Research Topics

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About Me

Currently

- Postdoctoral Research Fellow at the University of Denver, Denver, Colorado, USA.

Past

- Ph.D. at University of Denver, Denver, Colorado, USA, in 2023.
- M.S. at University of Denver, Denver, Colorado, USA, in 2019.
- B.S. Hebei University of Technology, Tianjin, China, in 2017.

Research Interest

- Microgrid control
- Renewable energy
- Power system dynamics
- Power system stability
- Power system economics and market
- Machine learning application in power system

Research and Project

- Distributed Energy Resources Manamegent System (DERMS)
- Adaptive Power System Protection with Inverter-based Resources (IBRs)
- Deep Reinforcement Learning based power system dynamic control
  - HVDC Oscillation Damping
  - DFIG Fault-Ride-Through (FRT)
  - Frequency Regulation

Distributed Energy Resources Management System (DERMS)

Why

- CYME lacks of OPF module (depreciated) as a power commercial distribution system analysis software

Goal

- Develop a distribution level OPF based strategy
- Work with Eaton research laboratory to develop a DERMS module for CYME software

Difficulties

- Unbalance and mixture of single-phase and three-phase (multi-phase) in distribution level
- Linearization of Original nonlinear and nonconvex OPF model in multi-phase system
- General and comprehensive devices support by CYME (overhead-lines, transformer, PV, BESS, regulator, capacitor, etc.)

Formulation of OPF model

$$\min \sum_{t=\Delta t..T} \left(c_{g,t}P_{inj,t} + \sum_{i=1..N} \alpha(|V_{i,t}| - |V_{i_{nom}}|)^2\right)$$

Subject to

```
powerflow equations

line and transformer constraints

bus voltage constraints

operational generation constraints
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Constraints

- Powerflow equations:

$$P_{i,t} = \sum_{j=1}^{N} |V_{i,t}||V_{j,t}|(G_{ij}\cos\theta_{ij,t} + B_{ij}\sin\theta_{ij,t}) = P_{gi,t} - P_{di,t}$$

$$Q_{i,t} = \sum_{j=1}^{N} |V_{i,t}||V_{j,t}|(G_{ij}\sin\theta_{ij,t} - B_{ij}\cos\theta_{ij,t}) = Q_{gi,t} - Q_{di,t}$$

- Line and transformer constraints:

$$|S_{ij,t}| \le S_{ij_{max}}$$

- Bus voltage constraints:

$$V_{i_{min}} \le |V_{i,t}| \le V_{i_{max}}$$

- Operational generation constraints:

$$0 \le P_{k,t}^{PV} \le P_{k_{t,max}}^{PV}$$

$$0 \le P_{k,c,t}^{BESS} \le P_{k,c,max}^{BESS}$$

$$0 \le P_{k,d,t}^{BESS} \le P_{k,d,max}^{BESS}$$

$$SOC_{k,t+1}^{BESS} = SOC_{k,t}^{BESS} + (\eta_c P_{k,c,t}^{BESS}\Delta t - \frac{P_{k,d,t}^{BESS}}{\eta_d}\Delta t)/E_k^{BESS}$$

Powerflow Equations

Branch-flow model (BFM)

- Nonlinear and nonconvex
- Good for unbalanced distribution system to linearize (LinDistFlow model)

- Single-phase LinDistFlow model

$$P_{ij} + p_j = \sum_{k:j\to k} P_{jk} \; \forall j \in \mathrm{N}^+$$

$$Q_{ij} + q_j = \sum_{k:j\to k} Q_{jk} \; \forall j \in \mathrm{N}^+$$

$$w_j = w_i - 2r_{ij}P_{ij} - 2x_{ij}Q_{ij} \; \forall j \in \mathrm{N}^+$$

- Three-phase LinDistFlow model

$$P_{ij,\phi} + p_{j,\phi} = \sum_{k:j\to k} P_{jk,\phi} \; \forall j \in \mathrm{N}^+$$

$$Q_{ij,\phi} + q_{j,\phi} = \sum_{k:j\to k} Q_{jk,\phi} \; \forall j \in> \mathrm{N}^+$$

$$w_j = w_i + M_{P,ij}P_{ij} + M_{Q,ij}Q_{ij}$$

$$M_{P,ij} = \begin{bmatrix} -2r_{11} & r_{12} - \sqrt{3}x_{12} & r_{13} + \sqrt{3}x_{13} \\ r_{21} + \sqrt{3}x_{21} & -2r_{22} & r_{23} - \sqrt{3}x_{23} \\ r_{31} - \sqrt{3}x_{31} & r_{32} + \sqrt{3}x_{32} & -2r_{33} \end{bmatrix}$$

$$M_{Q,ij} = \begin{bmatrix} -2x_{11} & x_{12} - \sqrt{3}r_{12} & x_{13} + \sqrt{3}r_{13} \\ x_{21} + \sqrt{3}r_{21} & -2x_{22} & x_{23} - \sqrt{3}r_{23} \\ x_{31} - \sqrt{3}r_{31} & x_{32} + \sqrt{3}r_{32} & -2x_{33} \end{bmatrix}$$

Bus-injection model (BIM) (presented in the previous slide)

- Nonlinear and nonconvex
- Good for balanced three-phase transmission system

Implementation

- A python package to parse general CYME model
- A Pyomo (open-source optimization modeling language) based LinDistFlow model
- A general mixed-integer (with battery storage) nonlinear solver mindtpy (combined with GLPK and IPOPT)
- Communication between CYME and LinDistFlow OPF module via message passing interface (MPI)

Case Study (in progress)

- 4-Node-YY-Bal_dss
- IEEE-13 Node
- IEEE-34 Node
- IEEE-123 Node
- IEEE-123 Node with DERs
- IEEE-123 Node with DERs and BESSs
- Modified IEEE-123 Node from CYME

Case Study - Modified IEEE-123 Node from CYME

System Structure

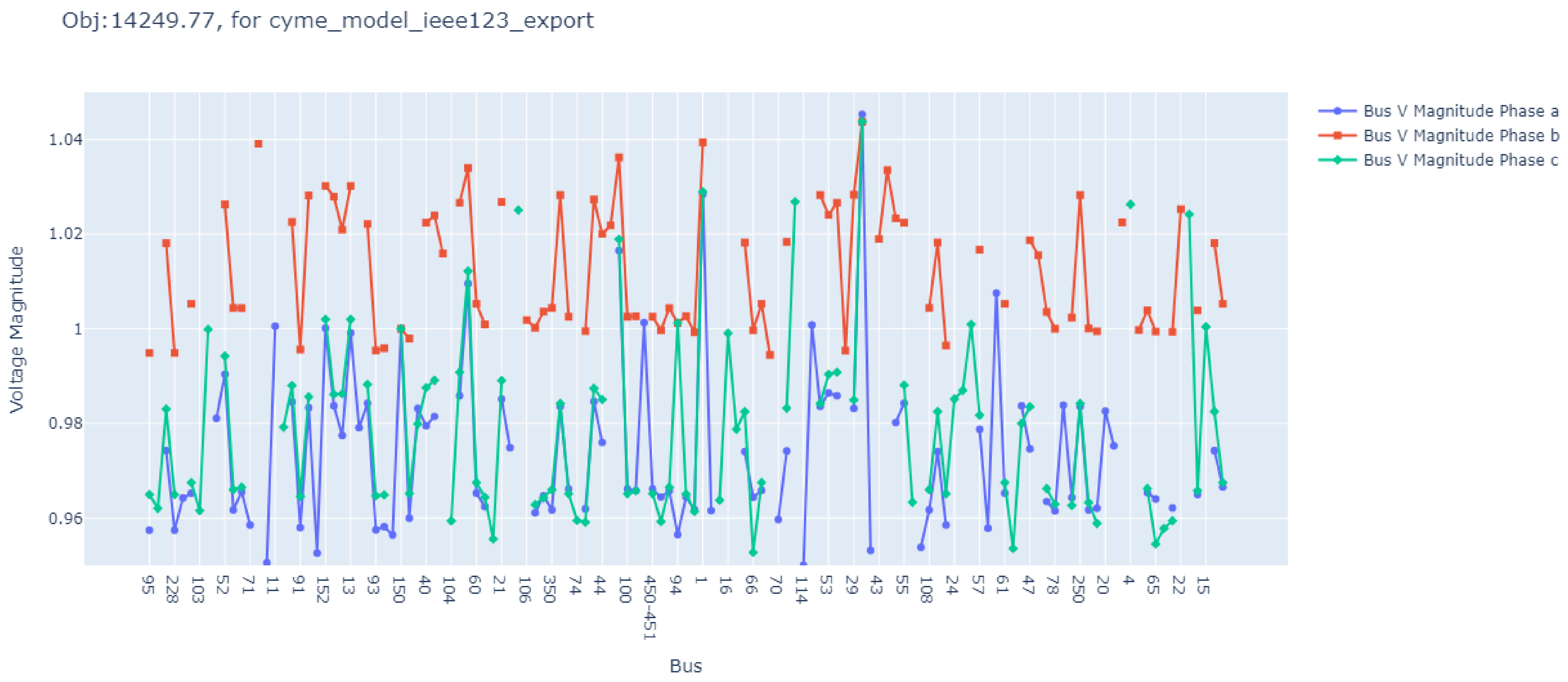
- Mixture of single-phase and three-phase
- Unbalanced overhead lines
- Regulators
- Capacitors
- PVs
- BESSs

Optimization Period

- 24 hours with 1 hour resolution
- Online optimization with feedback from the real-time power system data

Preliminary Results

No DERs

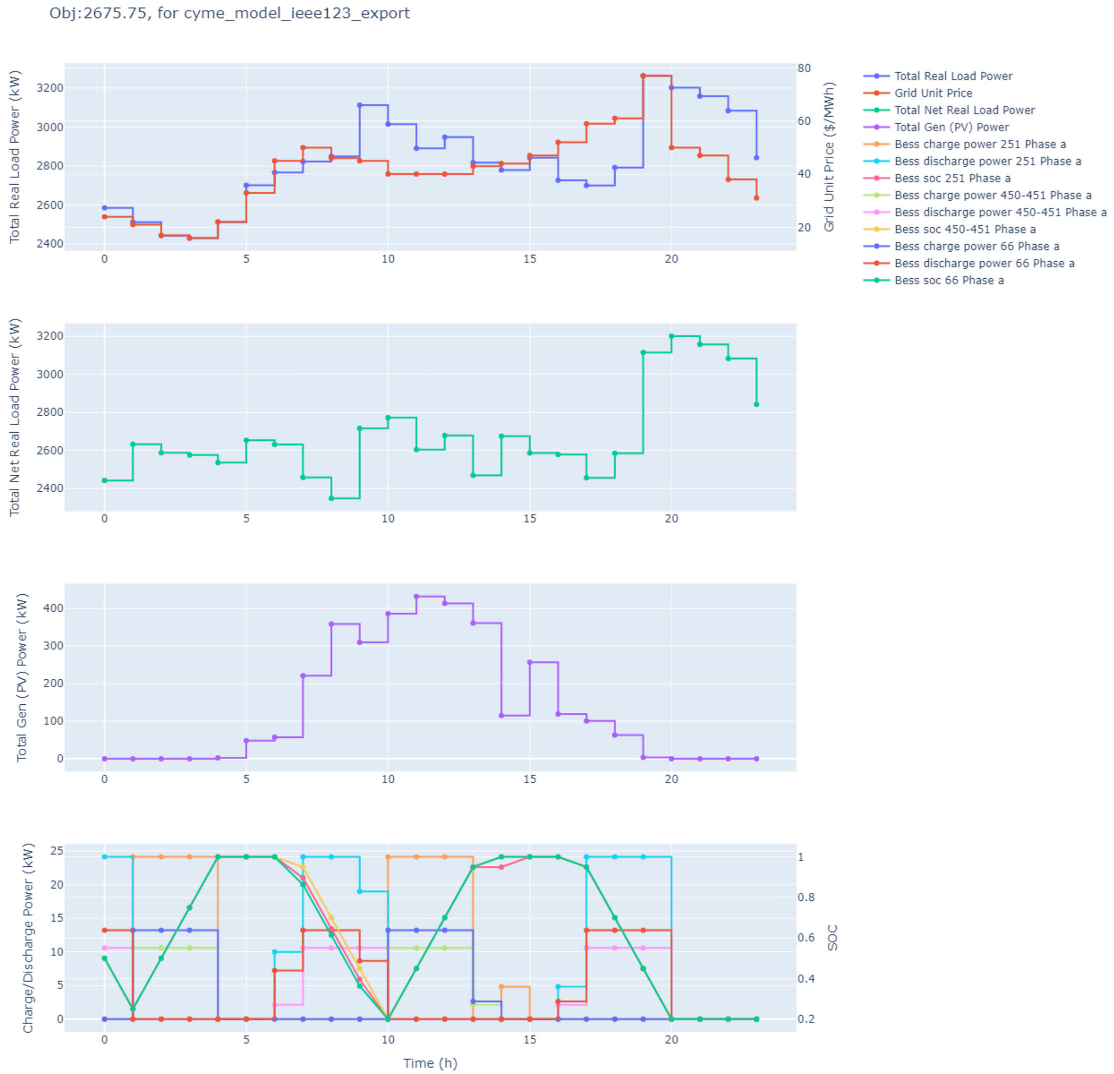


Preliminary Results

No DERs

Preliminary Results

50% DERs



100% DERs

Adaptive Power System Protection with IBRs

Why

- Existing protection relay settings are heavily relied on the time-domain based simulation and analysis (difficult and time-consuming)
- Existing protection relay settings are not performant or working due to the decreasing inertia of the system with more inverter-based resources (IBRs), as well the uncertainty of the IBRs

Goal

- Develop a protection relay setting framework with IBRs via DRL, especially for out-of-step and power swing conditions
- Work with SEL to integrate the DRL based adaptive protection settings into the physical relay via hardware-in-the-loop (HIL) testing

Difficulties

- Recognize out-of-step and power swing conditions for the system
- Integrate the DRL based settings into the physical relay
- HIL testing using RTDS platform

Out-of-Step and Power Swing Conditions

A large disturbance to the system such as faults, leads to two results:

- Out-of-step
  - Loss of synchronism between two or more generators
  - Cascading outages and system blackouts

- Stable power swing
  - Oscillations between generators are stable
  - System returns to new equilibrium point

Existing Dual-blinder Protection

- Impedance seen by relay in complex plane
- Rate of change of impedance
  - Moves slow during stable power swing
  - Moves fast during out-of-step
- Principle of the dual-blinder relay
  - Monitor the time of impedance trajectory crossing the two blinders
- Setting of the dual-blinder relay
  - Zone 5: resistance and reactance thresholds
  - Zone 6: resistance and reactance thresholds
  - Crossing time threshold

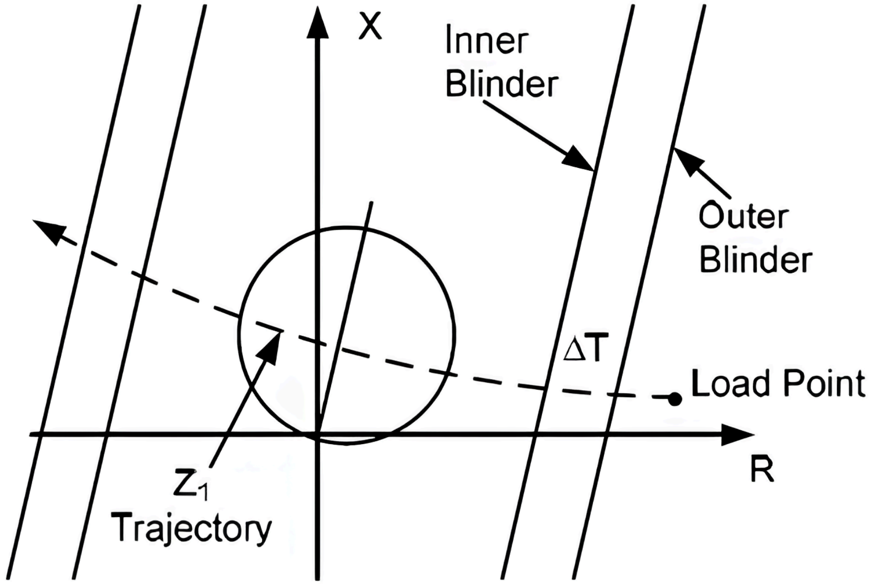


Fig. 6. Dual-blinder characteristic.

Source: Fischer, Normann et al. “Tutorial on Power Swing Blocking and Out-of-Step Tripping.” (2015)

Implementation (in progress)

- Power system simulation with synchronous generator and IBRs (PV and DFIG) in PSCAD/EMTDC

- DRL algorithm in Python with parallel computing in Ray framework

- HIL testing with RTDS platform

Deep Reinforcement Learning based power system dynamic control

Why

- Convertional control strategies usually require linearized model
- Fixed control parameters limit performance for various operating conditions
- DRL based algorithms
  - Data-driven, model-free
  - No linearization is required

Goal

- Develop a general DRL based control framework and platform for power system dynamic control

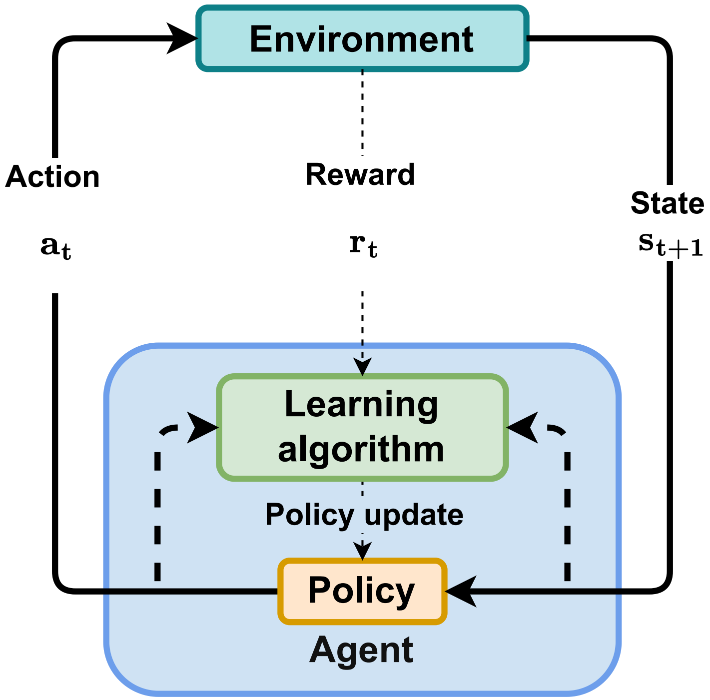
Difficulties

- Efficient training process
- Reliable action space
- Efficient reward function design

Reinforcement Learning and Meta Learning

Elements

- Agent - RL algorithm
- Environment - Physical or simulated power system
- States - Important system variables (differential and algebraic)
- Actions - Control actions (discrete or continuous)
- Reward - Measure the performance of the agent
- Policy - Function to generate action (linear or nonlinear such as neural network, i.e., DRL)



Goal

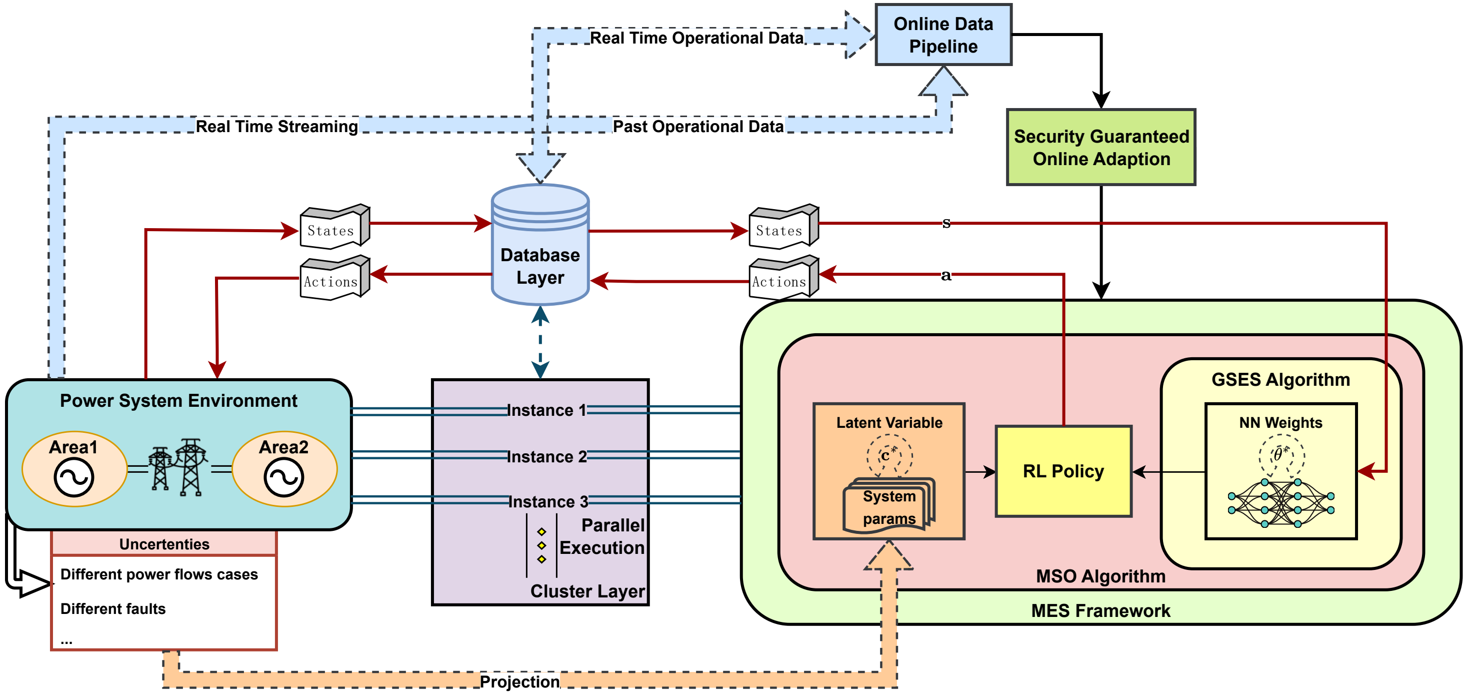
- Design an effective reward function to find the optimal policy in maximizing the expected cumulative rewards

Meta Learning

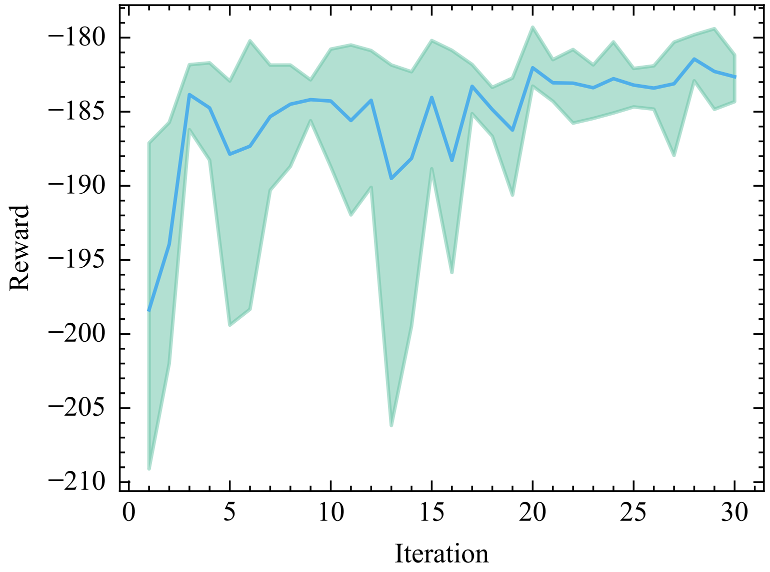
- Enhance DRL's capability even more by exposing to more diverse environments (tasks)
- Utilize the knowledge in one task to improve the performance in another task efficiently
- Safe and reliable action facing new environments (tasks)
- Apply to new environments (tasks) with little adaptation process

Meta-DRL Framework and Platform [1]

Framework



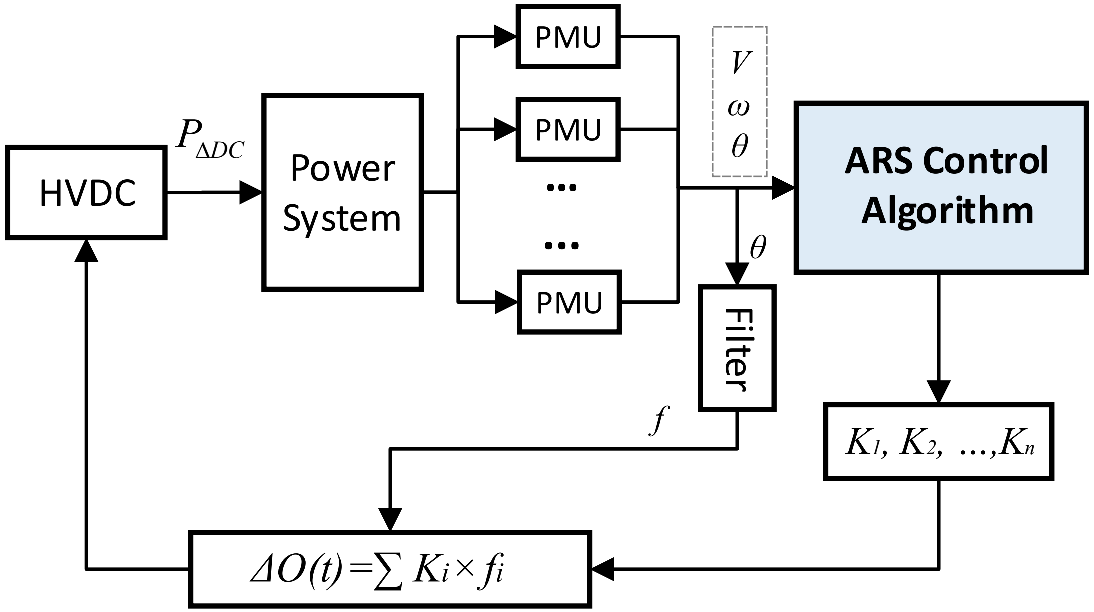
Robustness of Training Process



HVDC-based oscillation damping control using Meta-DRL [4]

Problem

- Inter-area oscillation threaten system stability
- HVDC modulates power between two areas to damp oscillation
- Conventional damping controller parameters are fixed and not performant for various operating conditions and faults



Conventional damping control

- Wide-area damping controller using PUM measurements
- Linearization of the system
- Fixed controller parameters

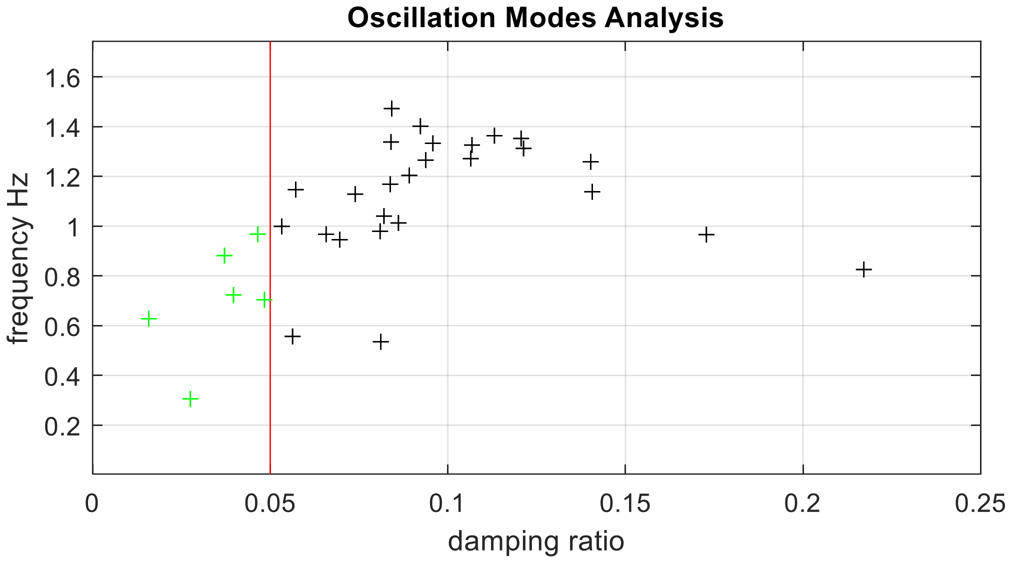
DRL-based damping control

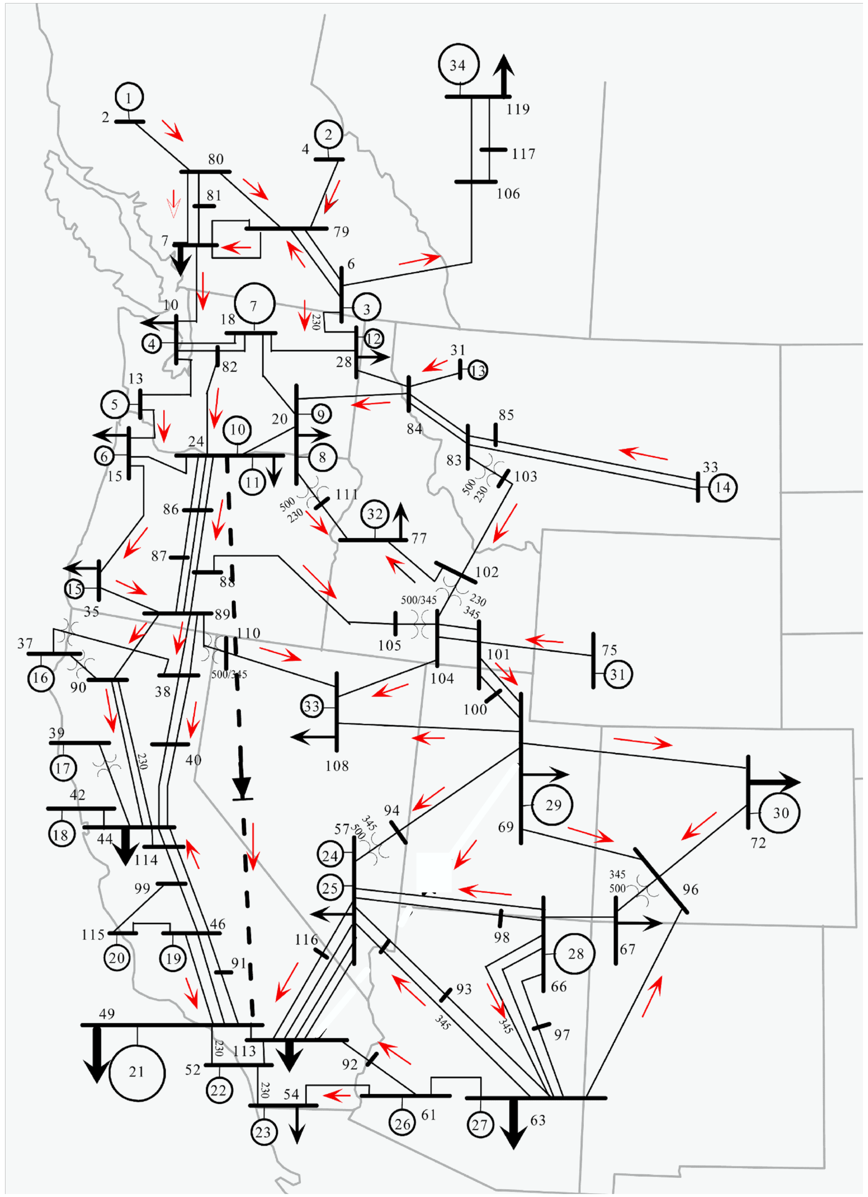
- Adaptively regulate the reference signal of the exsiting controllers

Case Study 1 [4]

Revised minniWECC system with PDCI HVDC transmission

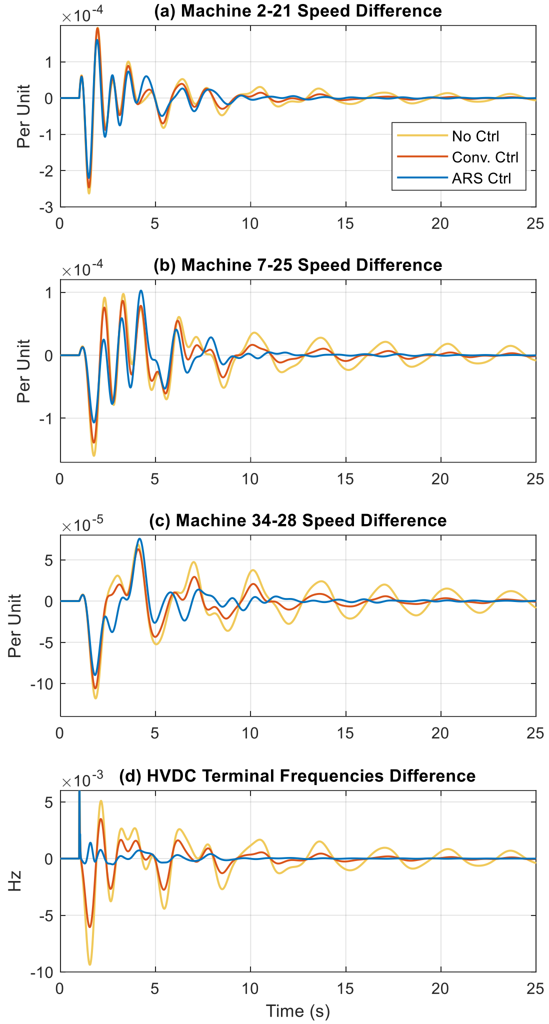
- Two dominant modes
  - 0.3 Hz Alberta mode
  - 0.65 Hz BC mode



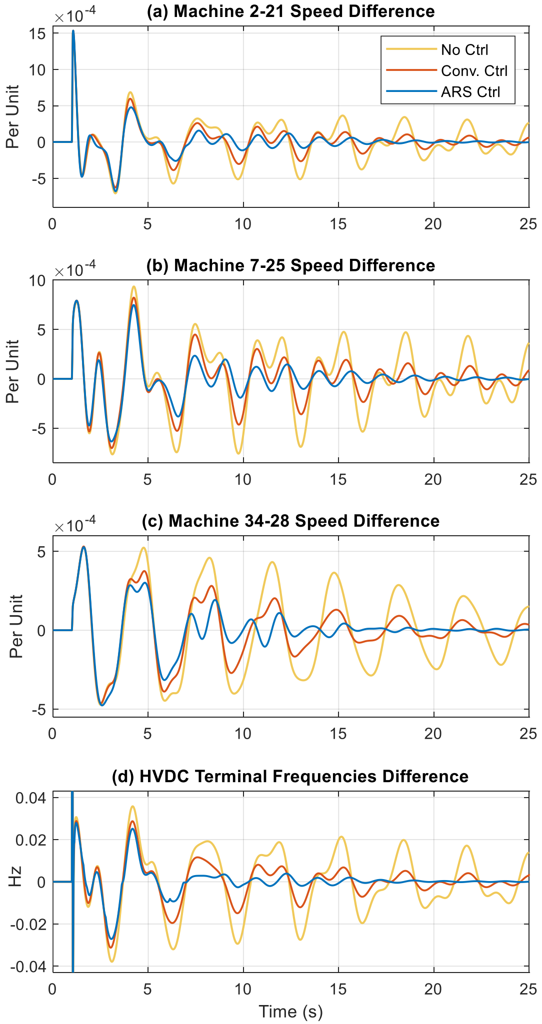


Result of Revised minniWECC [4]

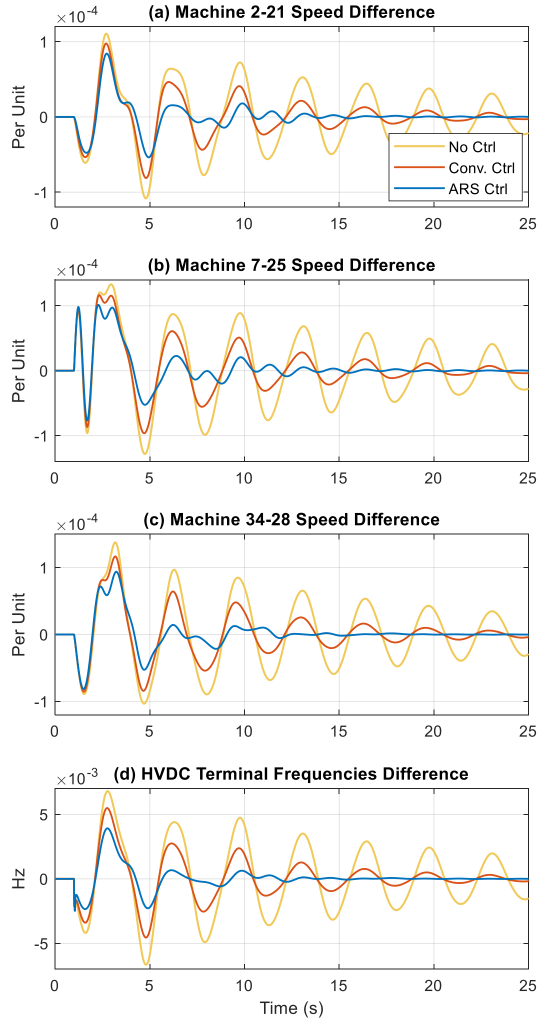
Loss of line (left), Single-phase fault (right)



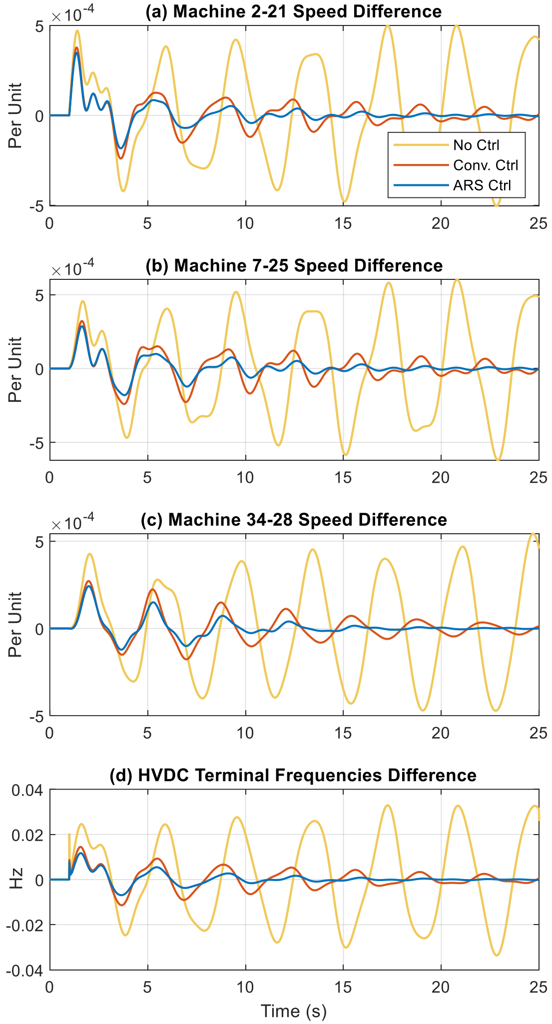
(i) Results of *Scenario I*



(ii) Results of *Scenario II*



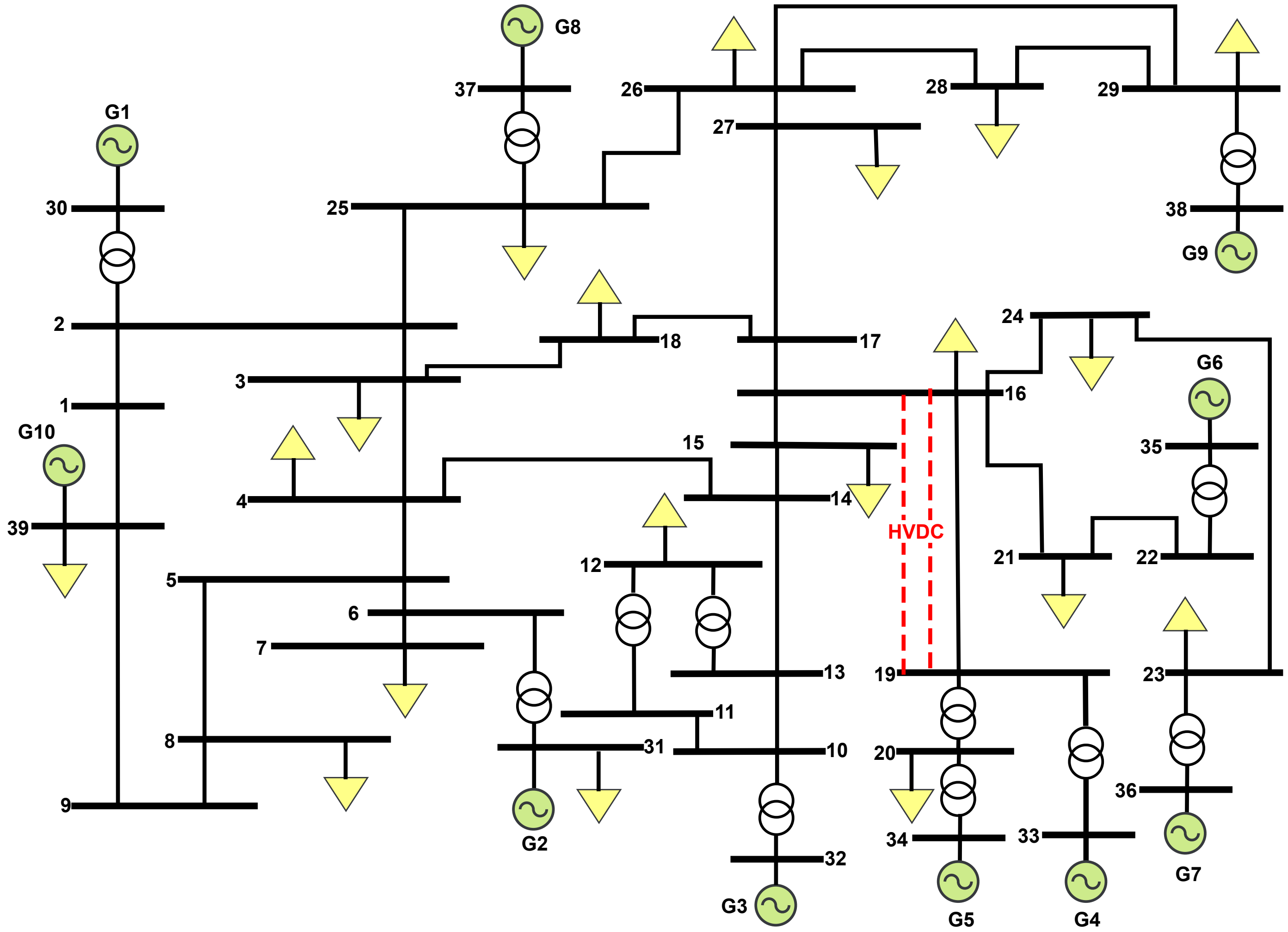
(i) Results of *Scenario III*



(ii) Results of *Scenario IV*

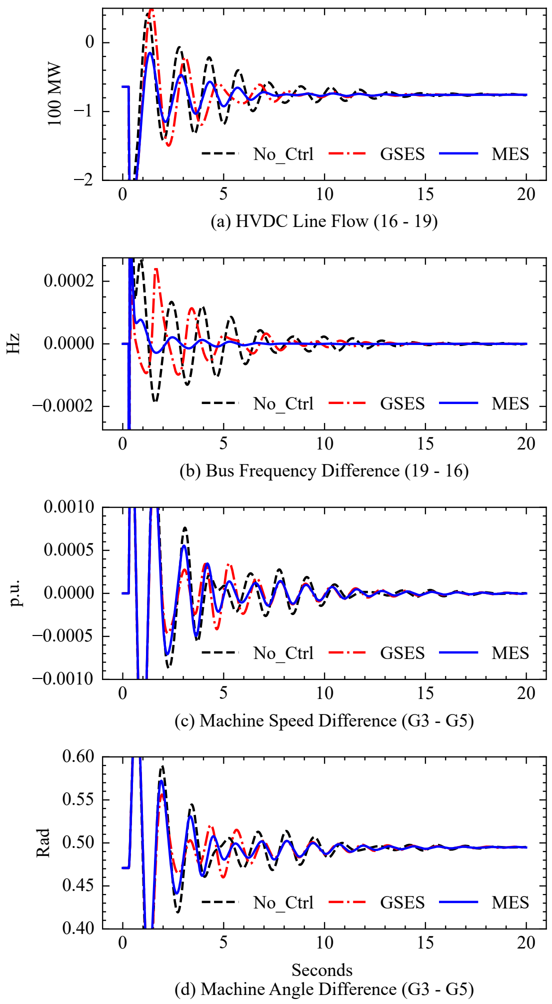
Case Study 2 [1]

Modified IEEE-39 bus system with HVDC

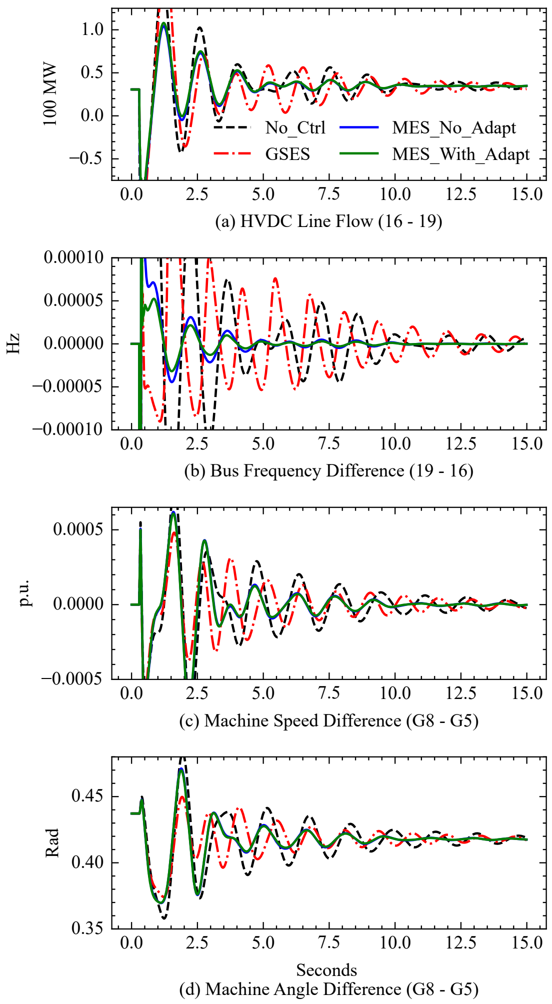


Result of Modified IEEE-39 bus system with HVDC [1]

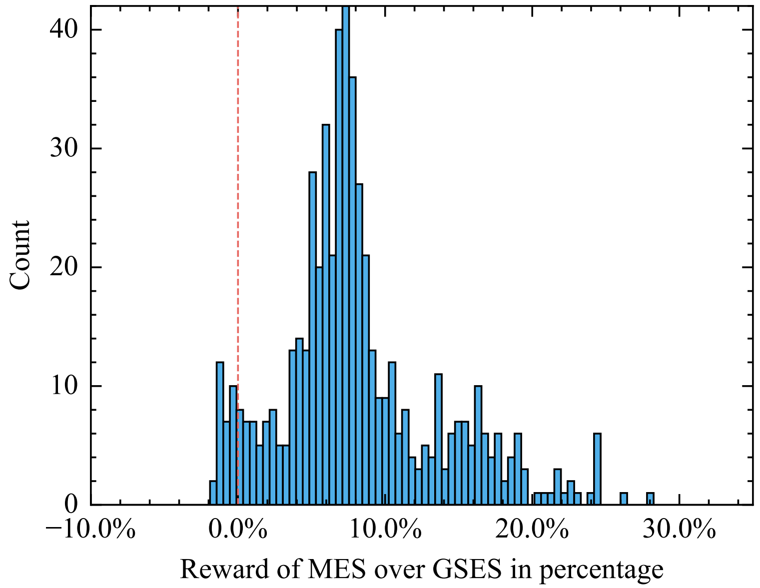
Training example of the system dynamics



Adaptation example of the system dynamics



Reward of MES over GSES in percent



DFIG-FRT using DRL [5]

Problem

- DFIG generates maximum power using MPPT during normal operation
- DFIG rotor over-current and DC-link over-voltage due to terminal voltage dip during faults

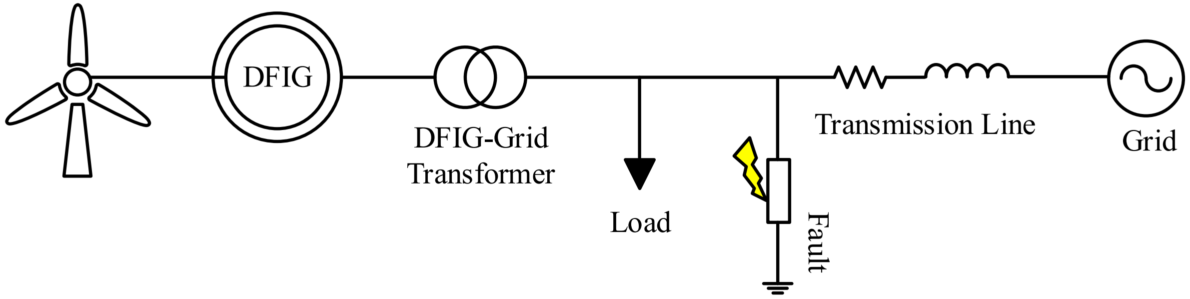
Conventional FRT

- Additional hardware (e.g., crowbar)
- Rely on accurate mathematical model of the system

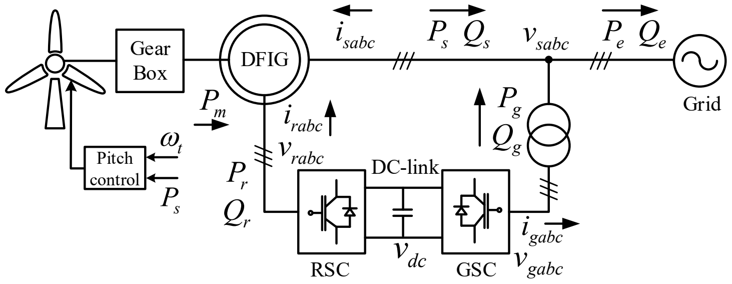
DRL-based FRT

- Adaptively regulate the reference signal of the DFIG active power and DC-link voltage
- Smooth transition to new steady-state

Case Study [5]

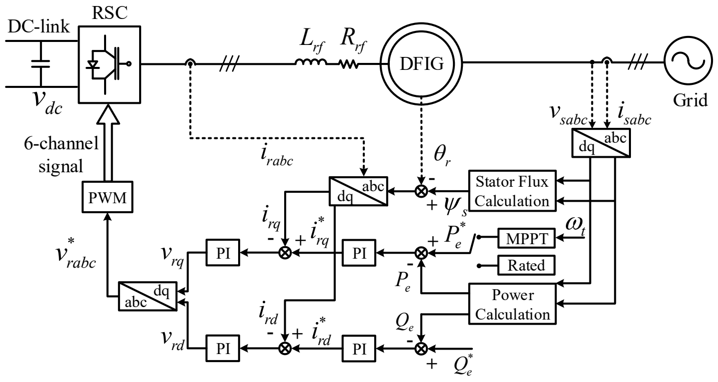


Grid-following-based DFIG



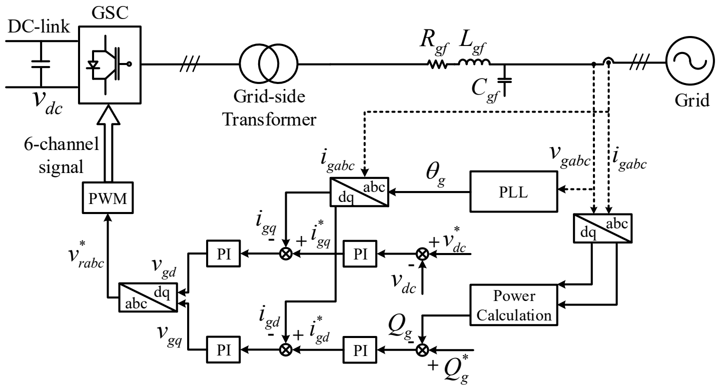
DFIG Rotor-side Converter

- Inner current loop
  - Rotor dq-axis currents i_{rd} and i_{rq}
- Outer power loop
  - Active power/rotating speed



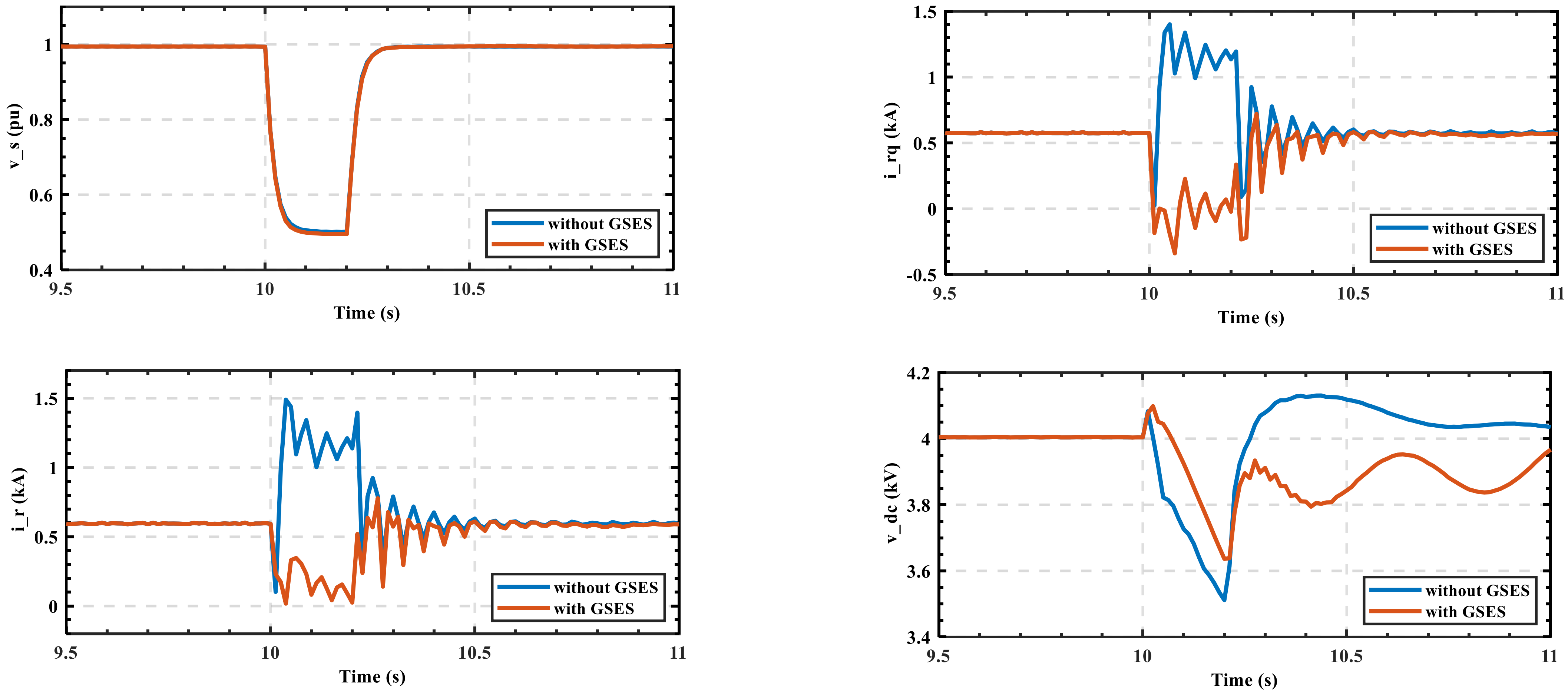
DFIG Grid-side Converter

- Inner current loop
  - Grid dq-axis currents i_{gd} and i_{gq}
- Outer power loop
  - DC-link voltage and grid reactive power



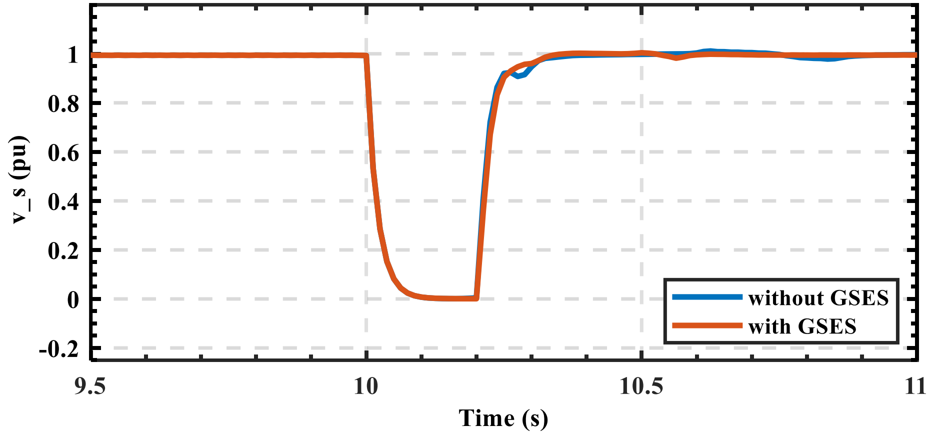
Result of DFIG-FRT [5]

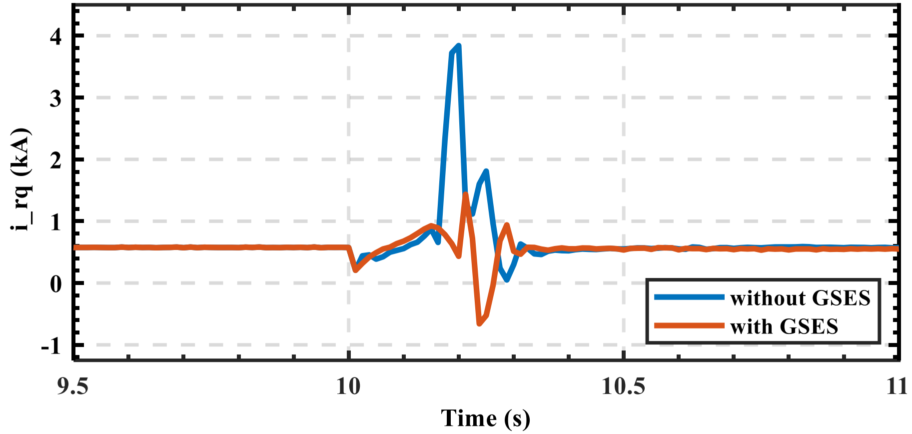
Three-phase fault with 50% voltage drop

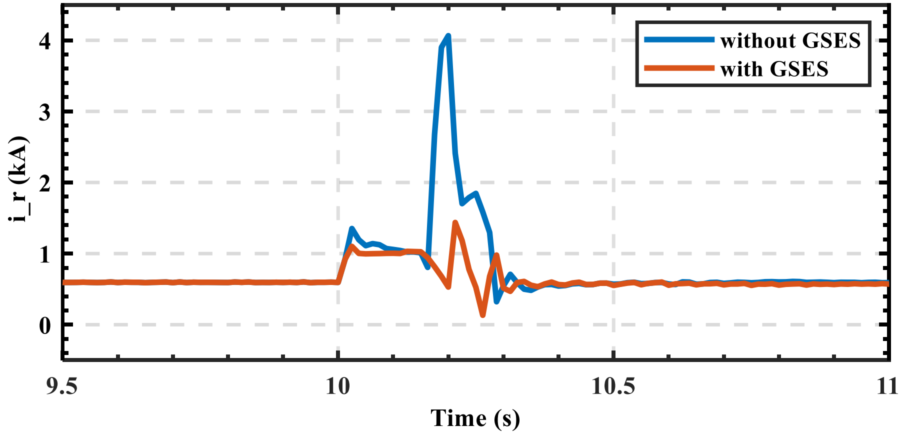


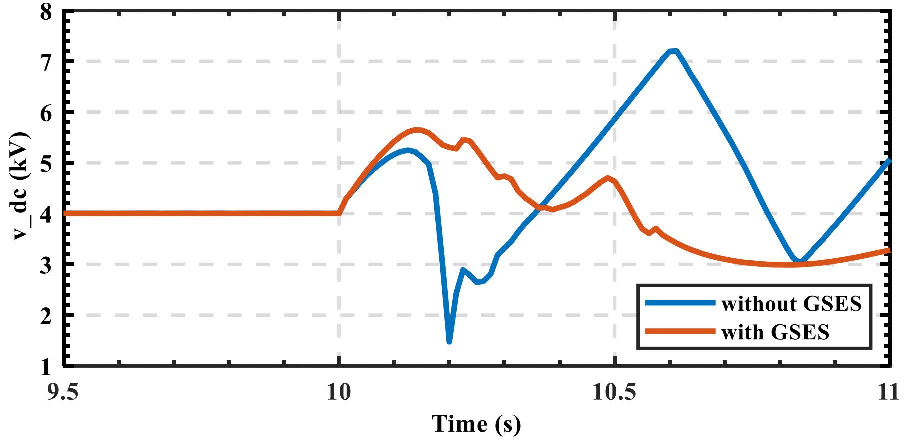
Result of DFIG-FRT [5]

Three-phase fault with 100% voltage drop



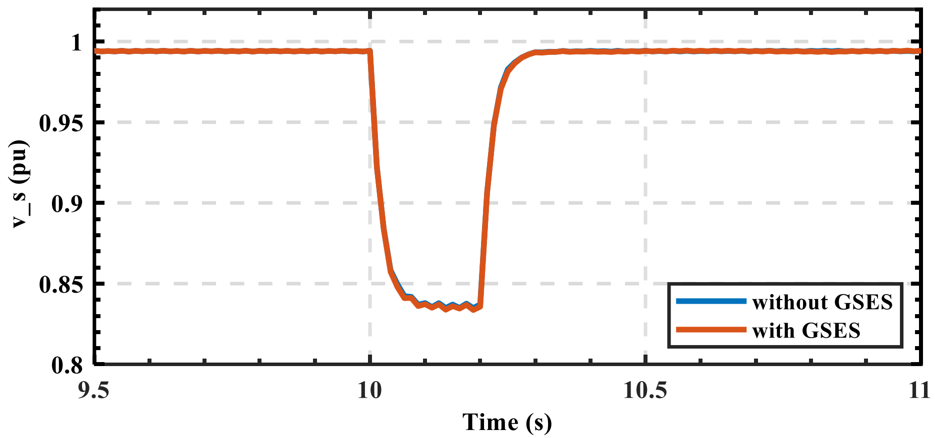


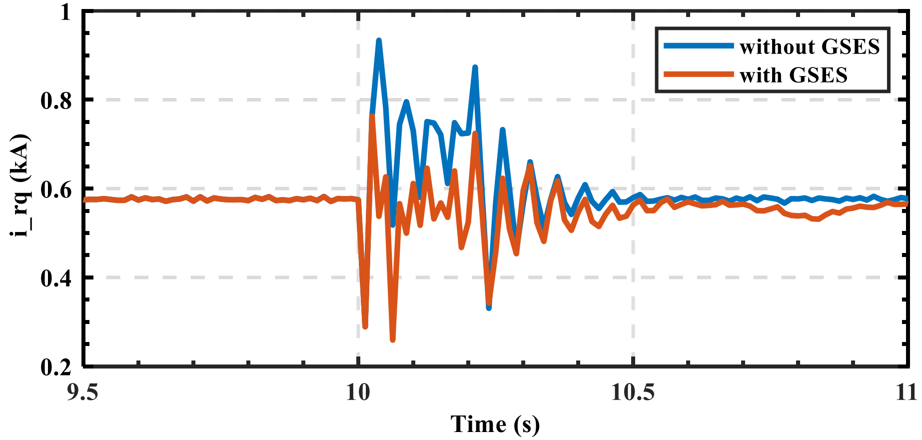


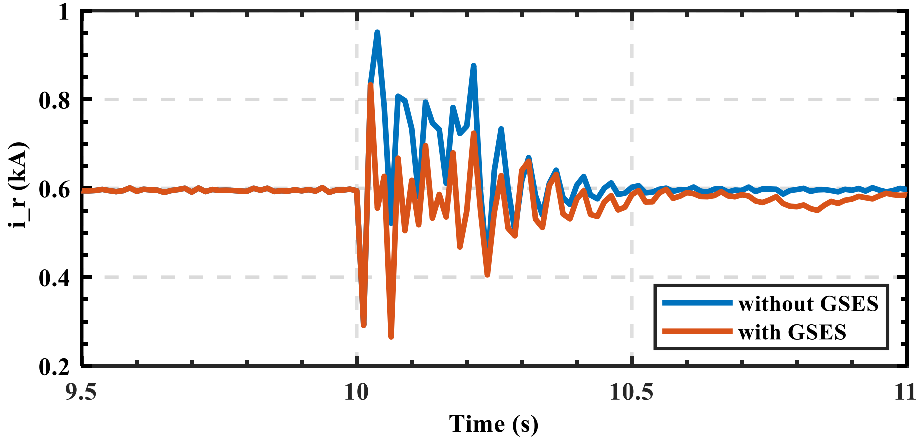


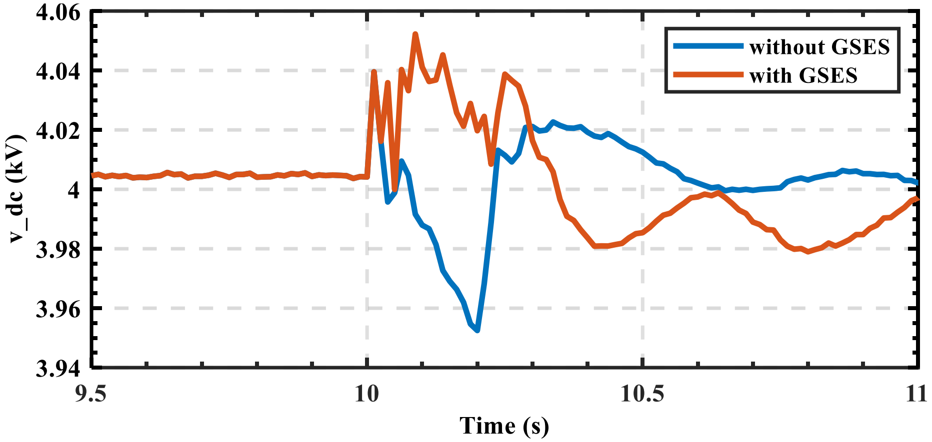
Result of DFIG-FRT [5]

Metallic single-line-to-ground fault









Frequency Regulation using DRL [2, 3]

Problem

- Frequency regulation is done by synchronous generators (SG) due to the natural inertia
- Low system inertia due to the increasing penetration of inverter-based resources (IBRs)

Conventional frequency regulation

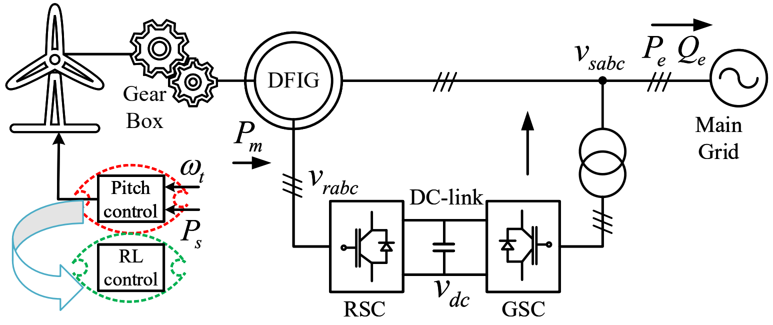
- Additional battery energy storage system (BESS)
- Pitch control of wind turbines system to regulate the power output and maintain the system frequency

DRL-based frequency regulation

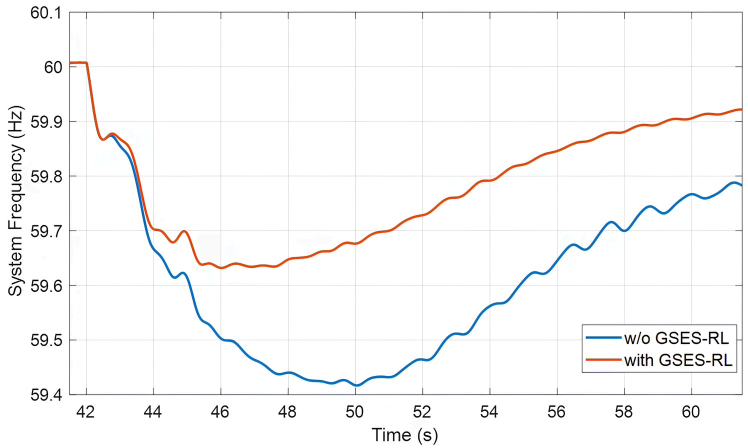
- Adaptively adjust the reference signal of the exisiting pitch angle controller
- Stabilize system frequency during events
- Avoid unnecessary load shedding

Case Study [2, 3]

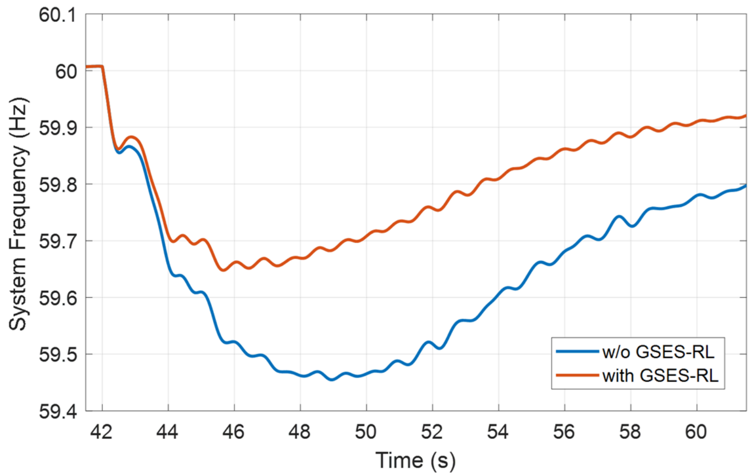
One SG replaced by DFIG in a modified IEEE-39 bus system



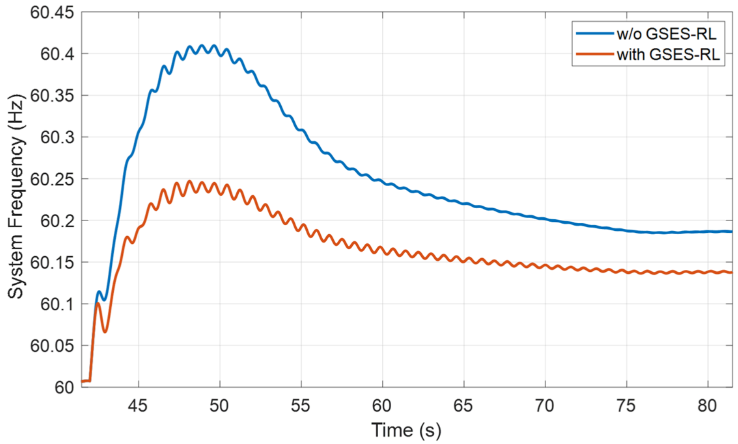
Loss of generator



Sudden increase of load



Sudden decrease of load



Publications

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2. **Gao, W.**, Fan, R., Qiao, W., Wang, S., & Gao, W. (2023). Deep Reinforcement Learning Based Control of Wind Turbines for Fast Frequency Response. IEEE Industry Applications Society (IAS) Transactions. (Submitted)
3. **W. Gao**, R. Fan, W. Qiao, S. Wang and D. W. Gao, "Fast Frequency Response Using Reinforcement Learning-Controlled Wind Turbines," 2023 IEEE Industry Applications Society Annual Meeting (IAS), Nashville, TN, USA, 2023, pp. 1-7, doi: 10.1109/IAS54024.2023.10406378.
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16. Y. Li, D. W. Gao, **W. Gao**, H. Zhang, and J. Zhou, “A distributed double-newton de- scent algorithm for cooperative energy management of multiple energy bodies in energy internet,” IEEE Transactions on Industrial Informatics, vol. 17, no. 9, pp. 5993–6003, 2020.
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