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Reactive Power Control for Fast-Acting Voltage Regulation of Distributed Wind Turbines Using Reinforcement Learning

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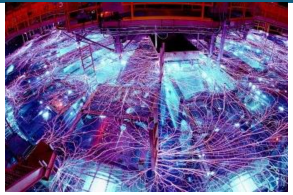

PRESENTED BY

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Introduction (I)

- DER integration benefits:
  - Loss reduction
  - Increased reliability
  - Increased flexibility

- DER integration challenges:
  - Voltage swings
  - Protection blinding

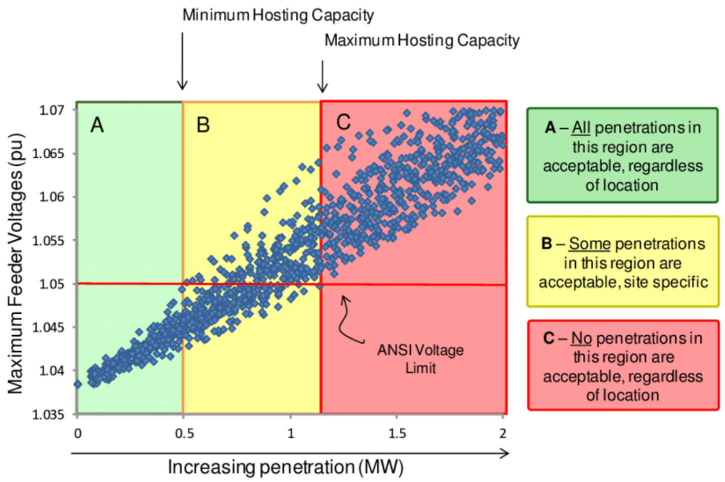

Fig 1. Hosting capacity schematic

Source: Smith, Jeff, Rylander, Matthew, Boemer, Jens, Broderick, Robert Joseph, Reno, Matthew J., and Mather, Barry. Analysis to Inform CA Grid Integration Rules for PV: Final Report on Inverter Settings for Transmission and Distribution System Performance. United States: N. p., 2016. Web. doi:10.2172/1431468.

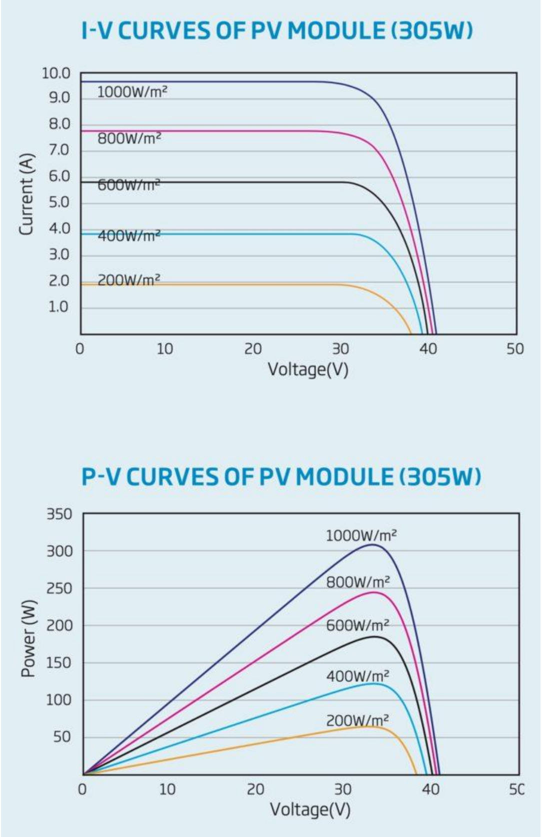

Fig 2. Solar power output dependence on irradiance

Source: https://www.victronenergy.com/blog/2020/02/20/pv-panel-output-voltage-shadow-effect/

Introduction (II)

Traditional voltage regulation devices on distribution systems

- Voltage regulators
- Capacitor banks
- Synchronous generator

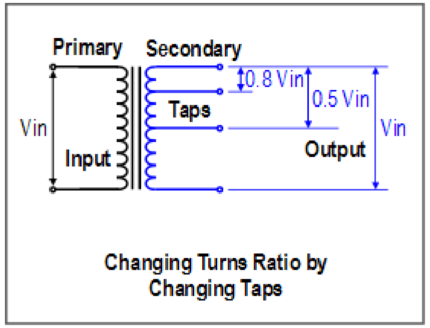

Fig 3. Voltage regulator taps schematic

Source: https://ustpower.com/comparing-automatic-voltage-regulation-technologies/avr-guide-mechanical-type-voltage-regulator/avr-guide-tap-changing-voltage-regulator-operation/

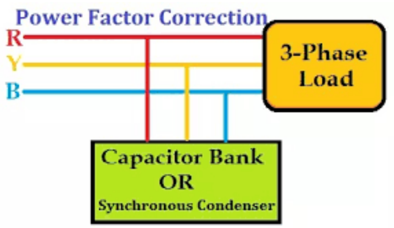

Fig 4. Capacitor bank and synchronous condenser placement schematic

Source: https://www.electrical-technology.com/2019/05/power-factor-correction.html

IEEE 1547-2108 standard encourages using DERs for voltage regulation

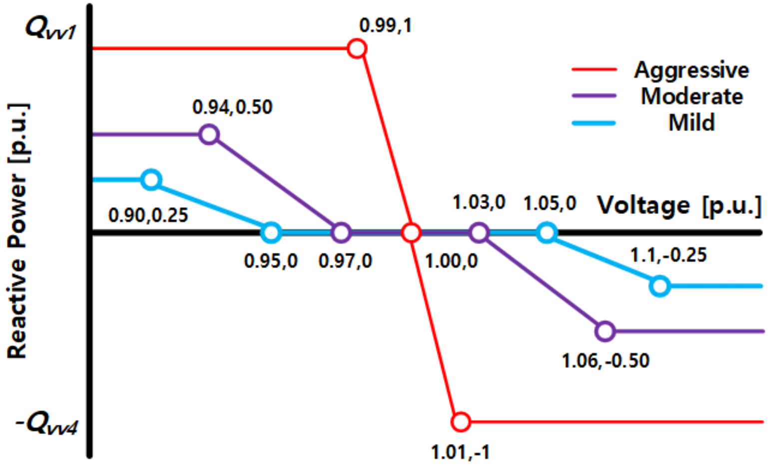

Fig 5. Volt-VAR curve control for voltage regulation

Source: Lee, Hyeong-Jin & Yoon, Kwang-Hoon & Shin, Joong-Woo & Kim, Jae-Chul & Cho, Sung-Min. (2020). Optimal Parameters of Volt-Var Function in Smart Inverters for Improving System Performance. Energies. 13. 2294. 10.3390/en13092294.

Background

- Power electronics on DERs can inject or absorb reactive power Q as long as:

$$|Q| \leq \sqrt{S^2 - P^2}$$

- Changes in Q setpoint as fast as from cycle to cycle

- Solar PV inverters have been widely researched for voltage regulation at both transmission and distribution levels
- **Voltage regulation using Wind Turbine Generators (WTGs) have only been researched for transmission systems**

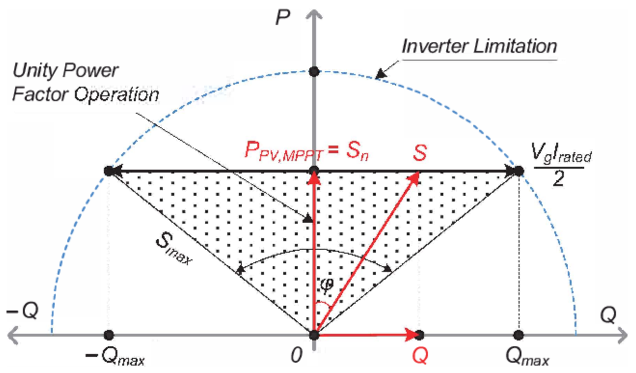

Fig 6. Solar PV inverter PQ diagram

Source: Yang, Yongheng & Enjeti, Prasad & Blaabjerg, F. & Wang, Huai. (2015). Wide-Scale Adoption of Photovoltaic Energy: Grid Code Modifications Are Explored in the Distribution Grid. IEEE Industry Applications Magazine. 21. 1-10. 10.1109/MIAS.2014.2345837.

Methodology (I)

Contributions:

- Voltage regulation controller using Reinforcement Learning (RL)
- Regulates on a tight band to avoid violations of ANSI C84.1 standard
- Dispatch interval of 50 milliseconds for fast voltage regulation
- Digital-twin model of a real distribution system in MATLAB/Simulink

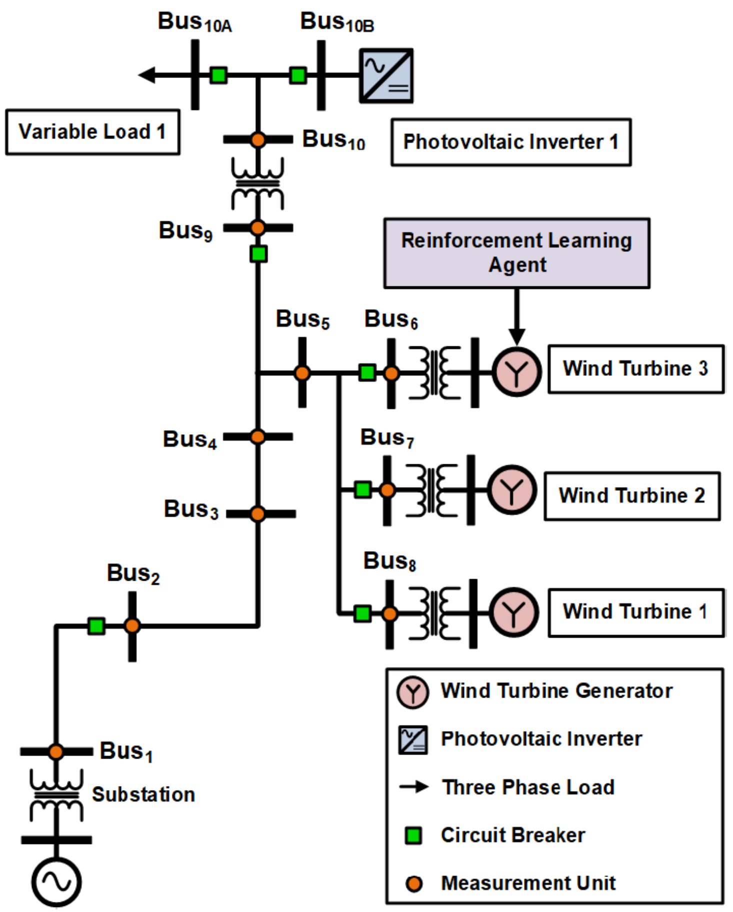

Fig 7. Diagram of SWiFT test site, Lubbock, TX

Methodology (II)

The proposed WTG controller is based on a RL **Deep Deterministic Policy Gradient (DDPG) agent:**

- Actor-Critic model
  - The actor tries to approximate the best policy that maps an observed state S to an optimal control action A
  - The critic estimates the expectation of the long term reward for such action
- Trained to maximize a defined reward
- NOTE: The agent has access to all system node voltages

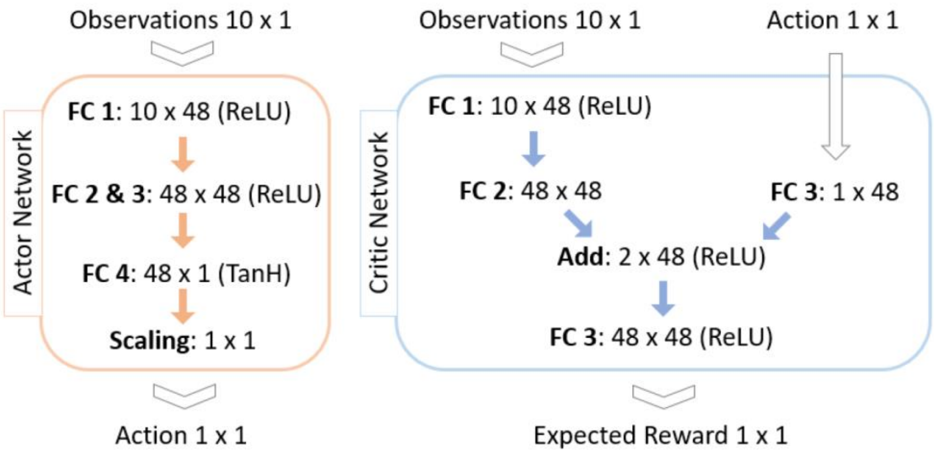

Fig 8. DDPG model structure

Methodology (III)

Goal: Regulate all node voltages between [0.98, 1.02] p.u.

Reward terms:

1) Control action (Q) magnitude
2) Number of node voltages outside range
3) Maximum under-voltage deviation
4) Exceed simulation bounds condition

Table 1. ANSI C84.1 standard Range A

Node voltage	Lower bound	Upper bound
≤ 600 V	-5%	+5%
> 600 V	-2.5%	+5%

Methodology (IV)

- Available data:

Table 2. Real-site data

Resource	Length (seconds)
Wind speed	2844
Solar irradiance	5000
Load	3540

- Training: 520 episodes, 200 seconds each (About ~10 days in real-time)
- Testing: 80 episodes

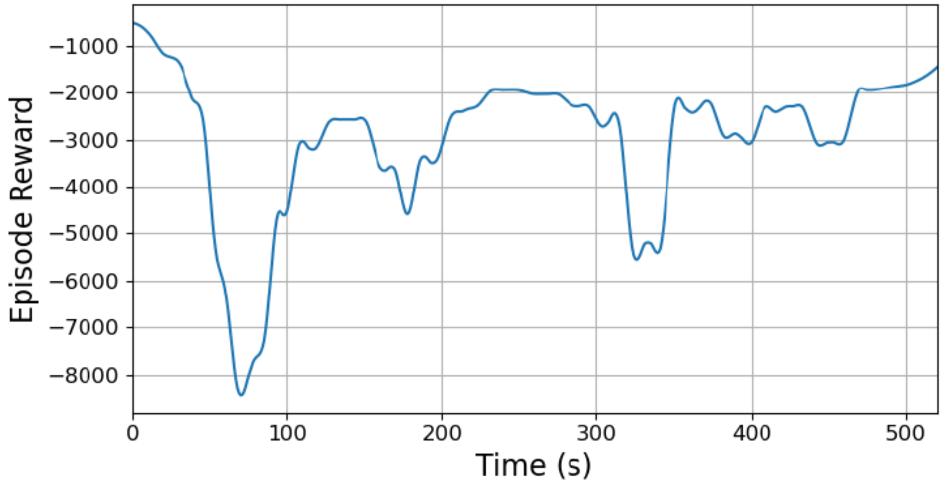

Fig 9. Averaged reward per episode during training

Results (I)

Analysis A:

Controller behavior over an episode of 400 seconds

Response to:

- Significant drop on PV generation (from $t = 100$ seconds to $t = 300$ seconds approx.)
- Load event (at $t = 250$ seconds)

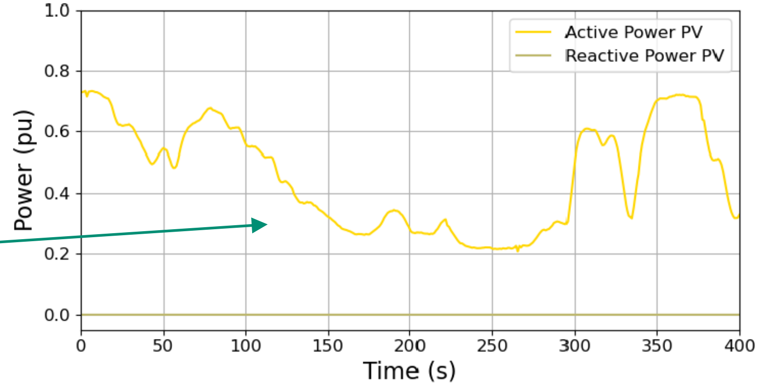

Fig 11. Solar PV active and reactive power generation

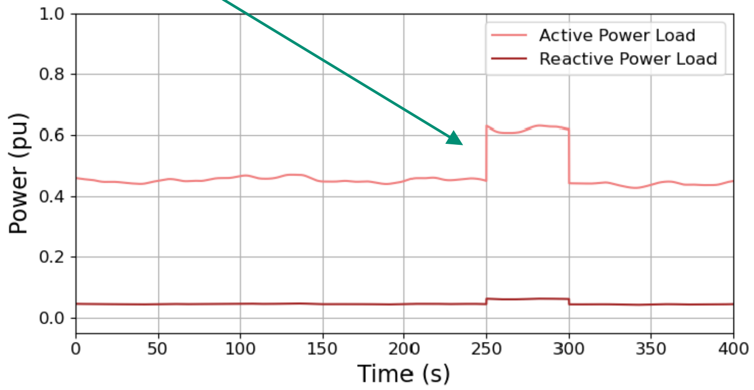

Fig 10. Load active and reactive power consumption

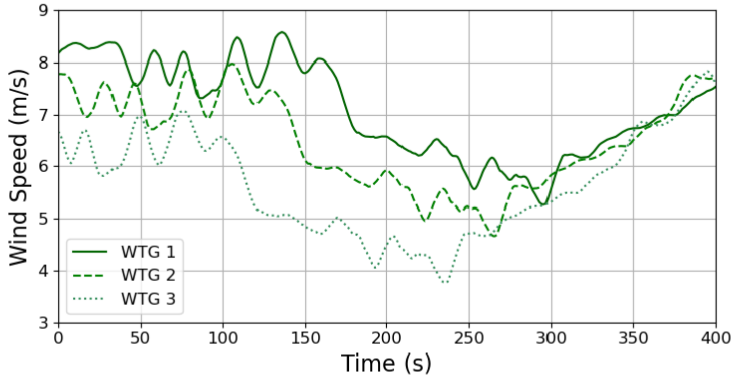

Fig 12. Wind speed profiles

Results (II)

Analysis A:

The RL agent on WTG 3 injects reactive power in the system to avoid under-voltage deviations

The injected Q is maximum during the load event

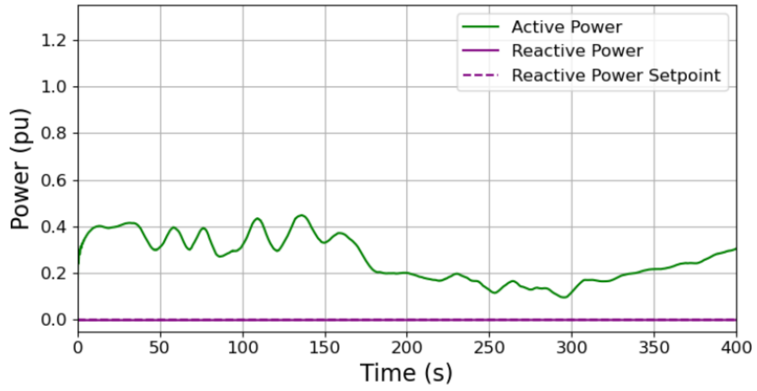

Fig 13. WTG 1 output

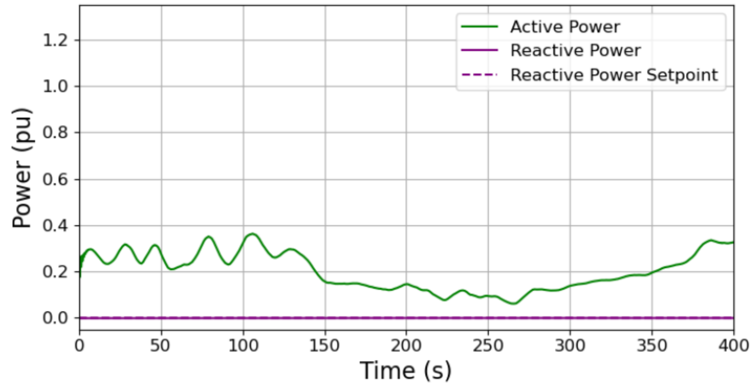

Fig 14. WTG 2 output

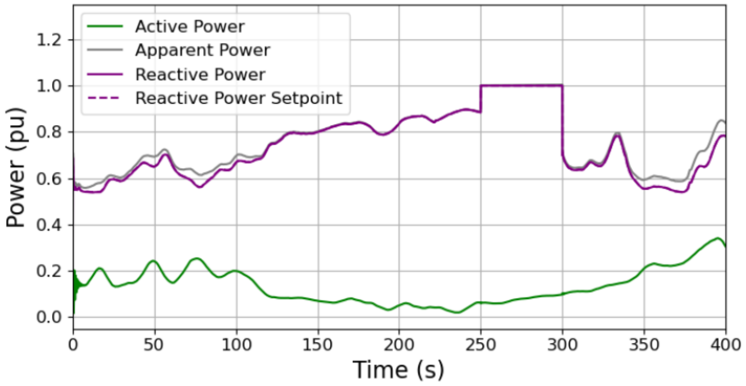

Fig 15. WTG 3 output

Results (III)

Analysis A:

The RL agent on WTG 3 injects reactive power in the system to avoid under-voltage deviations

A violation of the ANSI C84.1 standard is avoided on Bus 10 from $t = 250$ seconds to $t = 300$ seconds

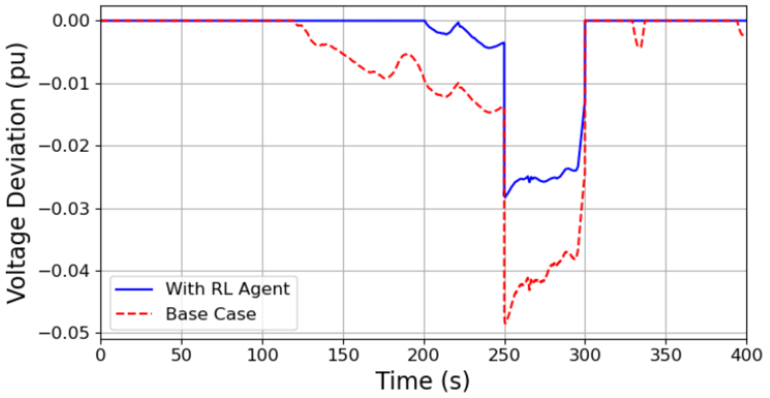

Fig 16. Total under-voltage deviations below 0.98 p.u.

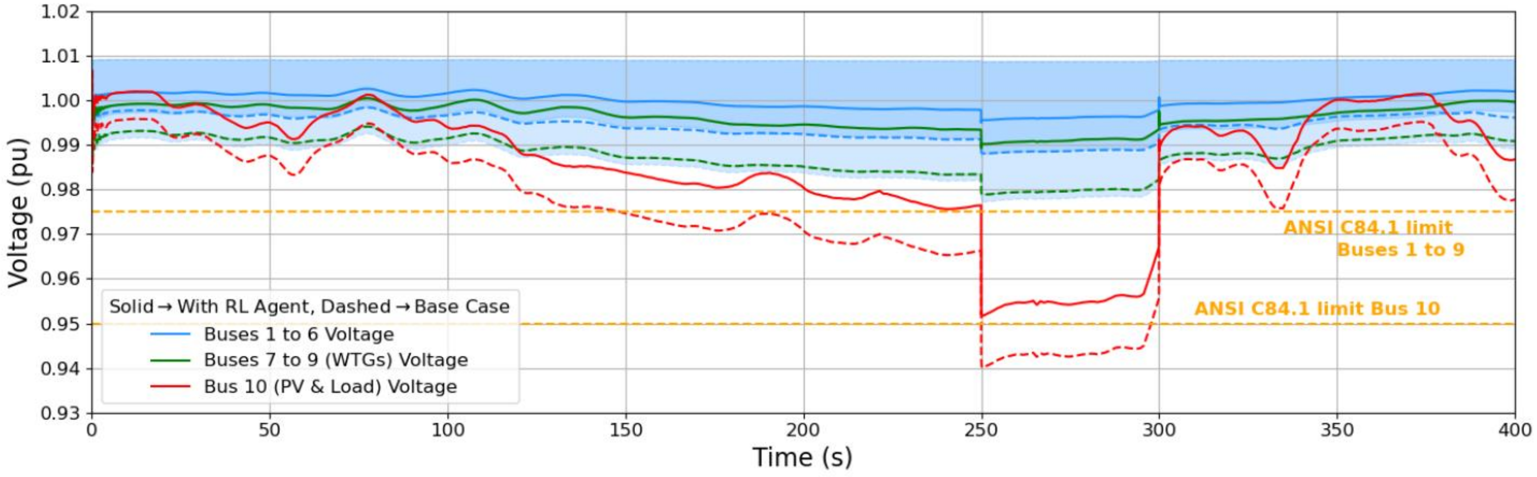

Fig 17. System voltages comparison with and without the proposed voltage regulation controller

Results (IV)

Analysis B:

Performance of the proposed controller on 80 test episodes of 200 seconds each

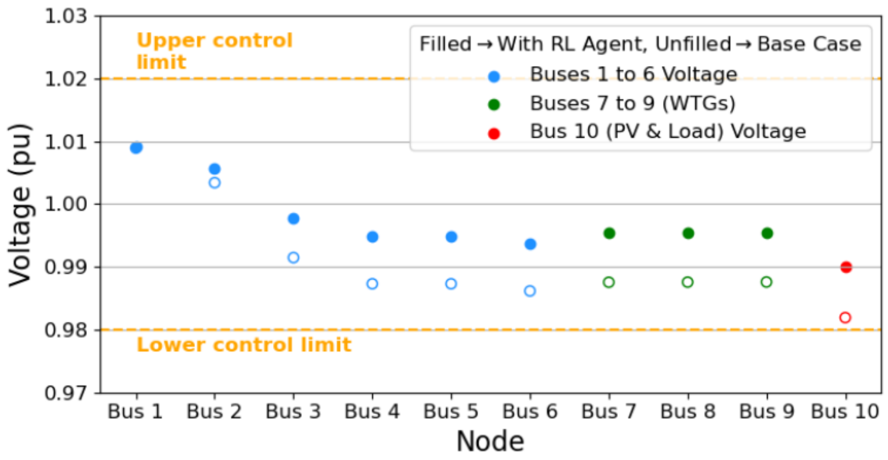

Fig 18. Mean bus voltages over 80 episodes

Table 3. Averaged performance metrics per episode

Use Case	S_e (p.u.)	WTG 3 P_e (p.u.)	WTG 3 Q_e (p.u.)
Base Case	-0.033	0.102	-0.001
With RL Agent	-0.006	0.100	0.699

Total under-voltage below 0.98 p.u.

Future work

- Study particle swarm optimization (use 3 WTGs and PV to regulate voltage simultaneously)
- Use more training data

Conclusions

- Voltage regulation controller using a RL DDPG model for WTG 3:
  - Trained to maintain node voltages in the range of [0.98, 1.02] p.u.
  - The control action is the injected/ absorbed reactive power
  - Avoids voltage deviations, especially under-voltage events
  - Fast response for sudden events