An Experimental Study on P-f and Q-V Droop Control of Photovoltaic Power Generation Contributing to Grid Frequency Operation

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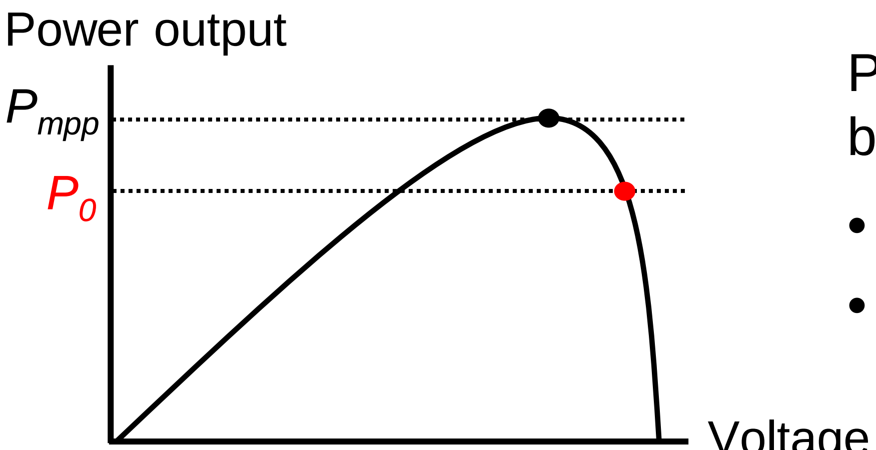
Background

Recently, photovoltaic power generation (PV) is expanded

- According to the decrease of ratio of thermal power plant which performs frequency control, decrease of frequency regulation capacity is concerned

Contribution to frequency control by PV is expected



P-V characteristic of PV panel

PV which preforms power curtailment can be utilized for active power control

- The headroom enables up-regulation
- Further power curtailment enables down-regulation

Objective

There are various types of frequency fluctuation

⇒ Different types of controls are required

- PV control contributing to GF or LFC
  - Reduces frequency fluctuation caused by change in load
  - Constantly activated
- PV control which supports inertial response of synchronous generators
  - Reduces frequency fluctuation caused by dropout of generator or load
  - Only responds in emergency case
  - Quick response

Objective

- Develop combined control method
- Confirm the performance by experiment

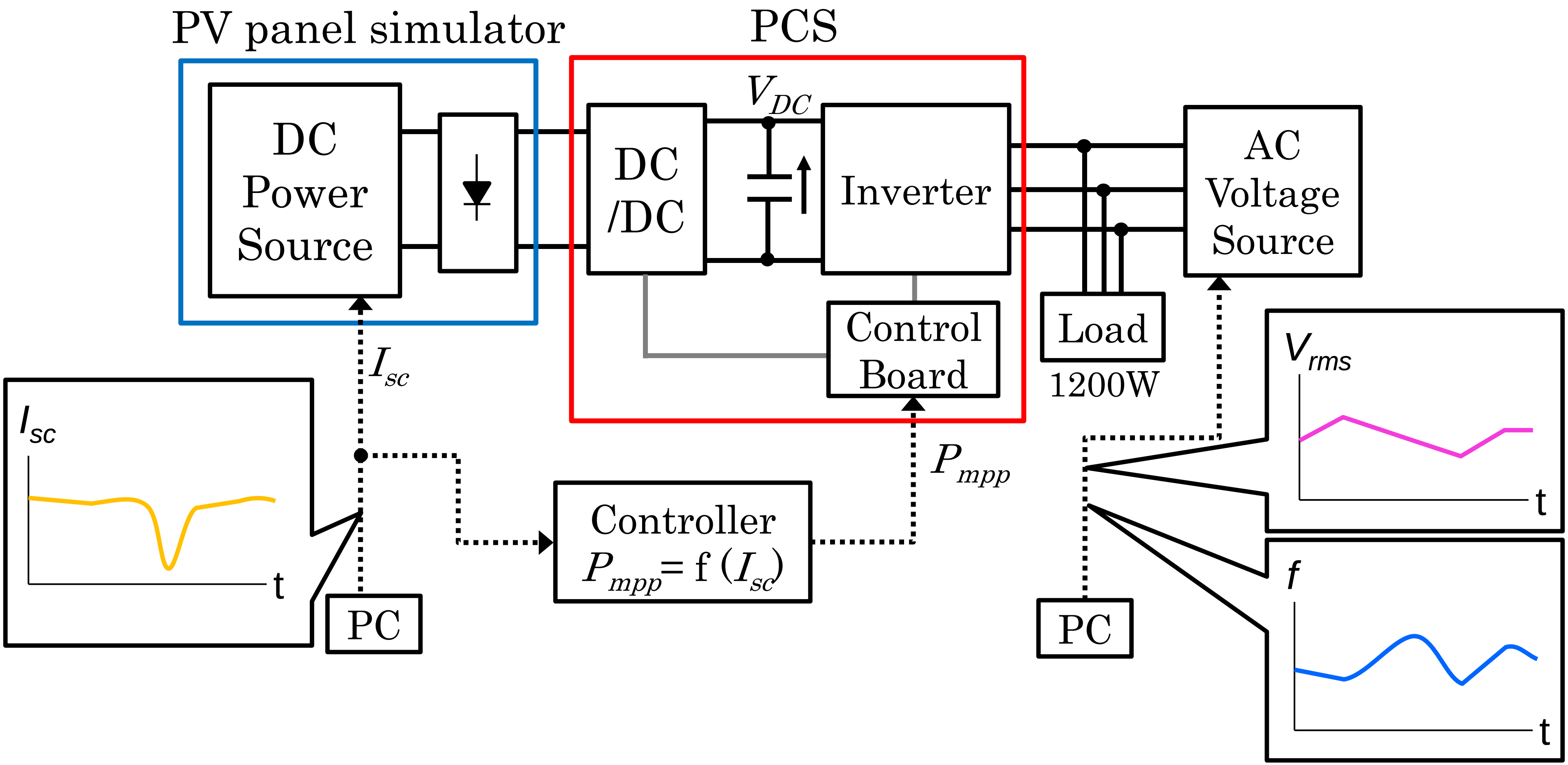
Outline

1. Introduction
2. Experimental setup and controllers
3. Operation test

   Test1: Slow frequency regulation and voltage regulation

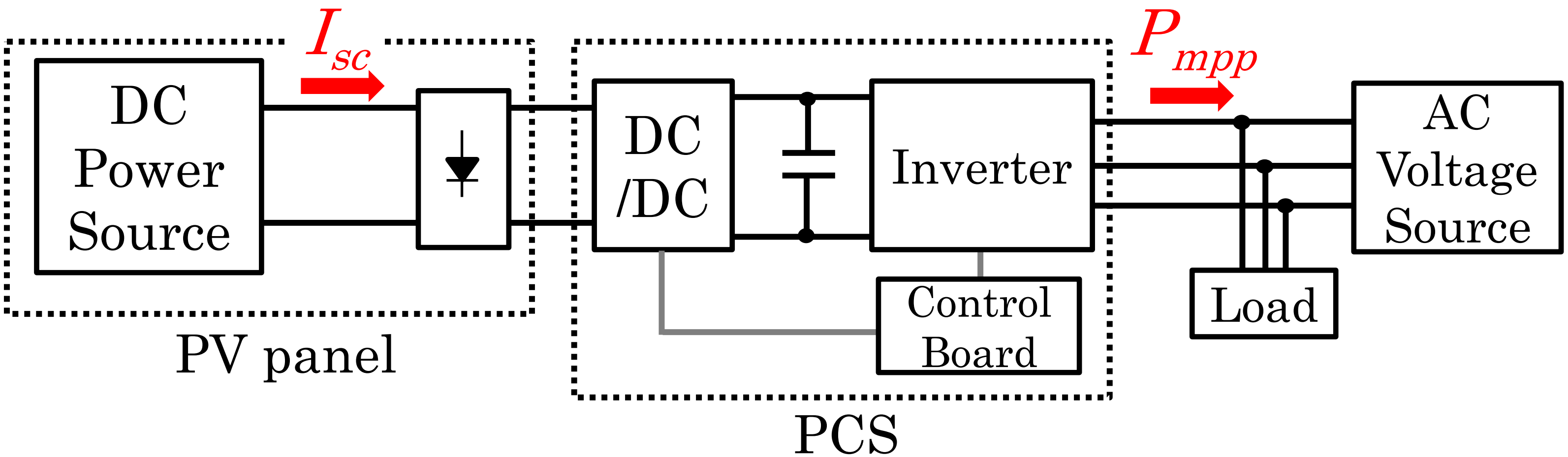
   Test2: Slow frequency regulation and fast frequency regulation
4. Conclusion

Experimental setup



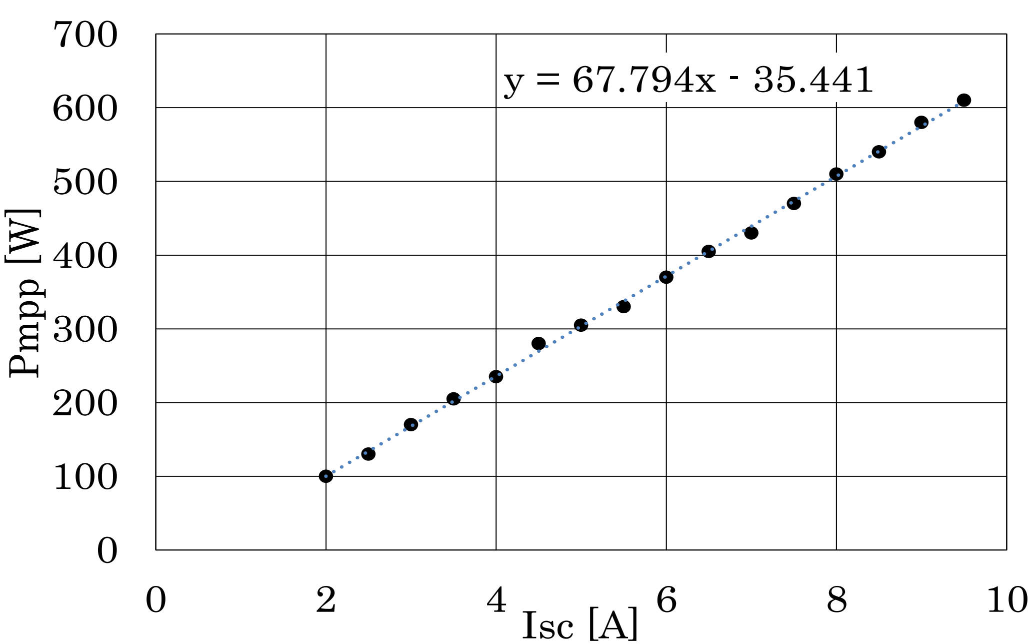
- Solar irradiance: Simulated by setting time variation of I_{sc}
- Grid voltage: Simulated by setting time variation of voltage level and frequency
- Estimation of P_{mpp} : Estimated by P_{mpp} = f (I_{sc})

Formulation of $P_{mpp} = f\ (I_{sc})$



Analyze the relationship between I_{sc} and P_{mpp}

Formulate $P_{mpp} = f\ (I_{sc})$



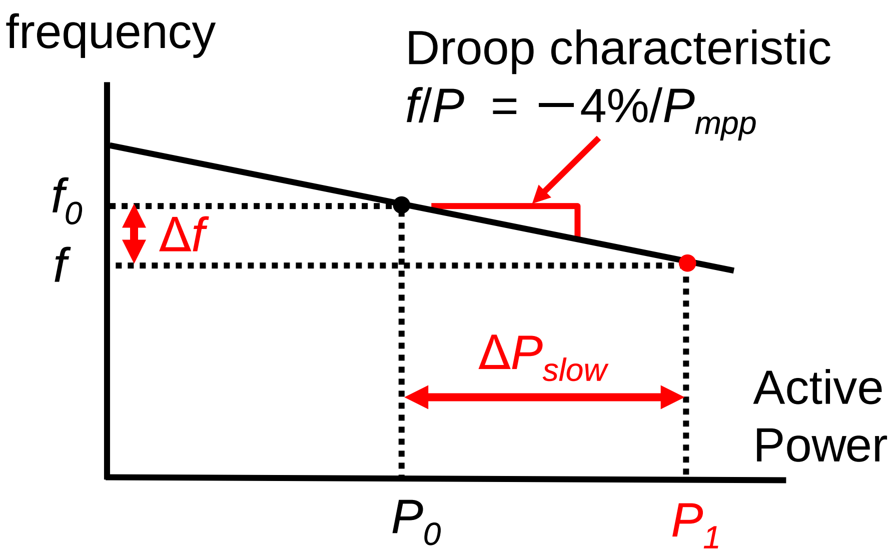
Slow P-f Droop Control

- Power curtailment

Pre-set point of active power output P_0 is calculated by multiplying P_{mpp} and power output rate δ, which is determined by system operator, etc.

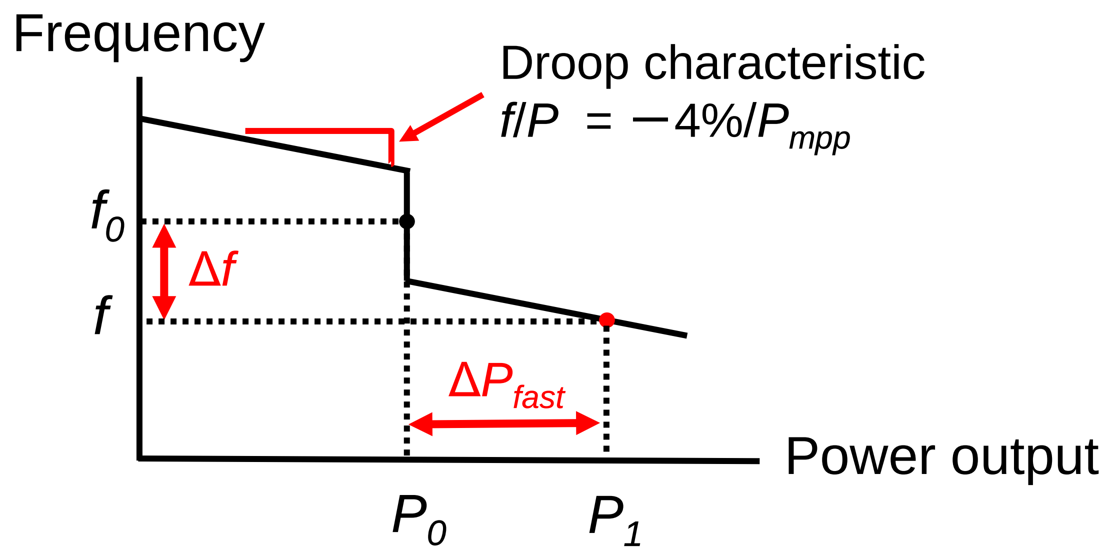
- P-f Droop control

The target value ΔP_{slow} is determined based frequency deviation Δf and droop characteristic



Fast P-f Droop Control

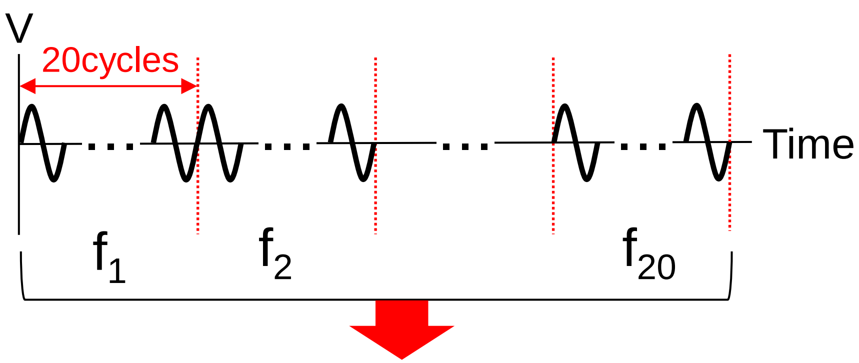
for quick response to frequency fluctuation caused by dropout of generator or load



- Dead band: ±0.2Hz
- Slow P-f droop control is deactivated when frequency fluctuation exceeding dead band is detected

Frequency measurement for droop controls

Frequency measurement for slow droop

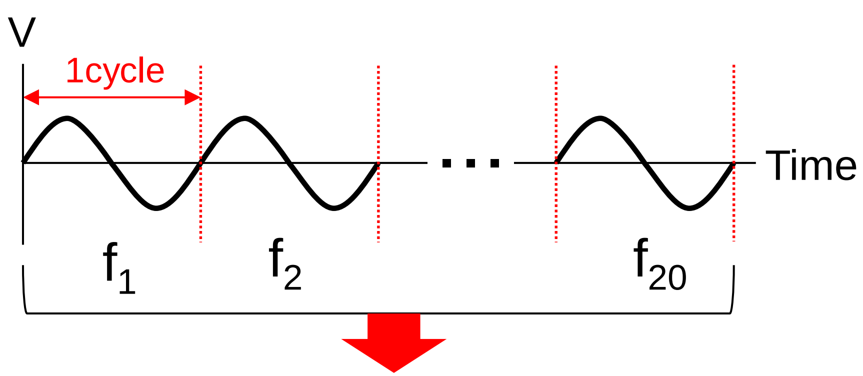


f_{slow}: Moving average of 20 samples

Short term and tiny frequency fluctuation does not affect the value of f_{slow} significantly

Prevent sudden and excessive change in target value of slow P-f control

Frequency measurement for fast droop



f_{fast}: Moving average of 20 samples

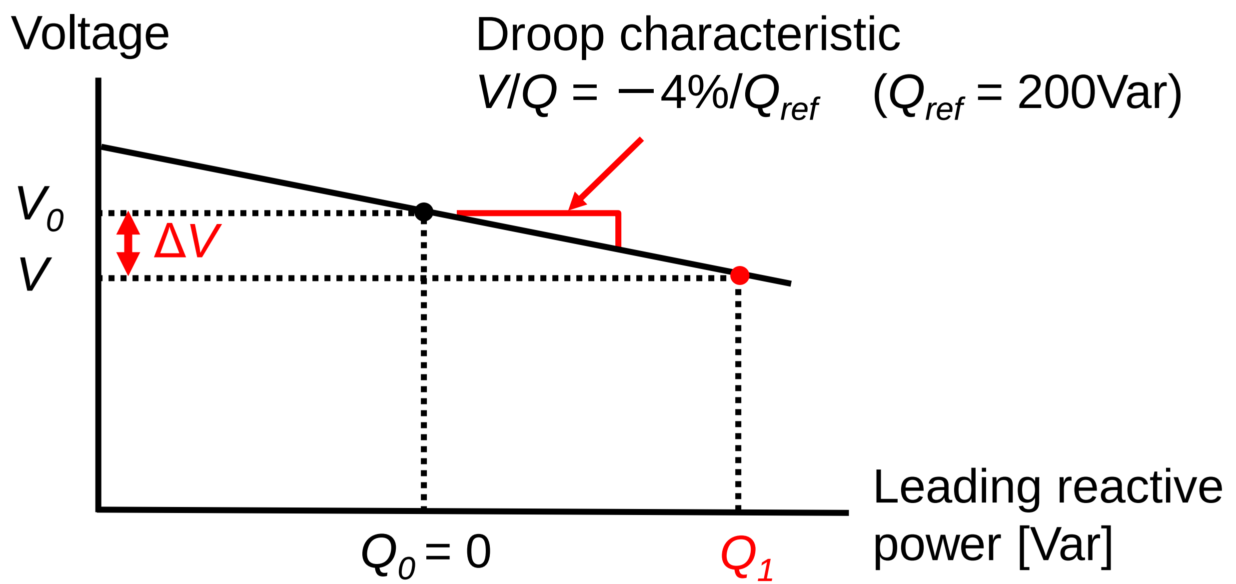
Target value of fast P-f control quickly responds because short term frequency fluctuation changes value of f_{fast} significantly

Q-V Droop Control

Contribution of PV to voltage regulation is expected in distribution network with high-penetration of PV

A function to inject leading or lagging reactive power according to voltage increase or decrease is installed

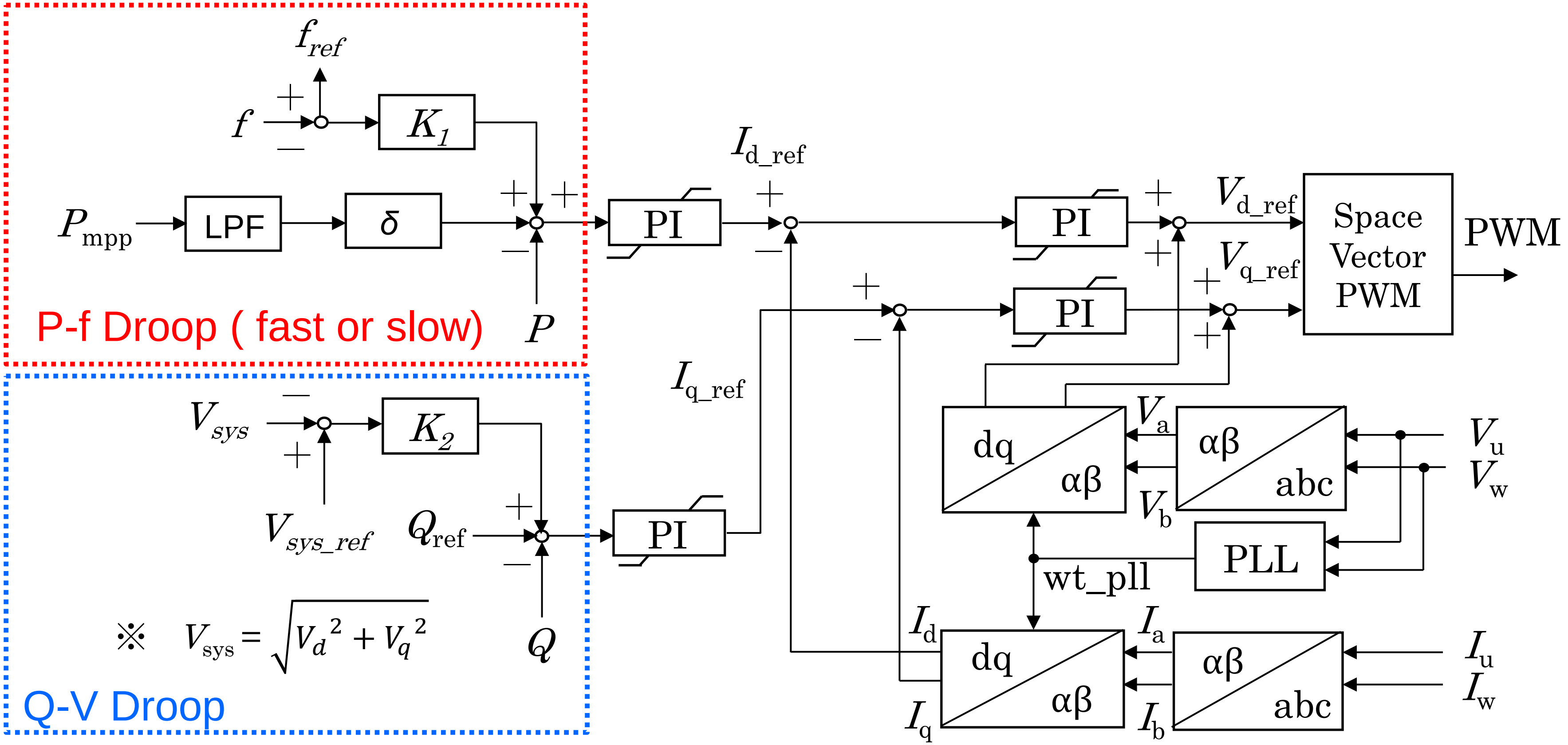
- Command value of reactive power Q_1 is determined by Droop control



Q-V droop control

Controller of the Inverter

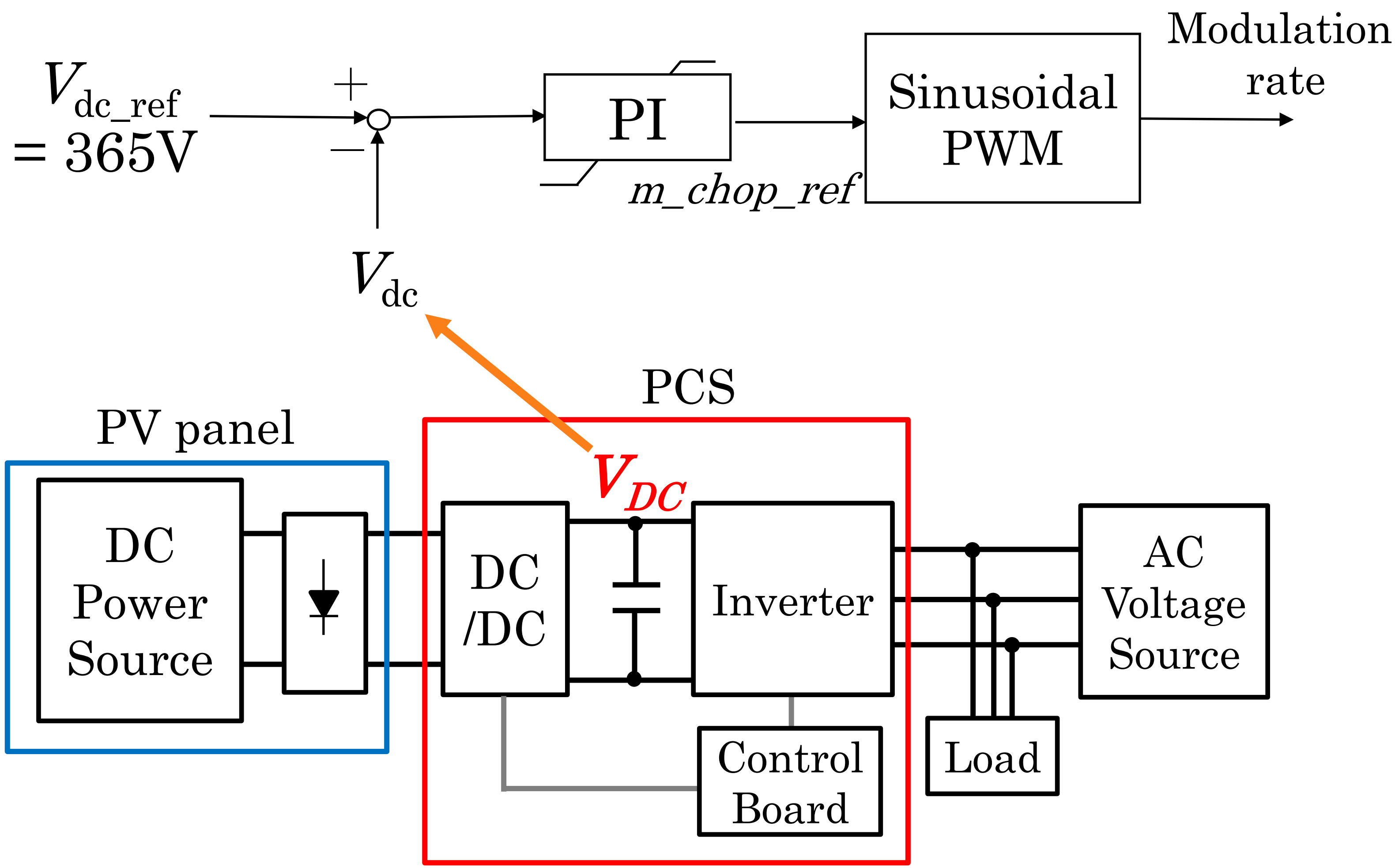
- Active power control by P-f droop
  - Droop characteristic: $f\,/\,P = -4\%\,/\,P_{mpp}$
- Reactive power control by Q-V droop
  - Droop characteristic: $V\,/\,Q = -4\%\,/\,Q_{ref}$ (Q_{ref} = 200Var)



Controller of the DC/DC Converter

Keep V_{dc} equals to 365V

⇒ DC/DC converter supplies the power required by the inverter



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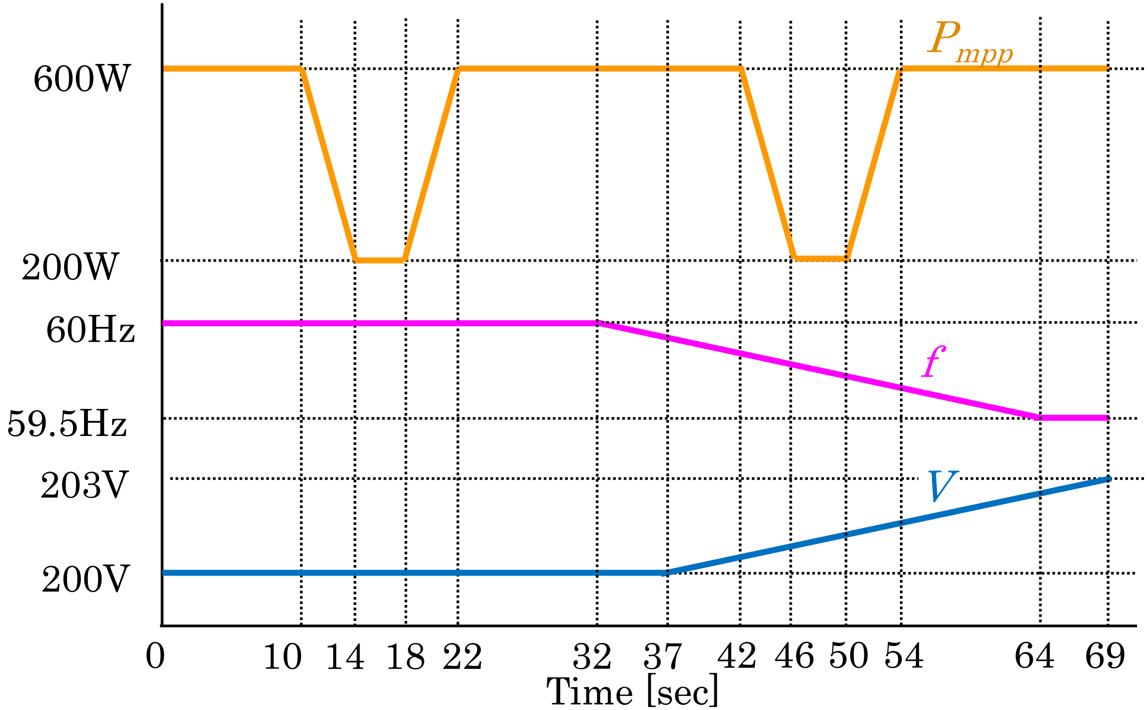
Operation test

	Slow P-f Droop Control	Fast P-f Droop Control	Q-V Droop Control
Test 1	○	×	○
Test 2	○	○	×

- Operation test was conducted in a step-by-step manner
- Power output rate of PV is 50% of P_{mpp}

- Operation of slow frequency regulation and voltage regulation was tested first

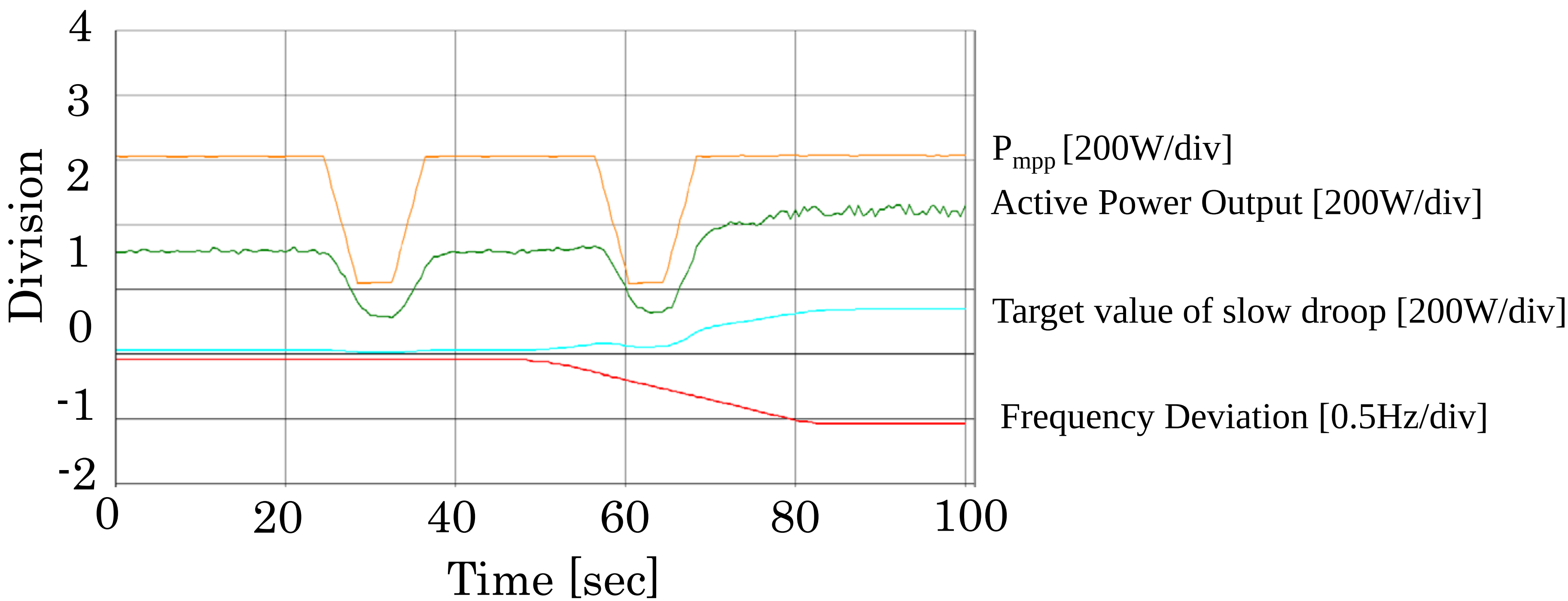
Operation test 1



Operation test 1 is aimed to confirm active and reactive power are properly controlled even during fluctuation of P_{mpp}

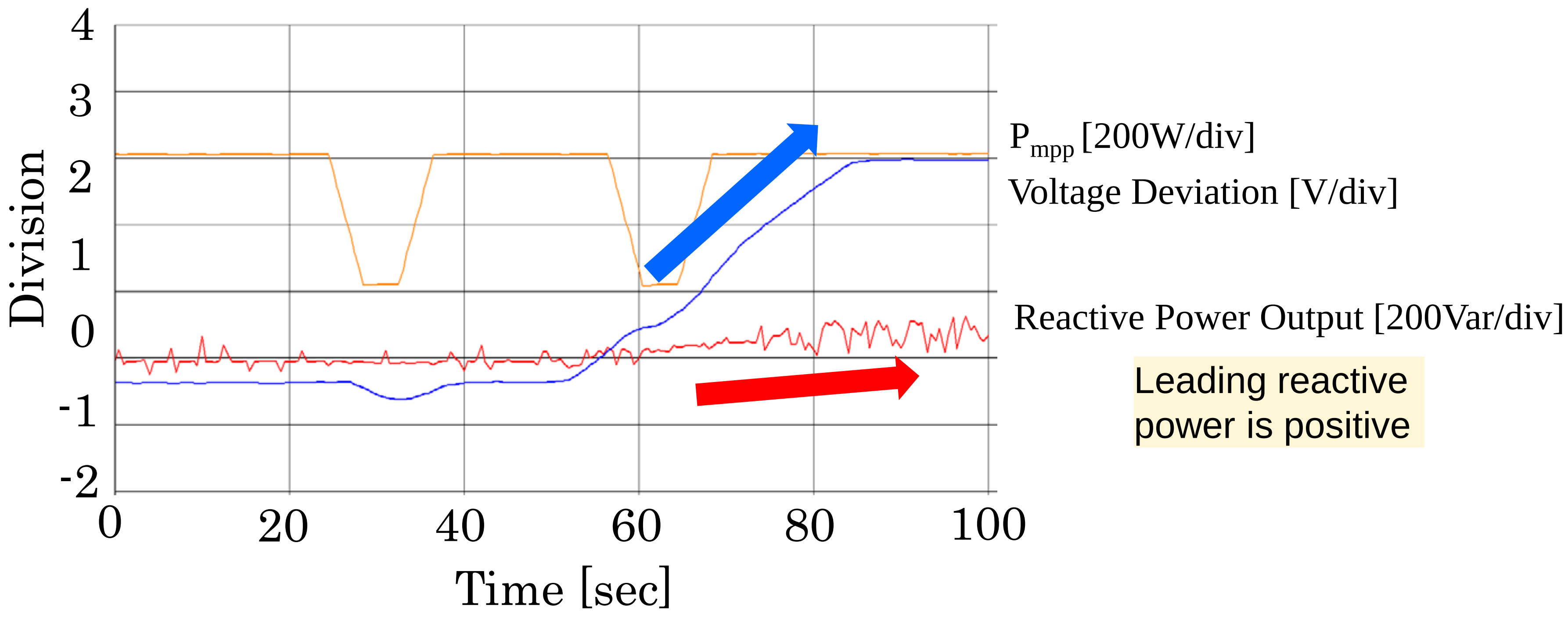
- During the 1st drop of P_{mpp}, frequency and voltage are kept at rated value
- During the 2nd drop of P_{mpp}, frequency is decreased and voltage is increased

Experimental result: active power



- Active power output of PV was properly increased from pre-set value by P-f Droop control when frequency dropped gradually

Experimental result: reactive power



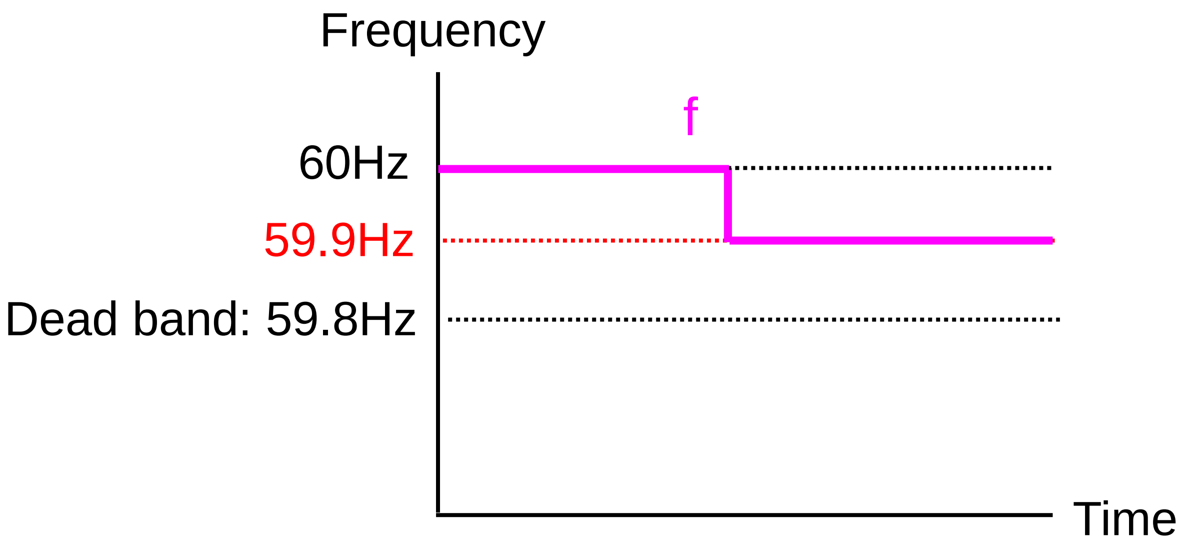
- Leading reactive power of PV was increased properly by Q-V Droop control when voltage increased
- Q-V Droop control worked properly independent with P-f Droop control

Operation test 2

	Slow P-f Droop Control	Fast P-f Droop Control	Q-V Droop Control
Test 1	○	×	○
Test 2	○	○	×

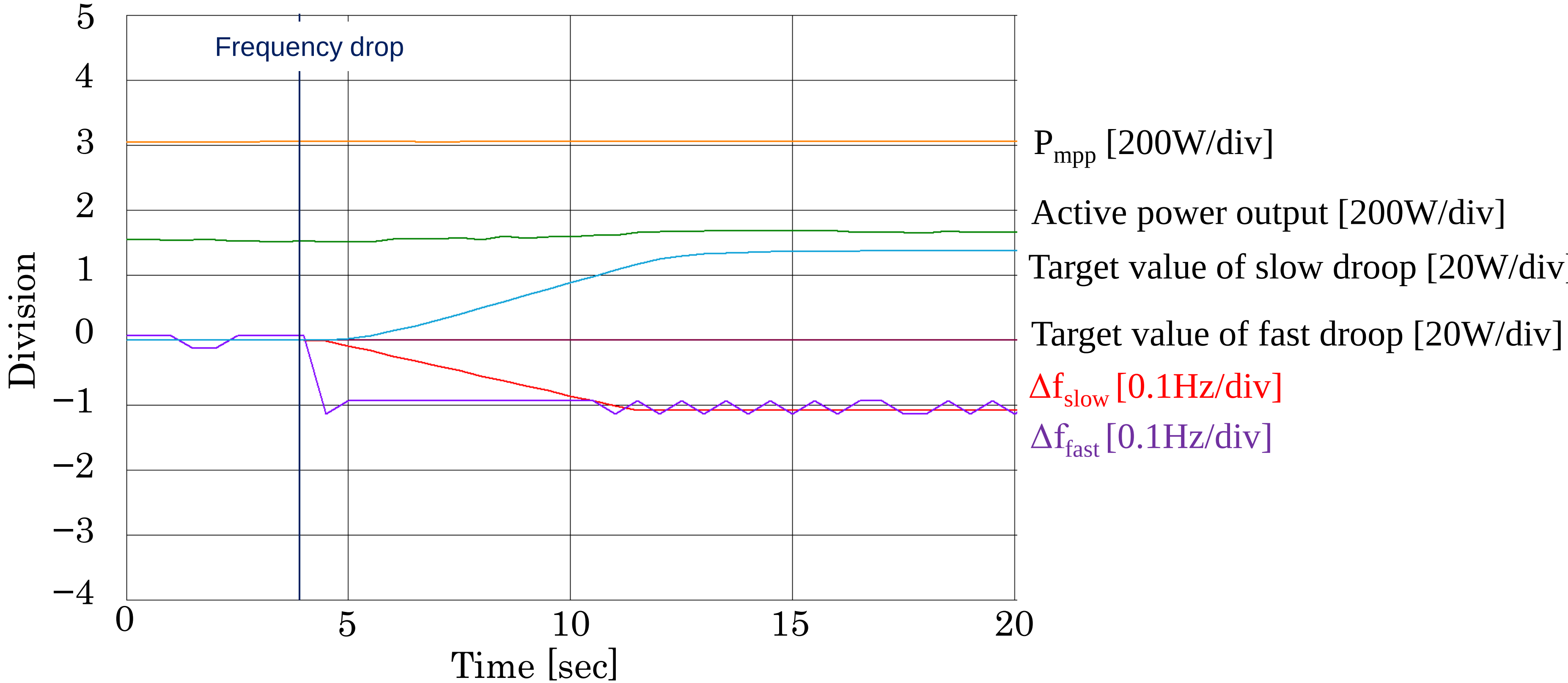
- Combined operation of slow and fast P-f Droop control was tested
- Q-V droop control was deactivated
- P_{mpp} is 600W
- Power output rate of PV is 50%

Operation test 2: Small fluctuation



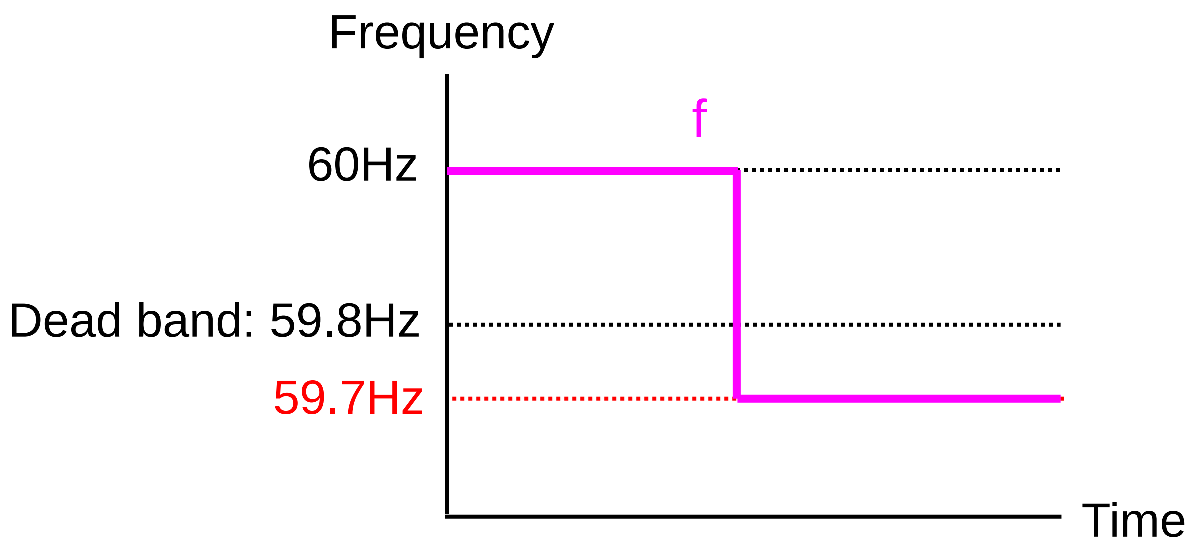
- Stepwise change of frequency: 60.0 Hz => 59.9Hz
- Small change within dead band

Experimental result



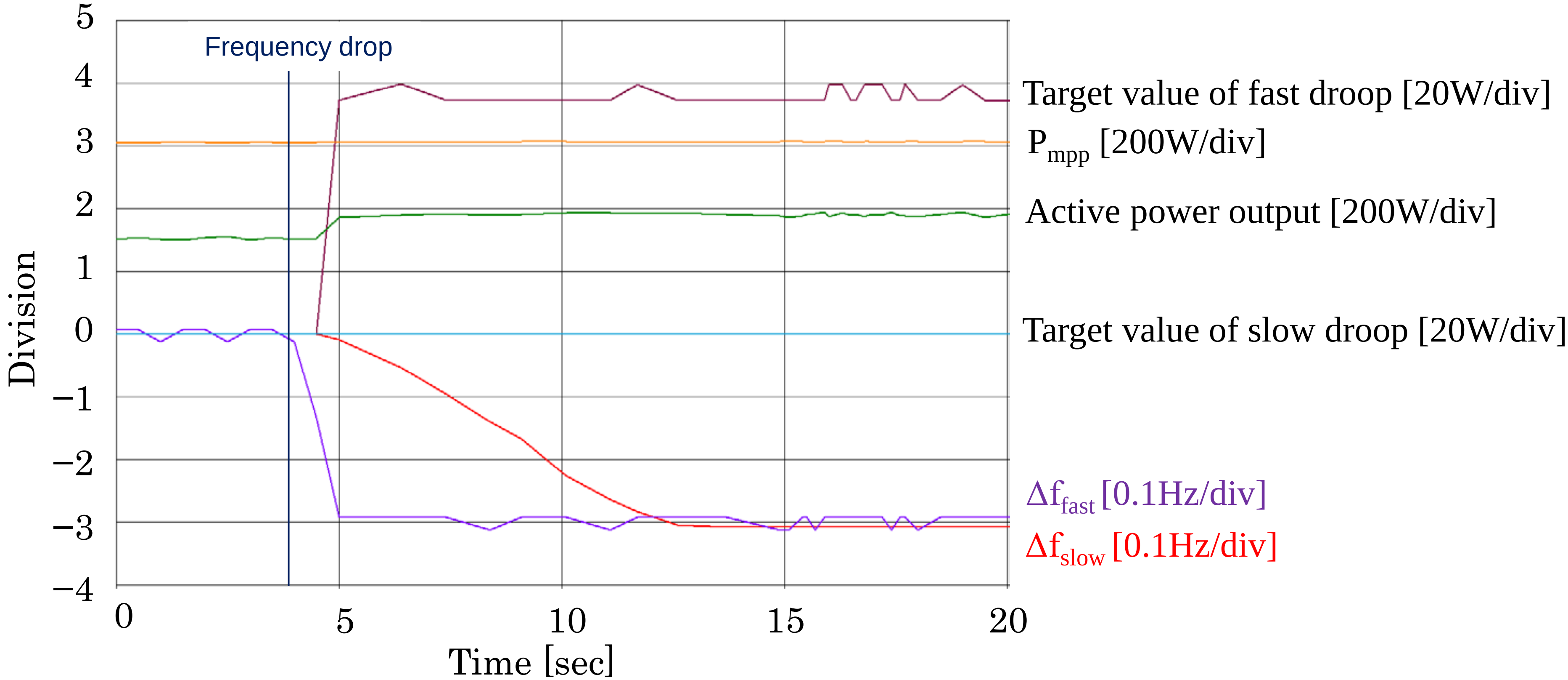
- Fast P-f Droop control did not respond
- Slow frequency regulation changed its set-point in about 10sec
- Actual power output was slightly increased according to increase of set-point in slow P-f Droop control

Operation test 2 : Large fluctuation



- Stepwise change of frequency: 60.0 Hz => 59.7Hz
- Large change exceeding dead band

Experimental result



- Fast P-f Droop control changed set-point immediately after frequency drop
- Slow P-f Droop control did not work because it was properly disabled after large frequency drop
- Active power output was increased only according to increase of set-point of fast P-f Droop control

Conclusion

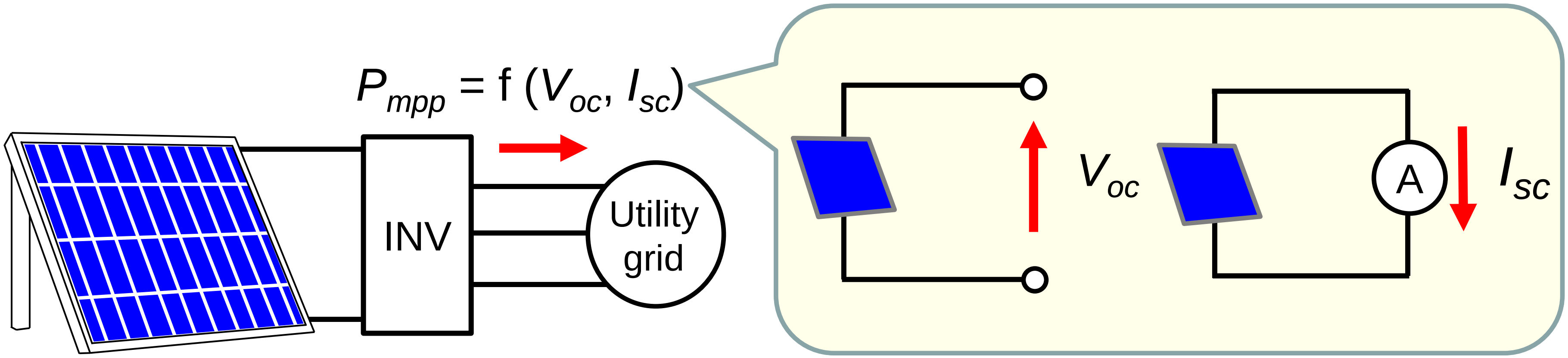
- Experimental test using PV inverter confirmed that
  - Active and reactive power output control based on Droop control worked properly independent each other according to change in both frequency and magnitude of grid voltage even during fluctuation of solar irradiance.
  - Slow and fast P-f Droop control worked independently.

Future work

- Performance test of proposed control in consideration of reaction of grid voltage against change in active and reactive power output of PV using a real time simulator or real synchronous generator.

Thank you for your attention

Estimation of P_{mpp}



Maximum power point tracking (MPPT) operates around P_{mpp} and cannot curtail power output of PV

$\Rightarrow$ P_{mpp} is estimated without using MPPT

Estimation method

1. V_{oc}, I_{sc} is measured by PV cells which have the same I–V characteristic with the PV panel
2. Estimate P_{mpp} by measured V_{oc}, I_{sc} $\Rightarrow$ $P_{mpp} = f(V_{oc}, I_{sc})$