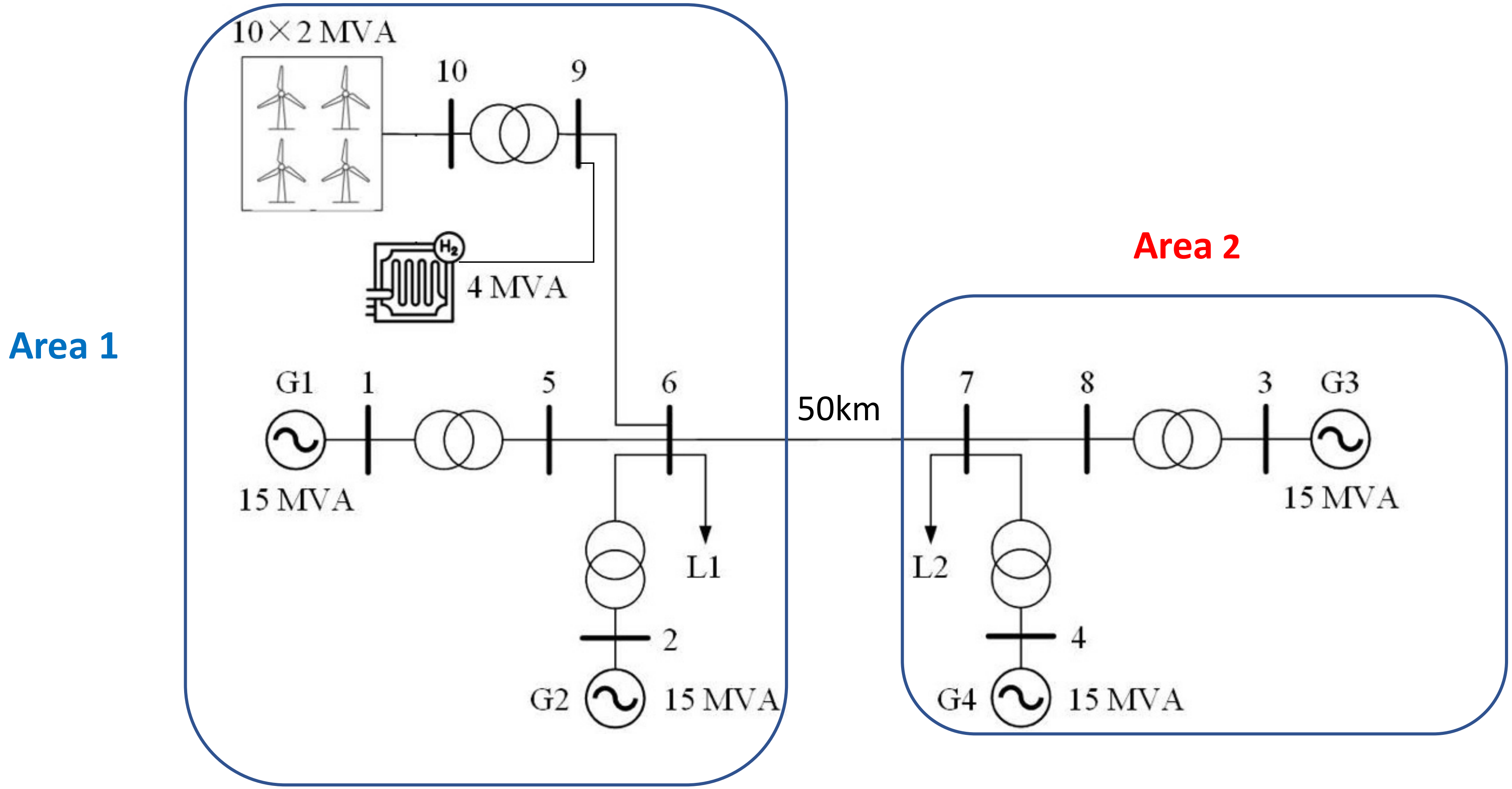
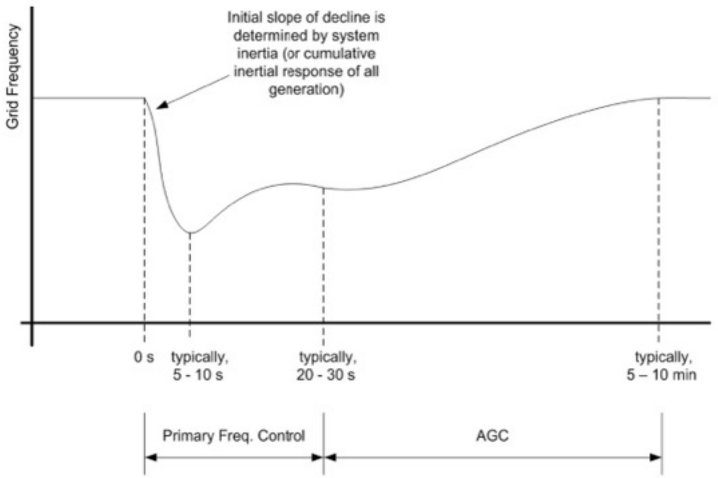
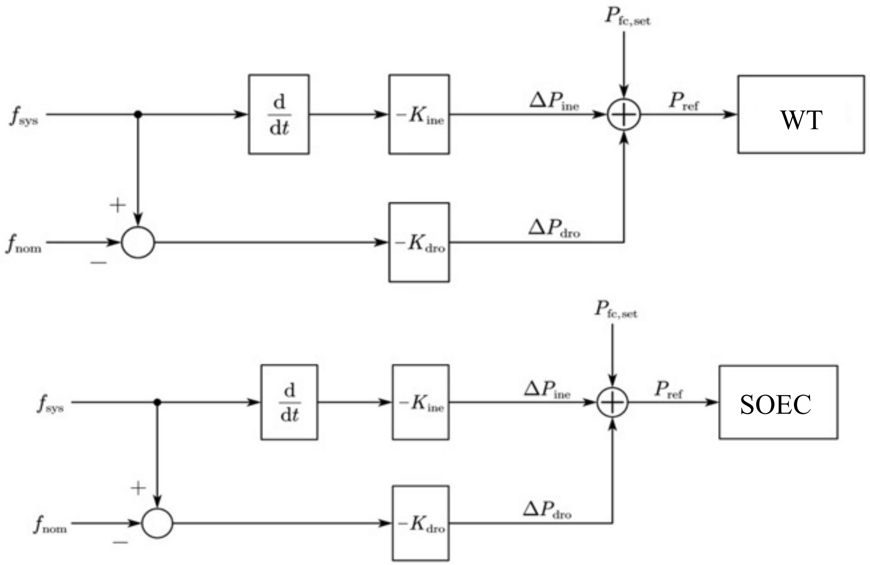
Frequency Response

- **Four-machine two-area test system with 10 WTs & a SOEC**

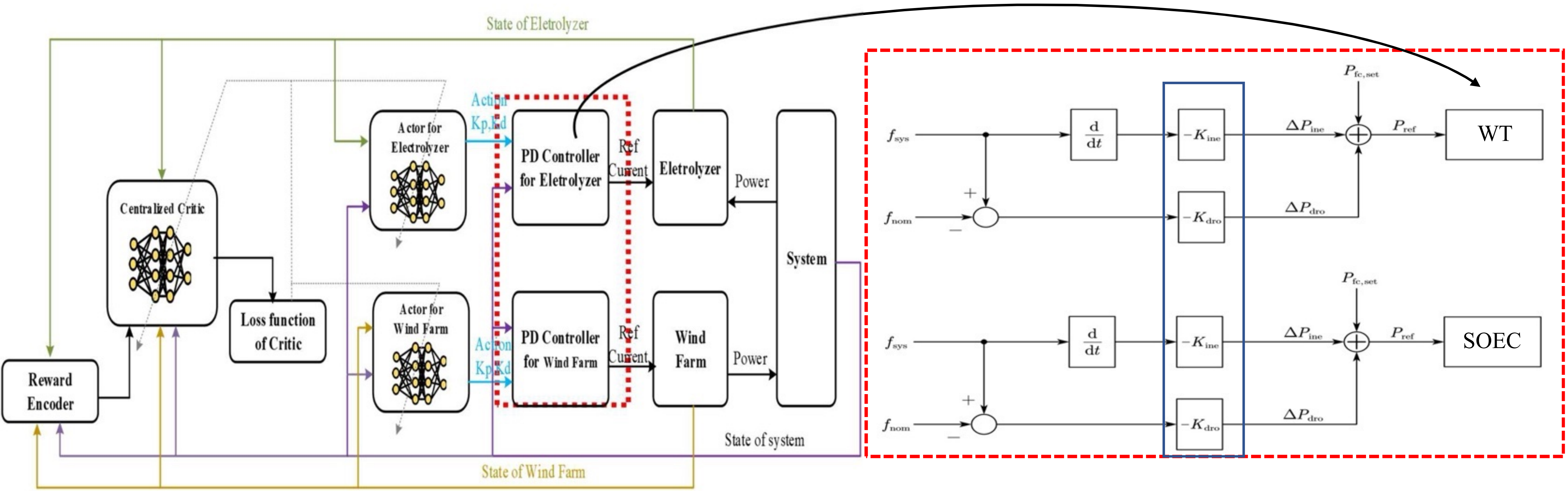


Frequency Response





Control Scheme Design



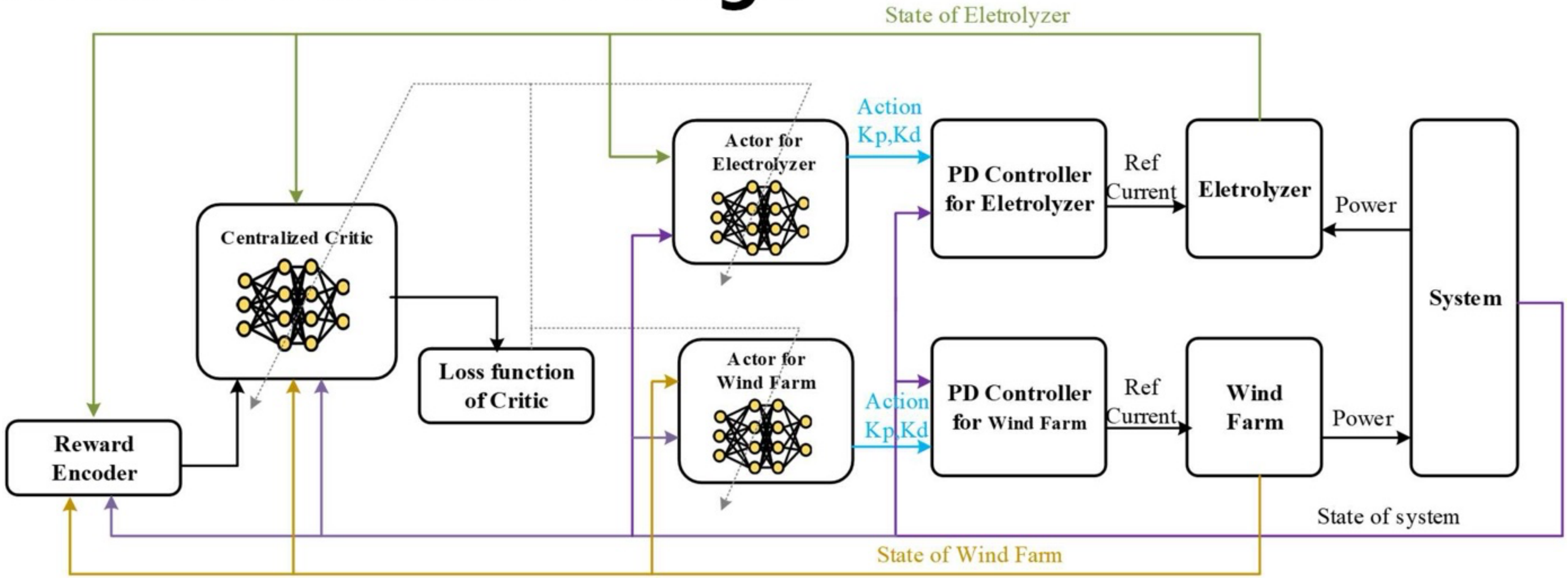
Multi-agent Heterogeneous PPO(Multi-agent Heterogeneous Proximal Policy Optimization)-based PD-Controller:

Adaptability to Complex Tasks: Suitable for Cooperative Tasks with Heterogeneous Agents in Complex Control Systems.

Learning from Data: PPO learns optimal strategies from data

Robustness to Variability: PPO offers robust performance under system variability and changing conditions

Control Scheme Design



$b_{\lim}$ is the boundary of error

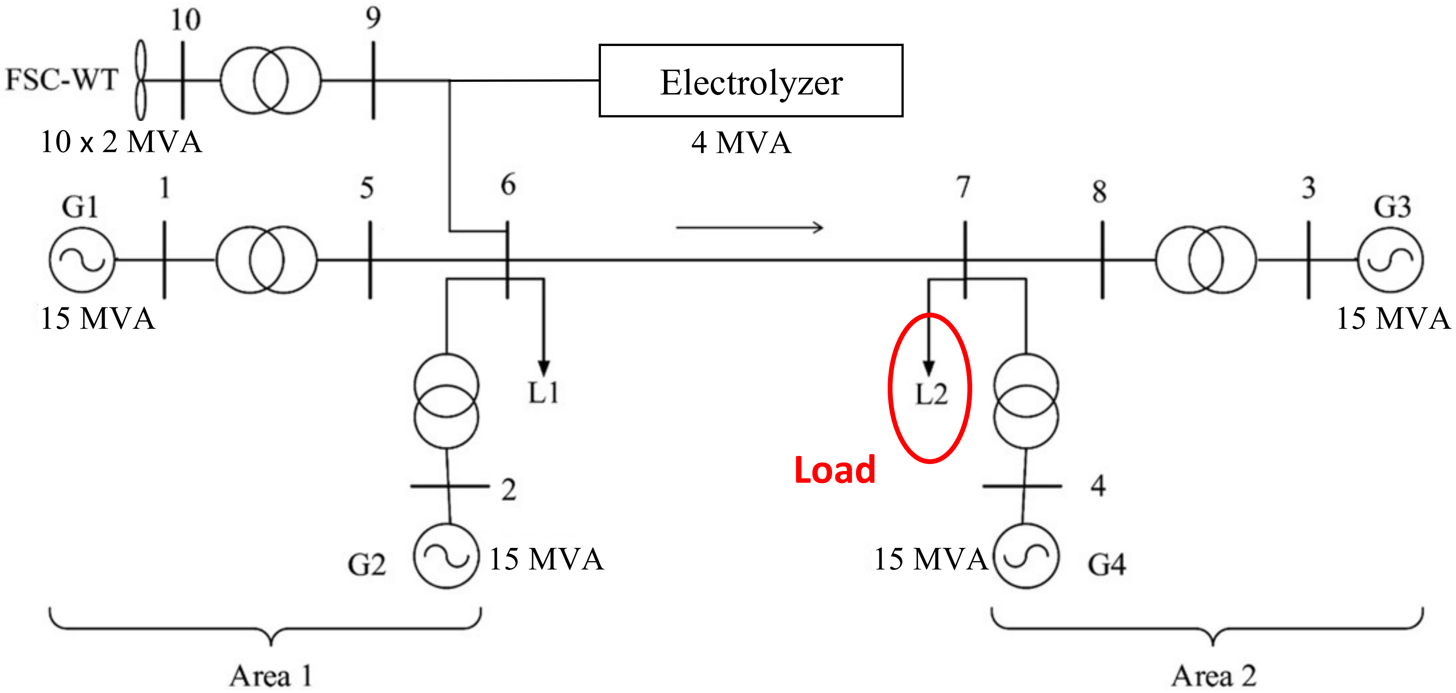
Reward Design

$$r = \underbrace{-c_1 e^2 - c_2 \dot{e}^2}_{\text{Reward for the error trend}} + \underbrace{c_3 \ln\left(1 - \frac{e^2}{b_{\lim}^2}\right)}_{\text{Reward for the error boundary}} \underbrace{- k(1 - p_w)^2}_{\text{Reward for deviation from rated power of wind farm (Making the most of wind energy)}}$$

p_w is the rated output power of a wind farm

Case Study

- **Wind farm with 10 x 2 MW WTs and a 4 MW Electrolyzer**



Four-machine two-area test system with a wind farm

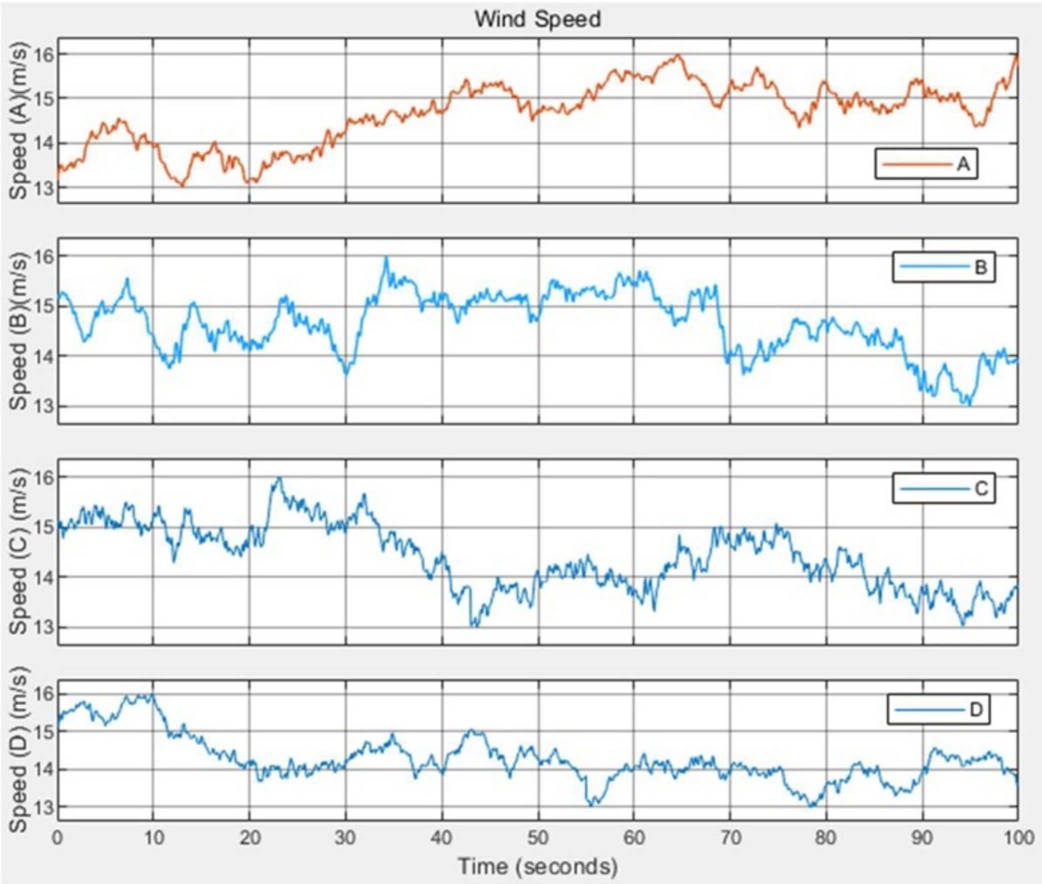
- PPO is used to adjust the PD parameters of WT and Electrolyser based on frequency measurement

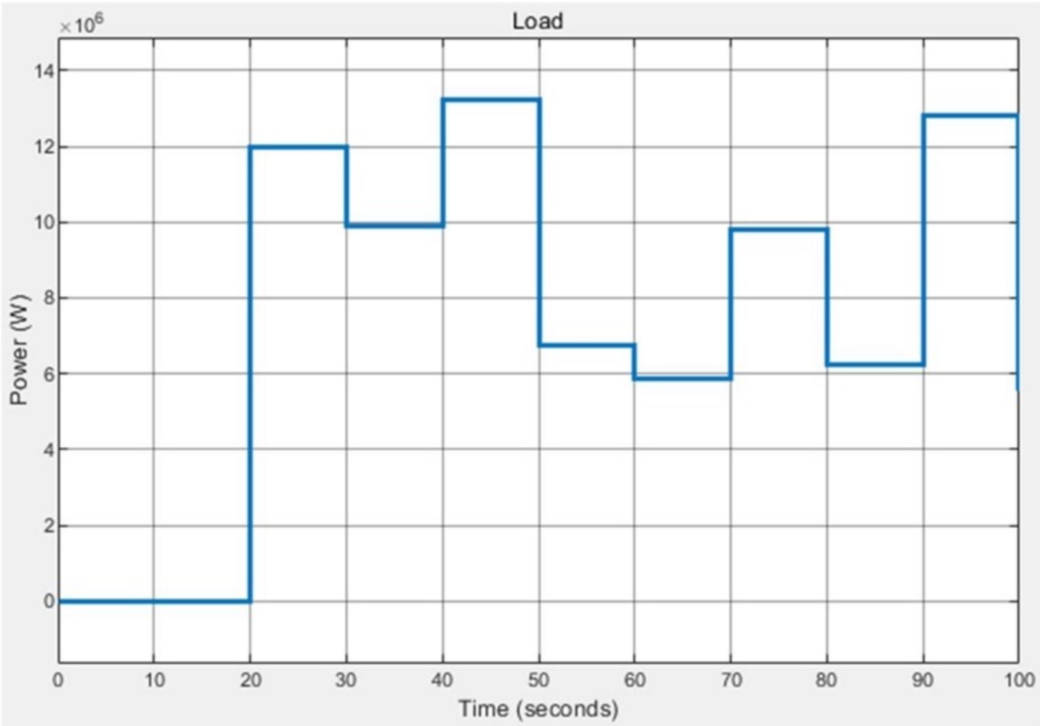
Case Study

- **Wind farm with 10 x 2 MW WTs and a 4 MW Electrolyzer**

- Load is variable

Windspeed is variable （4 cases）

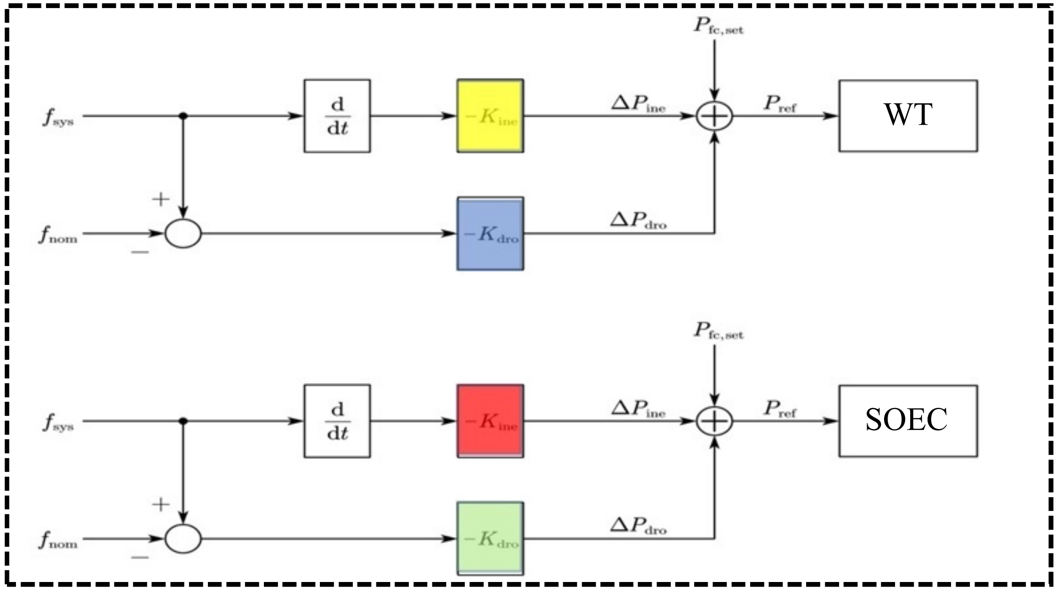




Experiments

The neural network architecture for both the actor and critic consists of: Input layer, Hidden layers (Two hidden layers, each with 256 neurons, using Tanh activation functions),Output layer (for actor also using a Tanh activation function).

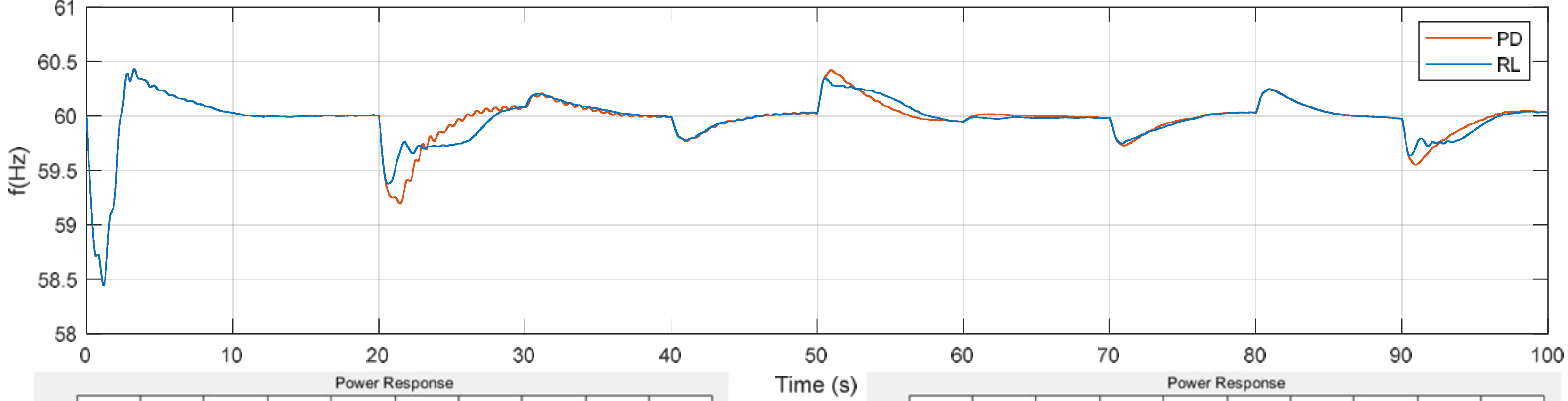
A total of 300 episodes are trained, with each episode involving parallel simulations of 12 sets of cases with different loads ranging from 8 to 12 MW. Each simulation consists of 350 steps, totaling 1,260,000 samples. Each training session lasts approximately 12 hours.

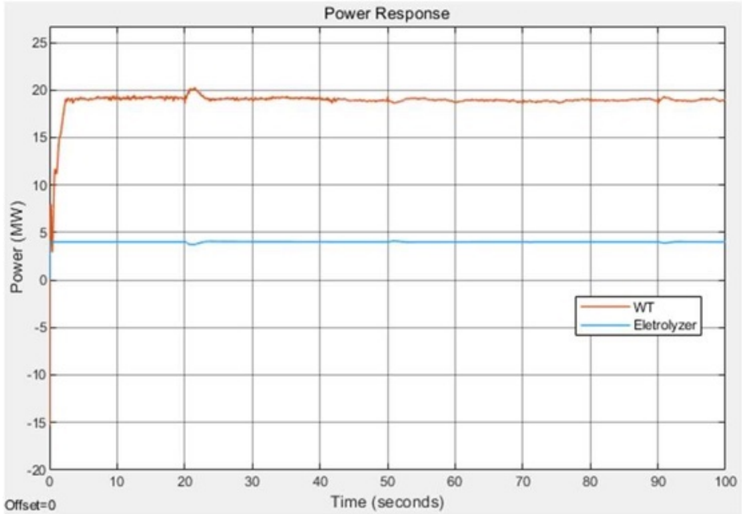


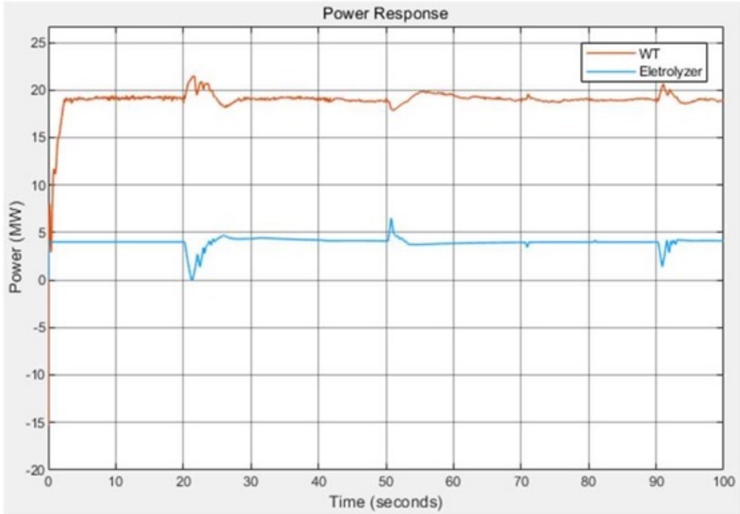
Experiments

- **Scenario A**

Frequence Response





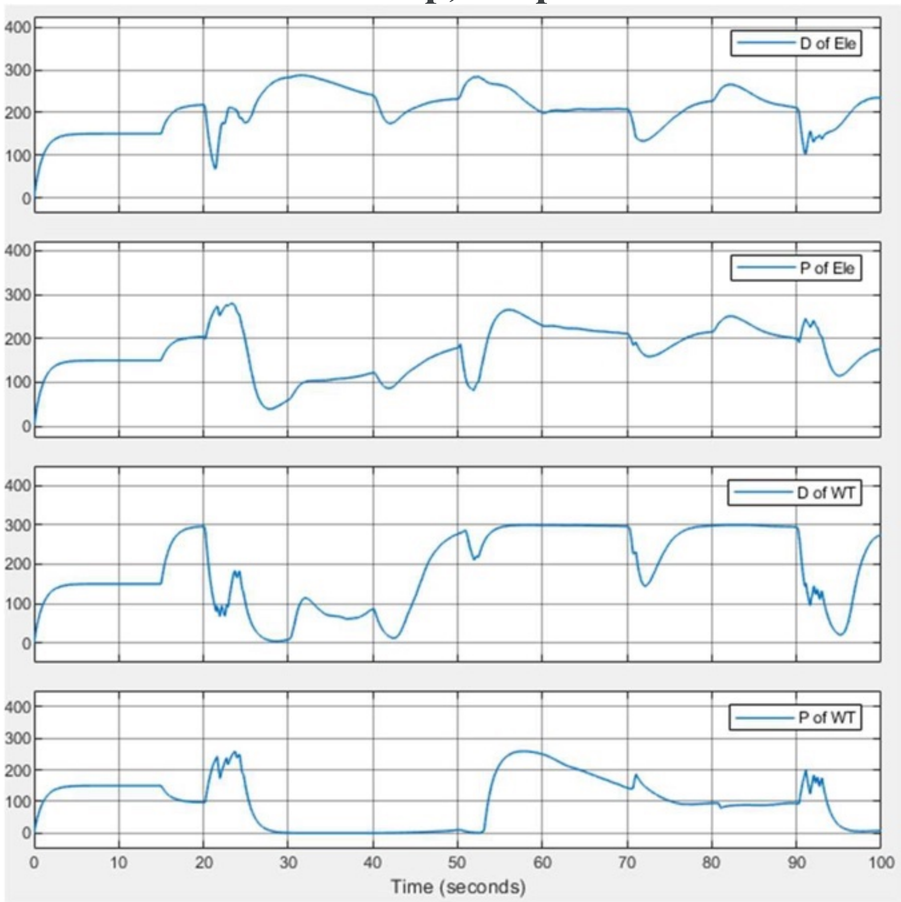


Classical PD **Multi-agent Heterogeneous PPO**

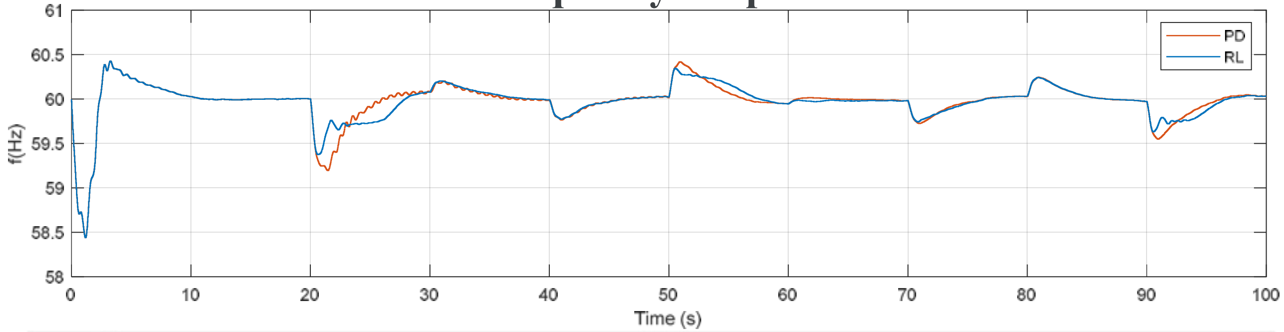
Experiments

- **Scenario A**

Action of Kp, Kd parameters



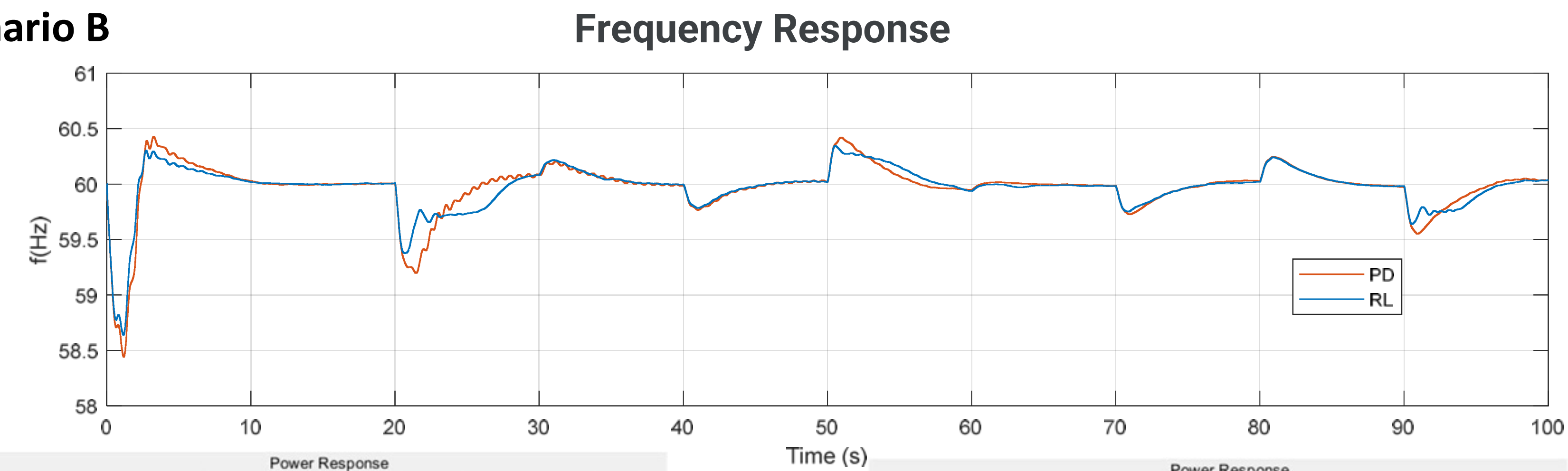
Frequency Response

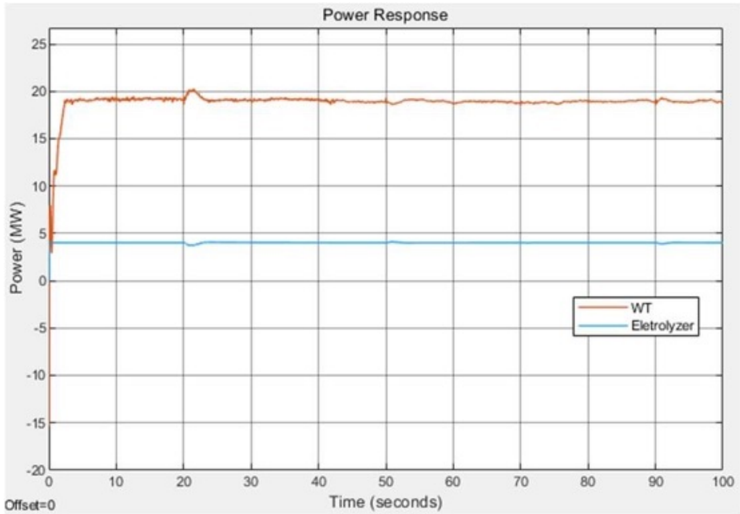


It can be seen that when the load changes (wind is also variable), the frequency nadir improves based on the Multi-agent Heterogeneous PPO method (label as RL), especially against larger load changes.

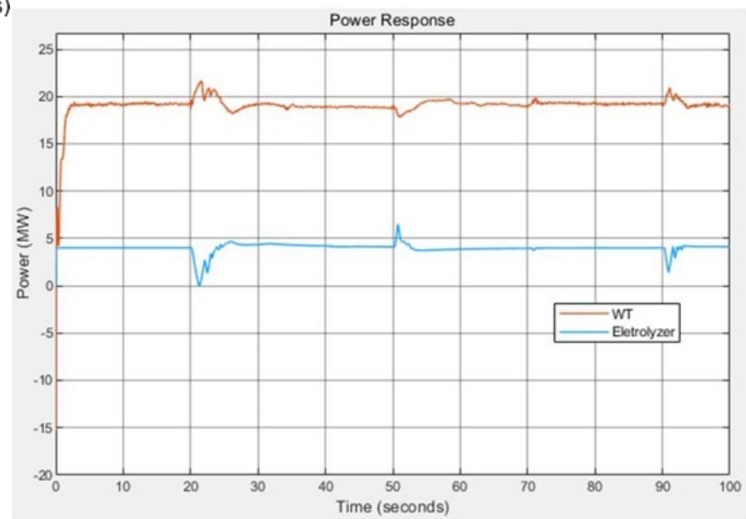
Experiments

- **Scenario B**





Classical PD

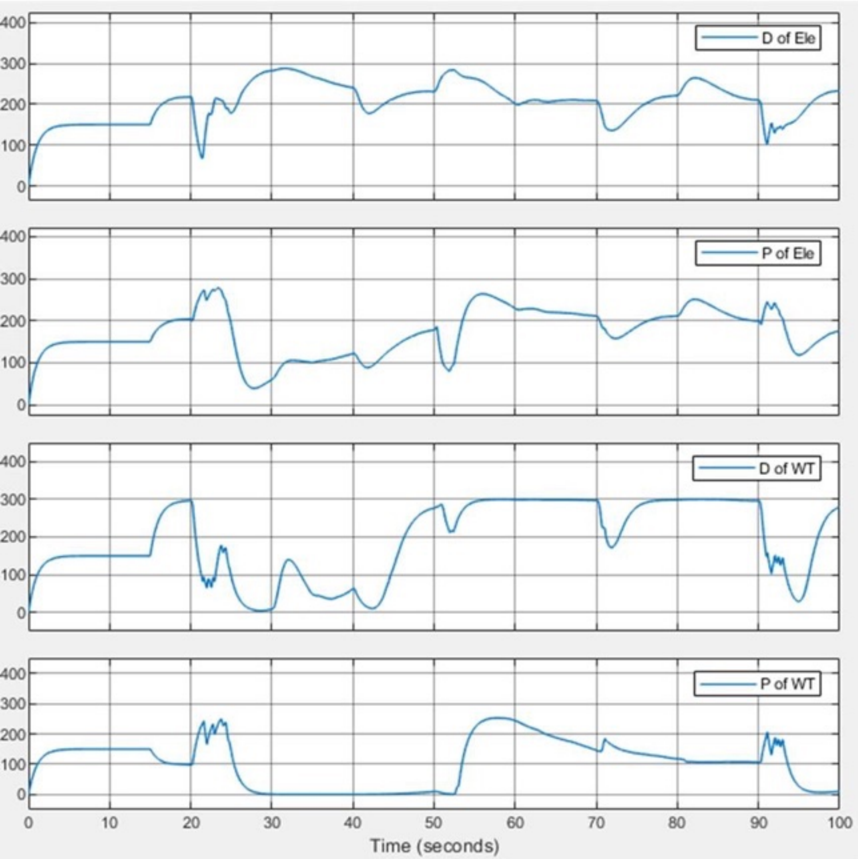


Multi-agent Heterogeneous PPO

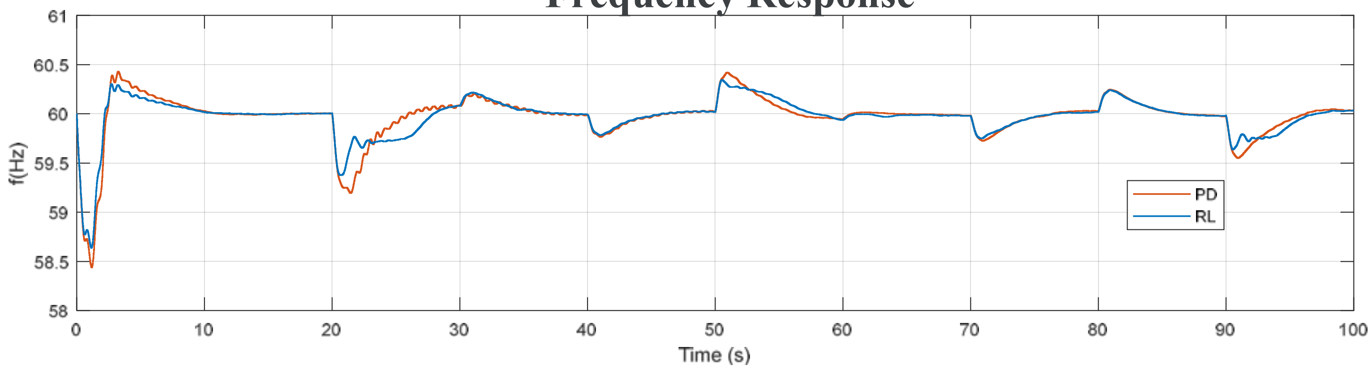
Experiments

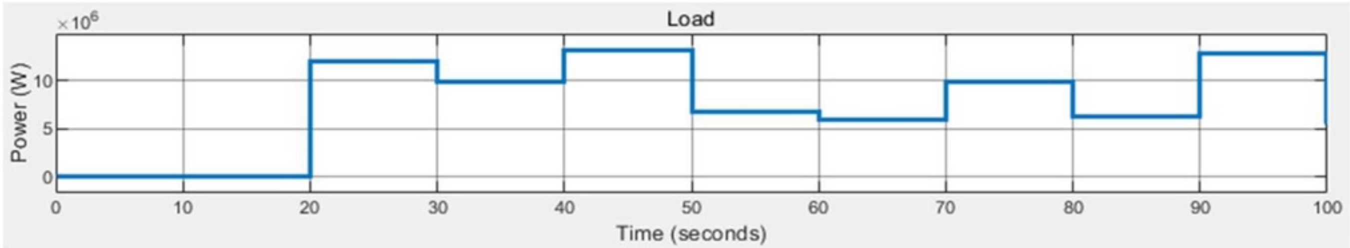
- **Scenario B**

Action of Kp, Kd parameters



Frequency Response



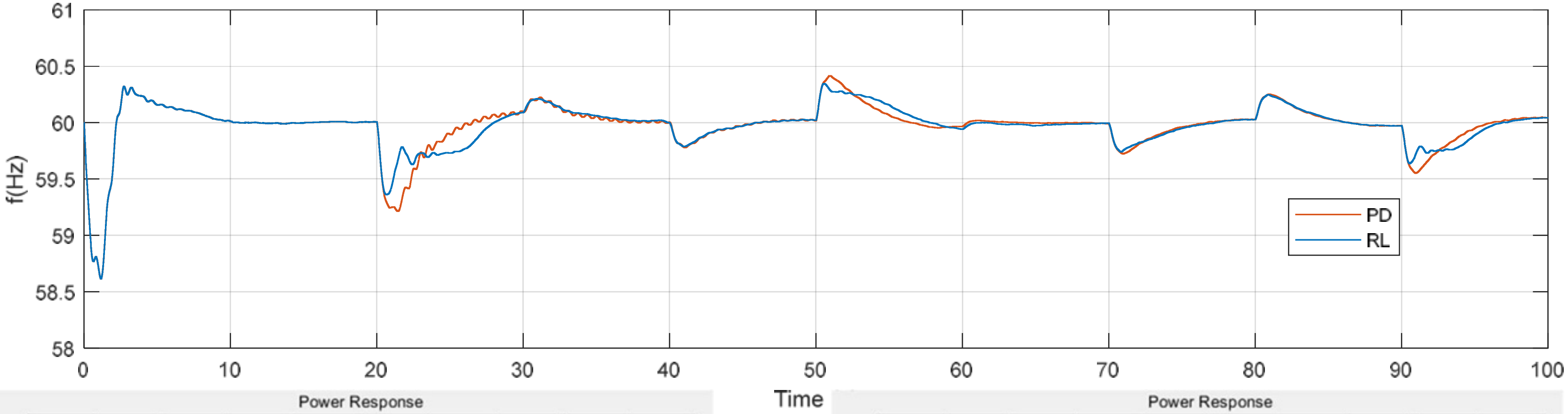


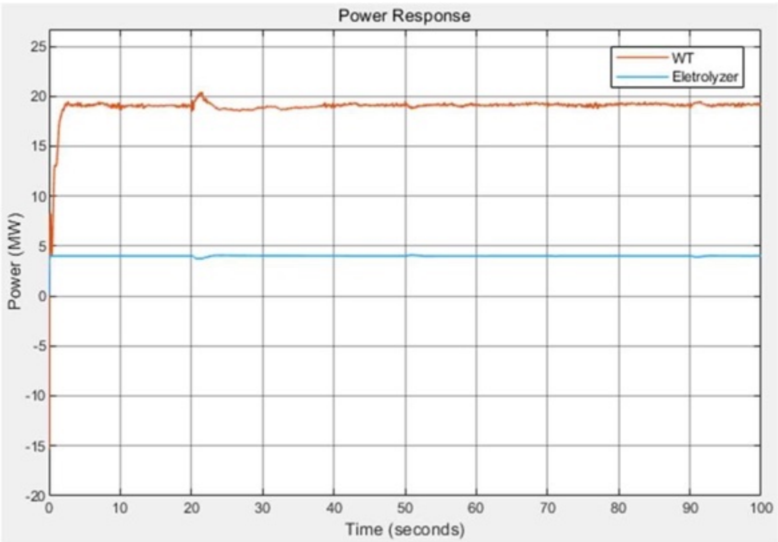
It can be seen that when the load changes (wind is also variable), the frequency nadir improves based on the Multi-agent Heterogeneous PPO method (label as RL), especially against larger load changes.

Experiments

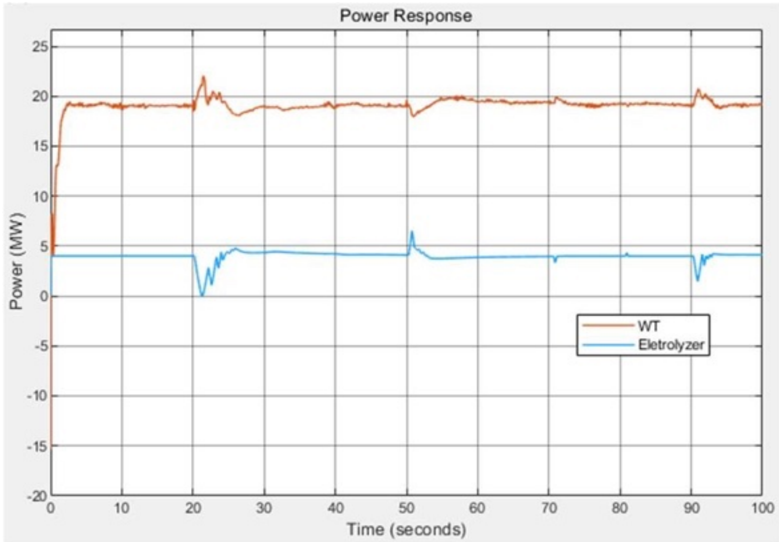
- **Scenario C**

Frequency Response





Classical PD

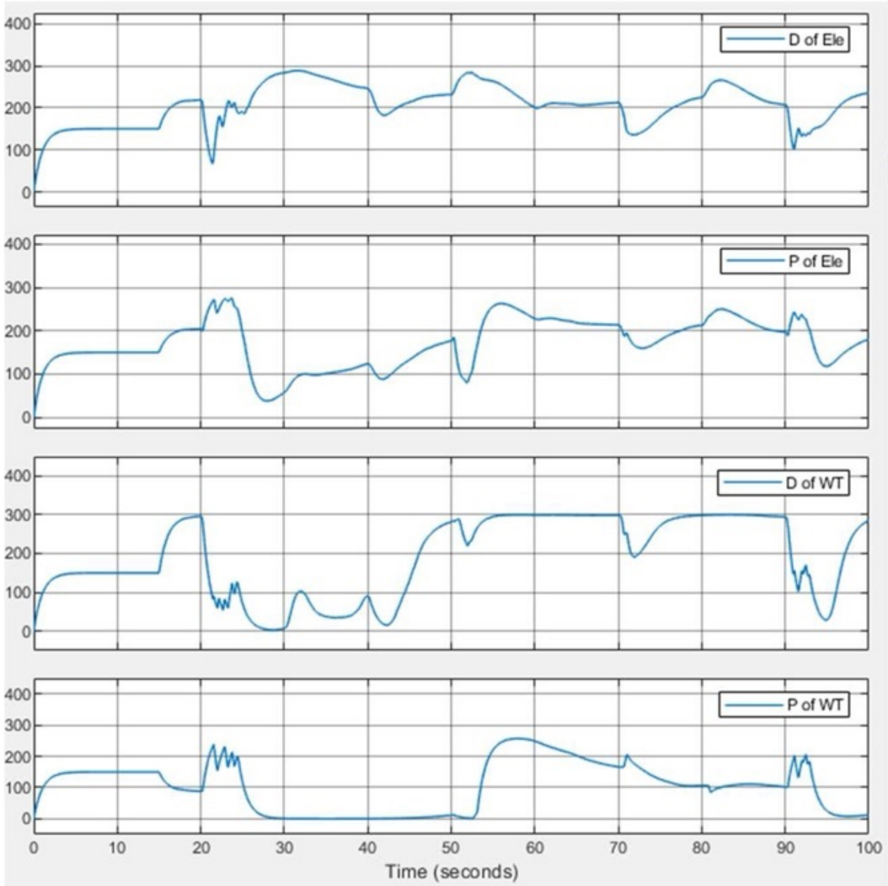


Multi-agent Heterogeneous PPO

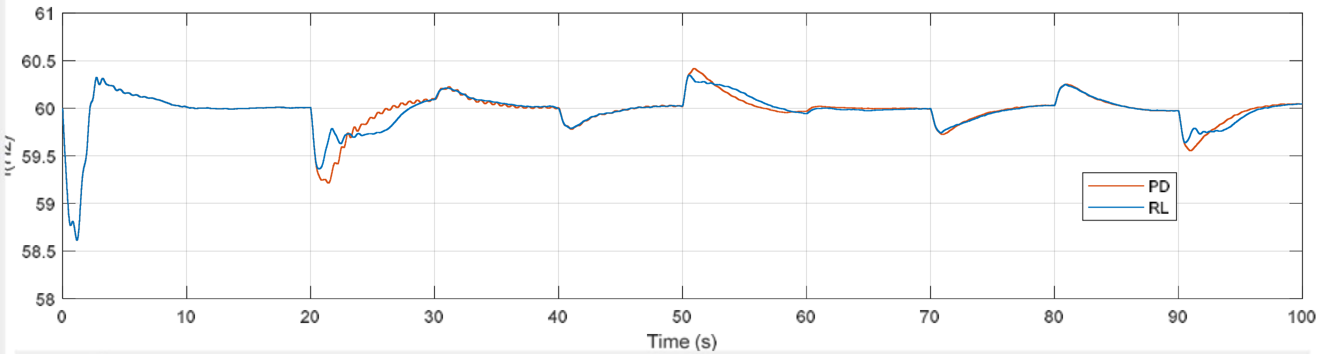
Experiments

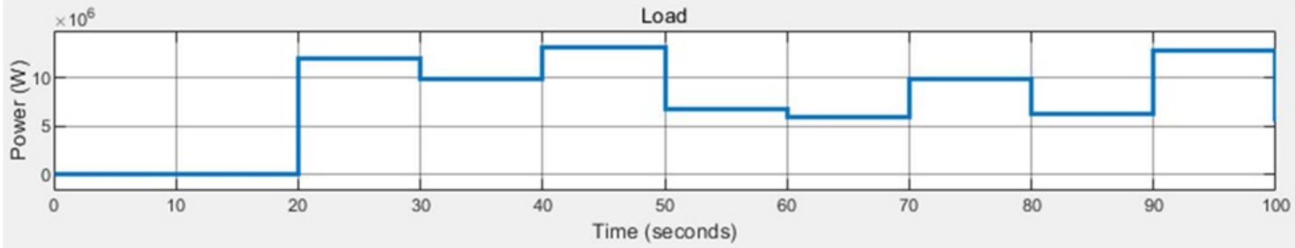
- **Scenario C**

Action of Kp, Kd parameters



Frequence Response



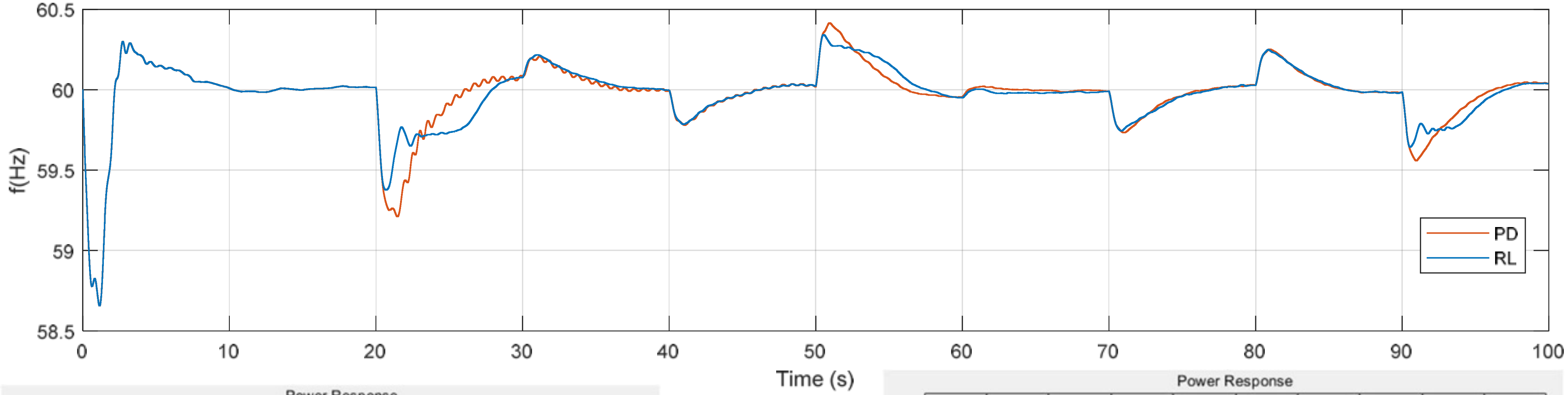


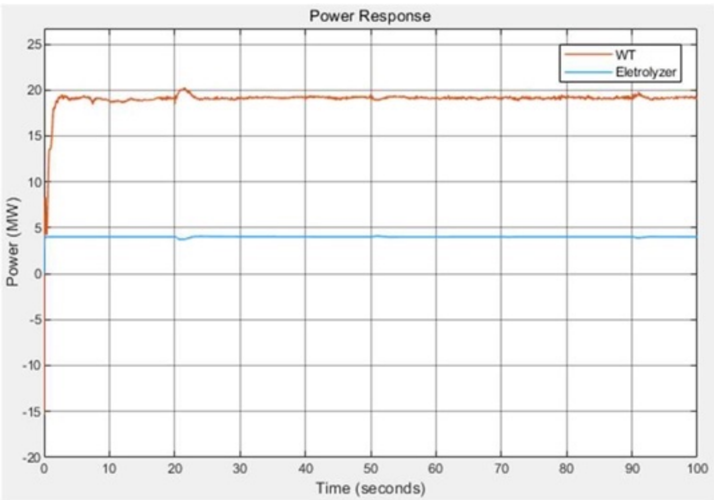
It can be seen that when the load changes (wind is also variable), the frequency nadir improves based on the Multi-agent Heterogeneous PPO method (label as RL), especially against larger load changes.

Experiments

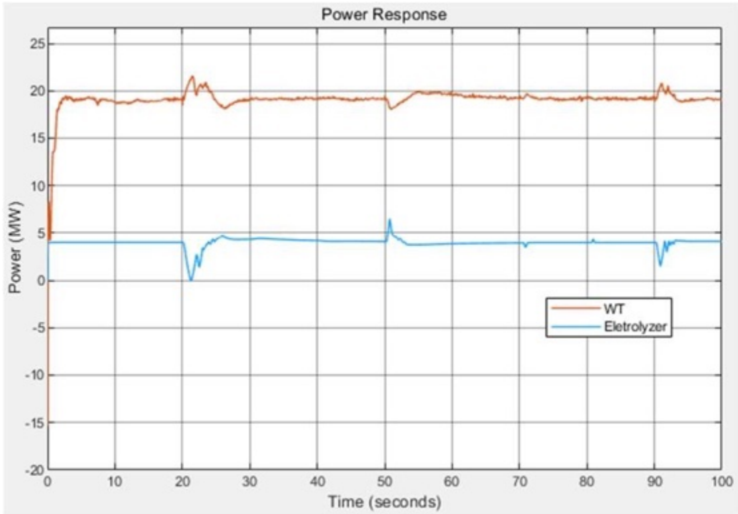
- **Scenario D**

Frequency Response





Classical PD

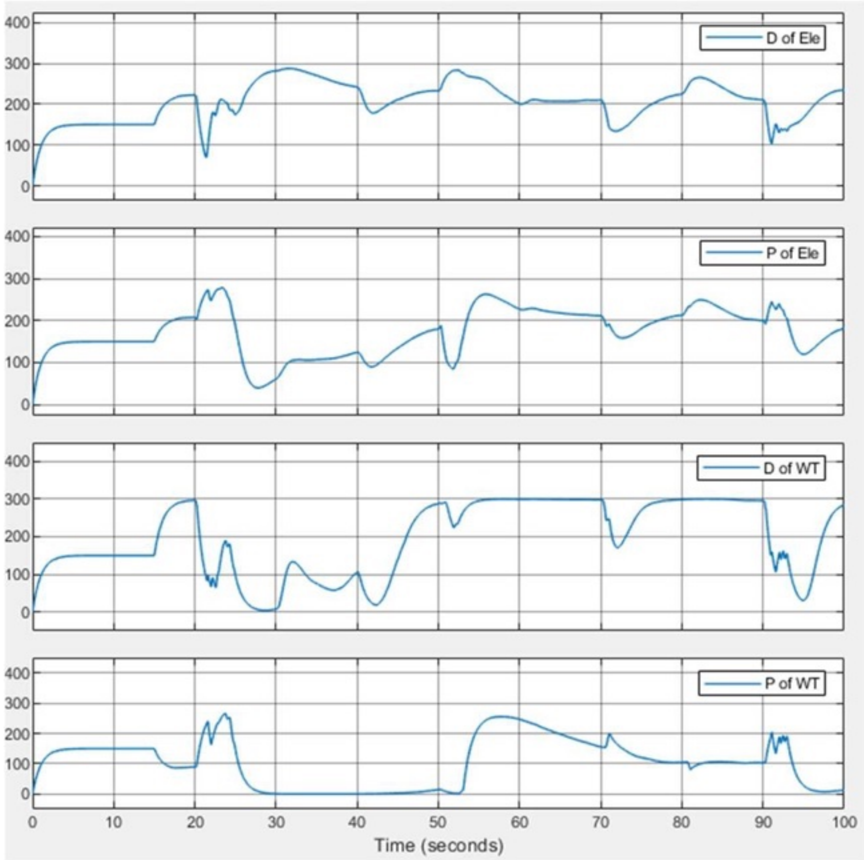


Multi-agent Heterogeneous PPO

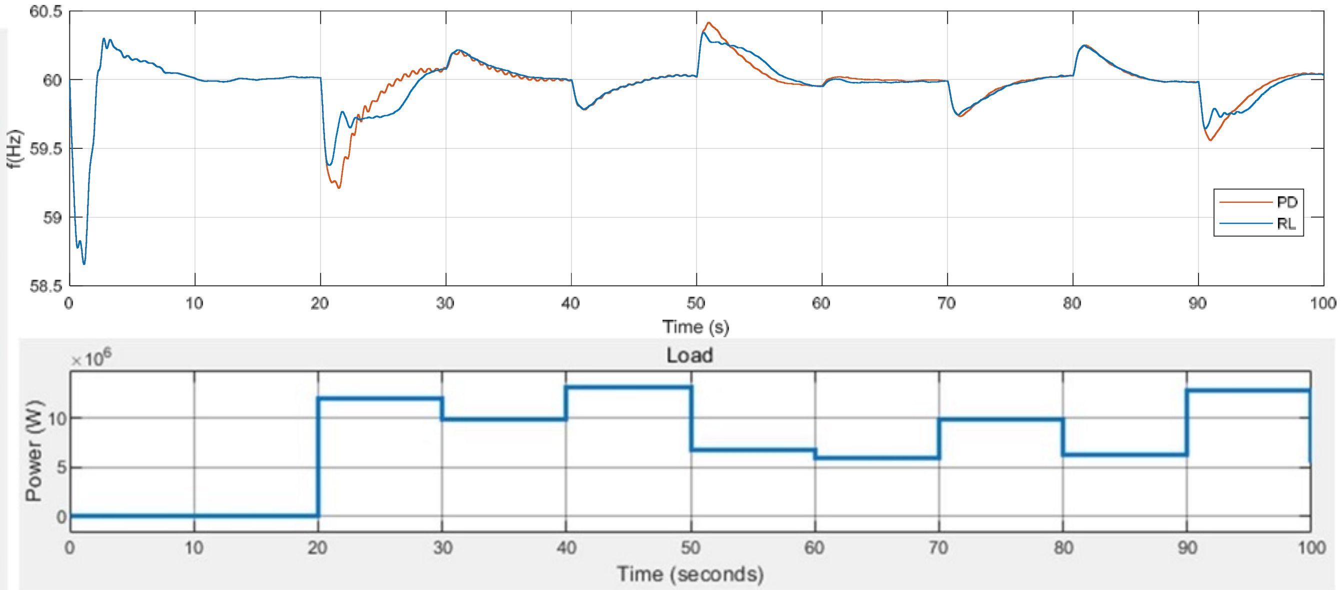
Experiments

- **Scenario D**

  Action of Kp, Kd parameters



Frequence Response



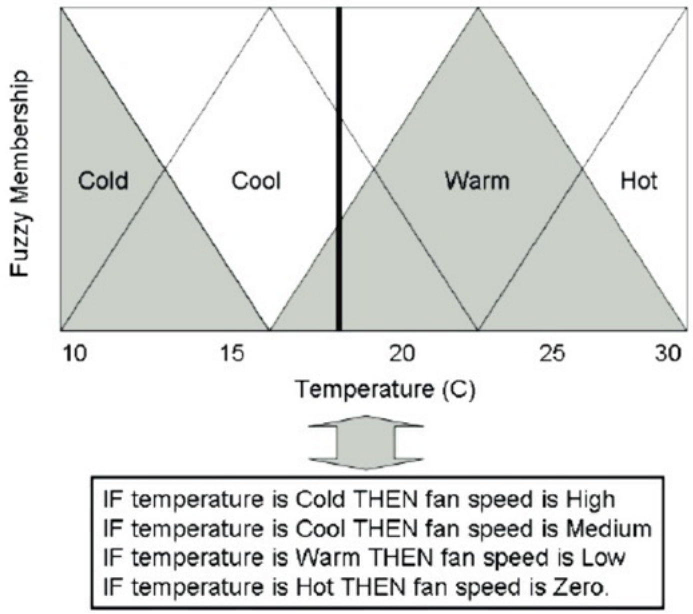
It can be seen that when the load changes (wind is also variable), the frequency nadir improves based on the Multi-agent Heterogeneous PPO method (label as RL), especially against larger load changes.

Fuzzy Control System

- Fuzzy logic is a form of logic that deals with reasoning that is approximate rather than precise.
- It mimics human decision-making, allowing computers to make decisions in uncertain or ambiguous environments.
- Fuzzy control, in contrast, handles "degrees of truth," allowing for a range of values between 0 and 1 (e.g., "partially true").

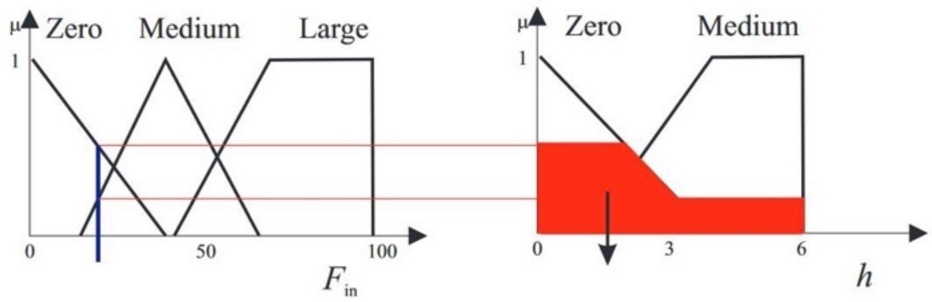
- **Example:**

Controlling temperature in a room: instead of switching the heater on or off, fuzzy control can decide to turn the heater partially on, based on how close the temperature is to the desired level.



Fuzzy Control System

- Step 1: Fuzzification
- Converts crisp inputs (like exact temperature or wind speed) into fuzzy values (e.g., "high," "medium," "low").
- Step 2: Rule Evaluation (Inference Engine)
- Uses a set of if-then rules (e.g., "**If** wind speed is high and grid frequency is low, **then** decrease electrolyser output").
- Combines fuzzy inputs using these rules.
- Step 3: Defuzzification
- Converts the fuzzy output (e.g., "medium increase") back to a crisp output that the system can use.



Compute a crisp (numerical) output of the model (center-of-gravity method).

Fuzzy Control System

Application of Fuzzy Control:

- Fuzzy control is applied to dynamically adjust the operation of an electrolyser and wind turbine.
- Helps stabilize grid frequency by responding to variations in wind power production, electrolysis and grid demands.

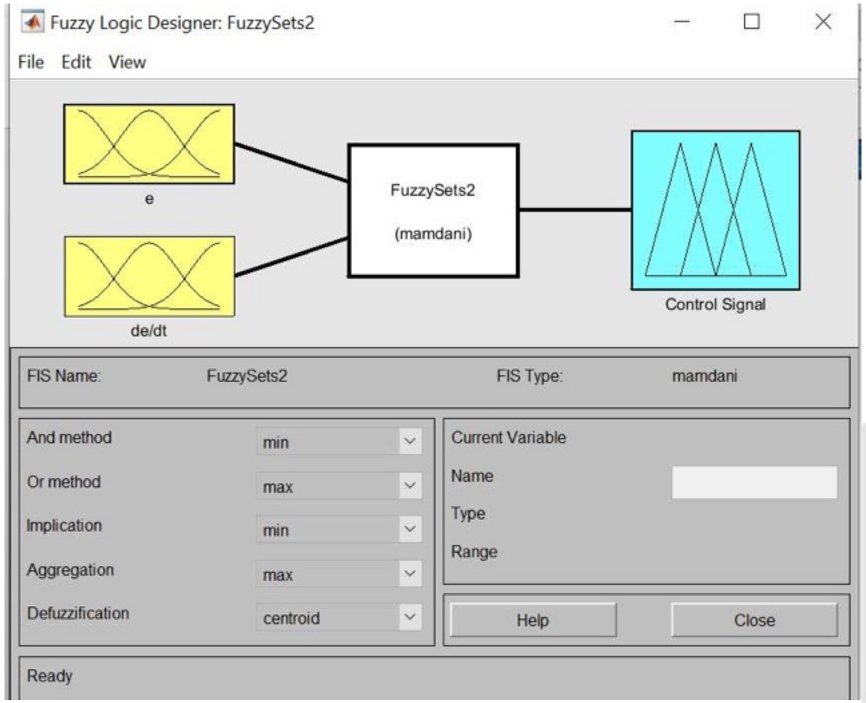
- **Advantages**:

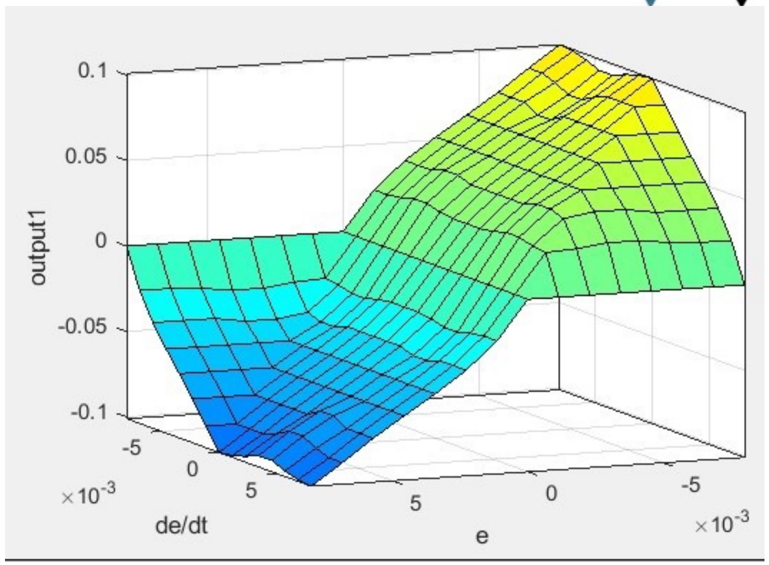
- Handles the non-linear and unpredictable behavior of wind/H2 and frequency fluctuations.
- Smoothly adjusts outputs without abrupt changes, improving system stability

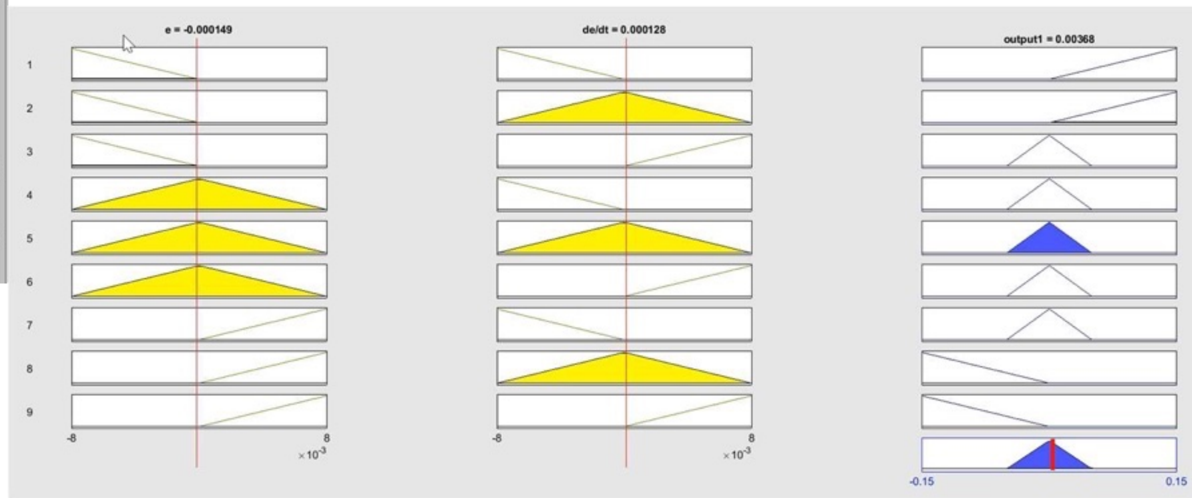
Fuzzy Control System

$e = f - f_{norm}$

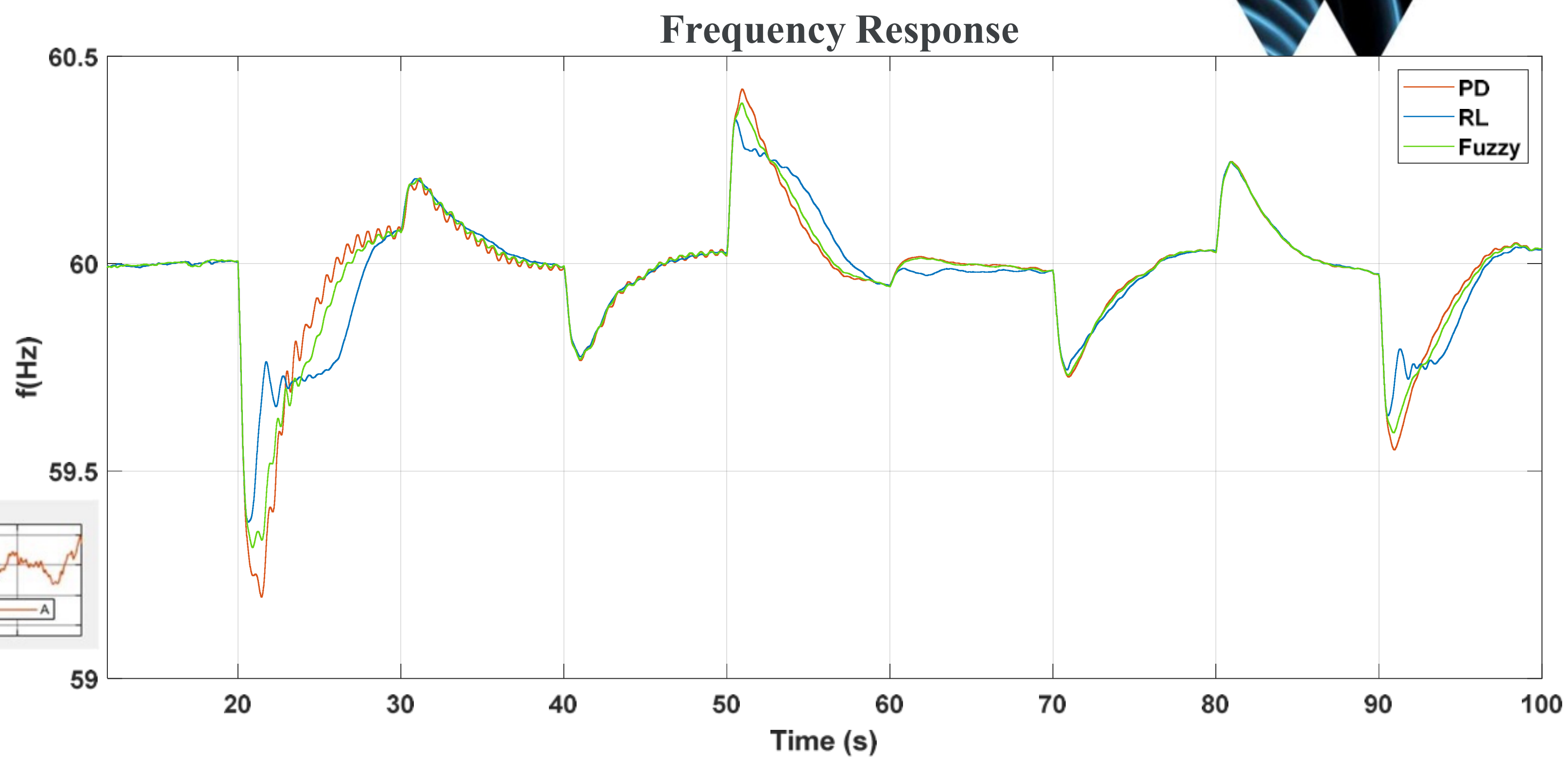
$$\dot{e} = \frac{df}{dt}$$

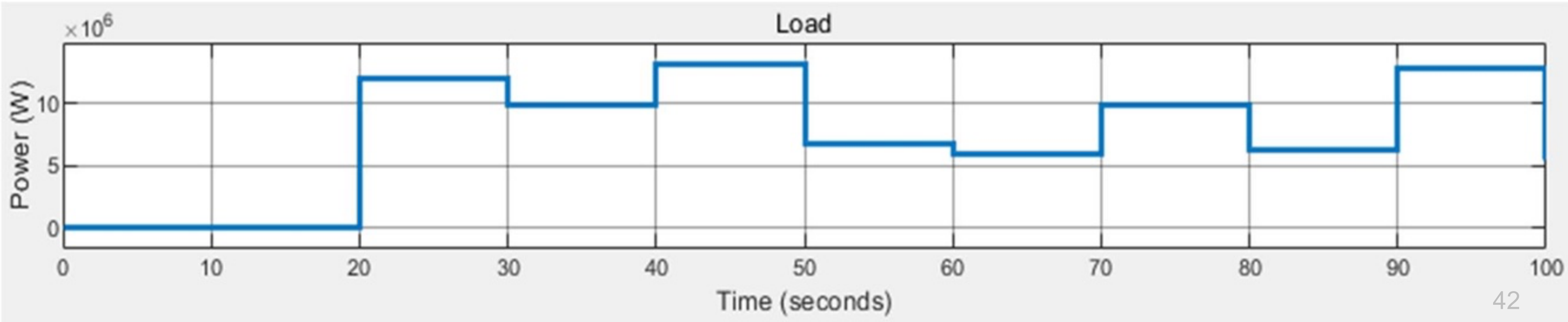




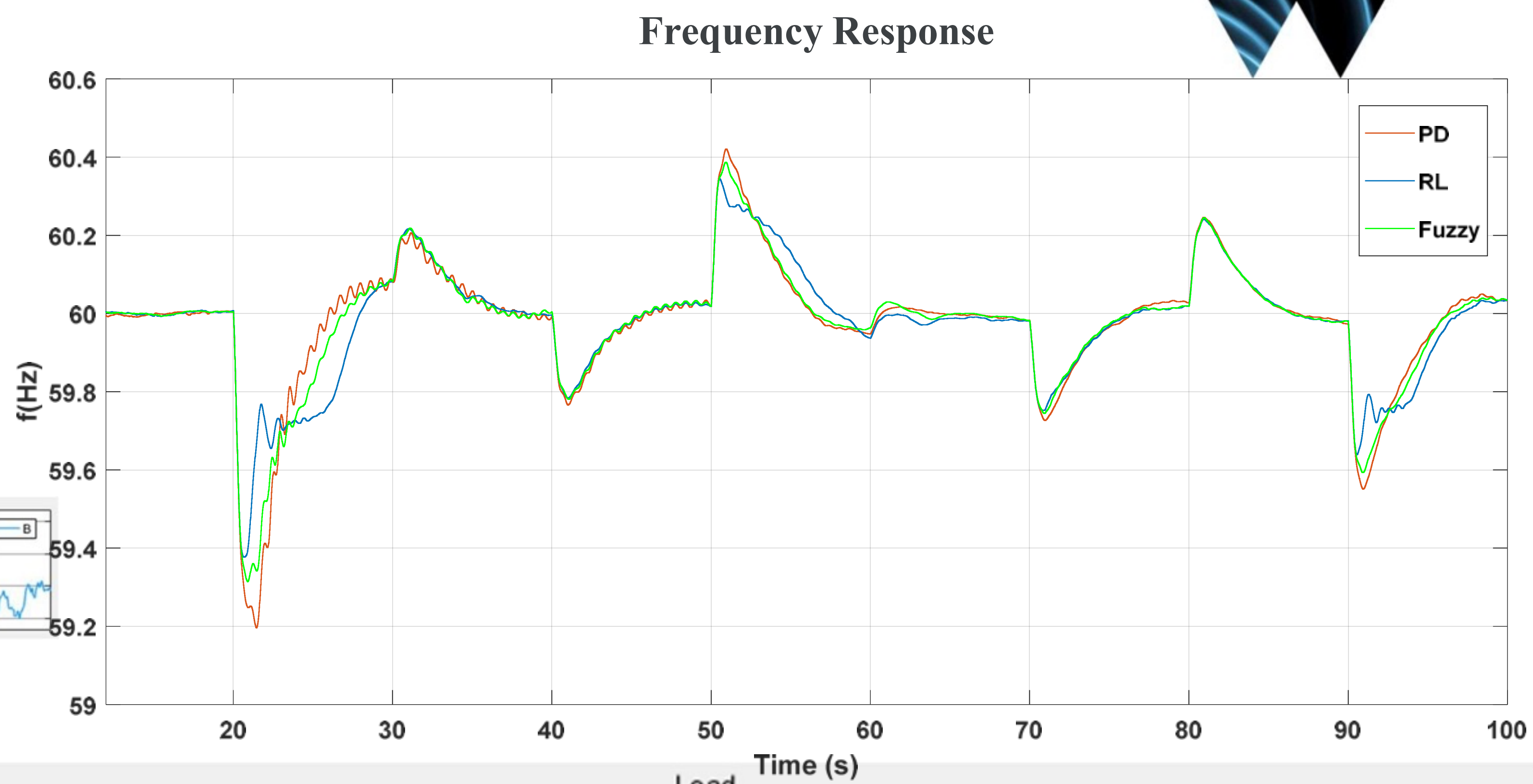


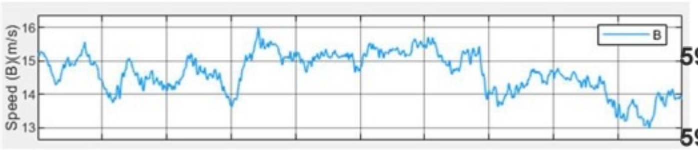
Experiments

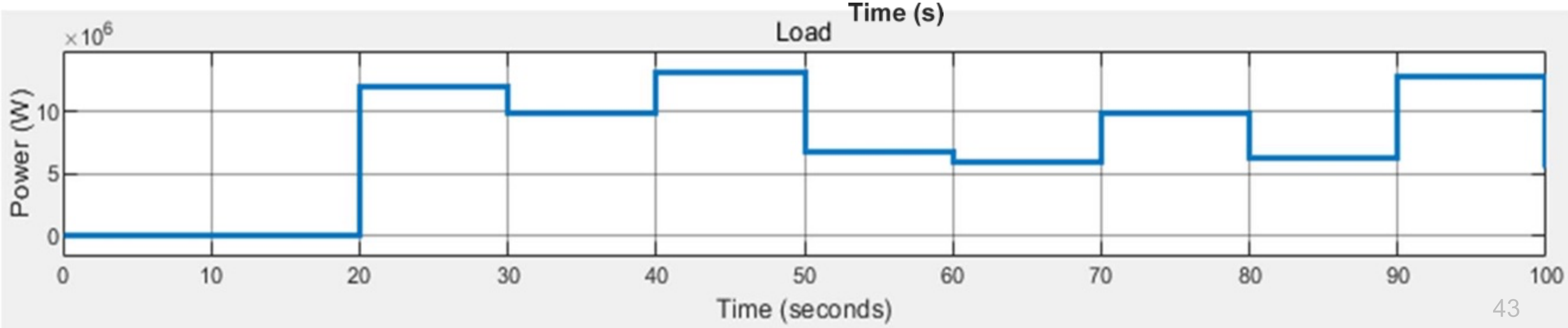




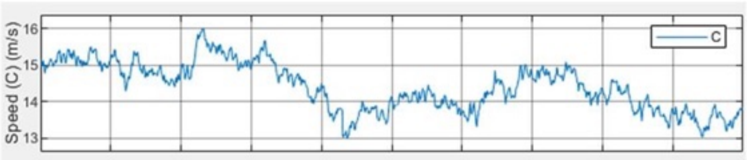
Experiments

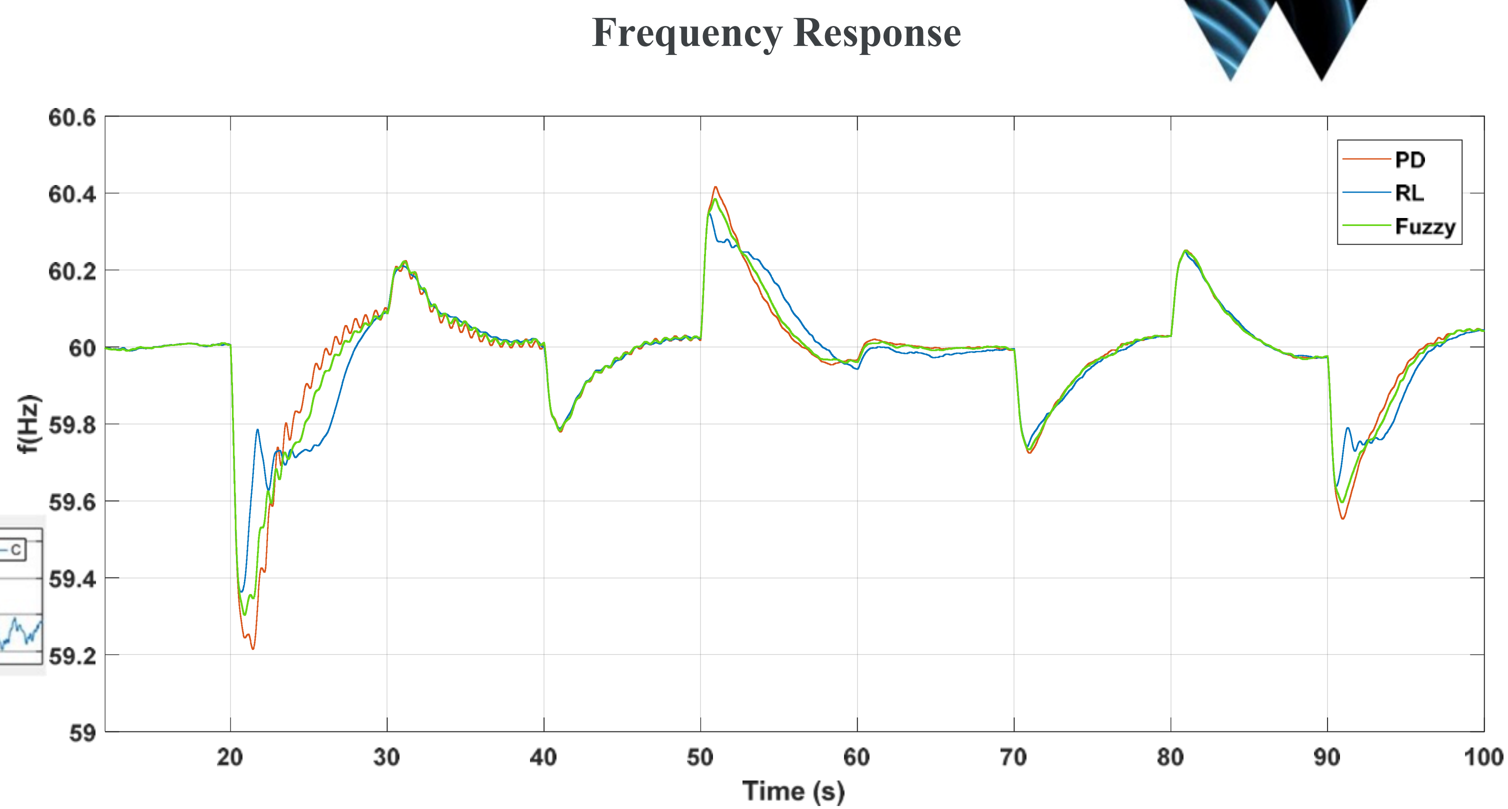


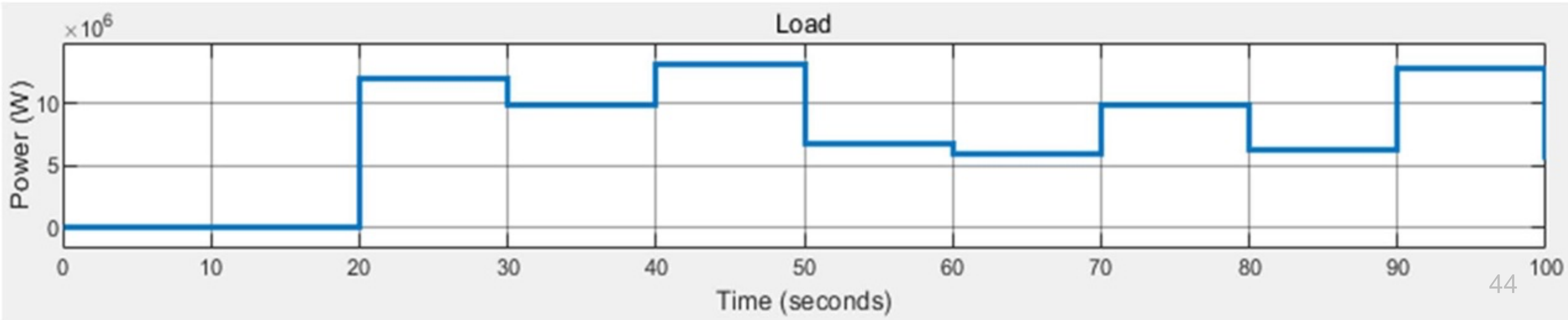




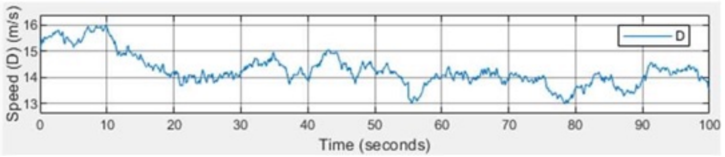
Experiments



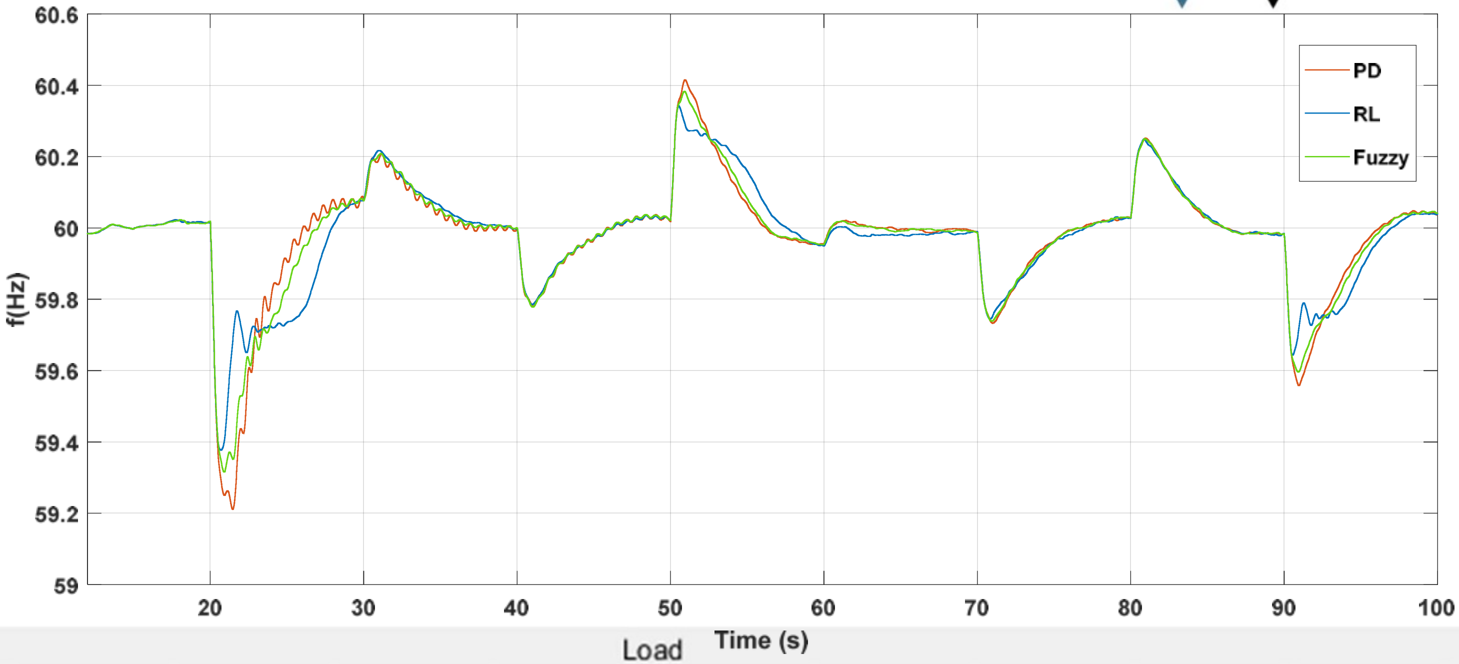


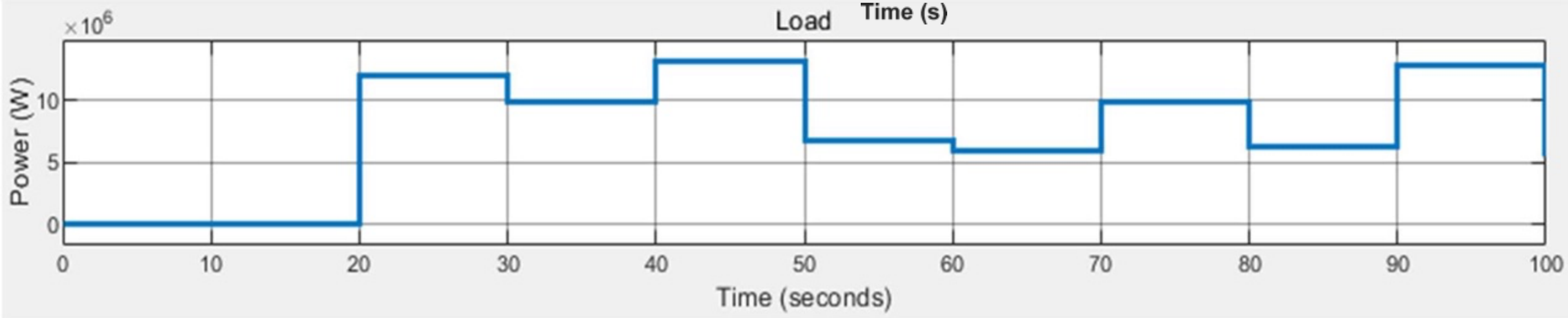


Experiments



Frequency Response





M. Kheshti, H. Yang, Y. Liang, W. Yue, X. Zhao, “Heterogeneous Multi-Agent Proximal Policy Optimization Based Control of Solid Oxide Electrolysis and Wind Turbine Generator for Fast Frequency Response” Applied Energy, 2025 (under review)

AIOLUS – To reshape wind energy via cutting-edge AI

≥ 5% increase in AEP
(annual power production)

Equivalent to **1,600MW of ‘free / virtual’ wind farms** for the UK, based on its current 32GW fleet.

A value-add of **£3.2B** (assuming £2m/MW), **£9B** by 2030

Annual reduction of **2 million tons** of CO_2 emissions based on current energy capacity.

Observations

- Coordinated control of rSOC and Wind farms for better ancillary service provision
- RL-based control system for complex system-wide and component-level nonlinearities
- Role of rSOC in ancillary service mechanisms depending on their response times
  - Fast response for FFR and primary frequency control
  - Slow response for Secondary frequency Control
- Black start and energy balance services
- Grid Codes development for hydrogen technology integration

Acknowledgement

- This presentation is based on the EPSRC-funded project (2022–2025): *High efficiency reversible solid oxide cells for the integration of offshore renewable energy using hydrogen* (EPSRC grant EP/W003694/1).