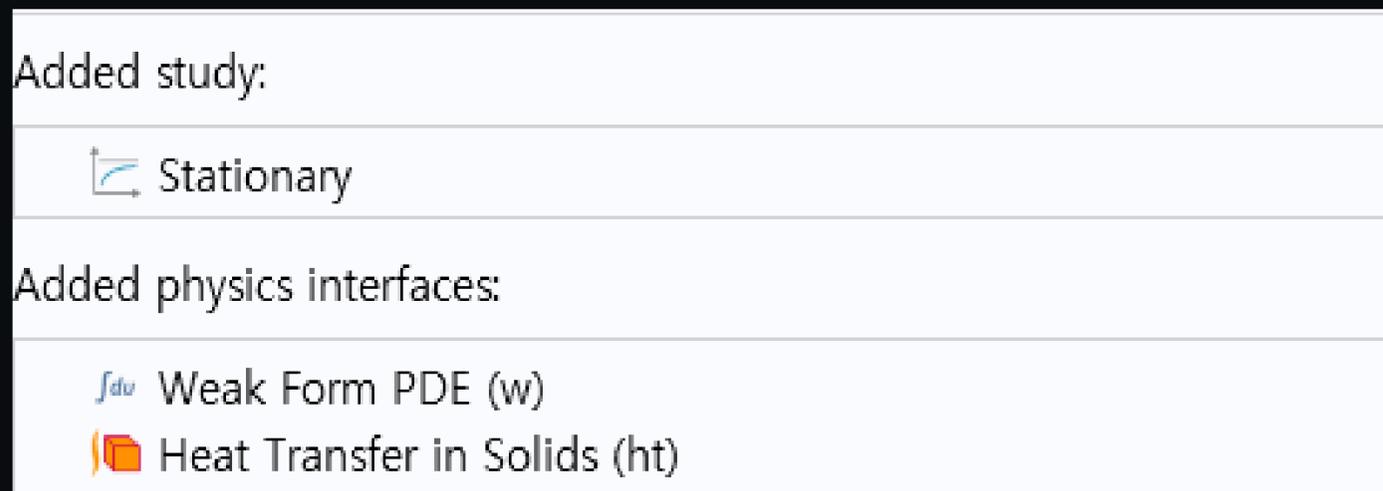
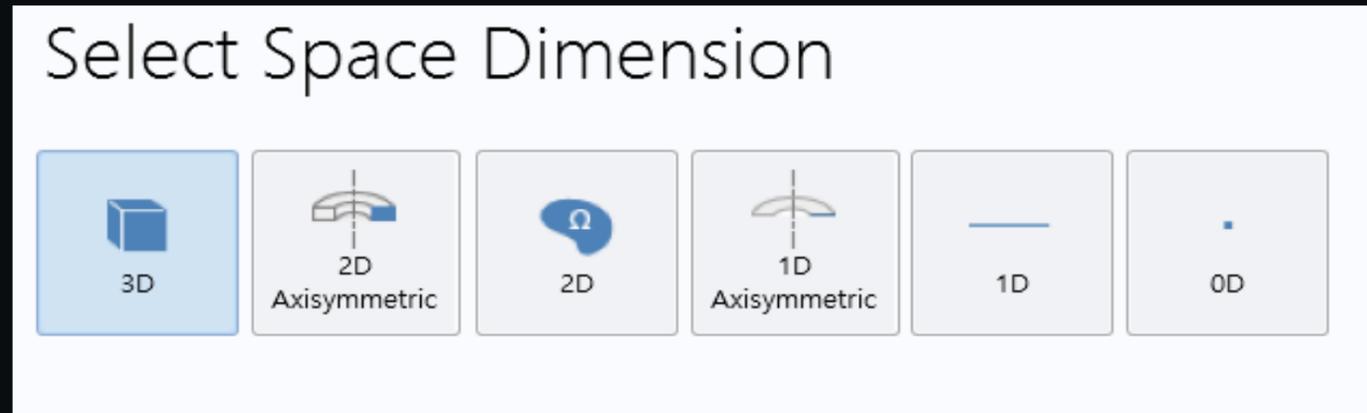
V_{app} : 인가전압[V]

J_0 : 포화전류밀도[A/m²]

J_{sc} : 태양광으로 만든 전류[A/m²]



COMSOL Settings



<Study>

3D – Weak Form PDE (w), Heat Transfer in solids – Stationary

(Semiconductor Module 부재로 인해 Weak Form으로 구현)

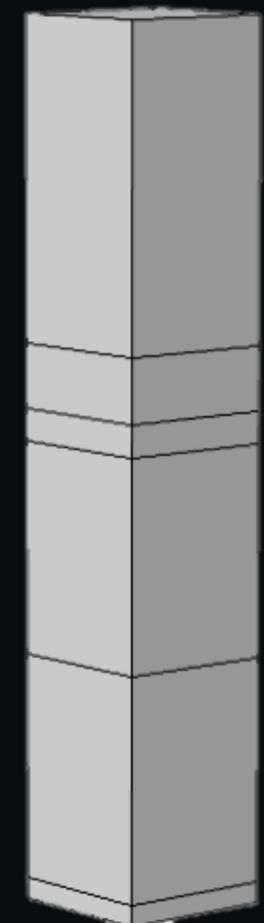
Start

COMSOL Settings

TABLE I
VALUES OF SELECTED SEMICONDUCTOR PARAMETERS AND ALL THE THERMAL PARAMETERS

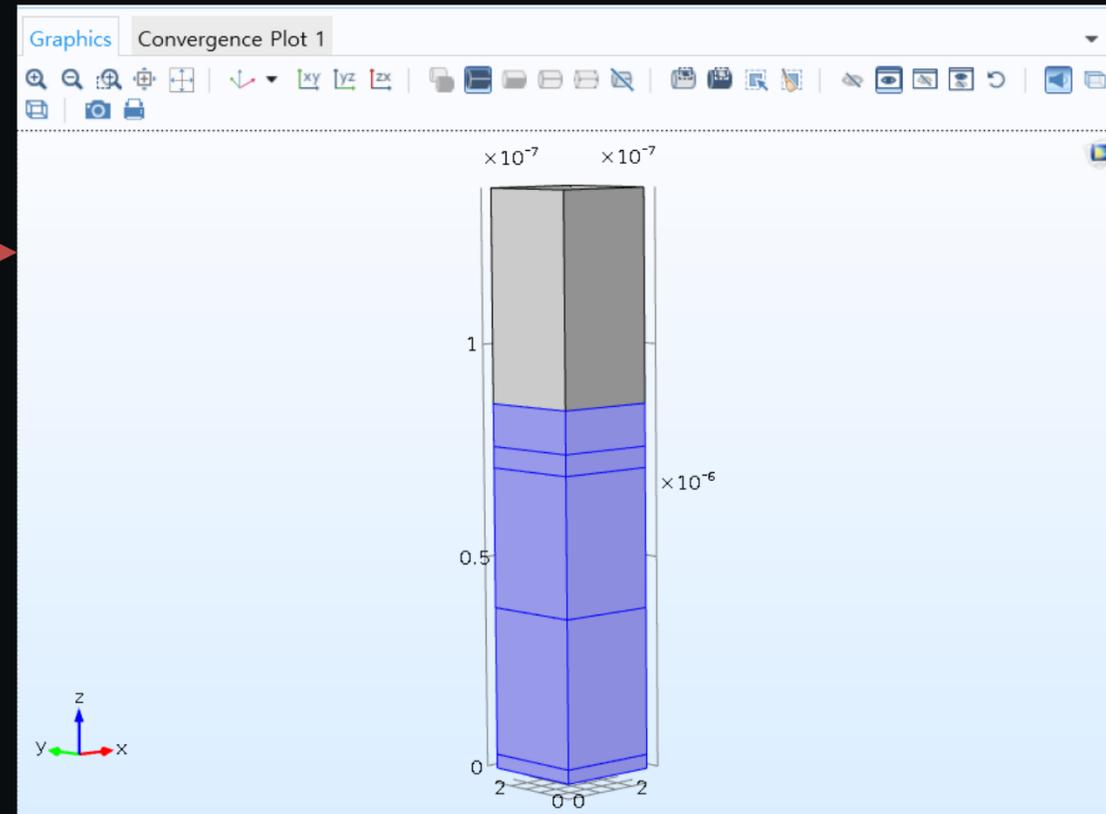
| | FTO | TiO2 | Perovskite | Spiro-MeOTAD | Au contact |
|-----------------------------|--------------------|--------------------|--------------------|--------------------|-------------------|
| N_A (cm ³) | ... | ... | 3×10^{15} | 2×10^{18} | ... |
| N_D (cm ³) | 2×10^{19} | 5×10^{18} | ... | ... | ... |
| K [W/m.K] | 31 | 4.8 | 0.5 | 0.49 | 318 |
| ρ [kg/m ³] | 5560 | 3900 | 4000 | 4128 | 19300 |
| C_p [J/kg.K] | 343 | 683 | 258 | 262 | 128 |
| h [W/(m ² K)] | 3.1×10^8 | 9.6×10^7 | 1.5×10^6 | 1.4×10^6 | 9.6×10^9 |

| Material | Height [nm] |
|---------------------|-------------|
| Air | 500 |
| FTO | 100 |
| TiO2 | 50 |
| Perovskite | 330 |
| Spiro-MeOTAD | 350 |
| Au | 33 |



COMSOL Settings

- Weak Form PDE (w)
 - Weak Form PDE 1
 - Zero Flux 1
 - Initial Values 1
 - Dirichlet Boundary Condition 1
 - Dirichlet Boundary Condition 2
 - Weak Contribution 1

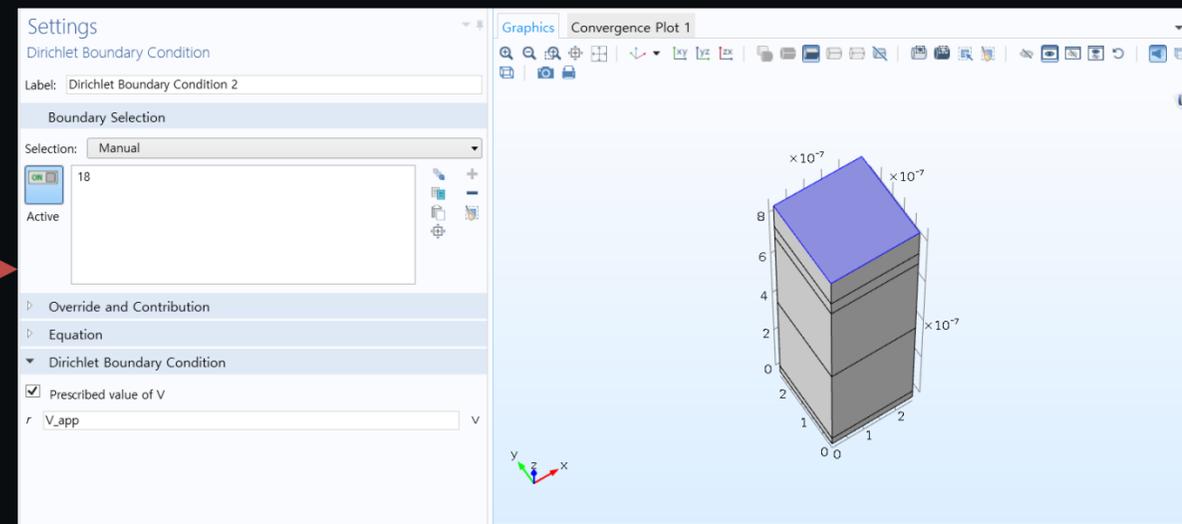
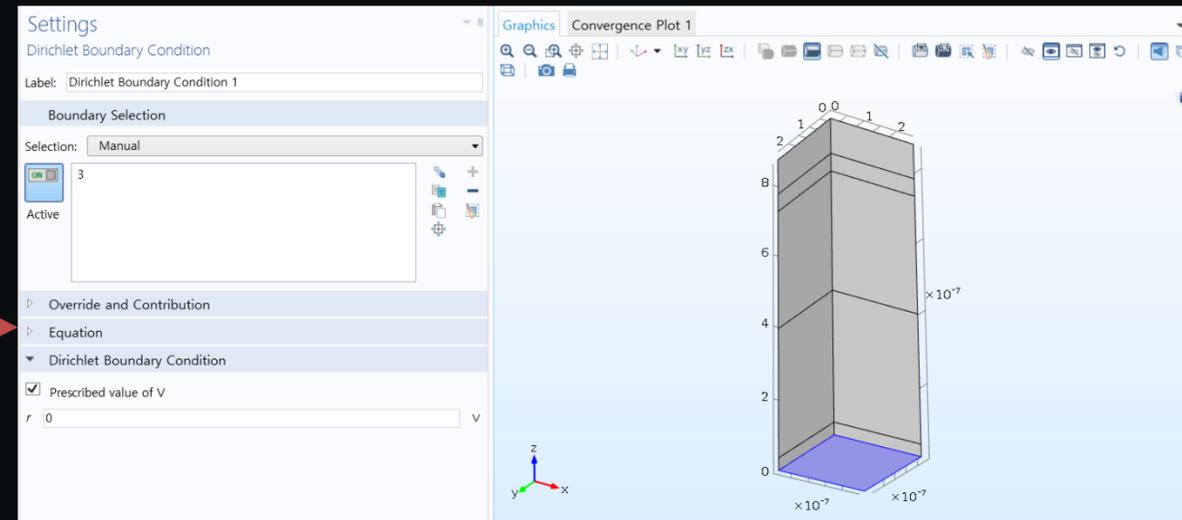


weak $-\text{sigma} * (\text{Vx} * \text{test}(\text{Vx}) + \text{Vy} * \text{test}(\text{Vy}) + \text{Vz} * \text{test}(\text{Vz}))$

Weak Form

COMSOL Settings

- Weak Form PDE (w)
 - Weak Form PDE 1
 - Zero Flux 1
 - Initial Values 1
 - Dirichlet Boundary Condition 1
 - Dirichlet Boundary Condition 2
 - Weak Contribution 1



Weak Form

COMSOL Settings

- $\int_{\Omega} w$ Weak Form PDE (w)
- Weak Form PDE 1
- Zero Flux 1
- Initial Values 1
- Dirichlet Boundary Condition 1
- Dirichlet Boundary Condition 2
- Weak Contribution 1**

Settings

Weak Contribution

Label: Weak Contribution 1

Domain Selection

Selection: Manual

3

Active

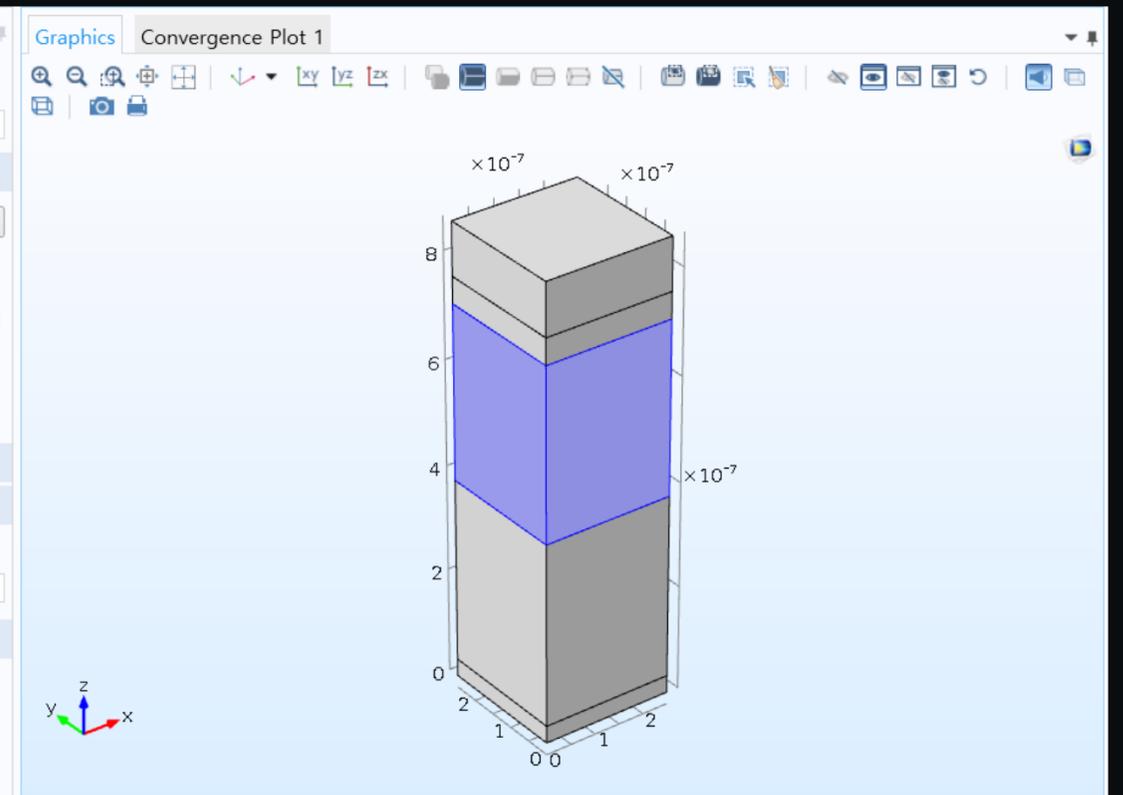
Override and Contribution

Weak Contribution

Weak expression:

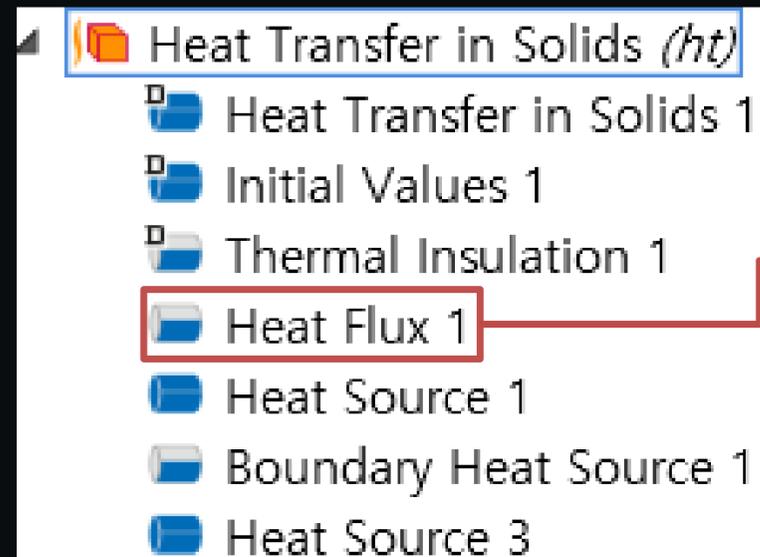
$Q_{gen} * test(V)$

Quadrature Settings



Weak Form

COMSOL Settings



Settings
Heat Flux

Label: Heat Flux 1

Boundary Selection

Selection: Manual

Active

19

Override and Contribution

Equation

Heat Flux

General inward heat flux

Convective heat flux

$q_0 = h \cdot (T_{\text{ext}} - T)$

Heat transfer coefficient:

h 10 w/(m²·K)

External temperature:

T_{ext} 293.15[K] K

Graphics Convergence Plot 1

×10⁻⁷ ×10⁻⁷

×10⁻⁶

1

0.5

0

2 2 2

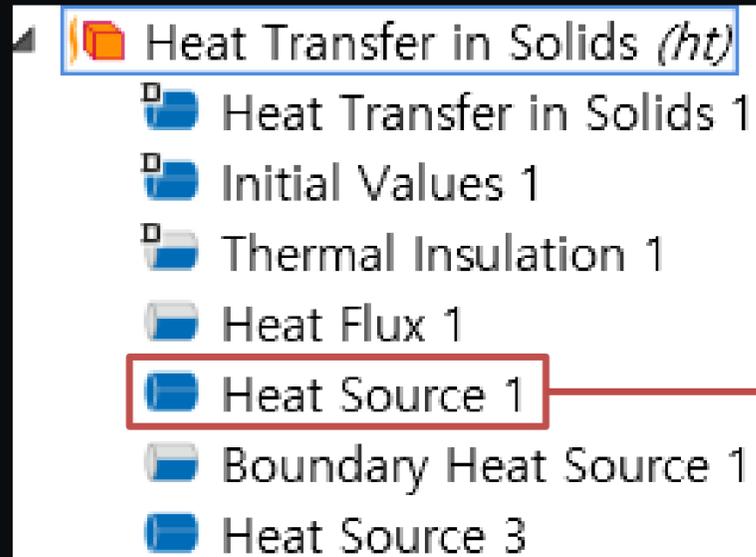
0 0

z

y x

Heat Transfer in Solids

COMSOL Settings



Settings
Heat Source

Label: Heat Source 1

Domain Selection

Selection: Manual

3
Active

Override and Contribution

Equation

Heat Source

General source

Q_0 User defined

157/330e-9 W/m³

Linear source
 $Q_0 = q_s \cdot T$

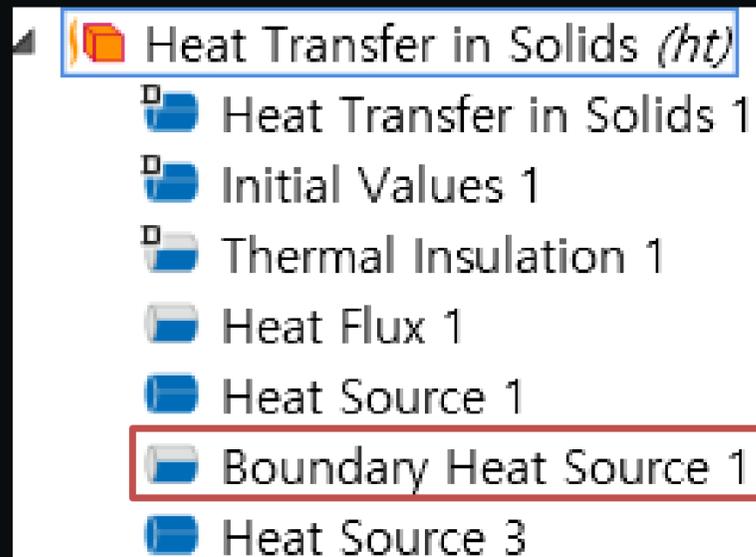
Overall heat transfer rate

Graphics Convergence Plot 1

3D plot showing convergence. The vertical axis ranges from 0 to 1. The horizontal axes range from 0 to 2. The plot shows a blue region in the middle of a gray structure. Scale factors are $\times 10^{-7}$ and $\times 10^{-6}$.

Heat Transfer in Solids

COMSOL Settings



Settings
Boundary Heat Source

Label: Boundary Heat Source 1

Boundary Selection

Selection: Manual

Active: 12

Override and Contribution

Equation

Boundary Heat Source

General source

Q_b : User defined

15 W/m²

Overall heat transfer rate

$Q_b = \frac{P_b}{A}$

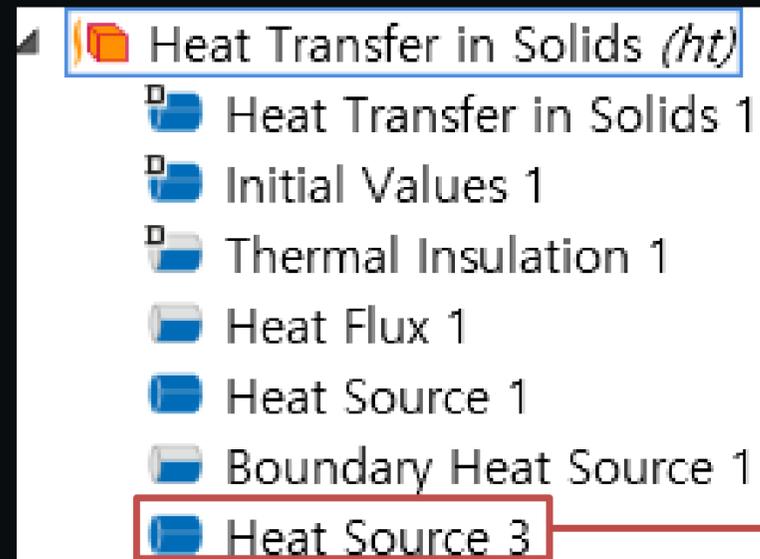
Graphics: Convergence Plot 1

3D plot showing convergence of heat loss calculation. The plot shows a vertical rectangular block with a blue line indicating the convergence of the heat loss calculation. The y-axis ranges from 0 to 1, and the x and z axes range from 0 to 2. The plot is scaled by $\times 10^{-7}$ and $\times 10^{-6}$.

Non-radiative Recombination에 의한 열 손실 구현

Heat Transfer in Solids

COMSOL Settings



Settings
Heat Source

Label: Heat Source 3

Domain Selection

Selection: Manual

Active: 3, 4, 5

Override and Contribution

Equation

Heat Source

General source

Q_0 : User defined

$(122[\text{W}/\text{m}^2] * (I_{\text{diode}} / I_{\text{sc}})^2) / (l_{\text{fto}} + l_{\text{tio2}} + l_{\text{pero}})$ W/m^3

Linear source
 $Q_0 = q_s \cdot T$

Overall heat transfer rate

Graphics Convergence Plot 1

3D plot showing a device structure with a central blue region. The vertical axis is labeled with 10^{-7} and 10^{-6} . The horizontal axes are labeled with 0, 2, and 0. A coordinate system (x, y, z) is shown at the bottom left.

Heat Transfer in Solids

Results

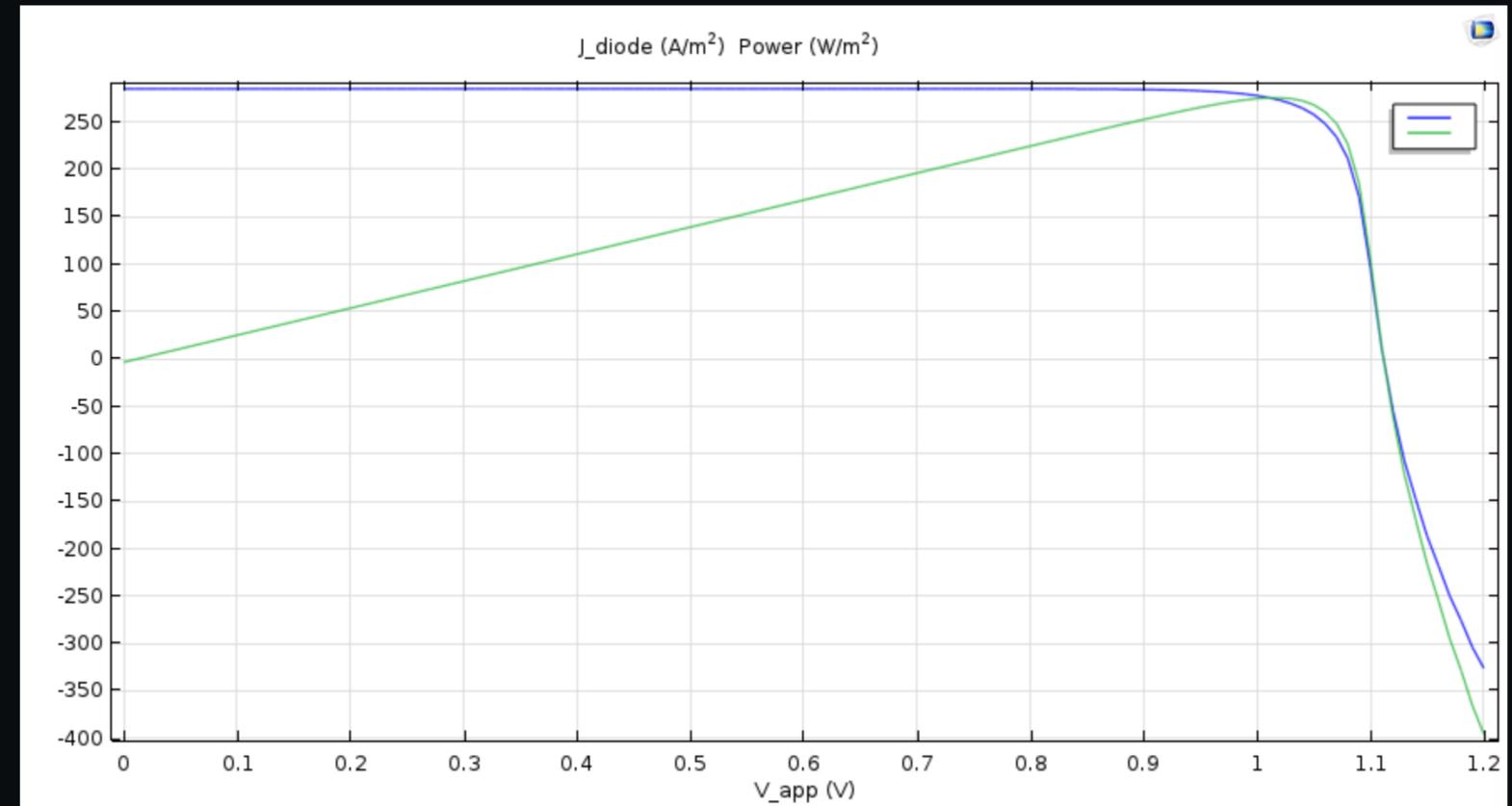
| 구분 | Analytical | Simulation | 오차 |
|------------------|----------------------|------------------------|--------|
| V_{oc} | 1.05 V | 1.1 V | ~4.76% |
| Max Power | 253W /m ² | 274.7W /m ² | ~8% |

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{J_{sc}}{J_0} + 1 \right) \text{ (Open-Circuit Voltage)}$$

$$v_{oc} = \frac{qV_{oc}}{nkT} \approx \frac{1 \cdot 1.05}{1.5 \cdot 0.0259} \approx 27.0 \text{ (Normalized Voltage)}$$

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \approx 0.846 \text{ (Green Model)}$$

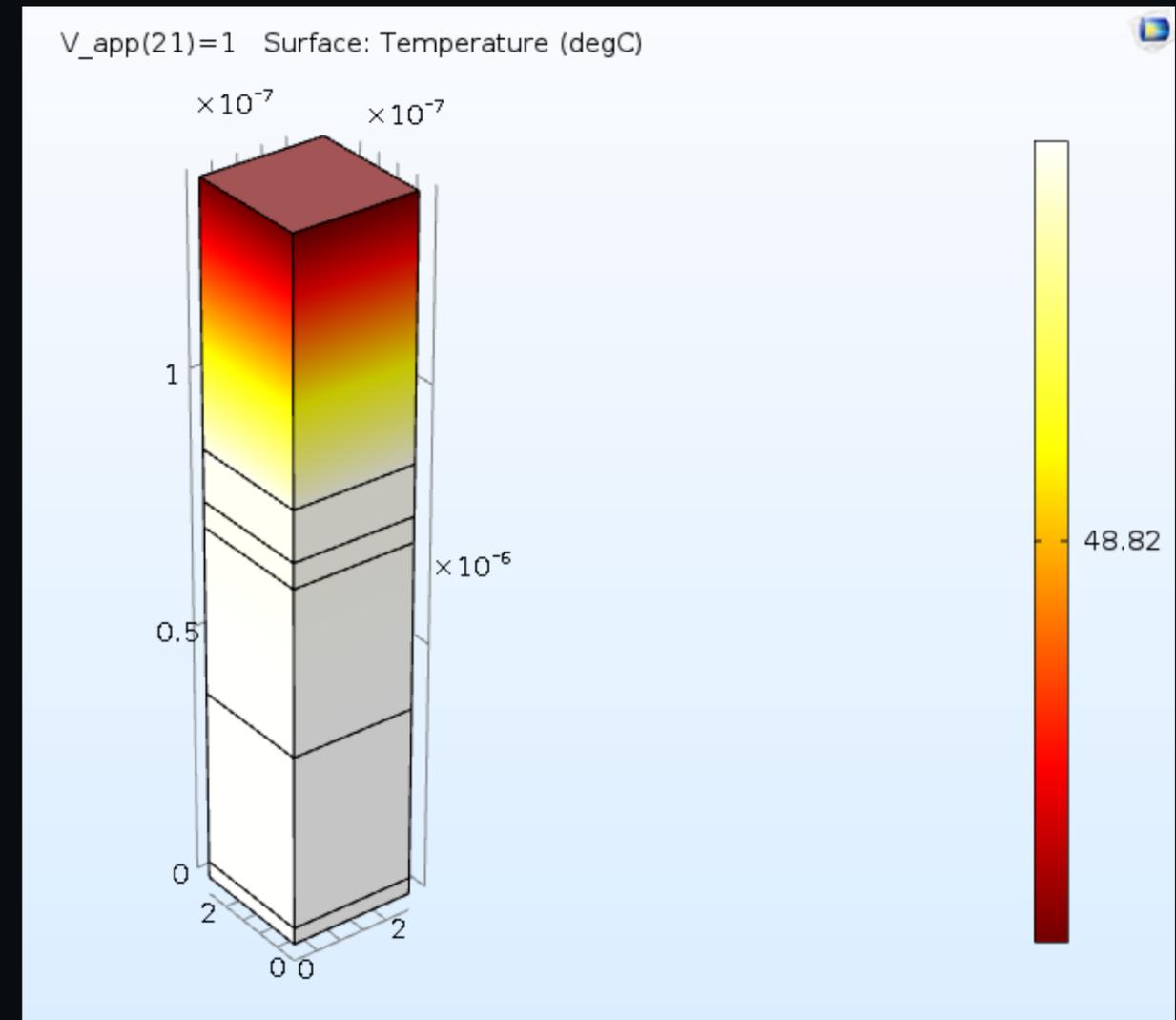
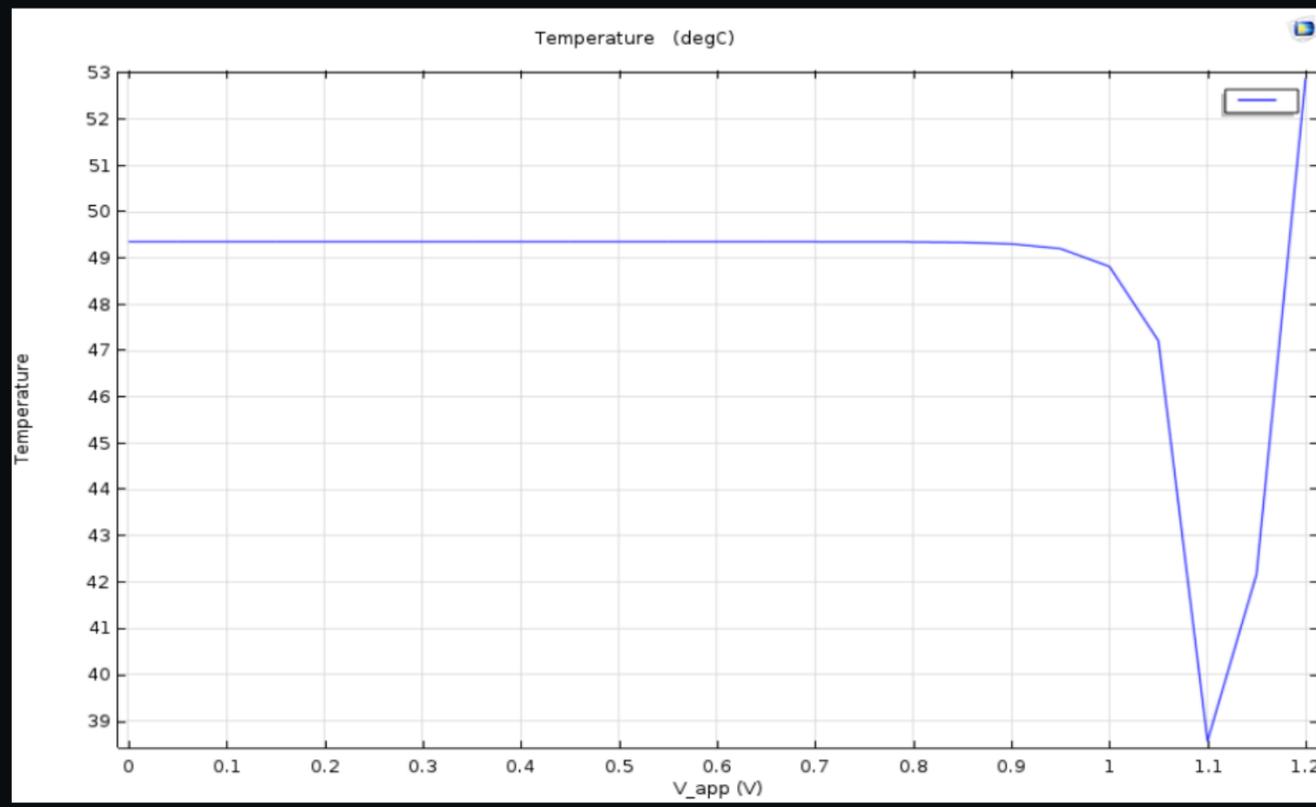
$$P_{max} = V_{oc} \cdot J_{sc} \cdot FF_{ideal} \approx 1.05 \cdot 285 \cdot 0.846 \approx 253W/m^2$$



I-V & Power Curve

Result

| 구분 | Analytical | Simulation | 오차 |
|-------------|---|------------|--------|
| Temperature | $T_{surf} = 20 + \frac{294}{10} = 49.4^{\circ}\text{C}$ | 49.358 °C | ~0.08% |



Temperature

2. Perovskite Cell : Safety Assessment

앞서 구한 모듈의 해석 결과를 바탕으로

$$\text{Input Energy} = 1,000 \text{ W / m}^2$$

$$\text{Electrical Output} = 274.7 \text{ W / m}^2$$

$$\text{Heat Loss} = 1000 - 274.7 = 725.3 \text{ W / m}^2$$

서로 다른 열팽창 계수를 가지고 있는 층들이 붙어있을 때 발생하는 열 응력 해석

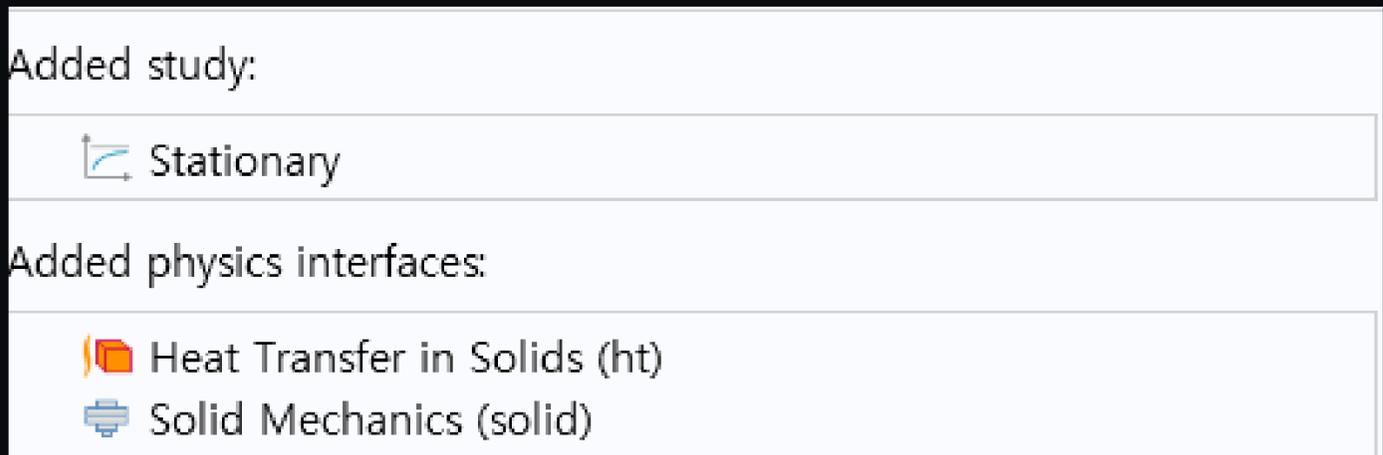
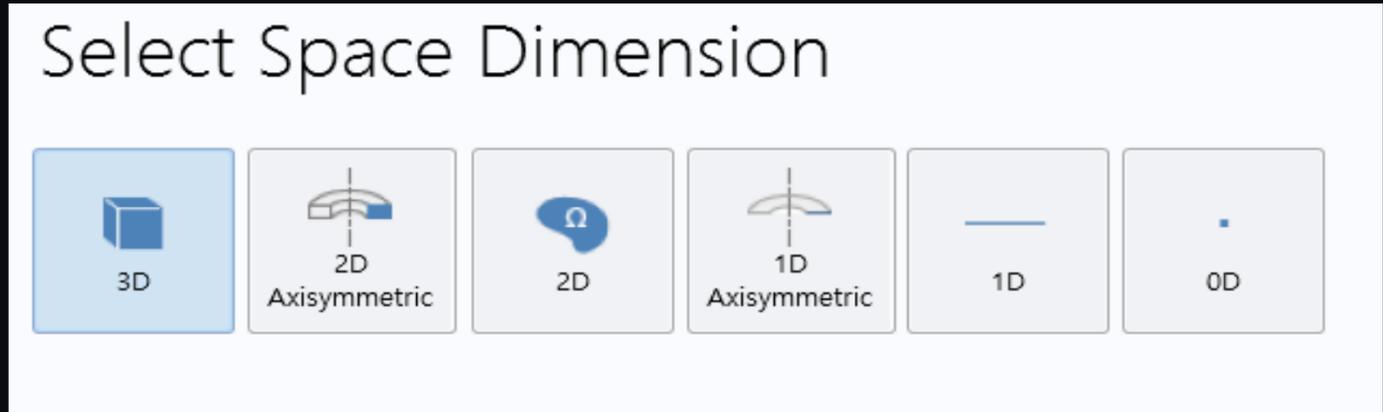
상단

$$\epsilon_{th} = \alpha \Delta T (\text{열변형률})$$

하단

$$\sigma_{th} = \frac{E}{1 - \nu} (\alpha_{film} - \alpha_{sub}) \Delta T$$

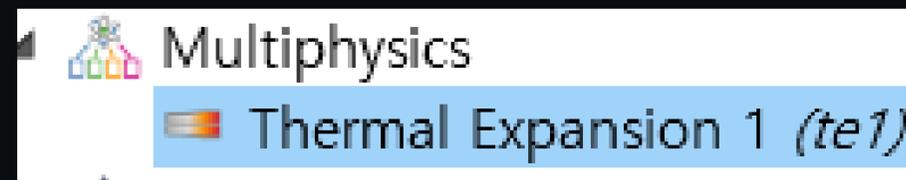
COMSOL Settings



<Study>

3D – Solid Mechanics(solid), Heat Transfer in solids – Stationary

Multiphysics
Thermal Expansion



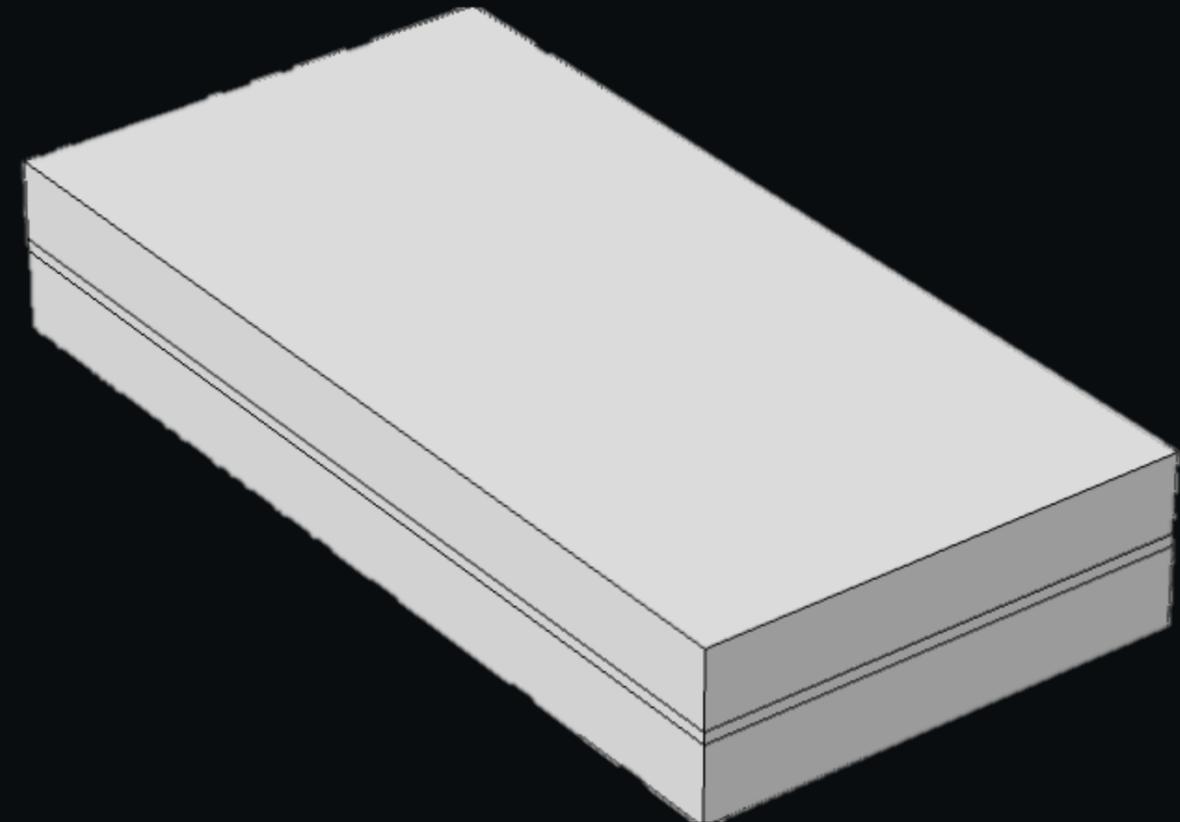
Start

COMSOL Settings

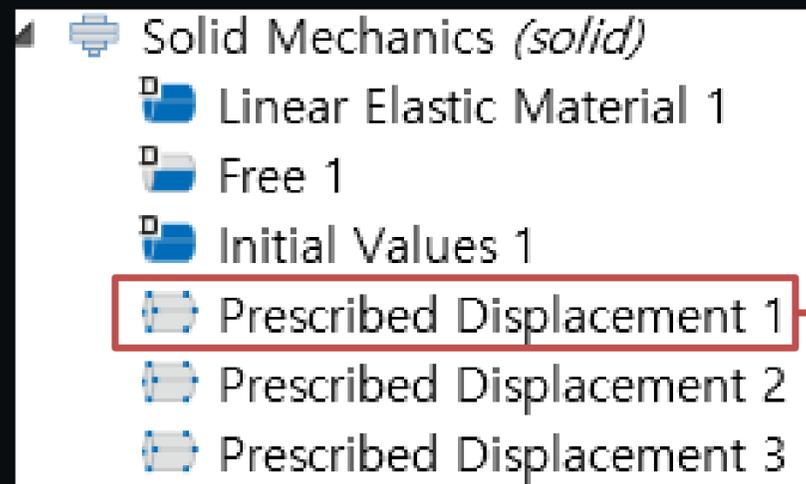
Table 1. Thermal parameters for the PV materials, extracted from [3].

| | k (W/(mK)) | ρ (kg/m ³) | C_p (J/KgK) | ϵ |
|-------|--------------|-----------------------------|---------------|------------|
| Glass | 1.8 | 2700 | 750 | 0.9 |
| EVA | 0.32 | 960 | 2090 | |

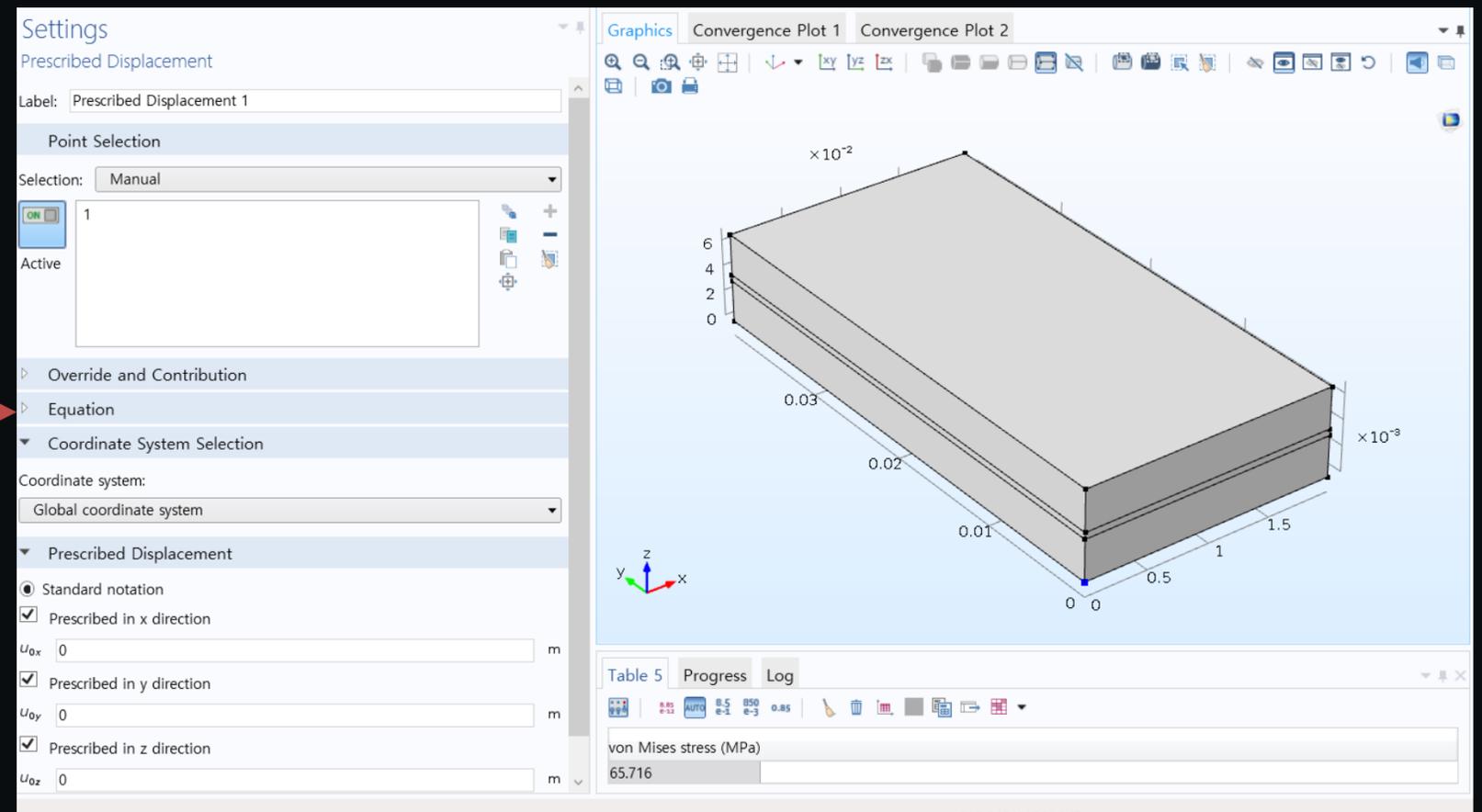
| Material | 높이 |
|------------|---------|
| Glass | 3.2[mm] |
| EVA | 0.5[mm] |
| Perovskite | 500[nm] |
| EVA | 0.5[mm] |
| Glass | 3.2[mm] |



COMSOL Settings



강체 운동은 막고 팽창은 가능하게 하기 위해
원점과 x축 위의 점, y축 위의 점을 고정하였다.



COMSOL Settings

- Solid Mechanics (*solid*)
 - Linear Elastic Material 1
 - Free 1
 - Initial Values 1
 - Prescribed Displacement 1
 - Prescribed Displacement 2**
 - Prescribed Displacement 3

The screenshot displays the COMSOL software interface. On the left, the 'Settings' window for 'Prescribed Displacement 2' is open. The 'Point Selection' is set to 'Manual' with point '11' selected. The 'Coordinate System Selection' is set to 'Global coordinate system'. Under 'Prescribed Displacement', the 'Standard notation' is selected, and the 'Prescribed in y direction' and 'Prescribed in z direction' checkboxes are checked. The displacement values are all set to 0 m.

On the right, the 'Graphics' window shows a 3D model of a rectangular block. The dimensions are 0.03 m in the y-direction, 0.02 m in the x-direction, and 1.5 m in the z-direction. A stress table is visible at the bottom right, showing the 'von Mises stress (MPa)' as 65.716.

| Table 5 | Progress | Log |
|------------------------|----------|-----|
| von Mises stress (MPa) | | |
| 65.716 | | |

Solid Mechanics

COMSOL Settings

- Solid Mechanics (*solid*)
 - Linear Elastic Material 1
 - Free 1
 - Initial Values 1
 - Prescribed Displacement 1
 - Prescribed Displacement 2
 - Prescribed Displacement 3**

The screenshot displays the COMSOL software interface. On the left, the 'Settings' window for 'Prescribed Displacement 3' is open. The 'Point Selection' is set to 'Manual' with point 6 selected. The 'Coordinate System Selection' is set to 'Global coordinate system'. Under 'Prescribed Displacement', the 'Standard notation' is selected, and the 'Prescribed in z direction' checkbox is checked, with a displacement value of 0 m. The 'Equation' and 'Override and Contribution' sections are collapsed. On the right, the 'Graphics' window shows a 3D model of a rectangular plate. The plate has dimensions of 0.03 m in the x-direction, 0.02 m in the y-direction, and 0.01 m in the z-direction. The z-axis is scaled by $\times 10^{-3}$. The plate is shown in a perspective view with a coordinate system (x, y, z) at the bottom left. Below the 3D model, there are two 'Convergence Plot' windows. At the bottom of the interface, a 'Table 5' window shows the 'von Mises stress (MPa)' with a value of 65.716.

Solid Mechanics

COMSOL Settings

- Heat Transfer in Solids (*ht*)
 - Heat Transfer in Solids 1
 - Initial Values 1
 - Thermal Insulation 1
 - Boundary Heat Source 1**
 - Heat Flux 1

The screenshot displays the COMSOL interface. On the left, the 'Settings' window is open for 'Boundary Heat Source 1'. The 'Label' is 'Boundary Heat Source 1'. Under 'Boundary Selection', the 'Selection' is set to 'Manual' and '12' is listed as an active selection. The 'Boundary Heat Source' section is expanded, showing 'General source' selected. The heat flux Q_b is set to 'User defined' with the expression $G_{\text{sun}} * (1 - \text{Eff})$ and units of W/m^2 . The overall heat transfer rate Q_t is set to $\frac{P_b}{A}$.

On the right, the 'Graphics' window shows 'Convergence Plot 1' and 'Convergence Plot 2'. The plot displays a 3D model of a rectangular block with a blue line representing the convergence of the solution. The vertical axis is labeled $\times 10^{-2}$ and ranges from 0 to 6. The horizontal axes are labeled $\times 10^{-8}$ and range from 0 to 1.5. A coordinate system with x, y, and z axes is visible at the bottom left of the plot area.

Heat Transfer in Solids

COMSOL Settings

- Heat Transfer in Solids (*ht*)
 - Heat Transfer in Solids 1
 - Initial Values 1
 - Thermal Insulation 1
 - Boundary Heat Source 1
 - Heat Flux 1**

The screenshot displays the COMSOL software interface. On the left, the 'Settings' window for 'Heat Flux 1' is open. It shows the following configuration:

- Label: Heat Flux 1
- Boundary Selection: Manual
- Selection: 3, 13
- Active: ON
- Heat Flux type: Convective heat flux
- Equation: $q_0 = h \cdot (T_{ext} - T)$
- Heat transfer coefficient: $h = 10 \text{ [W/(m}^2\text{K)]}$
- External temperature: $T_{ext} = 293.15 \text{ [K]}$

On the right, the 'Graphics' window shows a 3D model of a rectangular block. The top surface is highlighted in blue. The axes are labeled x, y, and z. The x-axis ranges from 0 to 1.5, the y-axis from 0 to 0.03, and the z-axis from 0 to 6. The top surface is at $z = 6 \times 10^{-2}$ and the bottom surface is at $z = 0 \times 10^{-3}$.

Heat Transfer in Solids

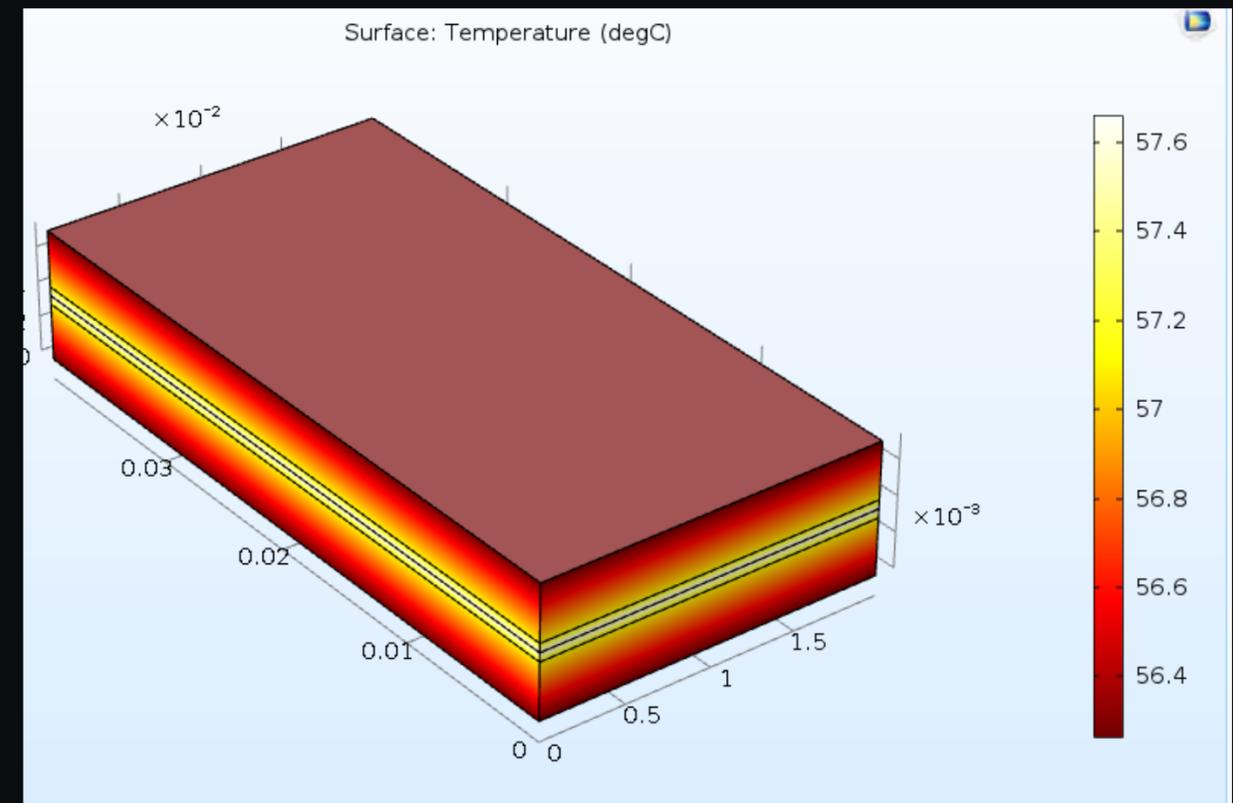
Result

| 구분 | Analytical | Simulation | 오차 |
|----|--|-------------------------|--------|
| T | $T_{theory} = T_{amb} + \frac{Q_{gen}}{2 \cdot h} \approx 56.27 \text{ } ^\circ\text{C}$ | 57.661 $^\circ\text{C}$ | ~2.47% |

오차 원인:

Analytical Solution은 열저항을 무시한 표면 온도(Surface Temp) 기준

Simulation은 Conductive Thermal Resistance가 반영된 내부 코어의 온도 이다.



Temperature

Results

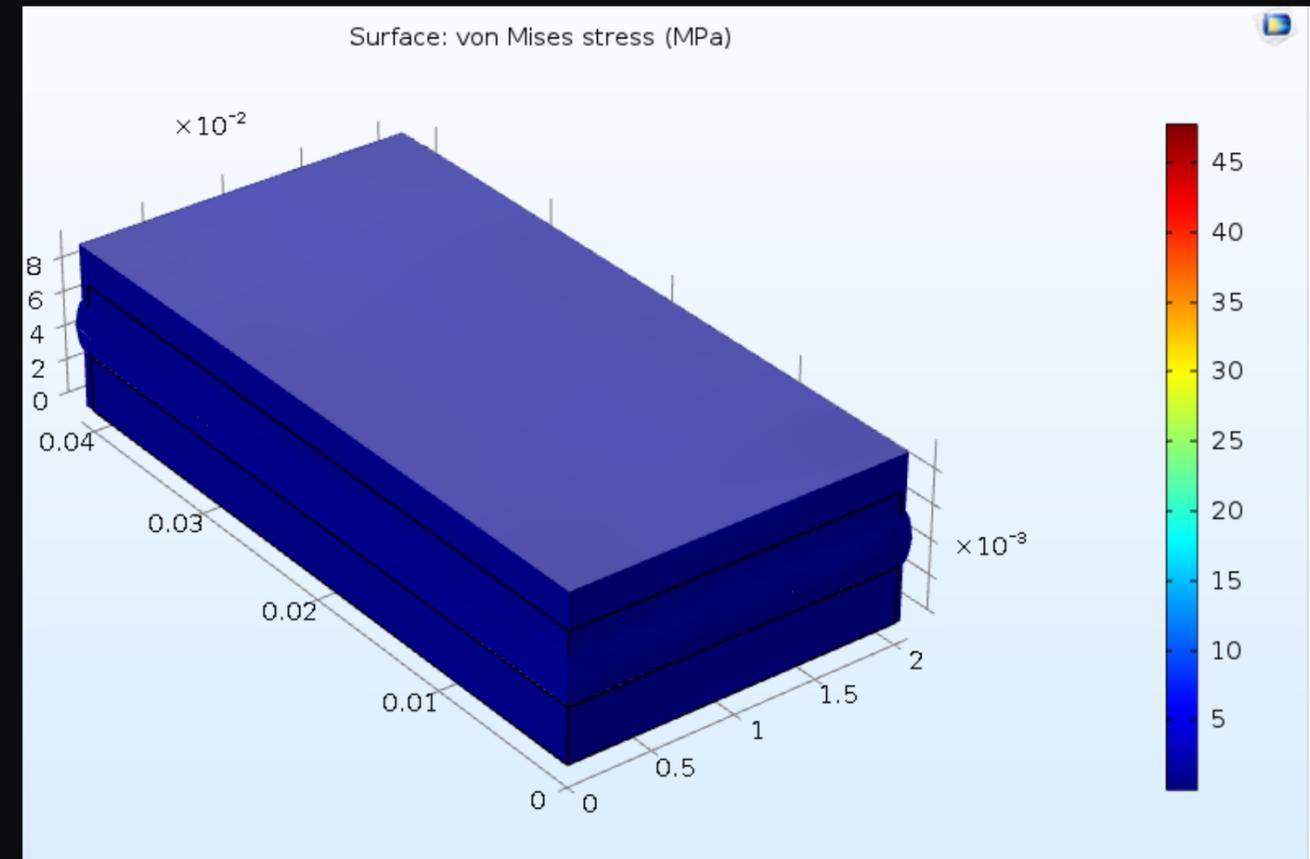
| 구분 | Analytical | Simulation | Difference |
|--------|-------------------------------|------------|------------|
| Stress | $\sigma_{th} \approx 50.9MPa$ | 58.57 MPa | ~15.1% |

$$\sigma_t h = E_{pero} / (1 - \nu) (\alpha_{pero} - \alpha_{sub}) \Delta T$$

오차 원인:

이론 식의 경우 상부가 개방된 2차원 평면 응력을 계산한 것이지만 실제 시뮬레이션에선 샌드위치 구조의 3차원의 구속 효과와 전단 응력이 반영되어 차이가 나며 시뮬레이션 보다 정확한 값이다.

이러한 값은 압축 응력으로 현재 결과는 구조적으로 안전한 범위를 확인할 수 있다.



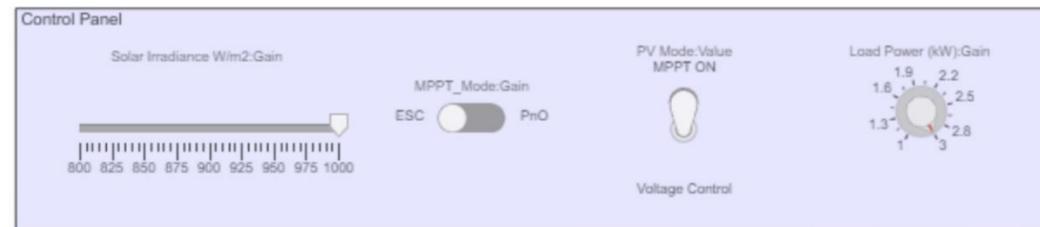
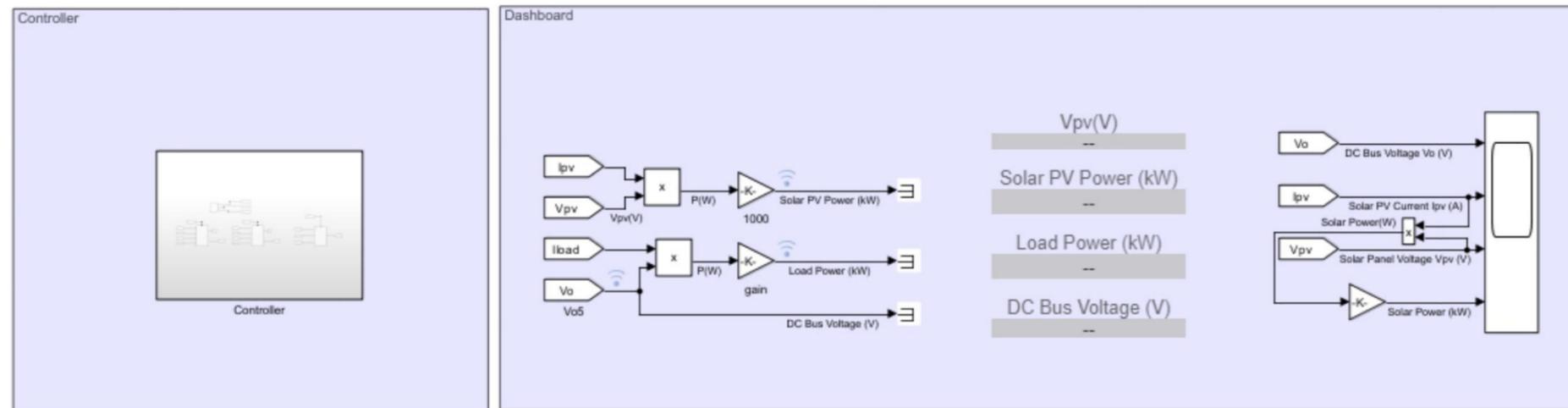
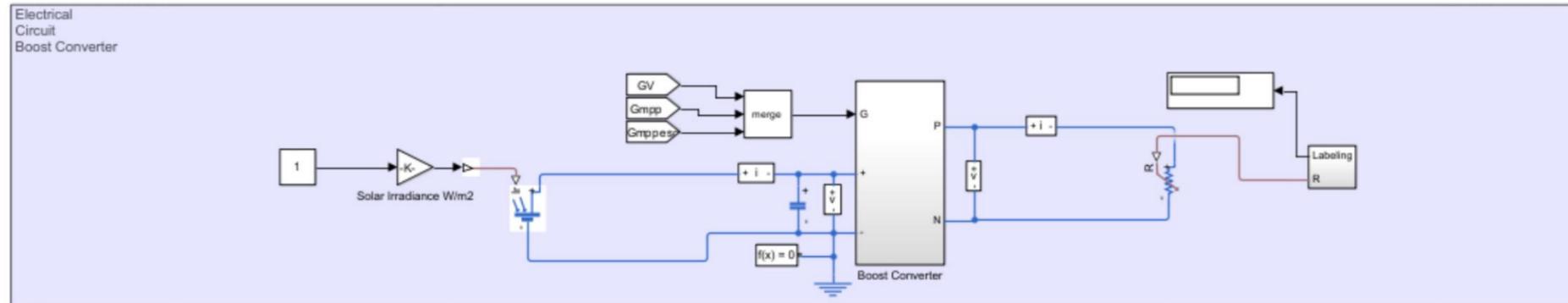
Scale Factor: 168

Simulink: MPPT Controller

Total System Topology

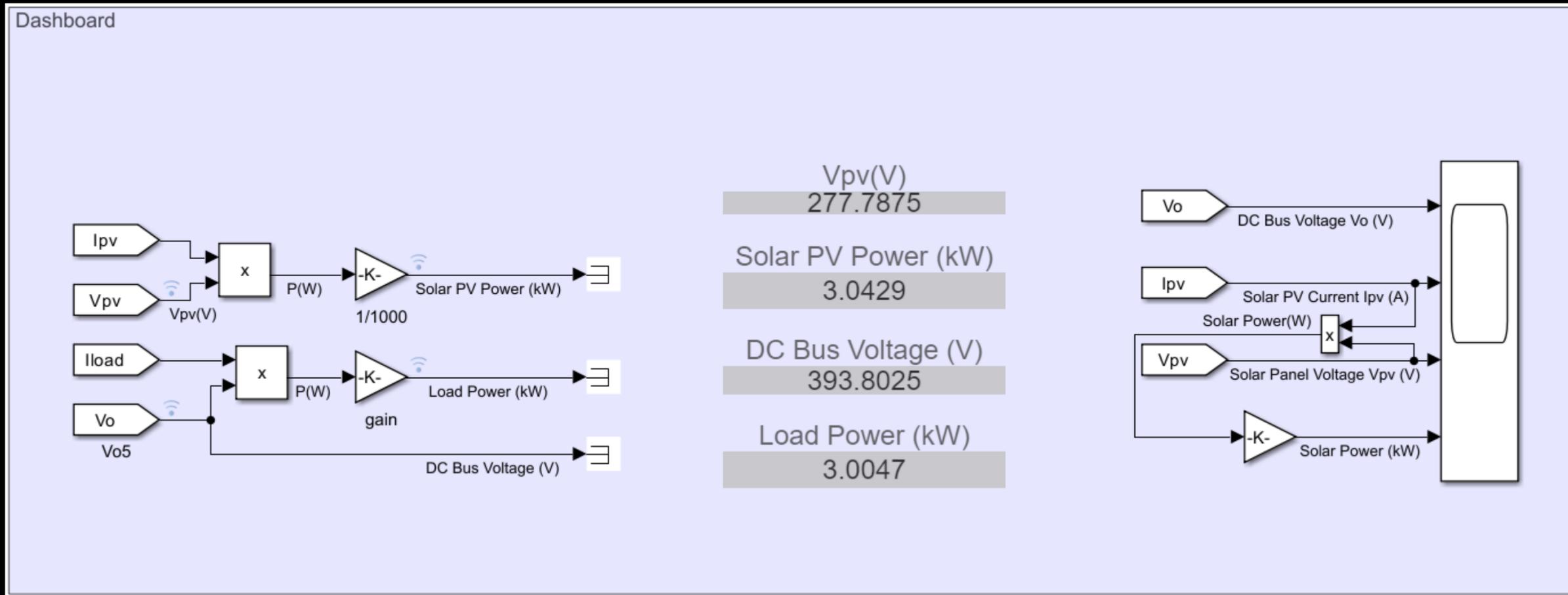
Click the Hyperlink First!

[heat work joule parameter configuration](#)



회로, 제어부, dashboard 및 파라미터 조작 패널

Dashboard



Simulation 실행 중 결과값을 실시간으로 확인 및 Debugging을 위한 Dashboard(Logging도 진행)

Control Panel

Control Panel

Solar Irradiance W/m²:Gain

MPPT_Mode:Gain

PV Mode:Value
MPPT ON

Load Power (kW):Gain

ESC PnO

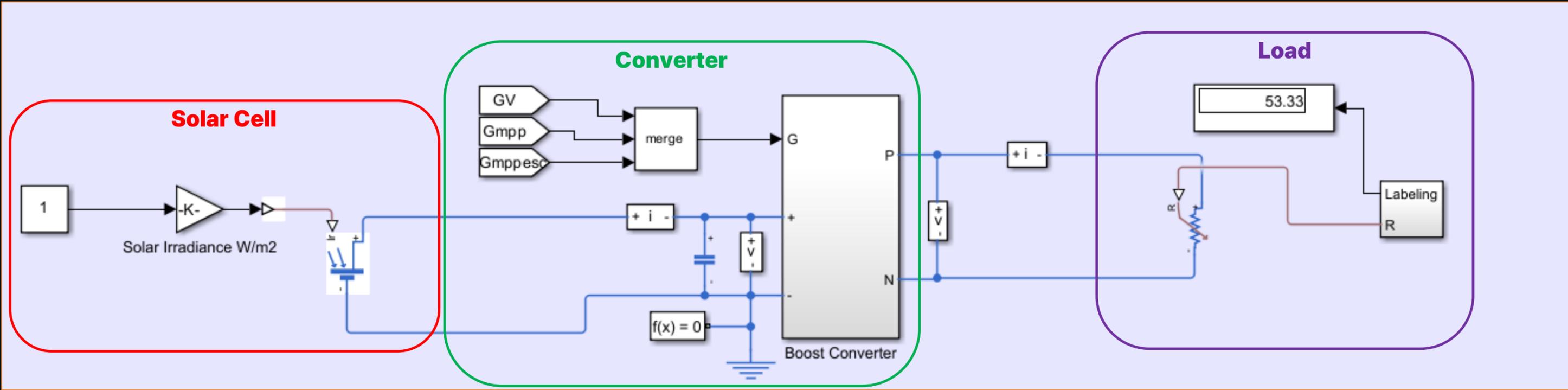
Voltage Control

The image shows a control panel with four main components: 1. A horizontal slider for 'Solar Irradiance W/m²:Gain' with a scale from 800 to 1000. 2. A toggle switch for 'MPPT_Mode:Gain' with 'ESC' on the left and 'PnO' on the right. 3. A knob for 'Load Power (kW):Gain' with a scale from 1 to 3.1. 4. A light indicator for 'PV Mode:Value' labeled 'MPPT ON' and the text 'Voltage Control' below it.

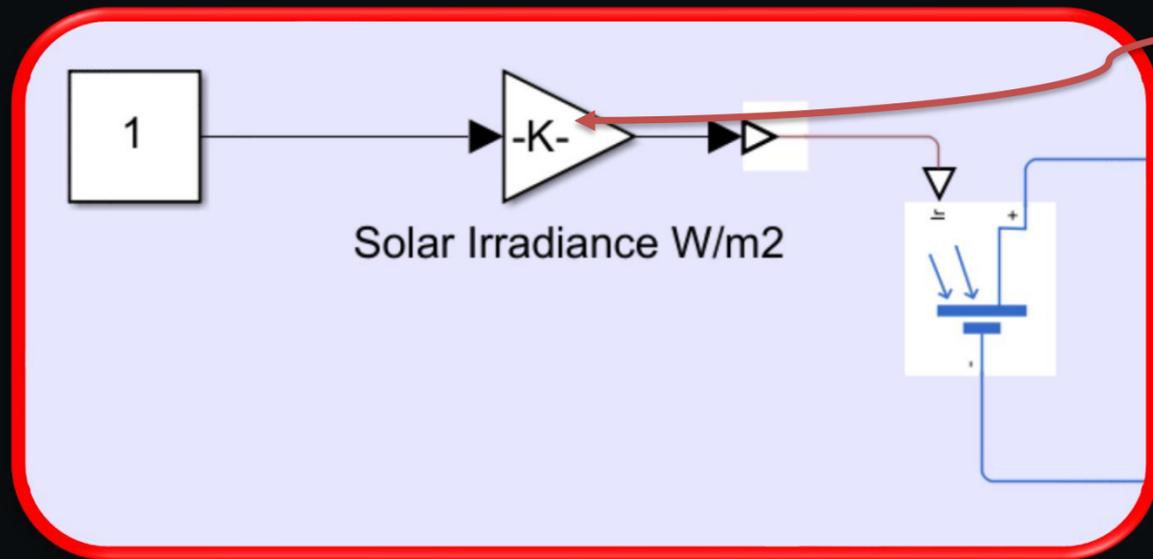
Simulation 실행 중 빠른 파라미터 변경 및 제어기 변경을 위한 Control Panel

Electrical Circuit

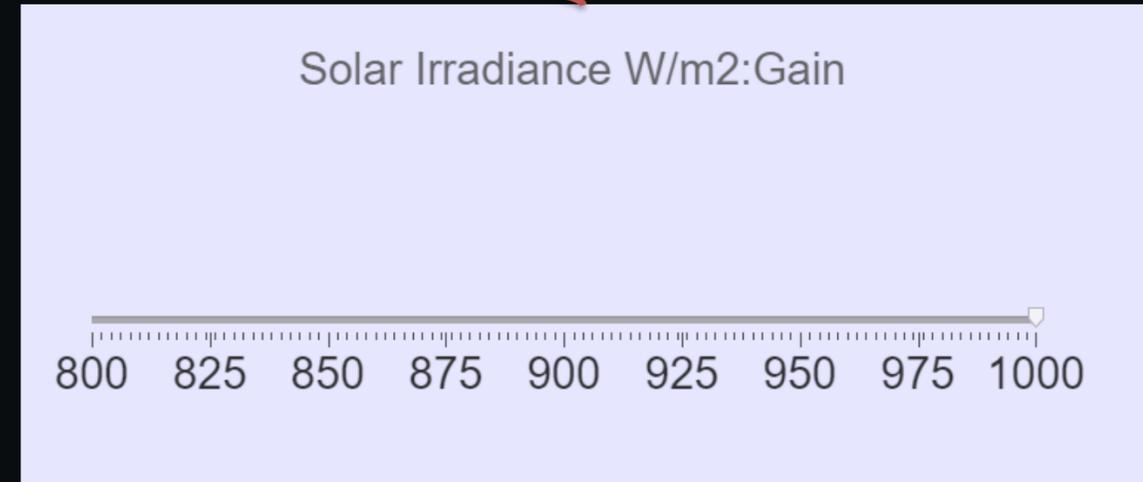
Electrical Circuit



Electrical Circuit: Solar Cell



Solar Cell



Irridance Control Panel

3kW 일반 가정 전력 사용량 Target System 용량 산정

Panel Configuration: 280s 4p(Vmpp:280V, Impp:11.42A, Pmpp: 3.11kW) from COMSOL Analysis

Electrical Circuit: Solar Cell

· 서울시 가구당 전력소비 현황

| 구분 | (단위) | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|-----------|---------|--------|--------|--------|--------|--------|--------|--------|
| 총 전력사용량 | (GWh) | 47,810 | 47,167 | 45,788 | 47,296 | 48,789 | 49,219 | 50,352 |
| 총 인구수 | (천명) | 10,049 | 10,011 | 9,911 | 9,736 | 9,668 | 9,639 | 9,332 |
| 총 가구수 | (천호) | 3,840 | 3,896 | 3,982 | 4,047 | 4,099 | 4,298 | 4,486 |
| 1인당 전력소비량 | (kWh/년) | 4,758 | 4,712 | 4,620 | 4,858 | 5,046 | 5,106 | 5,396 |
| 주택용 전력사용량 | (GWh/년) | 13,767 | 13,499 | 13,983 | 14,656 | 14,550 | 14,693 | 15,336 |
| 가구당 전력소비량 | (kWh/월) | 299 | 289 | 293 | 302 | 296 | 285 | 285 |

※ 가구 : 취사·취침을 같이하는 생활단위, 세대 : 주민등록법상 함께 등록된 단위
※ 가구당 전력소비량 : (주택용 전력사용량 ÷ 12개월) × 10⁶ ÷ 총 가구수

출처: 서울특별시 에너지정보

3kW 일반 가정 전력 사용량 Target System 용량 산정

$$3kW * 4hr = 12kWh (Conservative value)$$

$$\frac{285kWh}{month} = \frac{9.5kwh}{day}$$

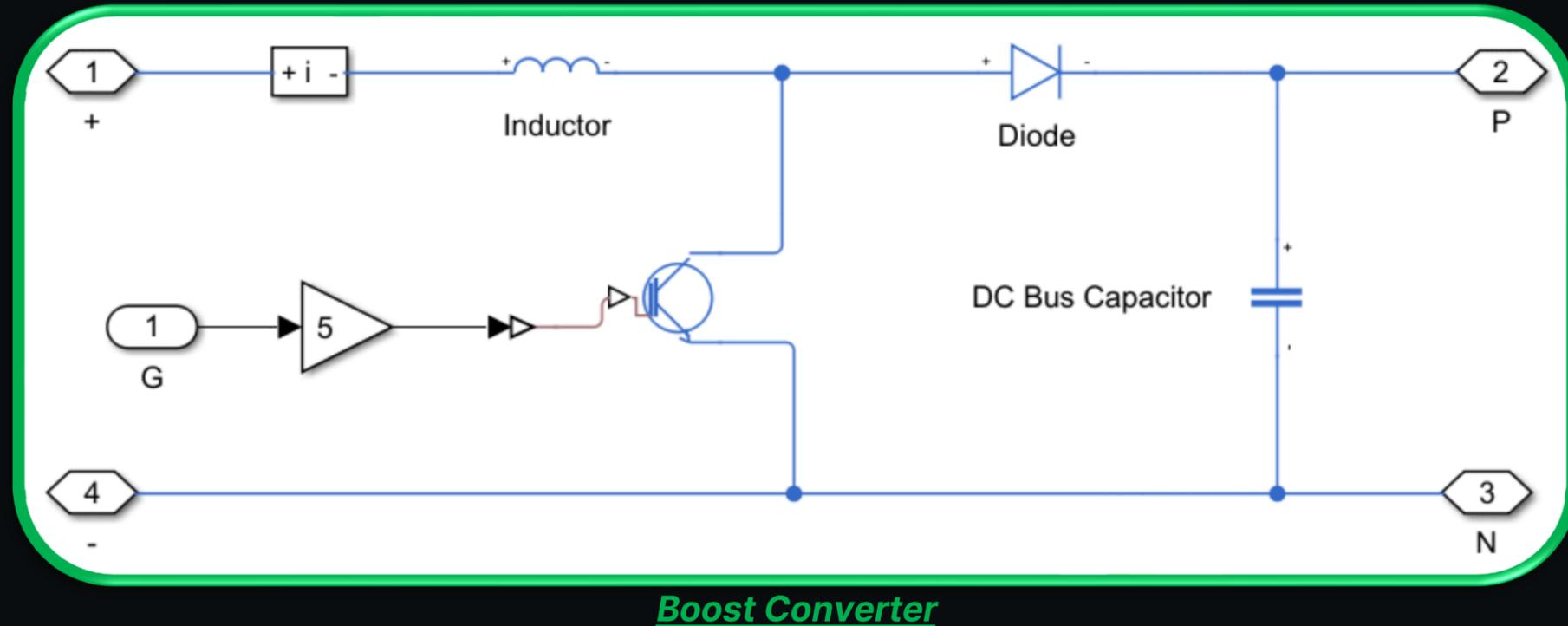
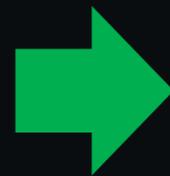
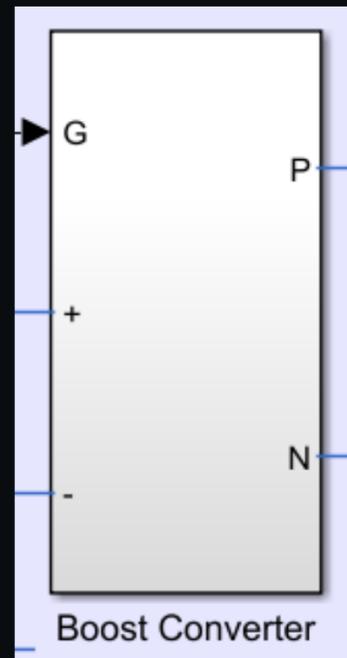
$$12kWh > 9.5kWh$$

전원 / 전력변환장치 / 부하

Electrical Circuit

Electrical Circuit: Boost Converter

Simscape Eletrical 기반 Boost Converter Topology 구현
Why Boost Converter? Microgrid, DC grid 400V 750V



Boost Converter

Electrical Circuit

Electrical Circuit: Boost Converter

Boost Converter: 승압형 DC/DC

$$V_i * D + (V_i - V_o)(1 - D) = 0$$

average = inductor voltsecond balance

$$G_v = \frac{V_o}{V_i} = \frac{1}{1 - D}$$

Gain

$$V_i \leq V_o (G_v \leq 3, \text{legacy value})$$

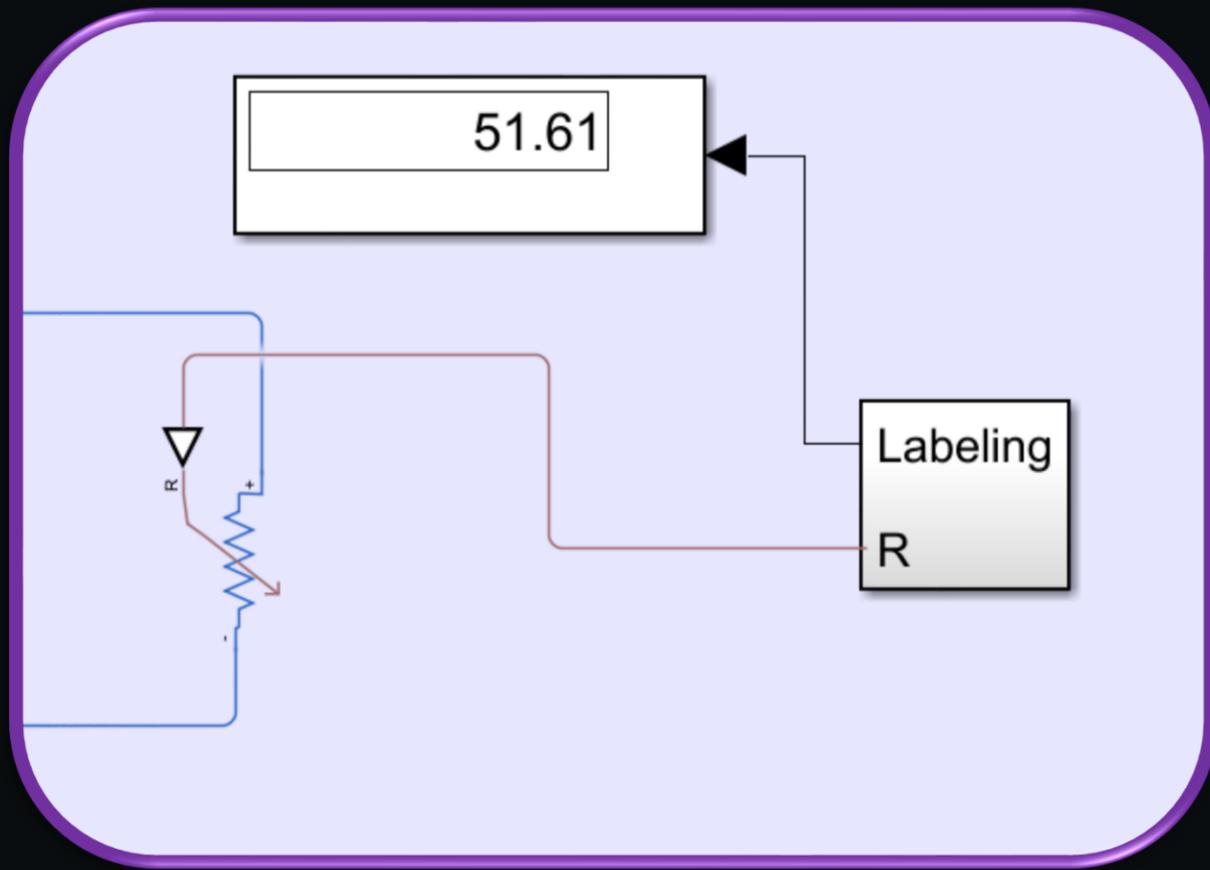
Inductor and Capacitor

Inductor: Output Current Ripple
Capacitor: Output Voltage Ripple

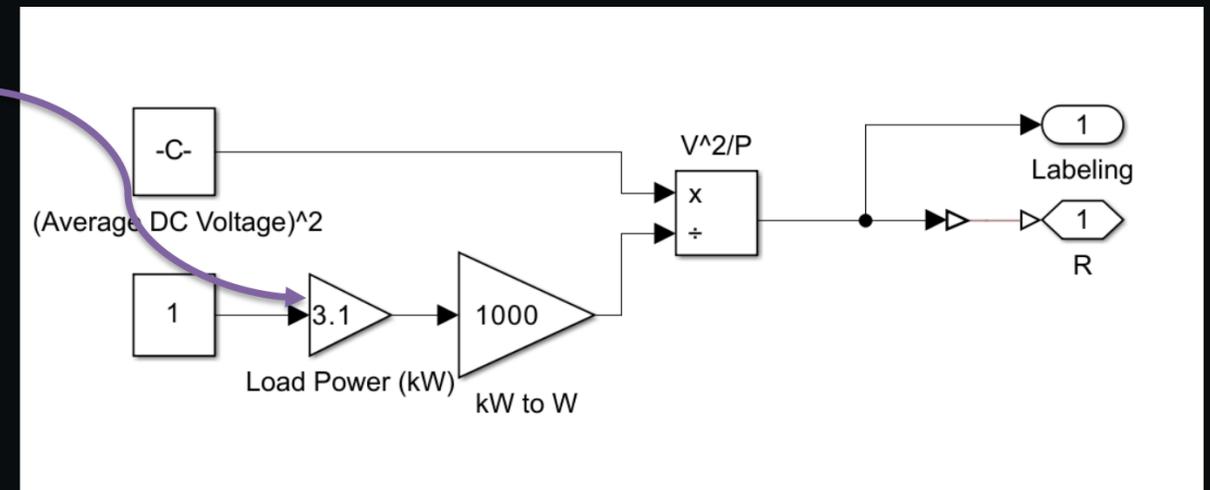
$$\Delta I_L = \frac{V_i}{L} * D * T$$
$$\Delta V_C = \frac{I_o * (1 - D) * T}{C}$$

Electrical Circuit

Electrical Circuit: Load



Load



$$R = \frac{V^2}{P} \quad (V: \text{target voltage } 400, P: \text{load power gain})$$

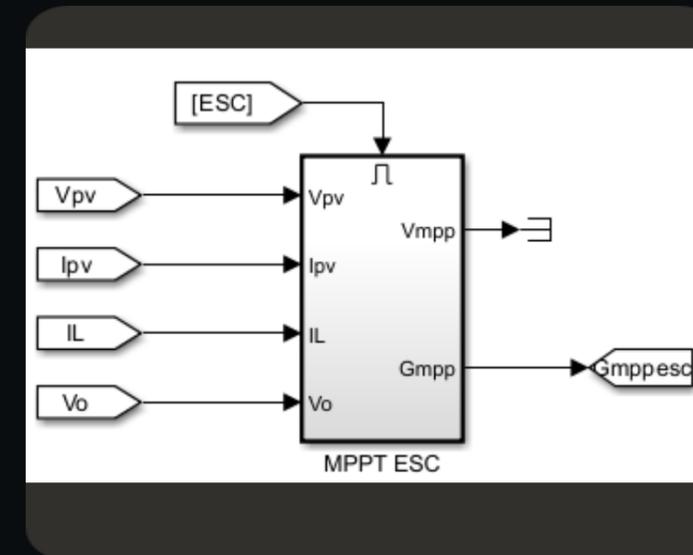
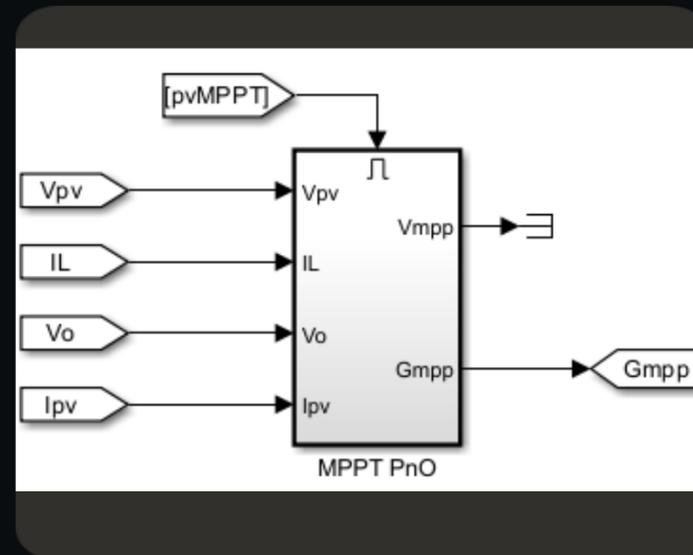
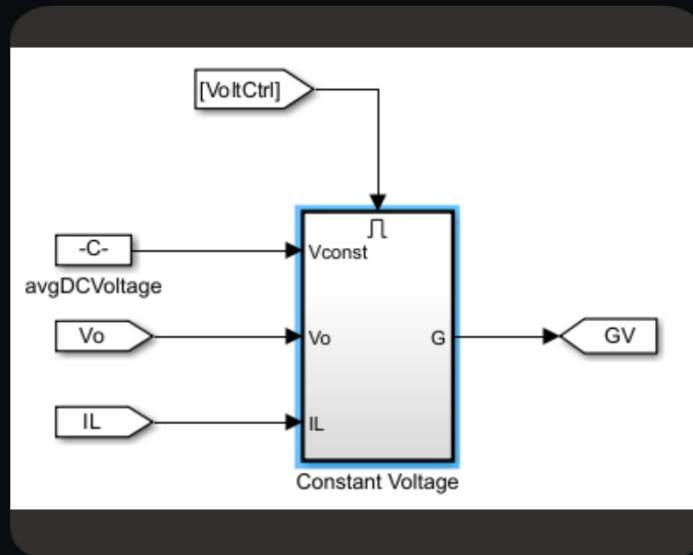
Controller

3 Types of Controllers

Voltage Controller
Constant Voltage

Perturbation and Observation
MPPT:P&O

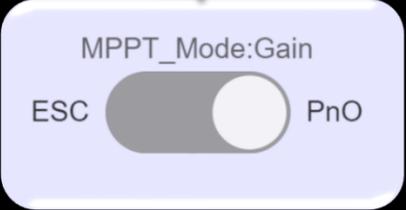
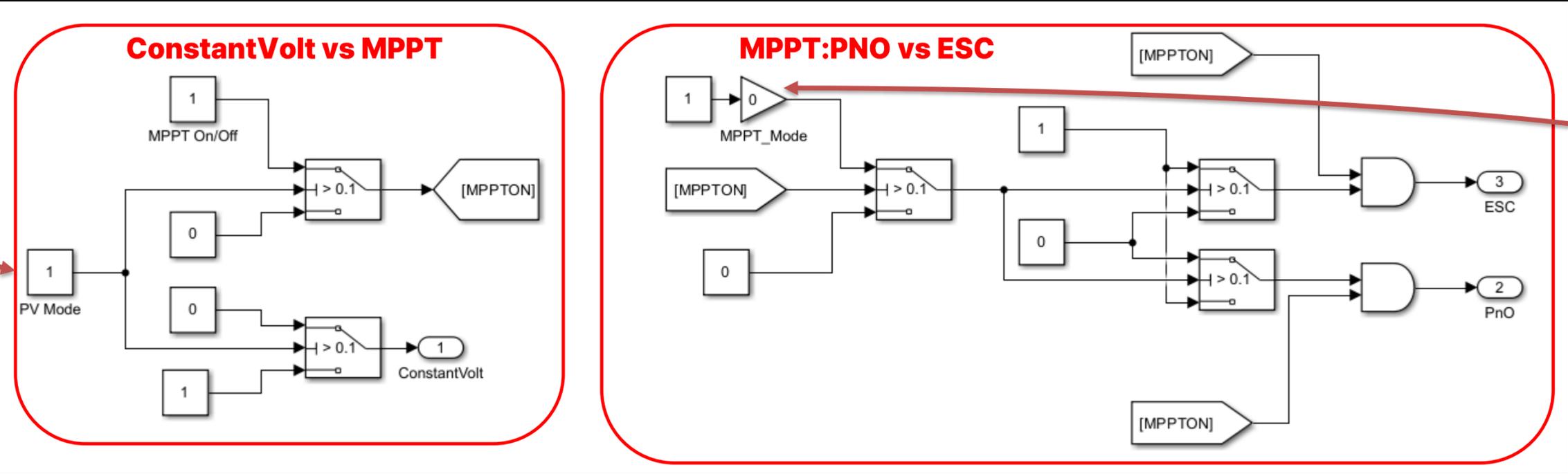
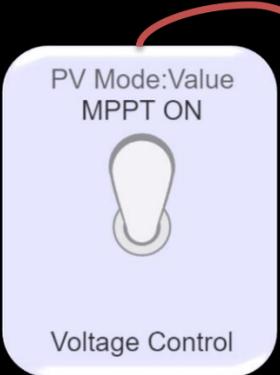
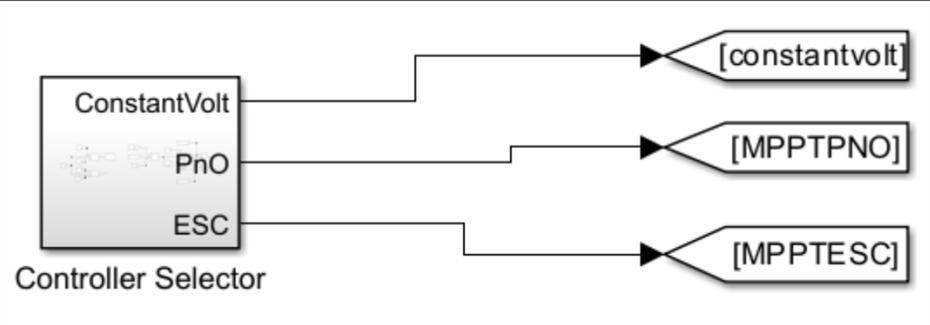
Extremum Seeking Control
MPPT:ESC



Controller

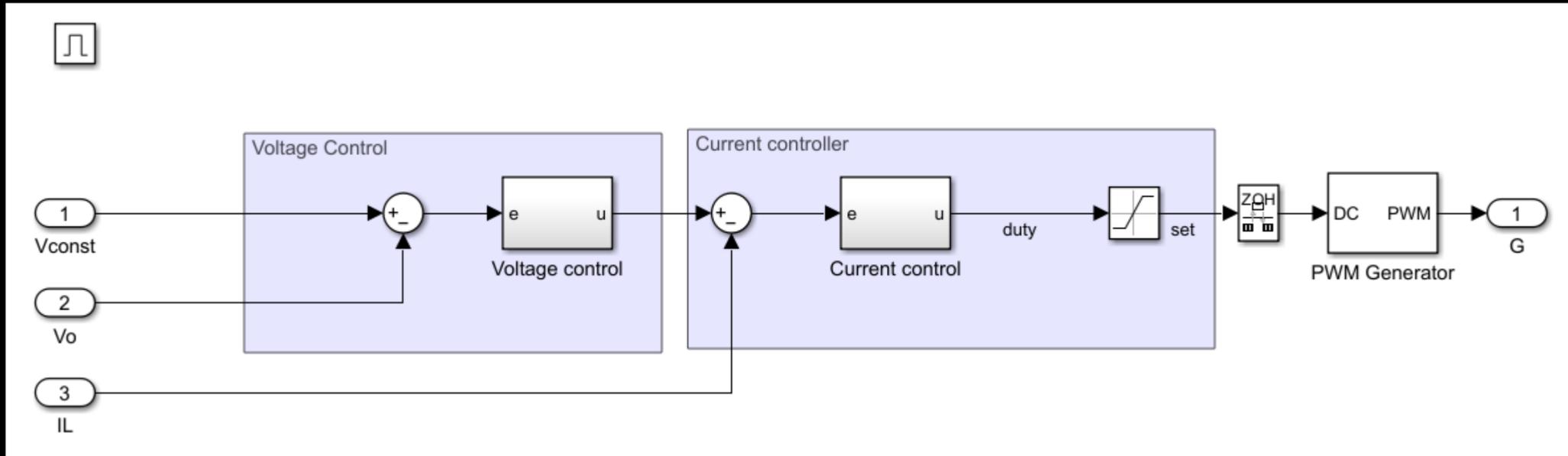
Controller: Selector

토글 스위치들로 모드들 어떻게 바뀌는지, Logic gate 활용해서 겹치는 상황 방지했다는 내용



Controller

Controller: Constant Voltage



PI Controller Gain

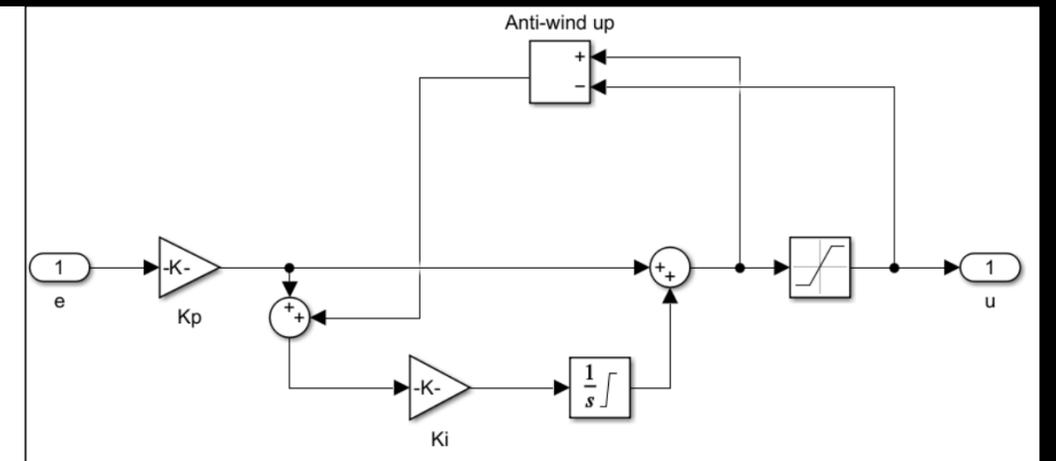
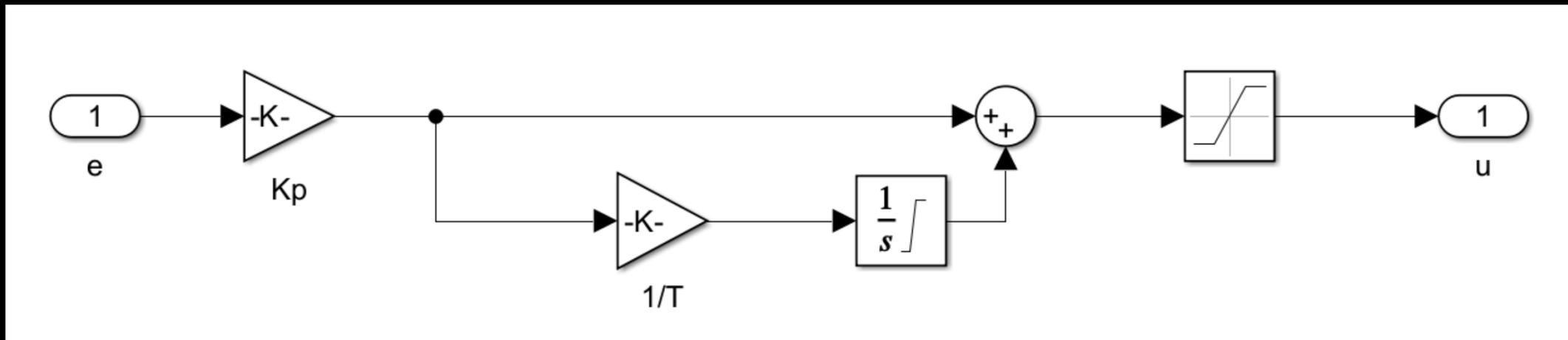
$$f_{sw} = 25kHz$$

전류제어기 대역폭:

- 니어퀴스트 조건 및 위상여유 고려하여
- $f_{sw}/20$

전압제어기 대역폭:

- 전류보다 느리게 잡아 수렴된 전류 내부 루프를 보도록 함
- $f_i/10$

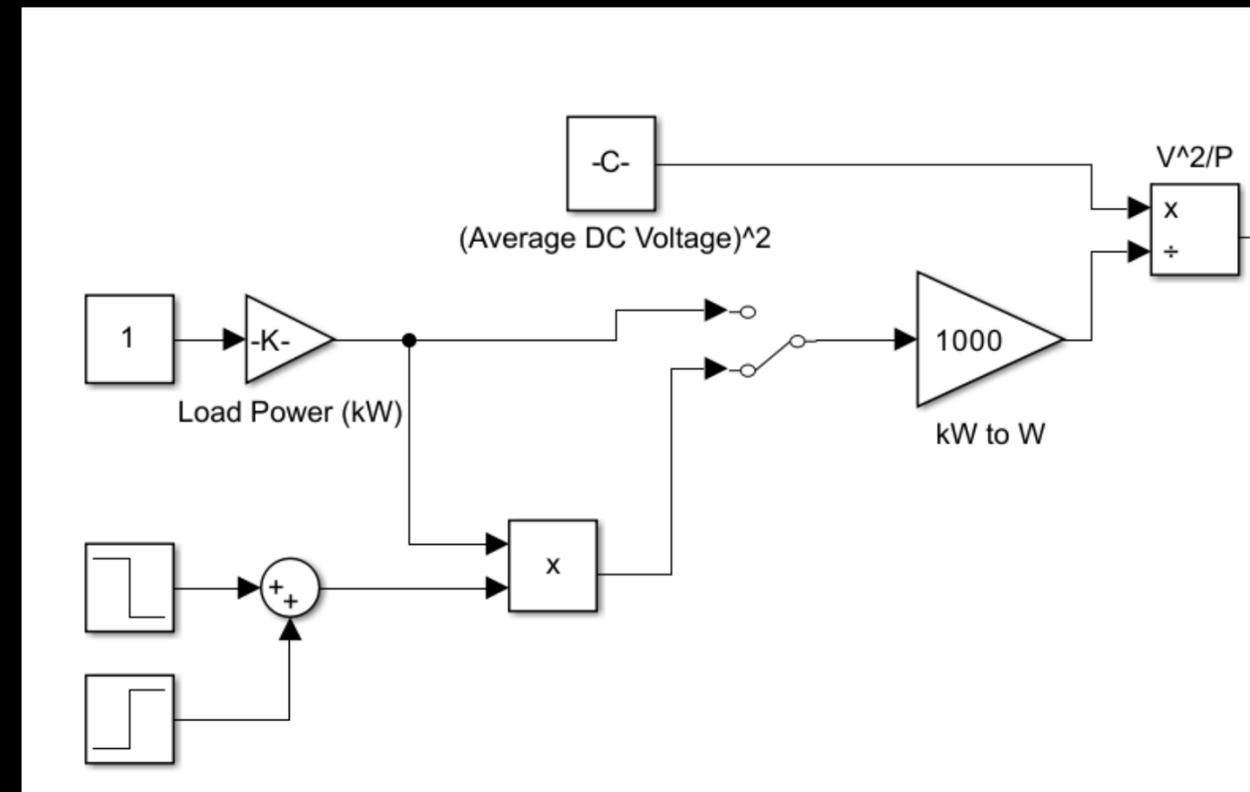
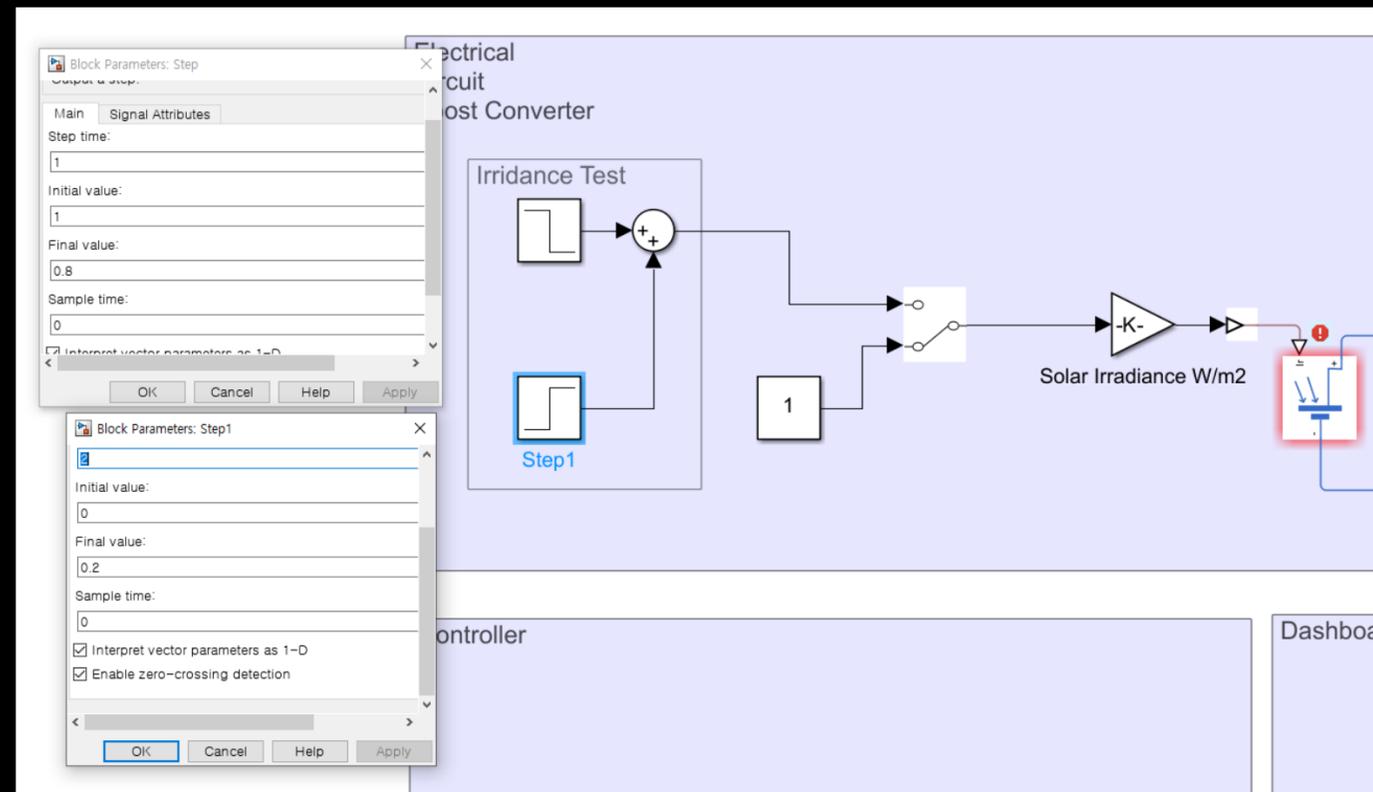


Voltage: PI Controller / Current: PI Controller(anti-wind up)

Test Scenario

Variant Irridance: 1000 initial value
1s step function 1000->800
2s step function 800->1000

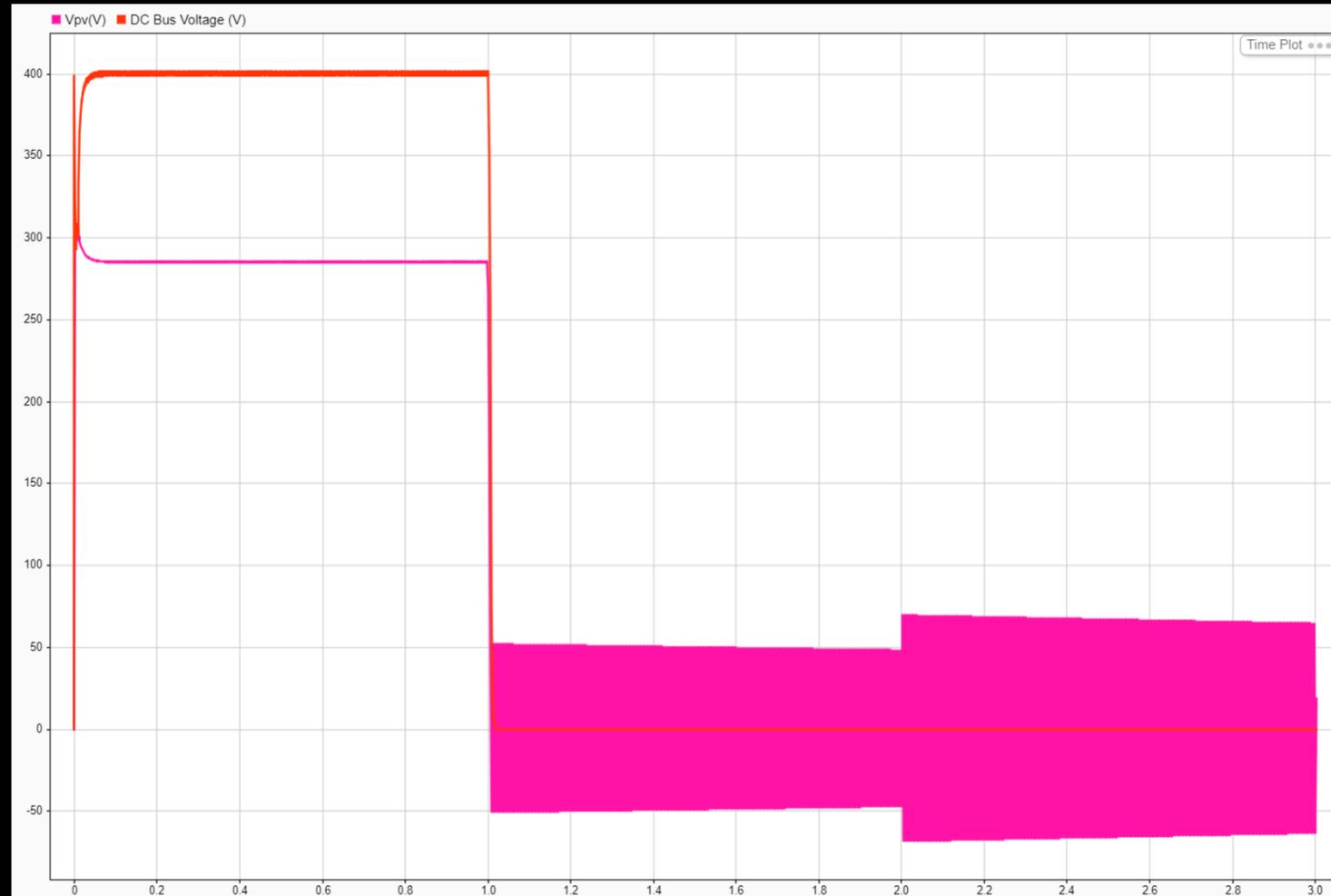
Variant Load: 3kW initial value
1s step function 3kW*0.8 = 2.4kW
2s step function 2.4kW->3kW



Test Scenario

Controller

Controller: Constant Voltage



Irridance 변화시 전원 특성 고려X -> system이 기능을 못 함

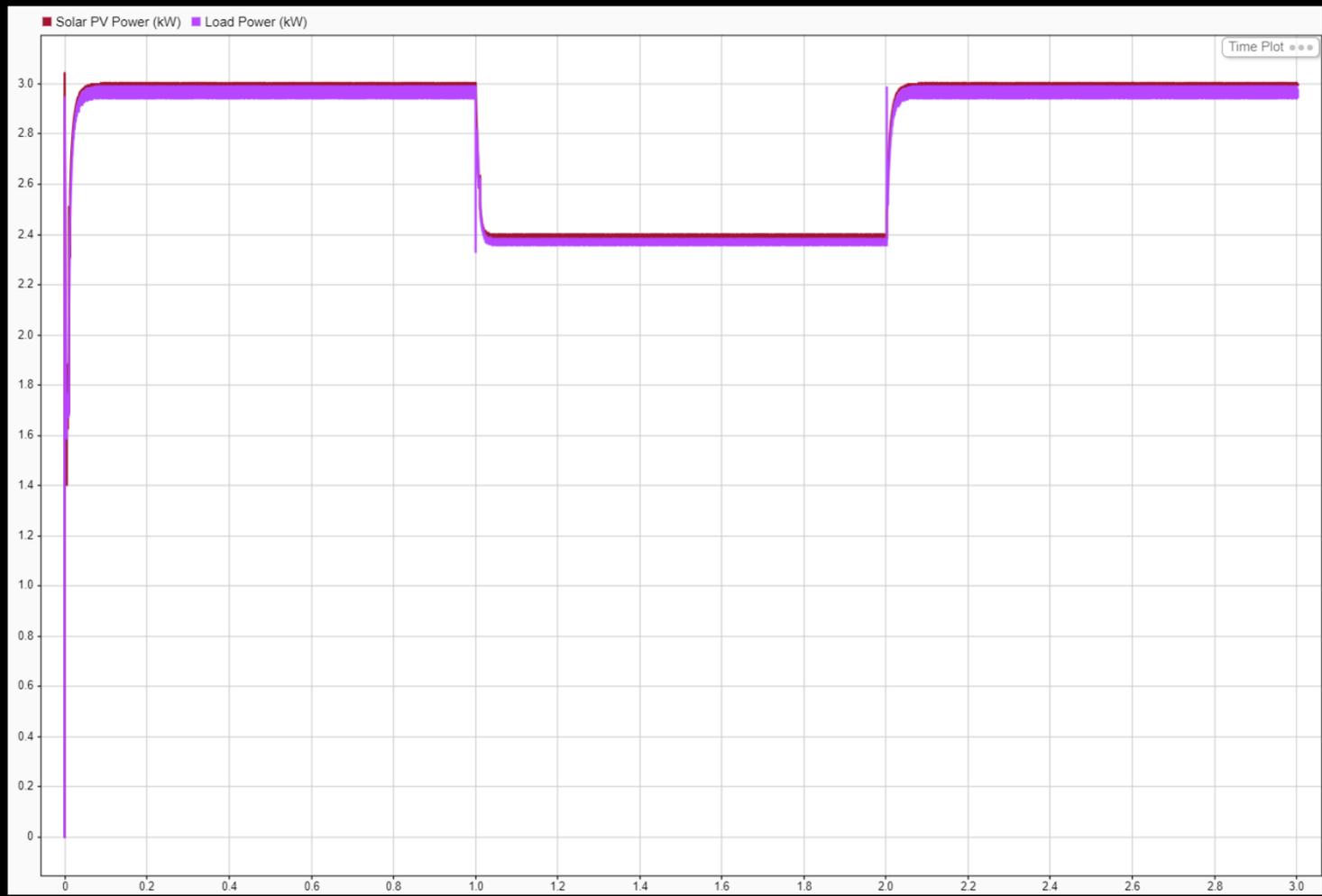
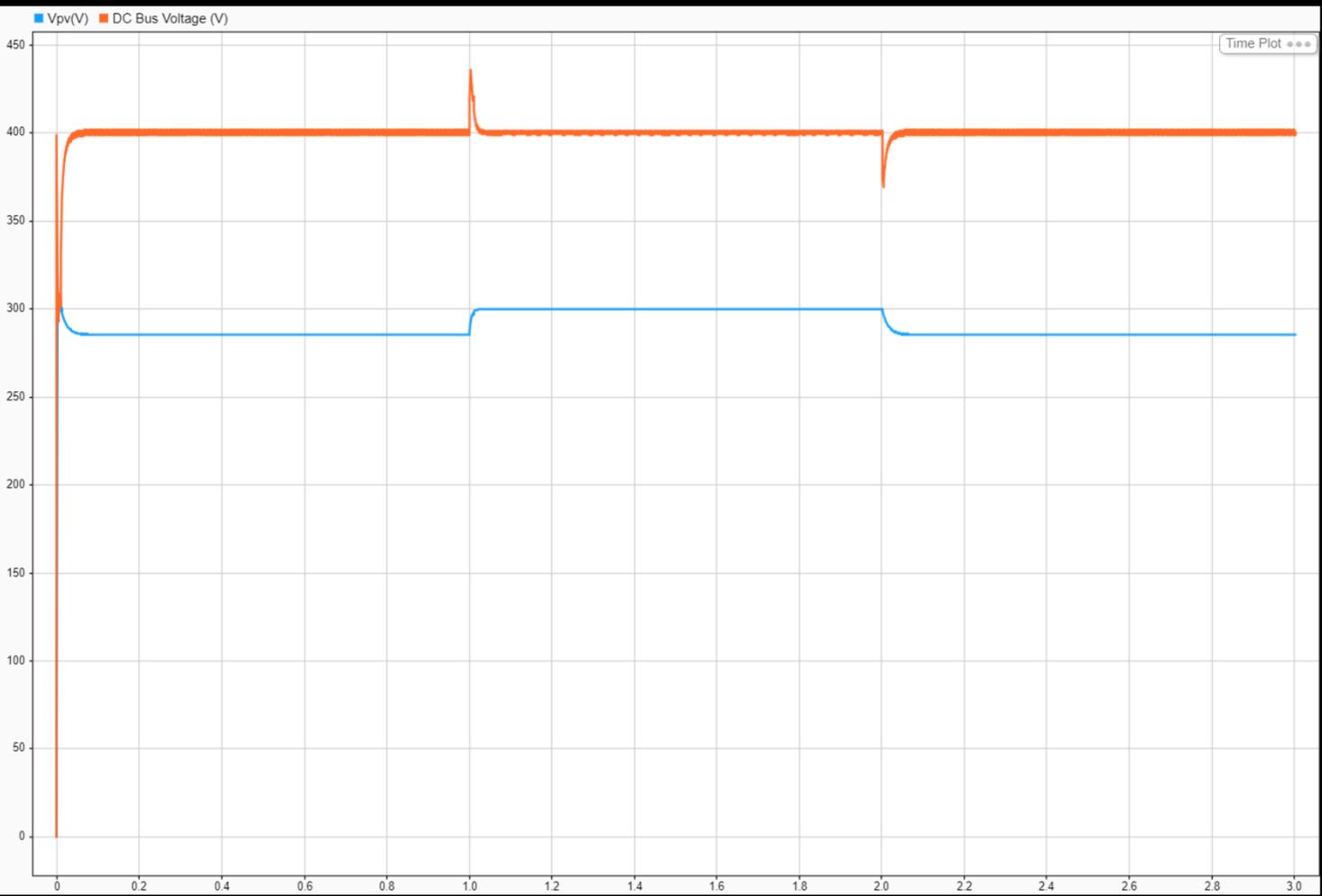


Irridance 변화시 system이 기능을 하지 못함

Variant Irridance

Electrical Circuit

Controller: Constant Voltage



Load 변화시, Constant voltage이기에 output voltage는 유지,
Solar Panel쪽 전압 변화

Load 변화시, 낼 수 있는 출력 감소(not mppt)

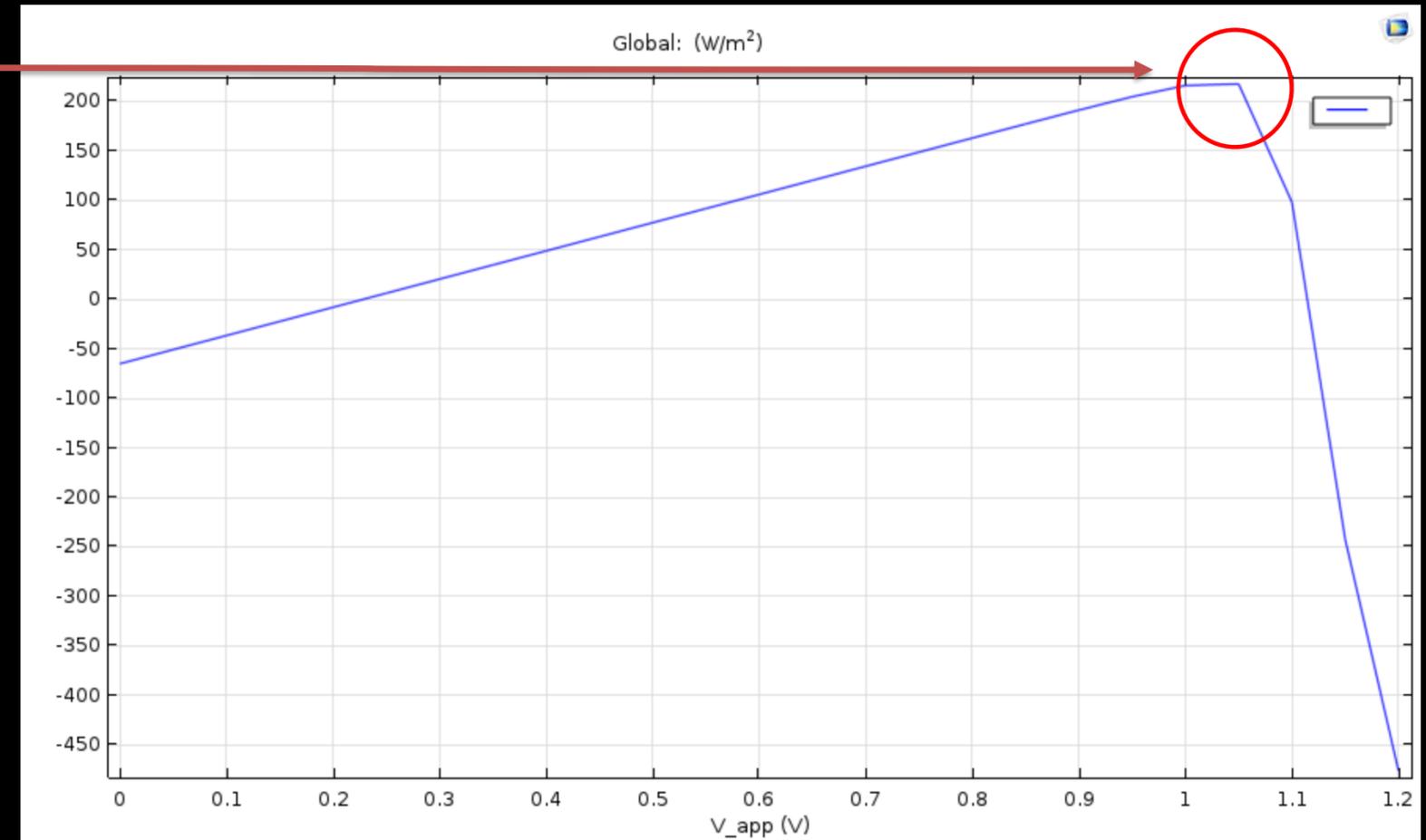
Variant Load

Electrical Circuit

Controller: MPPT Boost

What is MPPT (Maximum Power Point Tracking)

- 태양전지는 선형 전원(배터리)이 아니라, 전압-전류 곡선 $I-V$ 가 비선형인 소자다.
전력은 $P = V_{pv}I_{pv}$ 이고, 이 곡선 위에서 한 점에서만 최대가 된다.
- 전압·전류를 측정해서 실시간으로 “지금 MPP가 어디인지” 추정하고,
태양전지가 그 근처에서 동작하도록 전압/듀티를 조정하는 알고리즘
- 이 프로젝트에서는 Perturbation and Observation과 Extremum Seeking Control이라는 두 가지 제어를 활용하여 구현함



P-V Graph

Controller

Controller: MPPT Boost

Solar Panel / Boost Converter/ Load에서

Boost Converter에서 바라본 저항

$$\text{Solar Panel: } R_{mpp} = \frac{V_{mpp}}{I_{mpp}}$$

$$\text{Load: } R = \frac{V_o}{I_o}$$

$$\frac{V_o}{V_i} = \frac{1}{1 - D}$$

$$\frac{I_o}{I_i} = 1 - D$$

$$R_i = (1 - D^2) * R_{load}$$

제어 가능 한건 Duty비, 이 Duty 비를 통해 output 전압을 일정하게 유지하는 것이 아닌

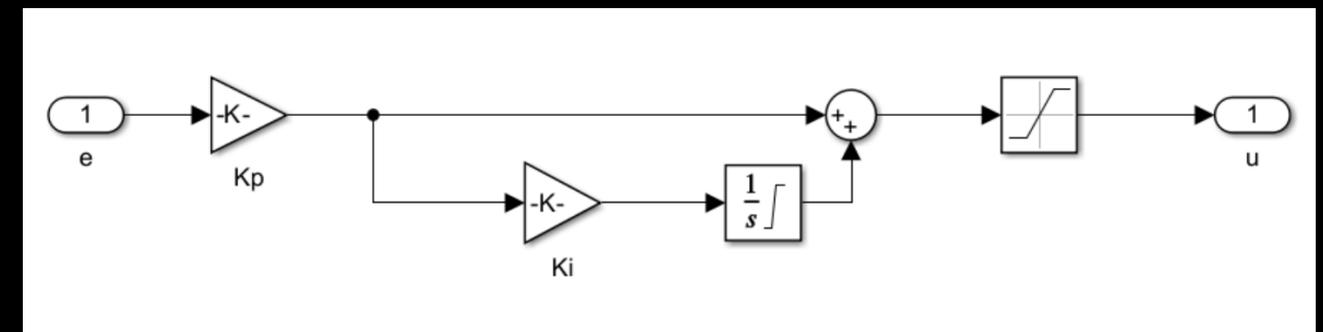
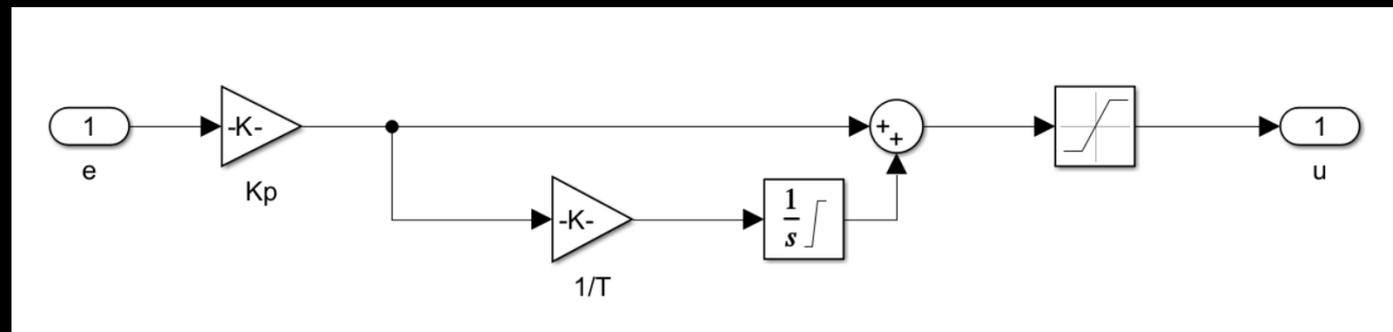
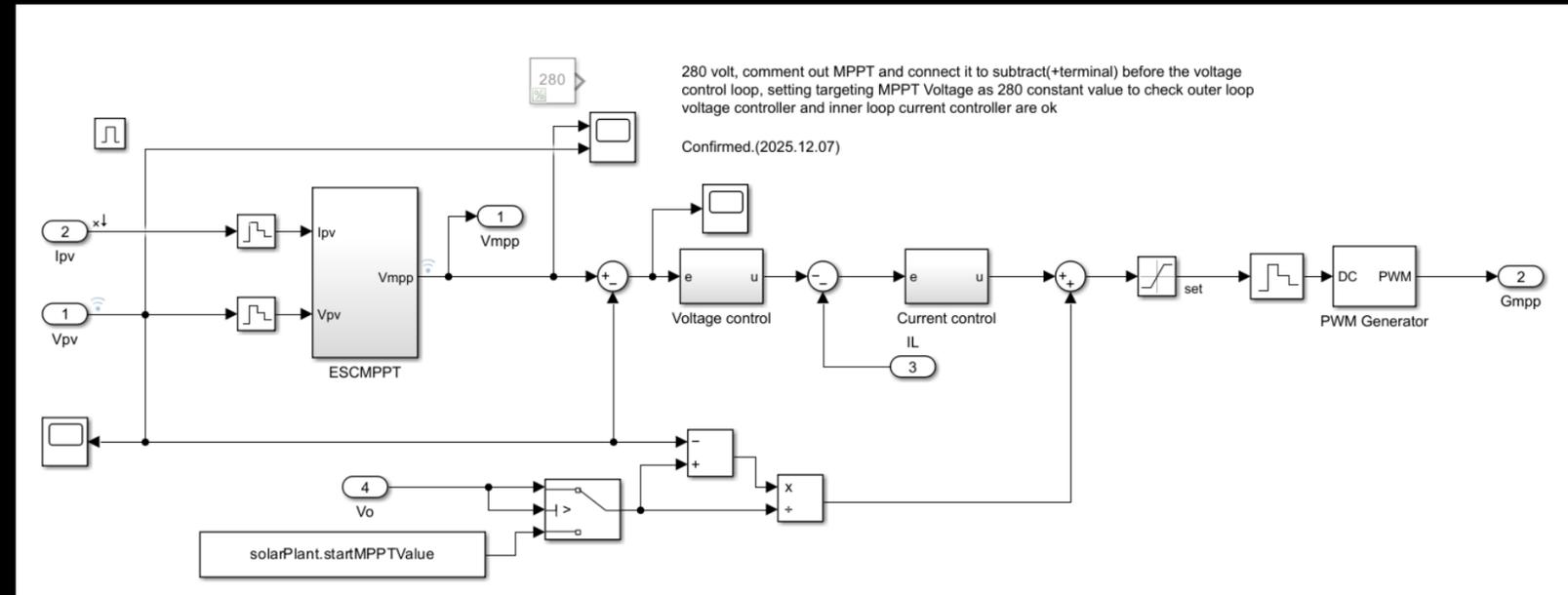
PV 쪽에 보이는 등가저항을 정해져있는 MPPT에서의 저항 R_{mpp} 에 맞춰

최대 출력 유지를 위한 임피던스비를 조절함

Controller

Controller: MPPT Boost Sub Controller

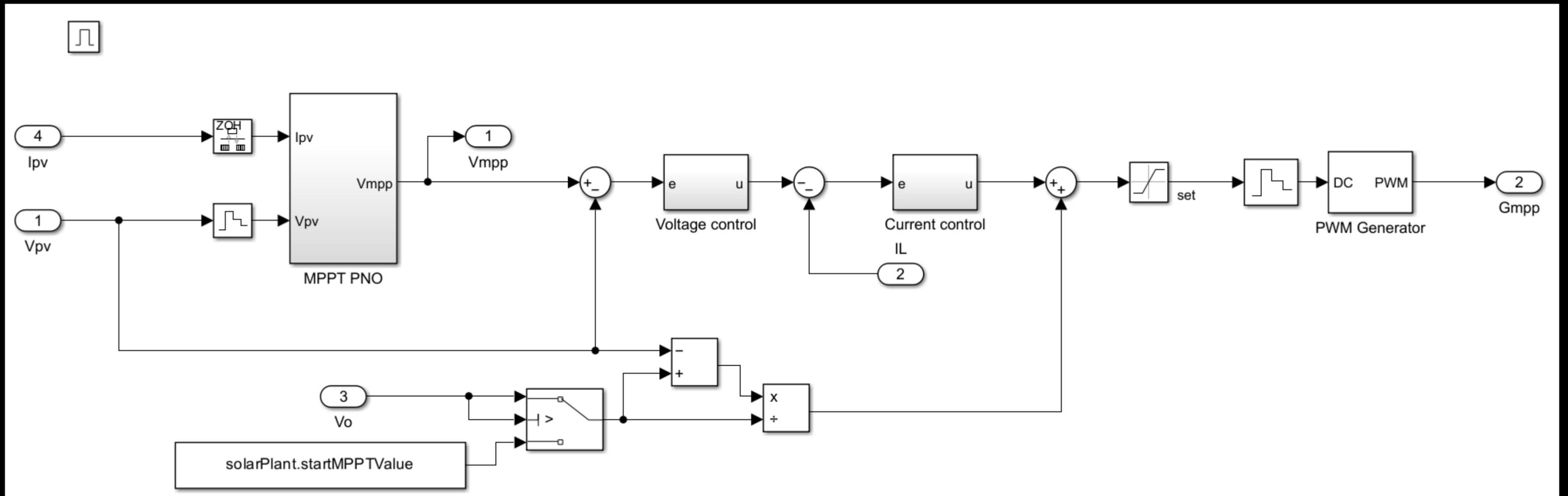
For both PNO and ESC



Voltage: PI Controller / Current: PI Controller
Vmpp를 Constant(280)으로 적용하여 MPPT Controller없이 Test

Controller

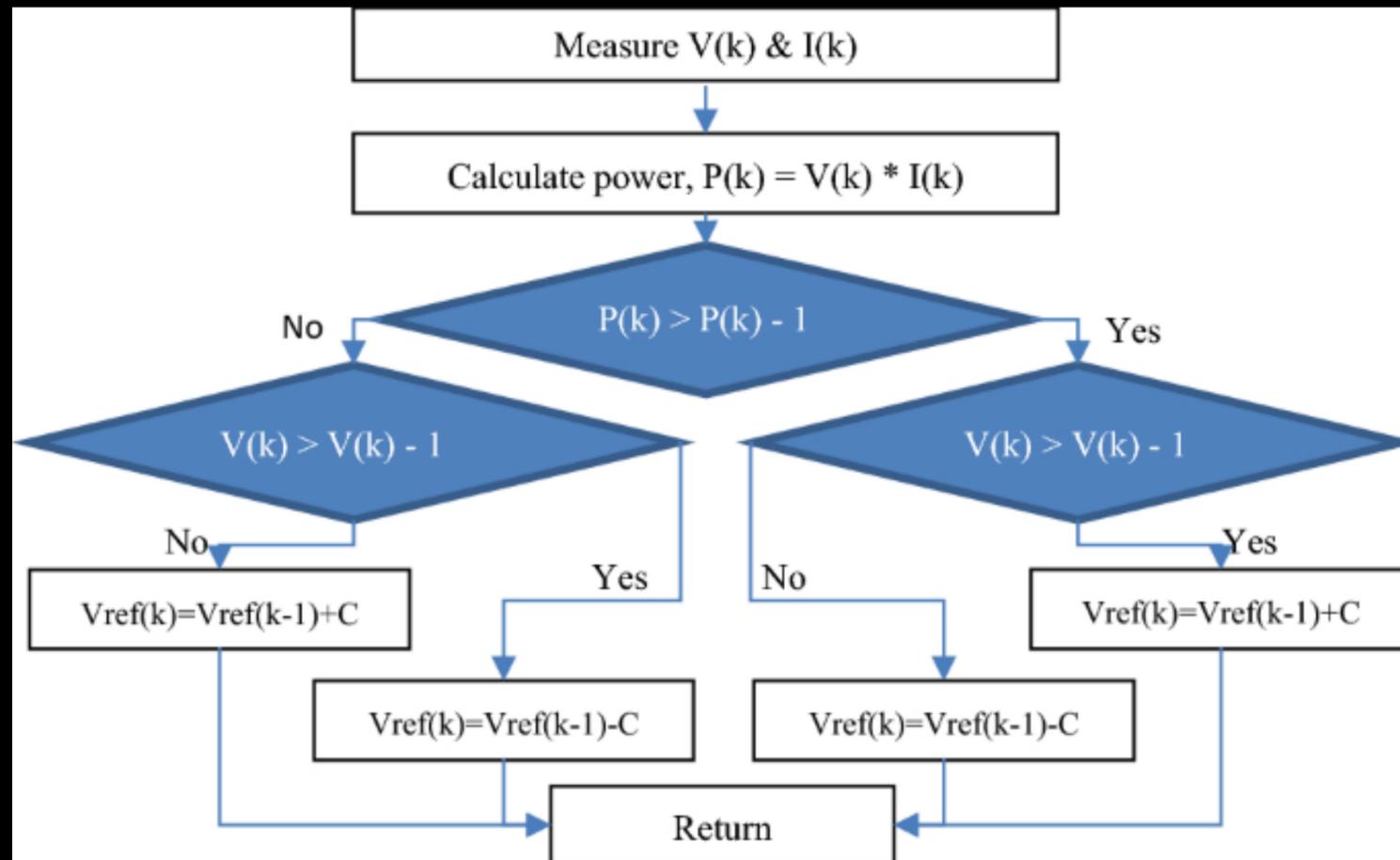
Controller: Perturbation and Observation



V_{pv} I_{pv} 값을 통해 V_{mpp} 도출

Controller

Controller: Perturbation and Observation



Perturbation & Observation

태양광 패널의 단자 전압과 전류를 주기적으로 측정

$P(k) = V(k) \cdot I(k)$ 로 순간 출력을 계산

현재 전력 $P(k)$ 와 직전 전력 $P(k-1)$,

현재 전압 $V(k)$ 와 직전 전압 $V(k-1)$ 를 비교

전압을 올릴지 내릴지의 방향만 결정

전력을 증가시킨 방향이면

$$V_{ref}(k) = V_{ref}(k-1) \pm C$$

로 같은 방향으로 한 스텝 더 이동

전력을 감소시킨 방향이면 부호를 바꿔서 반대 방향으로 이동

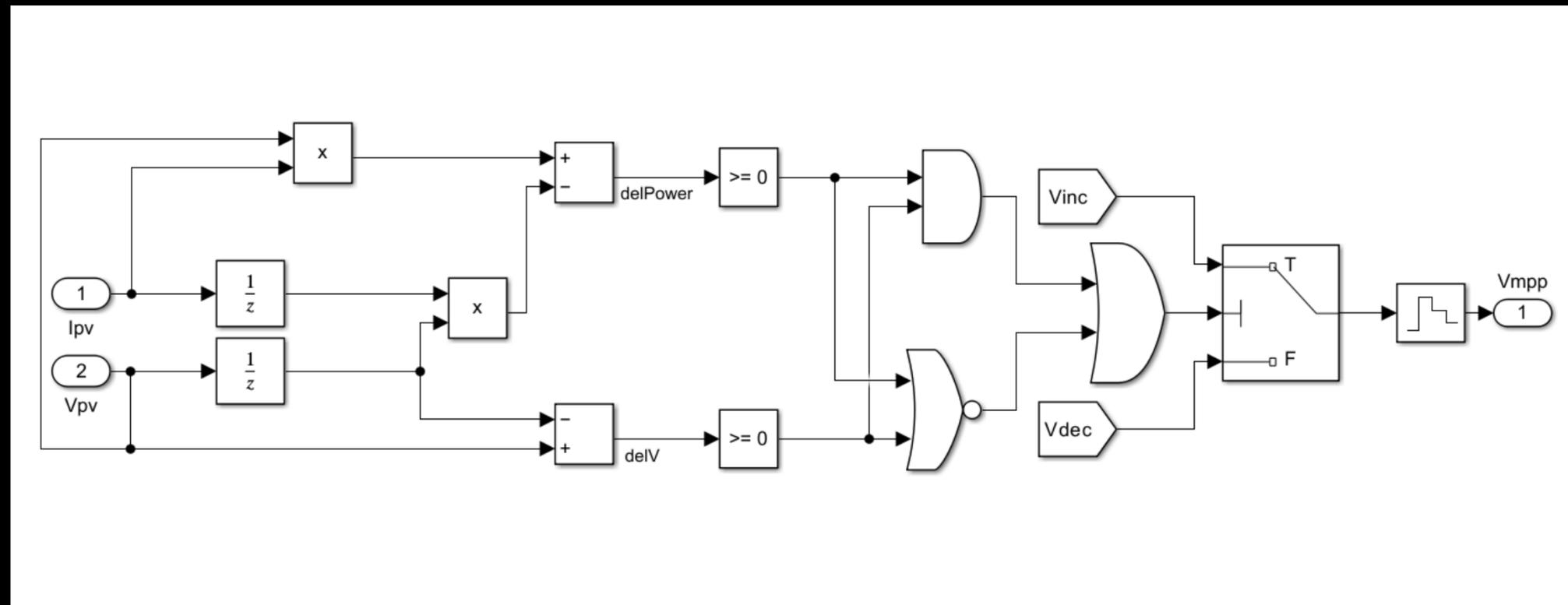
(C 는 스텝이며 클 경우 Ripple, 과하게 작을 경우 noise 취약 및 속도 문제)

이렇게 반복하면 dP/dV 가 0에 가까운 지점

즉 Maximum Power Point 근처에서 왔다 갔다 하는 상태로 수렴한다.

Controller

Controller: Perturbation and Observation



Test Scenario

Variant Irridance: 1000 initial value

1s step function 1000->800

2s step function 800->1000

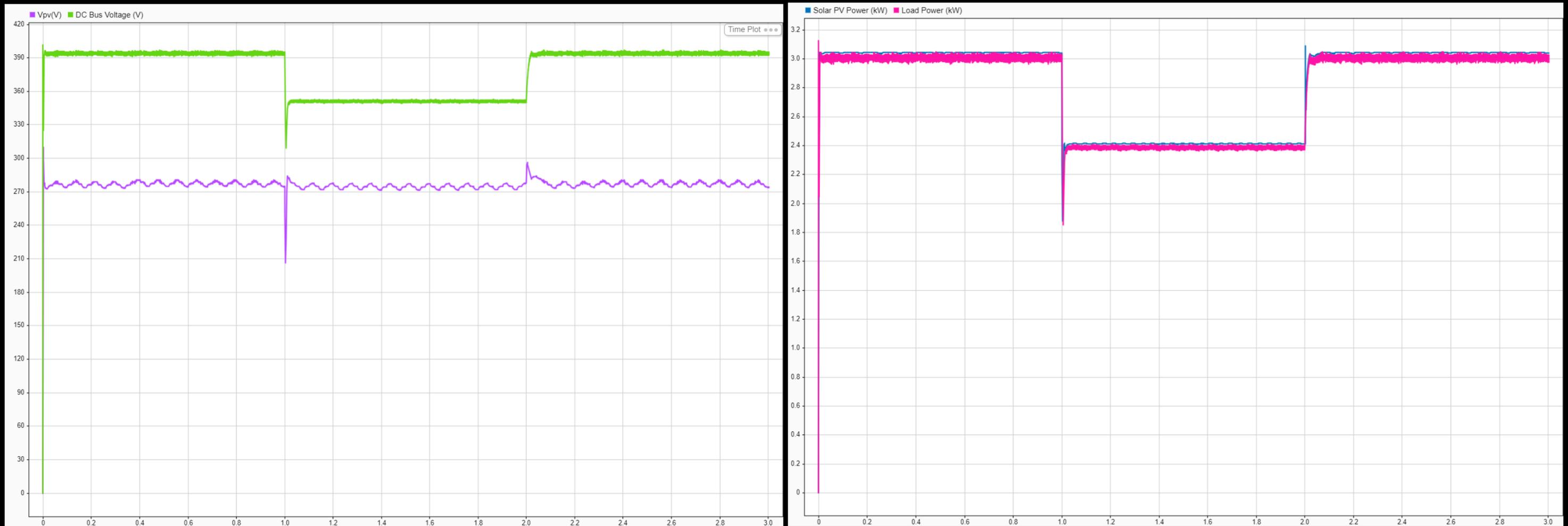
Variant Load: 3kW initial value

1s step function $3\text{kW} \cdot 0.8 = 2.4\text{kW}$

2s step function 2.4kW->3kW

Controller

Controller: Perturbation and Observation



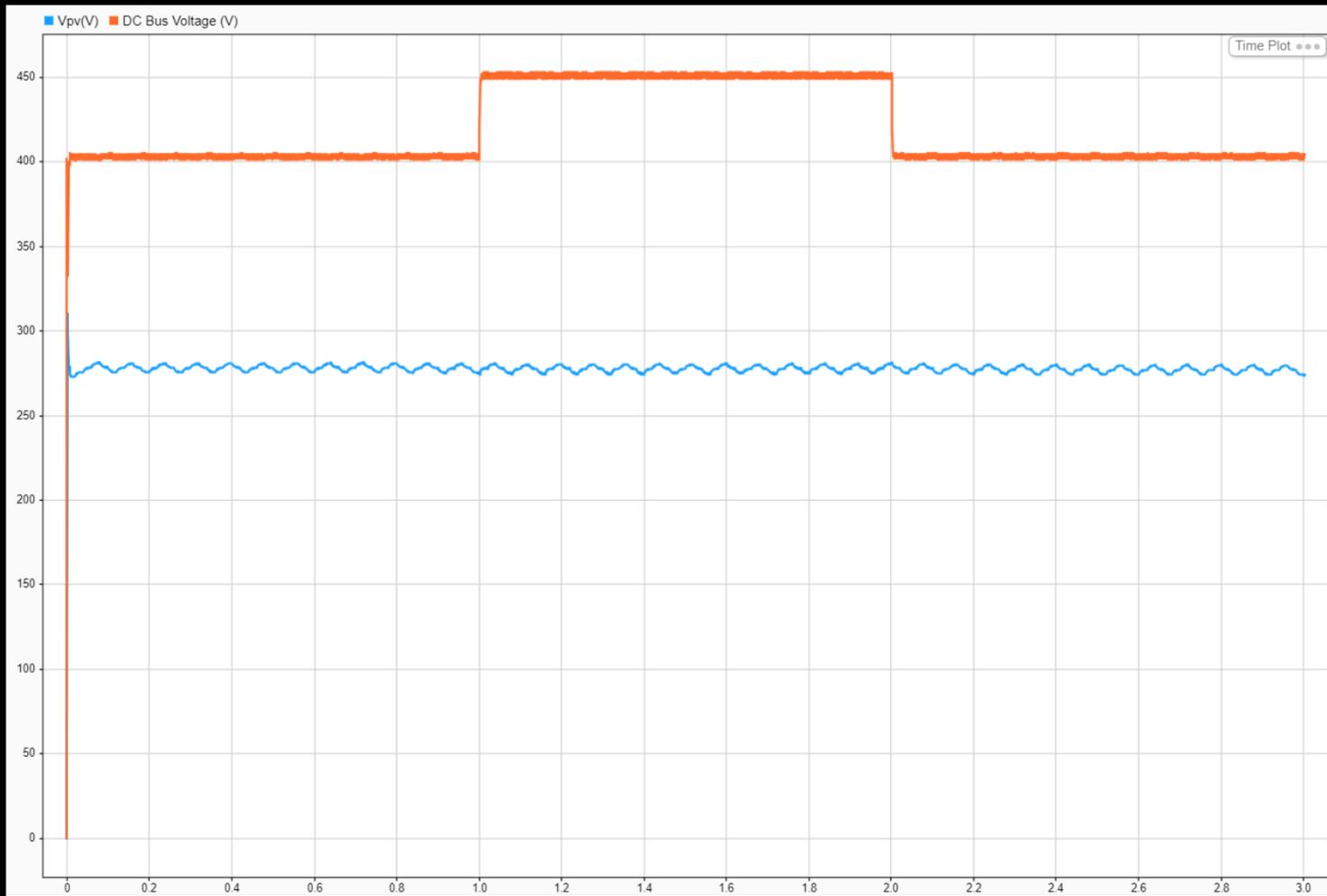
Irridance 변화 시 최대출력 감소로 인한 Output voltage 감소

Irridance 변화 시 최대출력 감소

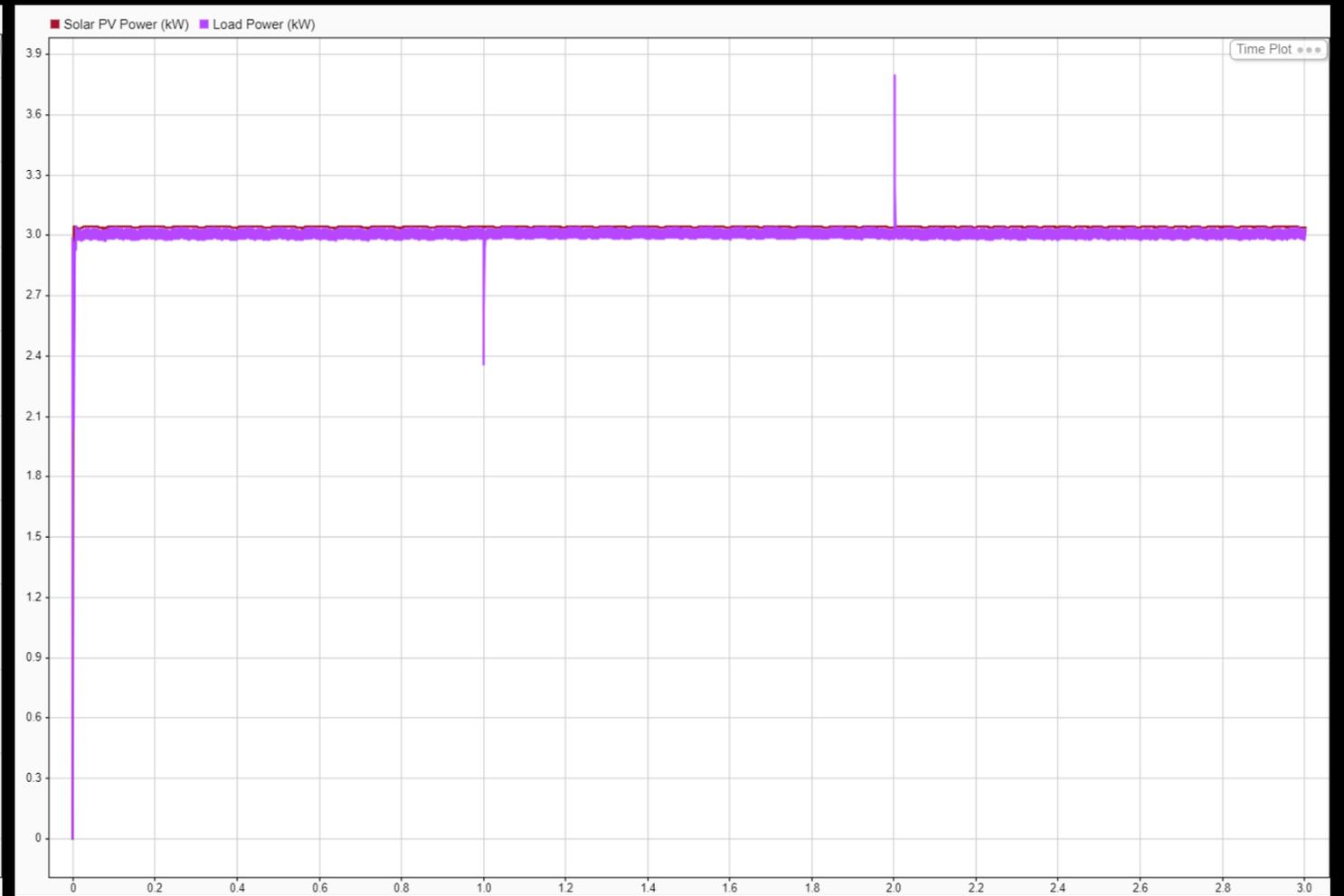
Variant Irridance

Controller

Controller: Perturbation and Observation



Load 변화 시 출력 유지를 위한 출력 전압 증가

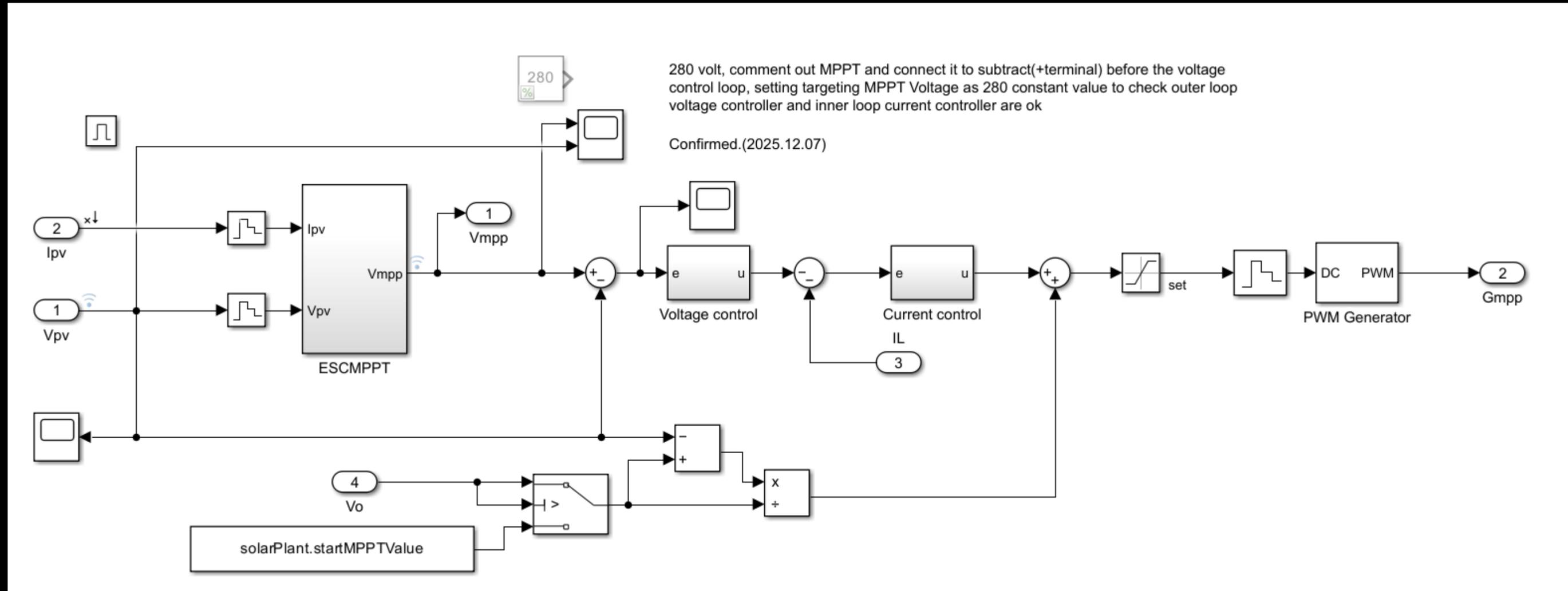


Load 변화에도 최대출력 유지

Variant Load

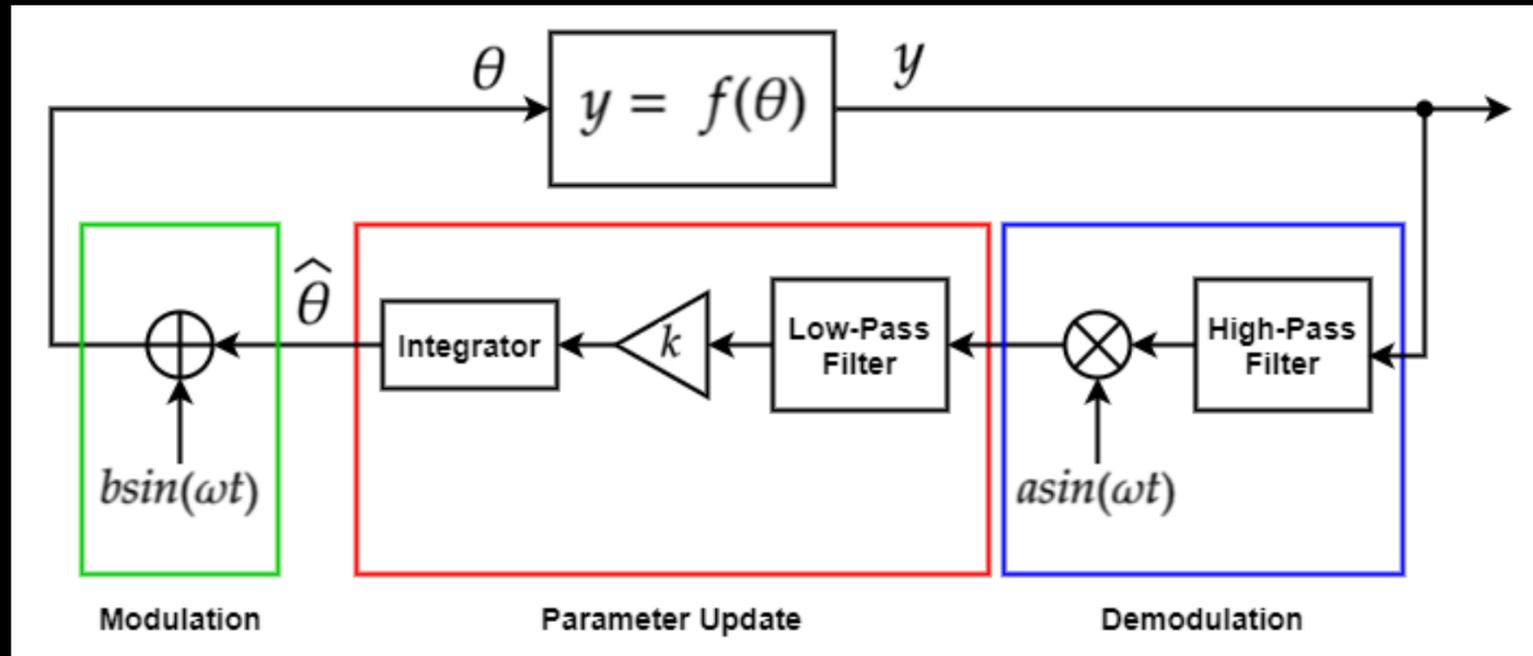
Controller

Controller: Extremum Seeking Control



Controller

Controller: Extremum Seeking Control



Extremum Seeking Control (ESC)

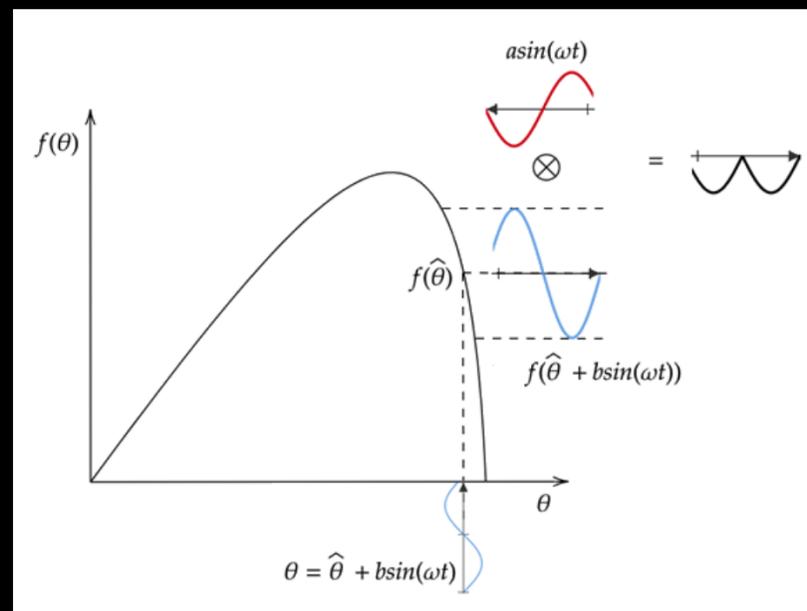
태양광 출력 전력 $y = P_{pv}(\theta)$ 이 최대가 되도록 (y 가 전체 plant) PV 단자 전압 기준값 $\theta = V_{mpp,ref}$ 를 **모델 없이** 실시간으로 조정하는 MPPT 알고리즘.

입력 dither (Modulation): 현재 추정값 θ 에 작은 사인파 $b \sin(\omega t)$ 을 더해 실제 플랜트 입력을 $\theta = \theta + b \sin(\omega t)$ 로 만들어 θ 주변을 계속 진동

출력 리플 추출 (High-Pass Filter): $y(t)$ 를 HPF에 통과시켜 DC 성분을 제거하고 리플 성분 $y_{HP}(t)$ 만 분리.

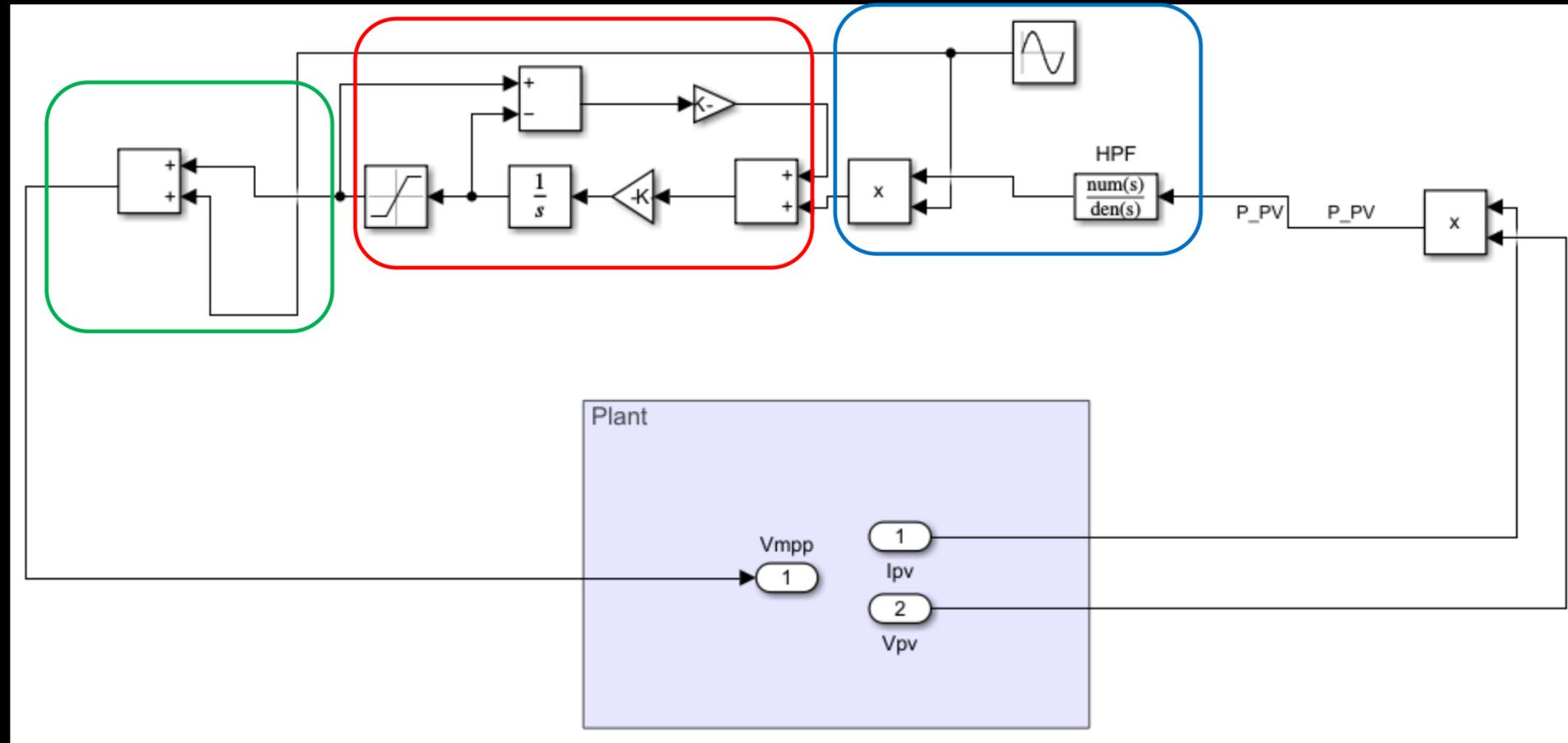
Gradient 근사 (Demodulation): $y_{HP}(t)$ 에 같은 사인파 $a \sin(\omega t)$ 을 곱해 평균을 내면 $y_{HP}(t) a \sin(\omega t) \propto df/d\theta(\theta)$ 가 되어, 현재 위치 θ 에서의 기울기 (gradient) 부호·크기를 얻을 수 있음.

θ 업데이트 (적분기): 이 값을 k -적분기에 넣어 θ 를 천천히 변경
 \rightarrow gradient > 0 이면 θ 증가, < 0 이면 감소, ≈ 0 이면 extremum 근처에 머무름.



Controller

Controller: Extremum Seeking Control



Test Scenario

Variant Irridance: 1000 initial value

1s step function 1000->800

2s step function 800->1000

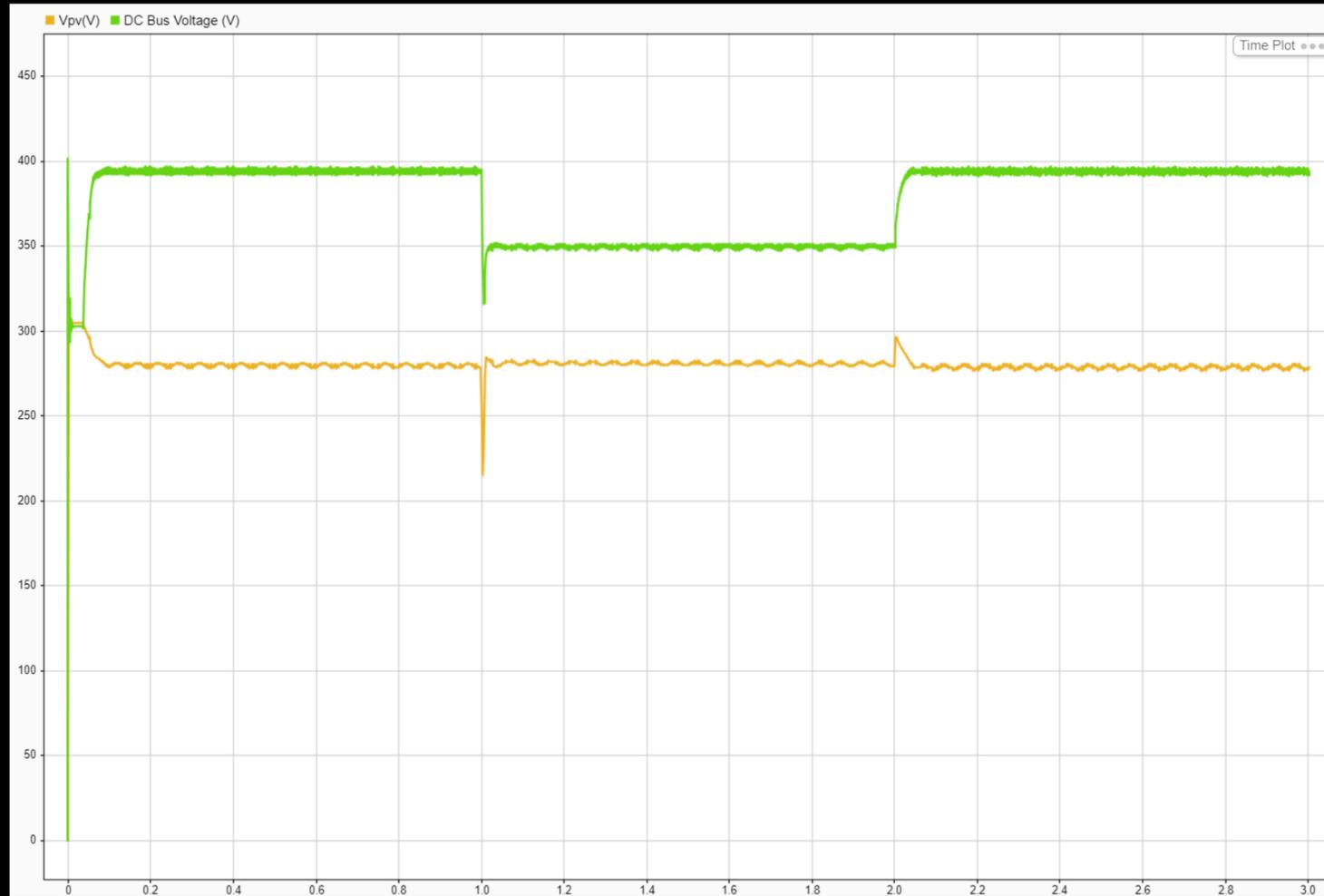
Variant Load: 3kW initial value

1s step function $3\text{kW} \cdot 0.8 = 2.4\text{kW}$

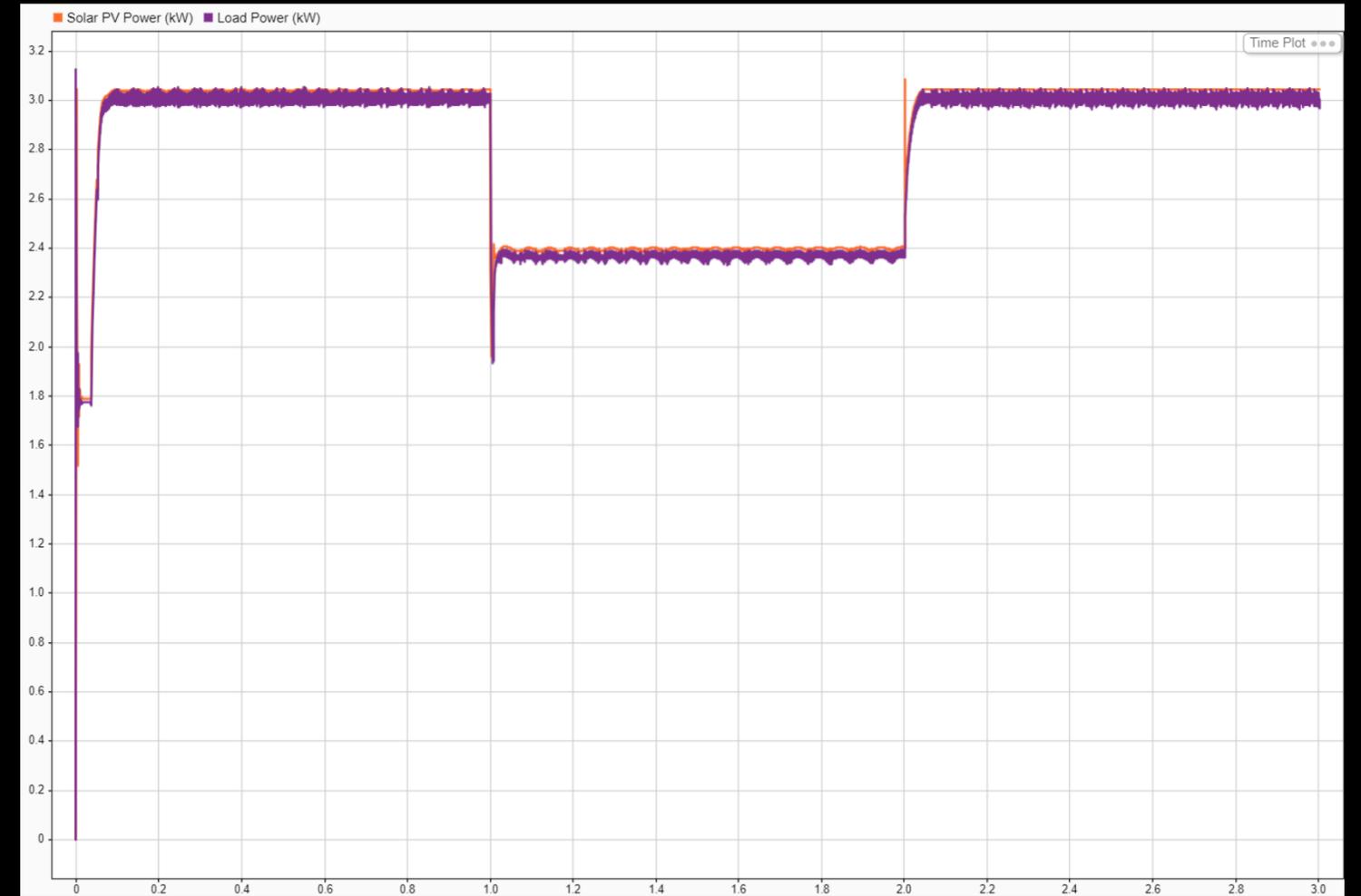
2s step function $2.4\text{kW} \rightarrow 3\text{kW}$

Controller

Controller: Extremum Seeking Control



Irridance 변화시 출력 감소에 따른 output voltage 감소

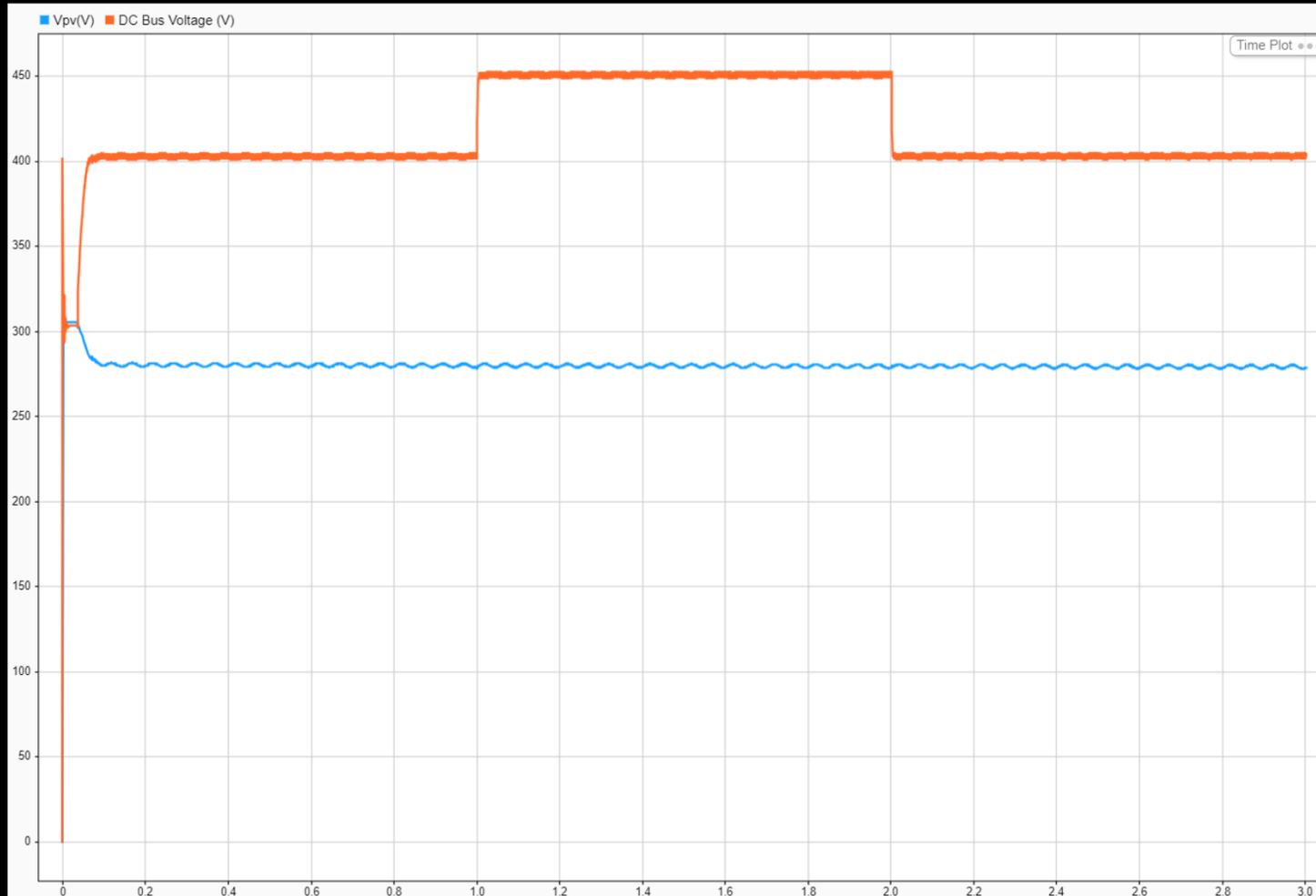


Irridance 감소시 최대 출력 감소

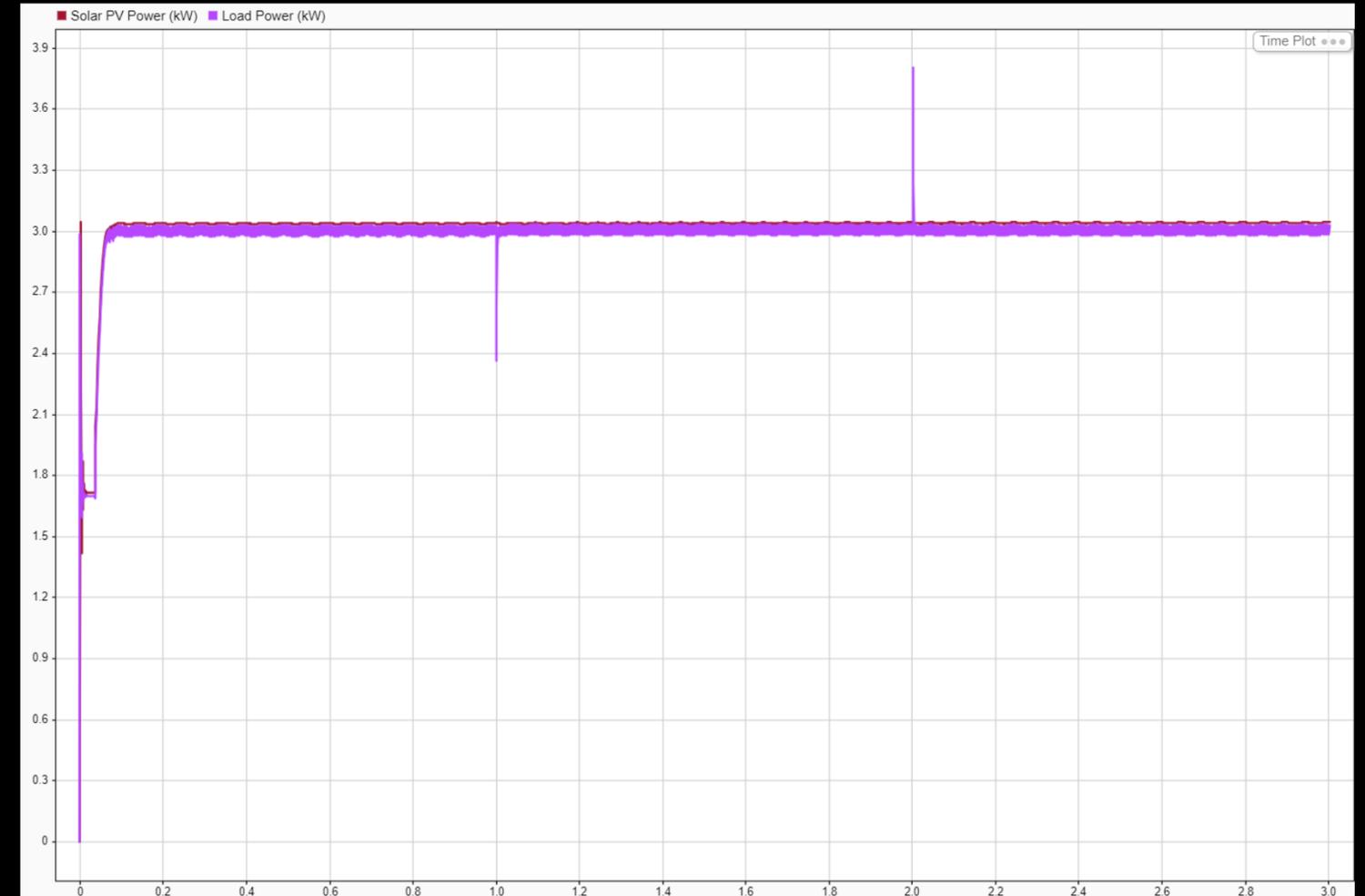
Variant Irridance

Controller

Controller: Extremum Seeking Control



Load Change시 전력 유지 -> Output 전압 상승



MPPT이기에 Load Change에도 Power는 유지

Variant Load

Analysis

Controller: Perturbation and Observation

| | Desired(COMSOL Analysis) | PnO(SS) | 오차율 |
|--------------|--------------------------|--------------------------|--------|
| $P_{pv}[kW]$ | 3.11 | 3.04(Ripple 0.1) | 2.251% |
| $V_{pv}[V]$ | 280 | 277.65(mean)(Ripple5.5V) | 0.839% |

Controller: Extremum Seeking Control

| | Desired(COMSOL Analysis) | PnO(SS) | 오차율 |
|--------------|--------------------------|-----------------------|--------|
| $P_{pv}[kW]$ | 3.11 | 3.035(Ripple0.1) | 2.412% |
| $V_{pv}[V]$ | 280 | 280.2(mean)(Ripple2v) | 0.071% |

Analysis

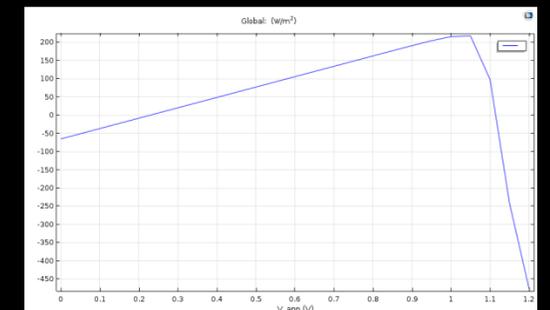
ESC가 전압 추종 및 리플 성능은 훨씬 좋은 성능을 보임

Power는 둘 다 거의 같은 값을 추종하며

이는COMSOL에서 진행한 해석과 Simulink 내부 몇몇 파라미터 차이로 인한 오차로 판단됨

두 제어기 모두 step을 밟거나 조금씩 경향성을 보며 추종하는 제어기이므로 가장 가까운 local최대점만 추종함

Solar Cell 의 P-V Curve(단봉형)를 고려했을 때, 구현 난이도 대비 성능 좋은 제어기



References

- K. Lee et al., "Improving the physical properties of polyolefin elastomer encapsulants by radical initiators for reliable photovoltaic modules," *Polymer Testing*, vol. 151, Art. no. 108954, 2025.
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