Stable RL for Voltage Control

Using Reinforcement learning for Real-time Voltage Control in Distribution Systems

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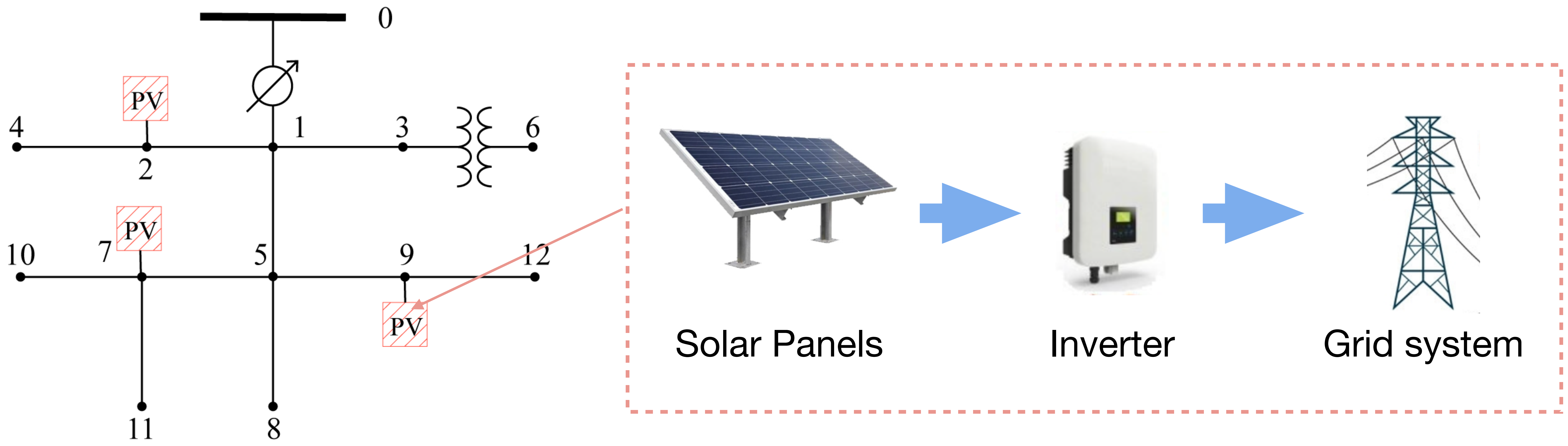
Background

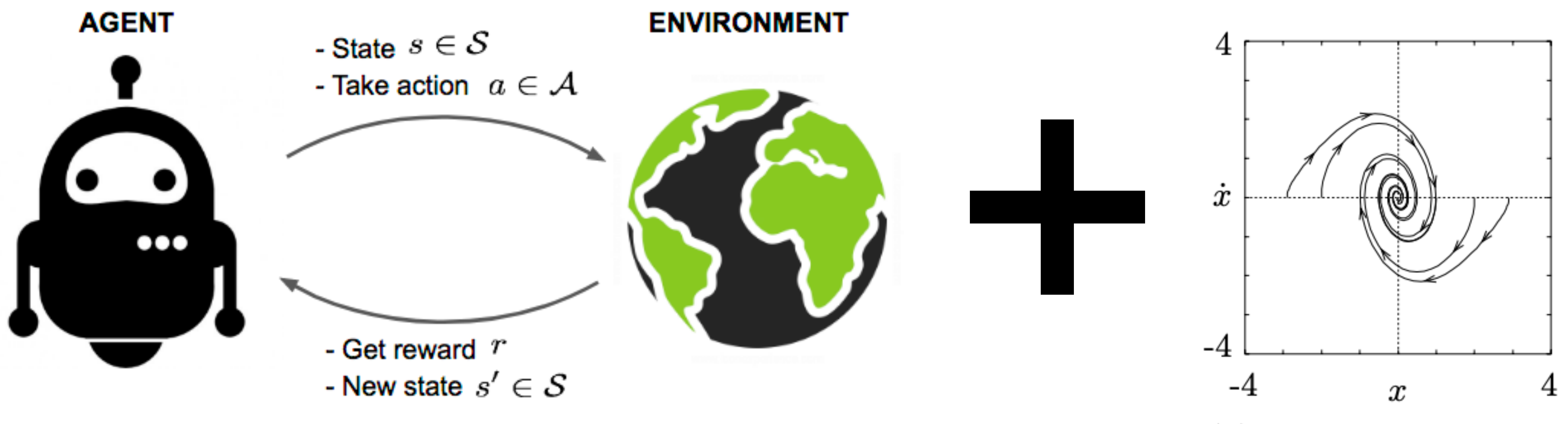
- Proliferation of distributed energy resources (DERs)
- Increasingly complex and rapid voltage violations
- Control of reactive power for voltage regulation
- Limited communication infrastructure → decentralized controllers



Overview of the proposed method

Key Motivation: Can we apply RL to voltage control with provable stability guarantee?

- Reinforcement learning provides a real-time control rule



- Lyapunov function gives a stability guarantee

Problem Formulation

Optimal Voltage Control Problem

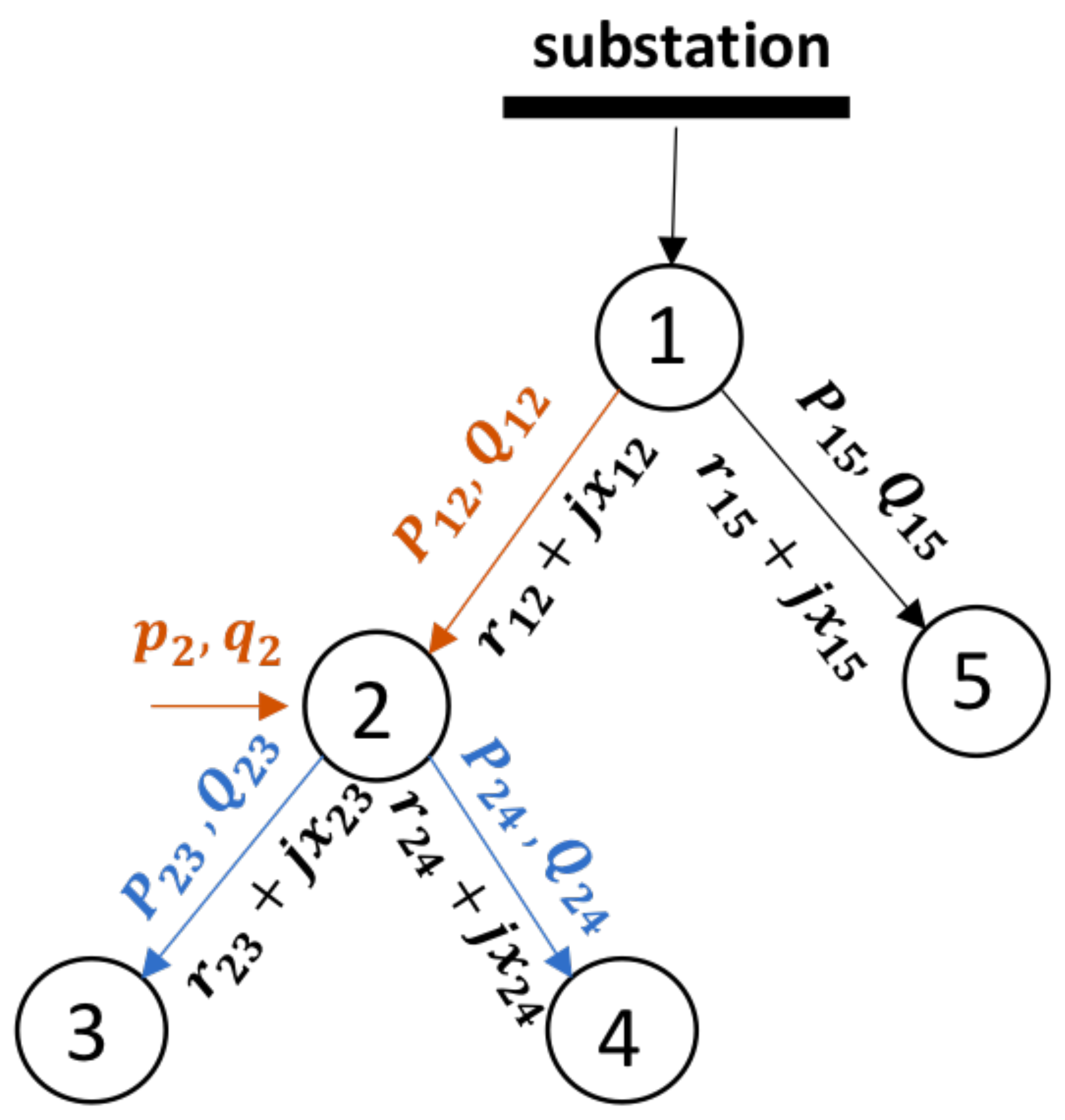
$$min_{\theta} \quad J(\theta) = \sum_{t=0}^{H} \gamma^t \sum_{i=1}^{n} c_i(v_i(t), u_i(t))$$

$$\mathbf{v}(t+1) = \mathbf{v}(t) + I_{\Delta T} X \mathbf{u}(t) = f_{\mathbf{u}}(\mathbf{v}(\mathbf{t}))$$

$$u_i(t) = -g_{\theta_i}(v_i(t))$$

Neural Network Controller

voltage stability holds.



- Objective function: $c_i(v_i(t), u_i(t)) = \eta_1 \| \max(v_i(t) - \bar{v}_i, 0) + \min(v_i(t) - \underline{v}_i, 0) \|_2^2 + \eta_2 \| u_i(t) \|_1$
- Update rule for q: $q_i(t+1) = q_i(t) + u_i(t)$

Voltage Stability Condition

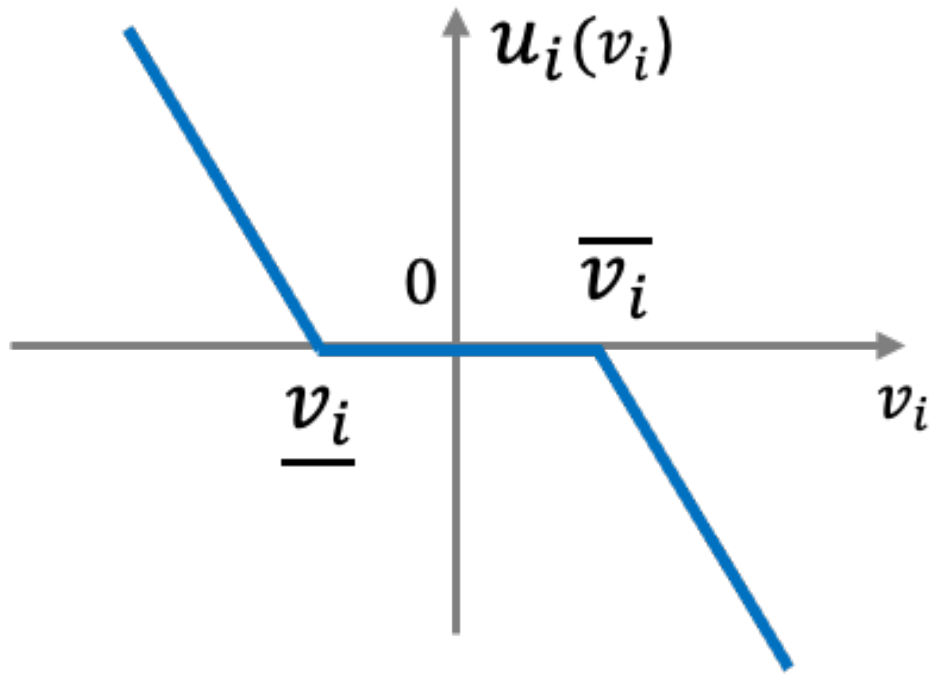
Lyapunov Function

$$V(\mathbf{v}) = (\mathbf{v} - f_{\mathbf{u}}(\mathbf{v}))^{\top} X^{-1} (\mathbf{v} - f_{\mathbf{u}}(\mathbf{v}))$$

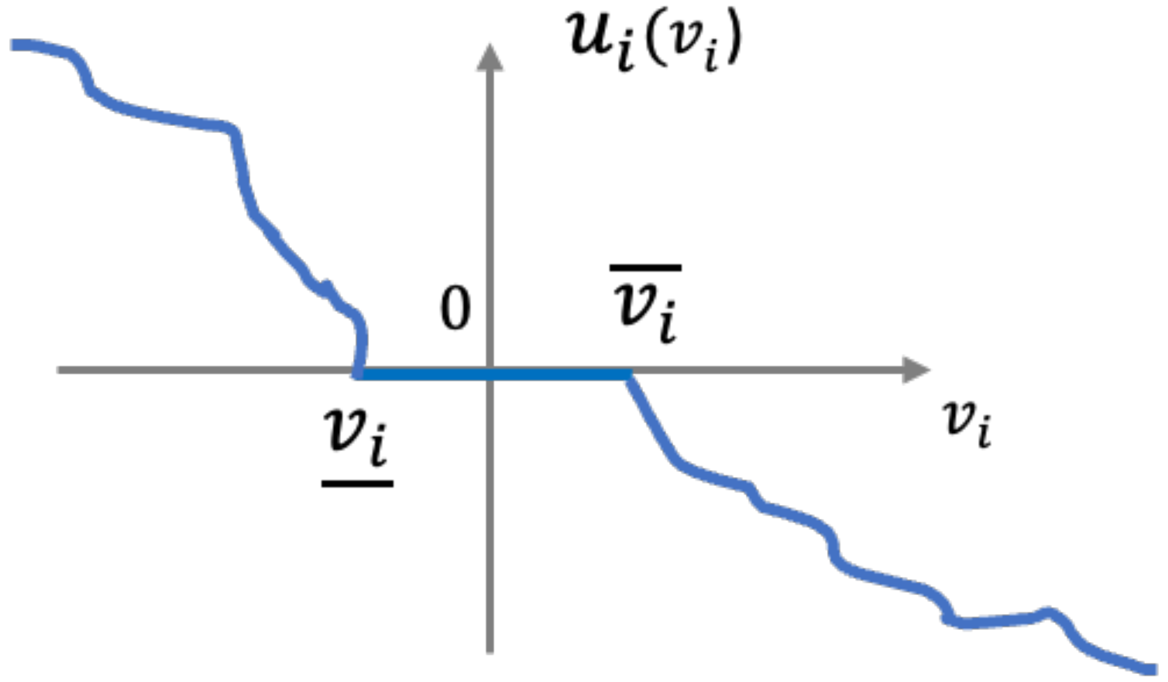
Stability Condition

$$-\frac{2}{\Delta T} X^{-1} < \frac{\partial u}{\partial v} < 0$$

- Monotonicity ➡ Stability



Linear

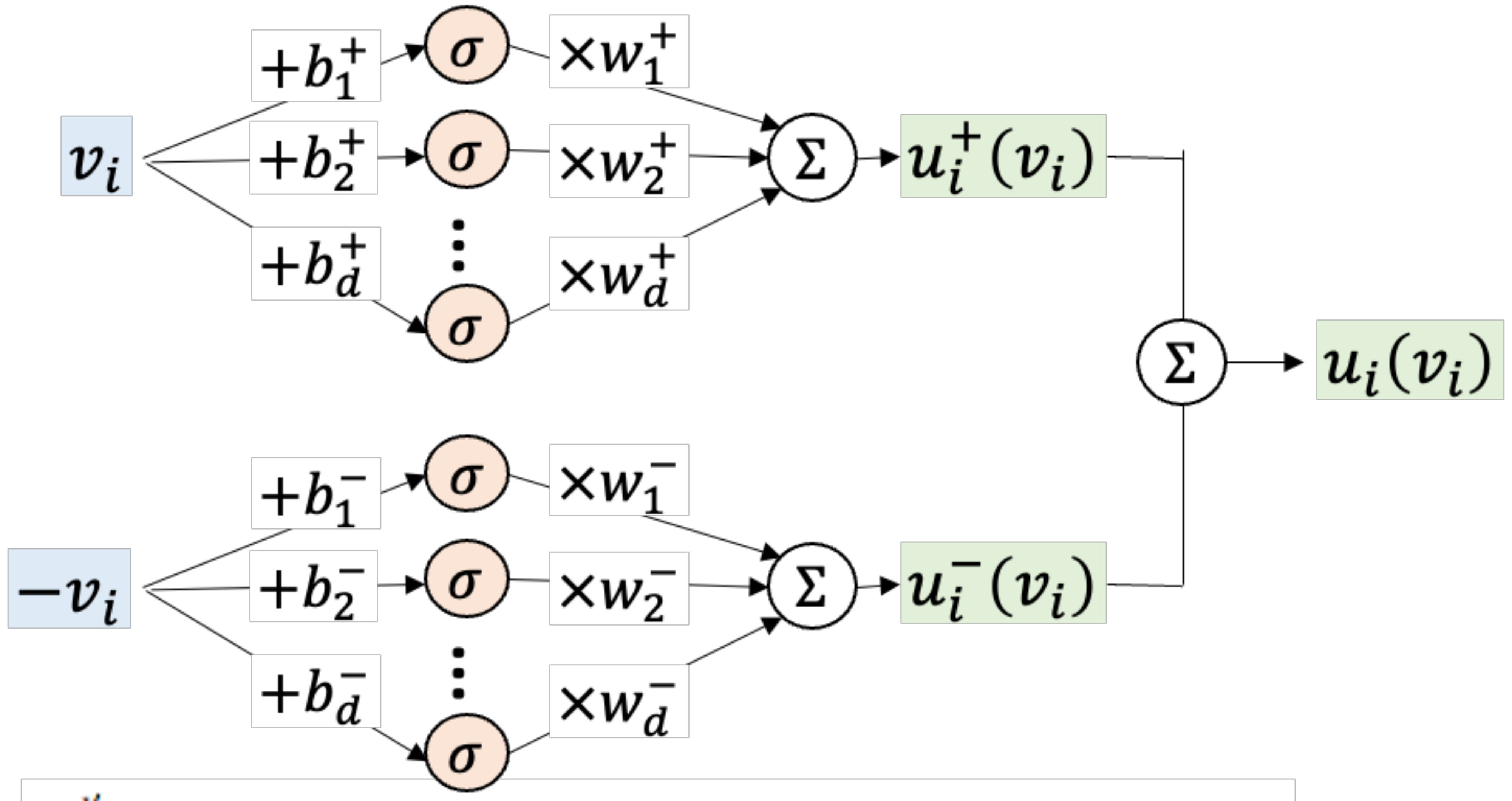


Monotone Neural Network

Stable-DDPG

Monotone Network Design

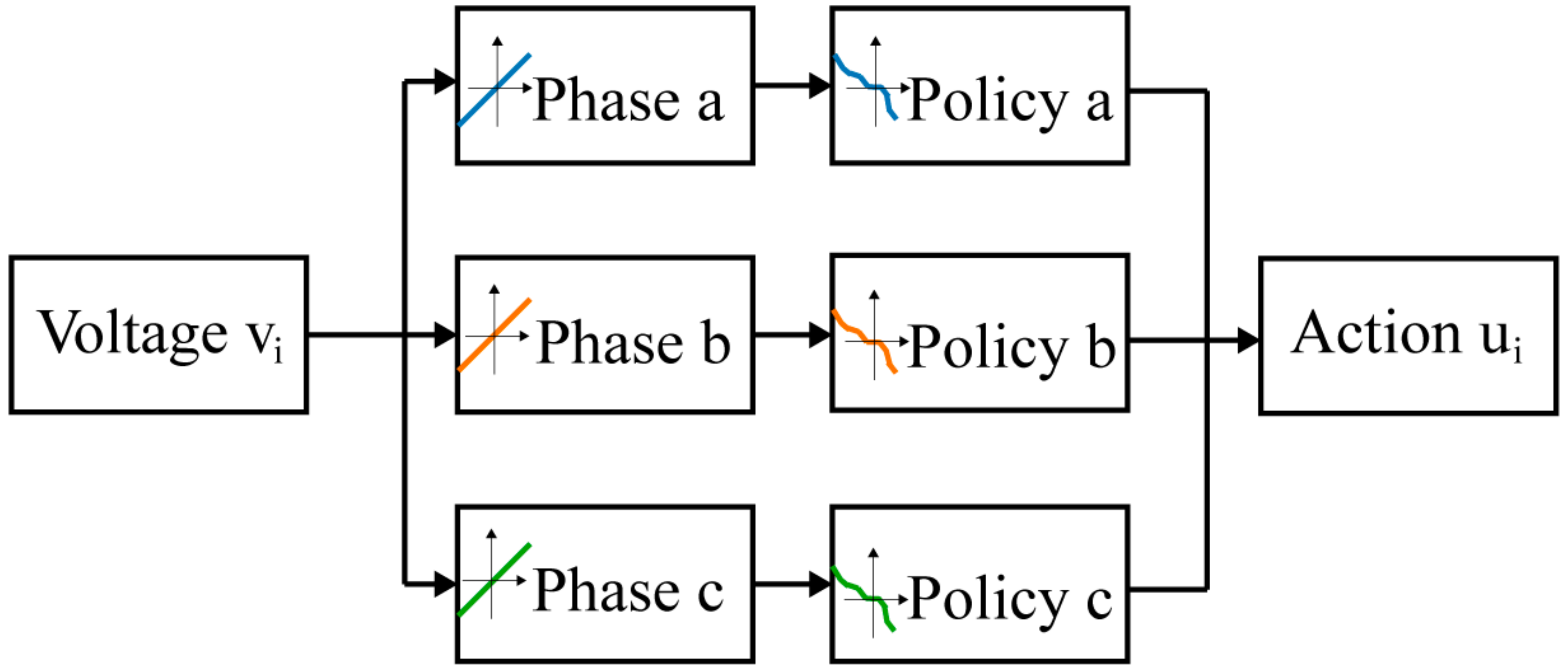
- Single-phase



$$\sum_{l=1}^{d'} w_l^+ > 0, \forall d' = 1, \ldots, d, b_1^+ = 0, b_l^+ \le b_{l-1}^+, \forall l = 2, \ldots, d$$

$$\sum_{l=1}^{d'} w_l^- < 0, \forall d' = 1, \ldots, d, b_1^- = 0, b_l^- \le b_{l-1}^-, \forall l = 2, \ldots, d$$

- Three-phase



Numerical result

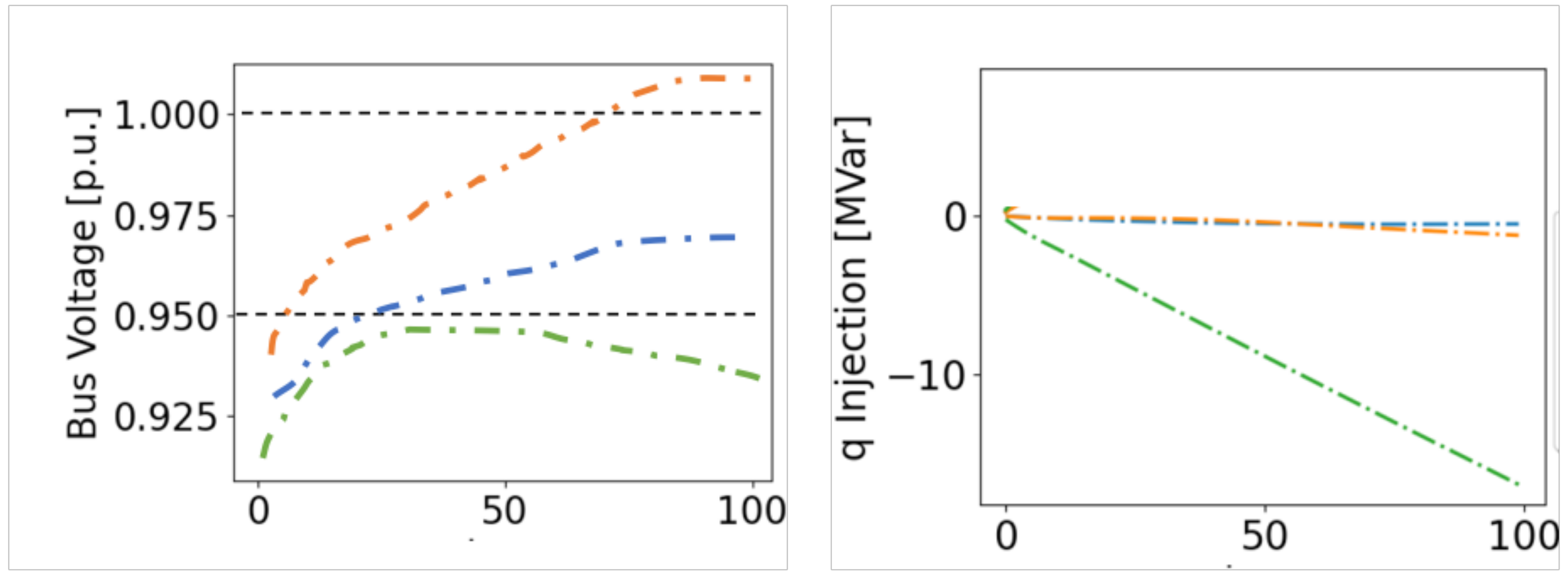
IEEE 13-bus system

- Transient Performance

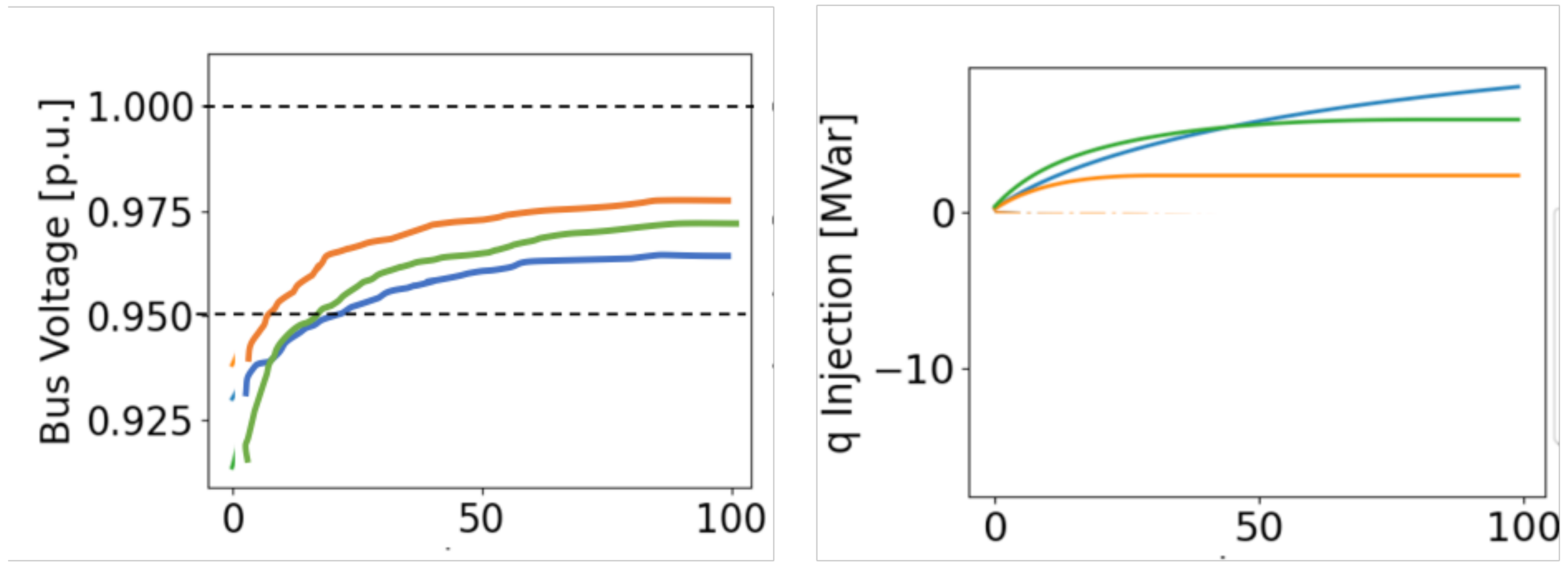
Method	Voltage recovery time (steps) Mean	Voltage recovery time (steps) Std	Reactive power (MVar) Mean	Reactive power (MVar) Std
Linear	5.31	3.19	8.22	10.72
Stable-DDPG	**4.47**	**2.43**	**6.75**	**8.08**
DDPG	6.61	20.67	30.20	120.24
DDPG*	2.31	1.18	3.65	3.21

The Stable-DDPG achieves best overall performance.
It saves 16% of response time and 18% of reactive power consumption compared to the optimal linear policy.

IEEE 123-bus system



(a) Dynamics of v(left) and q (right) for standard DDPG



(b) Dynamics of v(left) and q (right) for Stable-DDPG

Climate Change AI

NEURAL INFORMATION PROCESSING SYSTEMS

Stable RL for Voltage Control

Thank you for listening

Code is available at GitHub, please scan the QR code

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