

Drift-Aware False-Secure Mitigation in DNN-Assisted Virtual Inertia Scheduling (VIS) of PV-Dominated Microgrids

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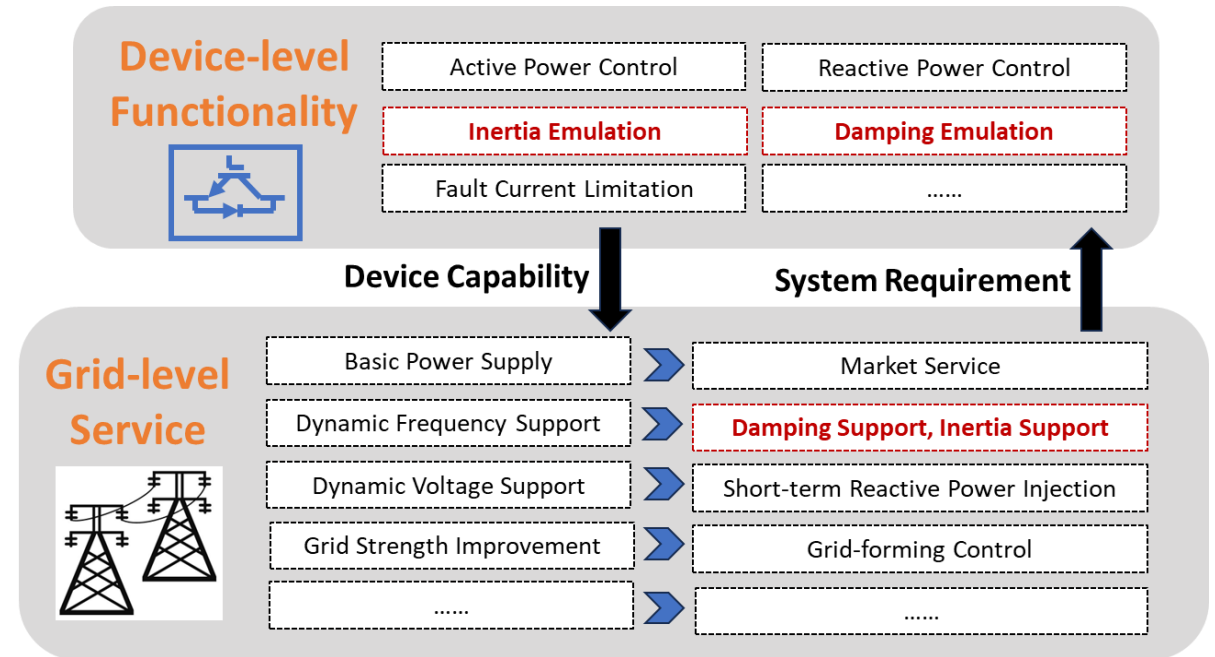


Outline

- Concept of Virtual Inertia Scheduling (VIS)
- False-secure Data-driven Constraints in VIS
- Drift-Aware False-secure Mitigation
- Case Study
- Conclusions

Background

- The increasing penetration of inverter-based resources (IBRs) reduces the physical inertia of microgrids, posing challenges to frequency security.
- As controller-driven devices, IBRs can provide active grid support, enabling their transition from passive components to active participants in grid operation.

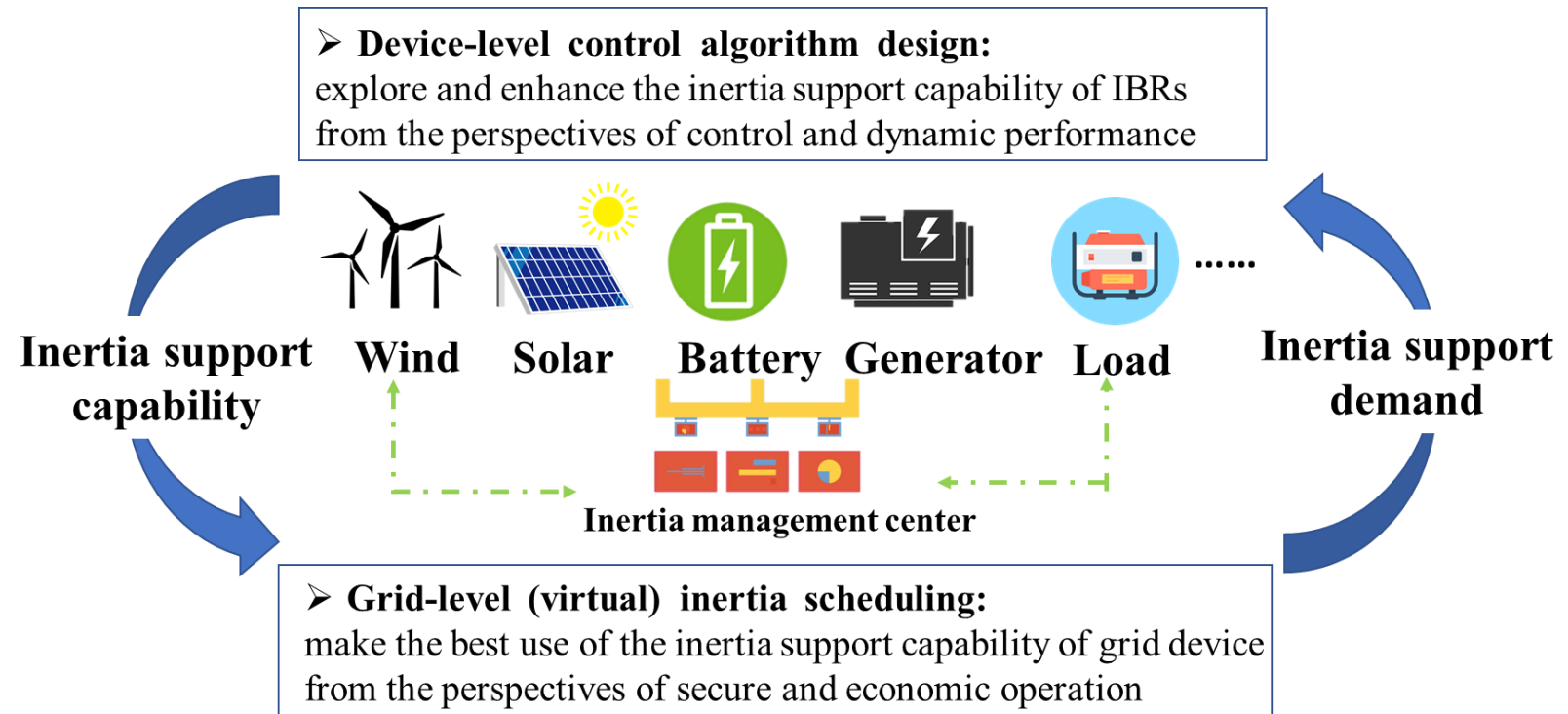


Role Transition of IBRs in Future Microgrids ^[1]

[1] She, Buxin, et al. "Virtual inertia scheduling (VIS) for microgrids with static and dynamic security constraints." *IEEE Transactions on Sustainable Energy* 16.2 (2024): 785-796.

Concept of Virtual Inertia Scheduling (VIS)

- VIS is a unified inertia management framework that combines the device-level control and grid-level economic operation and leverages the inertia support capability of grid components [1].



[1] She, Buxin, et al. "Virtual inertia scheduling (VIS) for real-time economic dispatch of IBR-penetrated power systems." *IEEE Transactions on Sustainable Energy* 15.2 (2023): 938-951.

Formulation of Virtual Inertia Scheduling (VIS)

- Upgraded from the conventional economic dispatch, VIS is formulated as an optimization problem, aiming to achieve an economic objective function while satisfying physical constraints.

$$\min_{\Theta} \sum_{t \in T} C_t^{gen} + C_t^{dyn}$$

Decision Set (points to Θ)

Generation Cost (points to C_t^{gen})

Dynamics Support Cost (points to C_t^{dyn})

Optimization Interval For $\forall t = 1, 2, \dots, T$ and $\psi_t \in \Psi$, **Contingency Set** (points to Ψ)

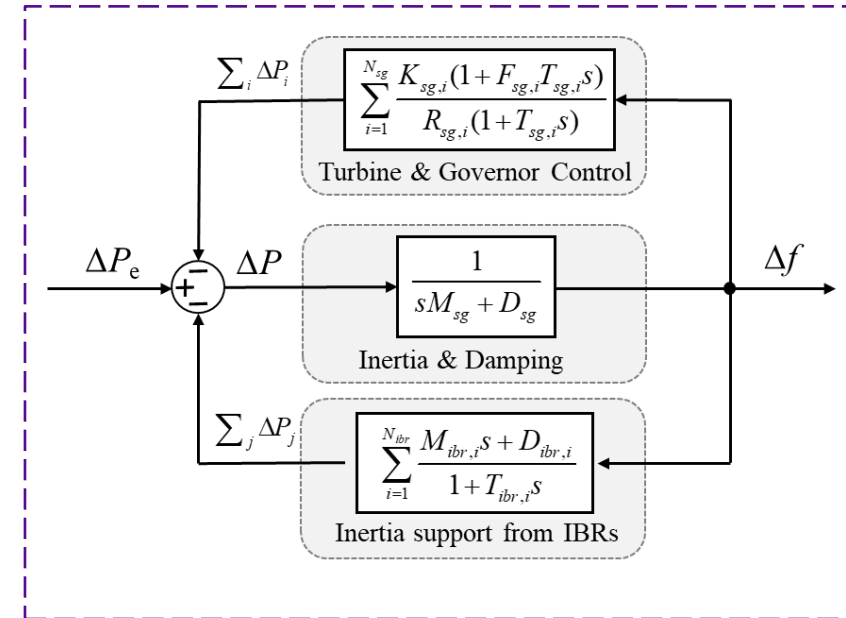
Constraints

$s.t. \begin{cases} i). \text{ Static economic dispatch constraints} \\ ii). \text{ Transient performance constraints} \\ iii). \text{ Stability constraints} \end{cases}$



Deep Neural Network-Assisted Approximation

- Deep neural networks (DNNs) can help approximate the frequency dynamics of microgrids and be integrated into VIS.
- Data-driven approaches suffer from generalization issues, as a fixed DNN may lose reliability when operating conditions deviate from the training data.



Frequency dynamics

$$\begin{cases} \Delta f_{nadir} = NN_1(\Delta P_e, M, D, R, F, T) \\ \Delta P_{max}^{ibr} = NN_2(\Delta P_e, M, D, R, F, T) \end{cases}$$

False Secure Issues in Data-driven VIS

Operating-condition drift: Changes in PV capacity and disturbance characteristics shift operating conditions beyond the DNN training distribution.



False secure: The DNN incorrectly predicts frequency security, causing VIS to produce a scheduling solution that violates the actual frequency-security constraints.

False-secure rate

$$\text{FSR (\%)} = \frac{N_{\text{false-secure}}}{N_{\text{predicted-secure}}} \times 100$$

Adaptive VIS Framework

From fixed dynamics approximation to a verified schedule

1. Generate simulation data and train the initial DNN
2. **Detect security prediction drift by monitoring prediction errors**
3. Update the DNN and solve the VIS problem

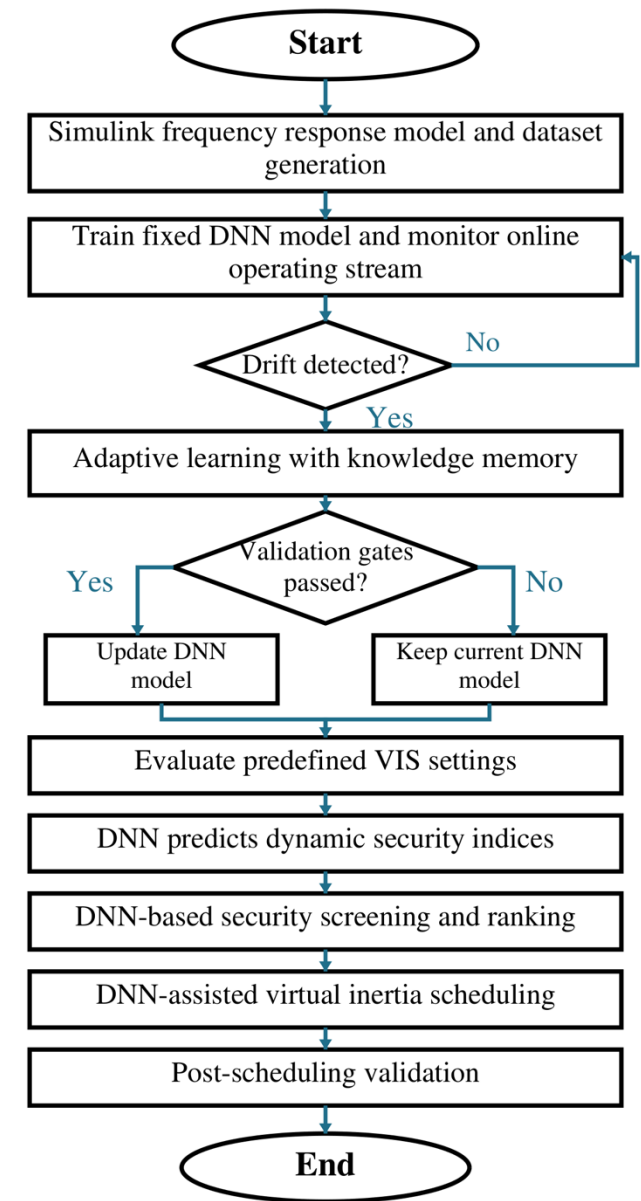


Diagram of drift-aware adaptive VIS

Frequency Security Metrics

Frequency Security Metrics with Margins

$$f_{\text{nadir}} \geq 59.5 \text{ Hz}$$

$$\hat{f}_{\text{nadir}} \geq 59.53 \text{ Hz}$$

$$\text{RoCoF}_{\text{max}} \leq 1.0 \text{ Hz/s}$$

$$\widehat{\text{RoCoF}}_{\text{max}} \leq 0.98 \text{ Hz/s}$$

$$\Delta P_{\text{BESS,peak}} \leq 0.9 \Delta P_{\text{BESS,max}}$$

$$\widehat{\Delta P}_{\text{BESS,peak}} \leq 0.88 \Delta P_{\text{BESS,max}}$$



Evaluated based on New Scenarios

$$\begin{cases} \Delta f_{\text{nadir}} = NN_1(\Delta P_e, M, D, R, F, T) \\ \Delta P_{\text{max}}^{\text{ibr}} = NN_2(\Delta P_e, M, D, R, F, T) \end{cases}$$

Drift Detection and Adaptive Updating

Monitor prediction error

$$\bar{e}_t = \frac{1}{W} \sum_{i=t-W+1}^t e_i$$

W: number of evaluated scenarios

$$\bar{e}_t > \gamma = \mu_{e,\text{ref}} + 3\sigma_{e,\text{ref}}$$

- Compare rolling error with the winter reference statistics.
- Combine normalized errors of all three security indices.

Validate the proposed update

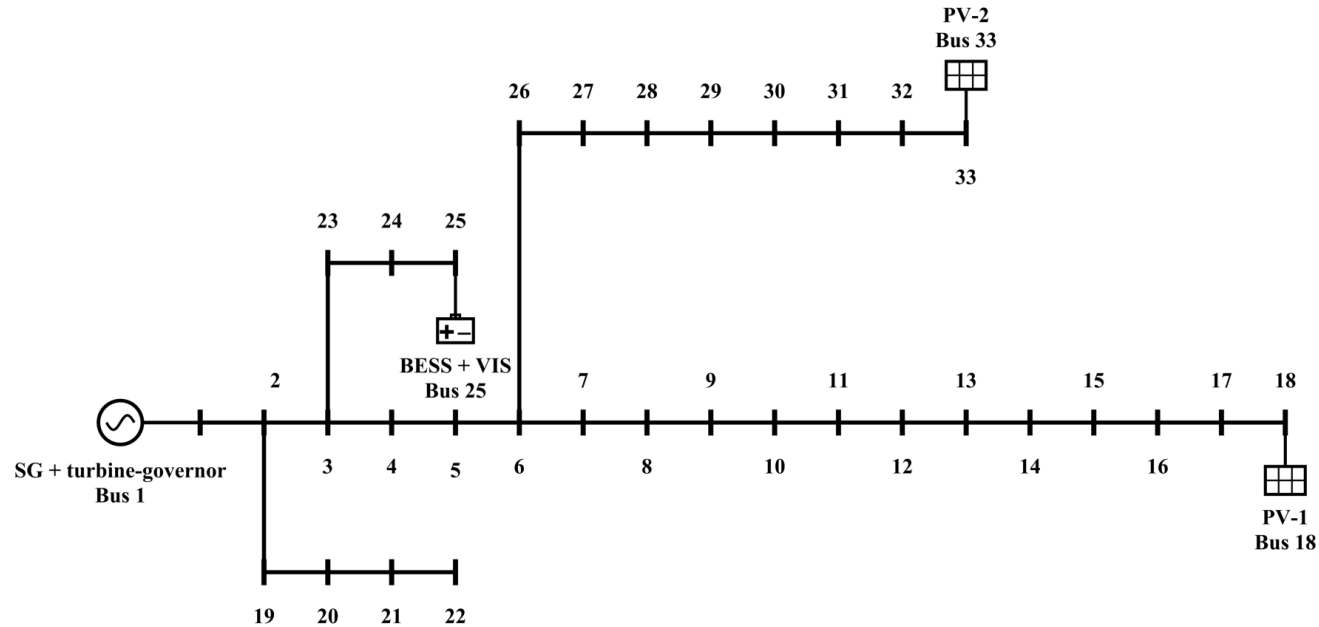
- Update the knowledge memory based on seasonal change scenarios

$$E_{\text{upd}} \leq E_{\text{cur}} - \varepsilon$$

$$\text{FSR}_{\text{upd}} \leq \text{FSR}_{\text{cur}}$$

E: validation error. $\varepsilon = 0.001$.

Case Study



Microgrid modified from IEEE 33-bus distribution system

Seasonal Changing Conditions

Period	PV (%)	ΔP_e (p.u.)
Winter	20–55	0.25–1.0
Monsoon	30–85	0.25–2.0
Summer	55–90	0.5–2.5
Rare	20–90	2.5–5.0



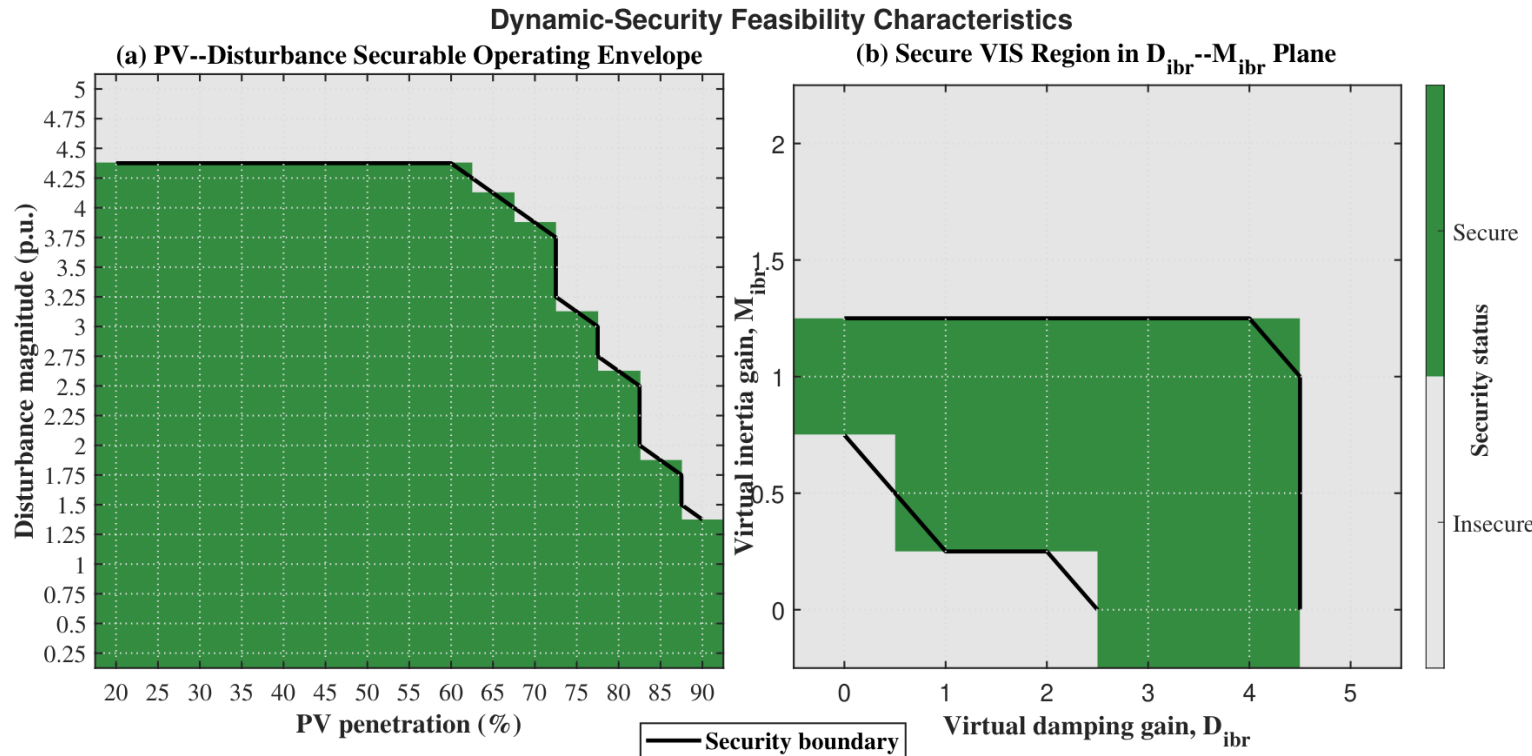
Credit disturbances

Dataset and DNN model

Parameter	Simulation sweep
PV capacity	20–90%, step 5%
Disturbance	0.25–5.0 p.u.
Virtual damping	0–5, 6 levels
Virtual inertia	0–2.0, 5 levels
BESS reserve	0.5–2.0 p.u., 4 levels

- **Winter as base knowledge season**
- **Inputs:** PV capacity, effective inertia, disturbance, damping, virtual inertia and reserve.
- **Outputs:** frequency nadir, maximum |RoCoF| and peak BESS power.

Dynamic-security Feasibility Regions



Panel (a)

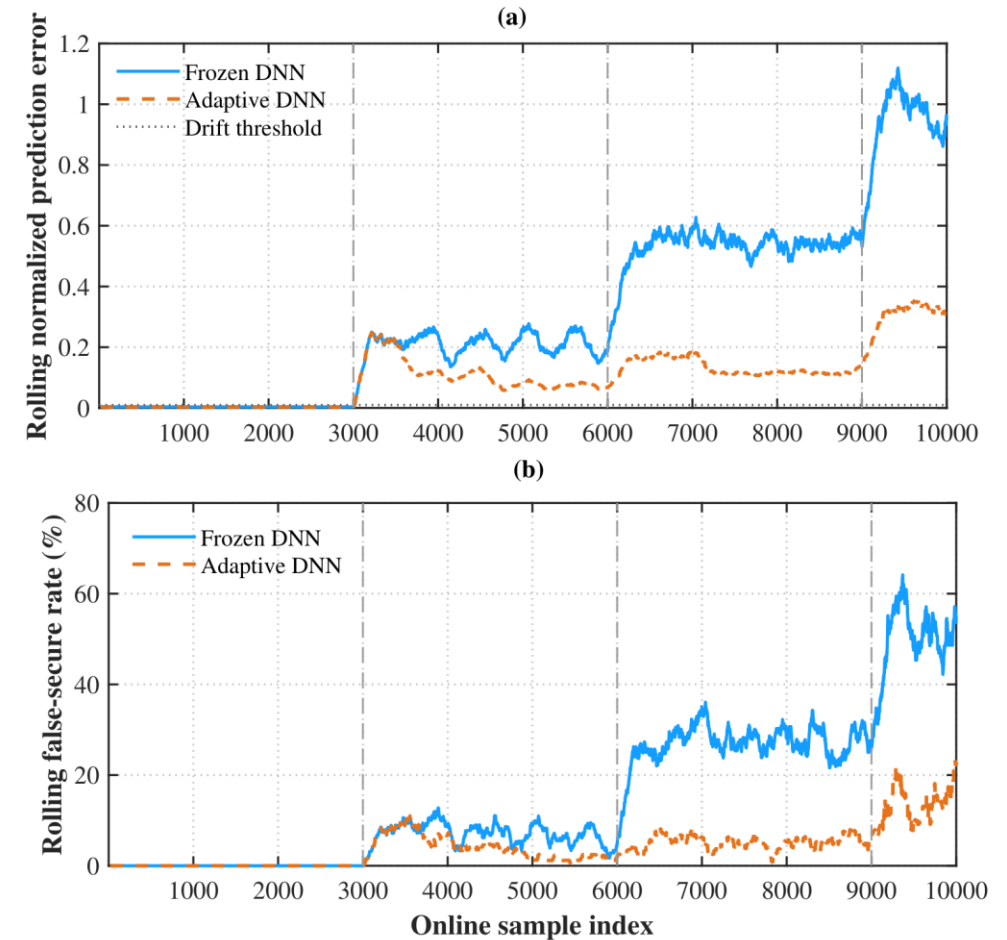
- The secure envelope shrinks as PV share and disturbance increase.

Panel (b)

- Security depends on the damping–inertia combination under 80% PV and 2.5 p.u. disturbance.

Seasonal Reliability under Operating Drift

- (a) Frozen-model error rises after the winter training range.
- (a) Summer mean error: 0.5398 to 0.1339, a 75.20% reduction.
- (b) Summer FSR: 27.52% to 5.35%, an 80.55% reduction.
- Rare-event FSR remains 14.53% after adaptation.



Rolling error (a) and false-secure rate (b).

False-secure Decisions in VIS

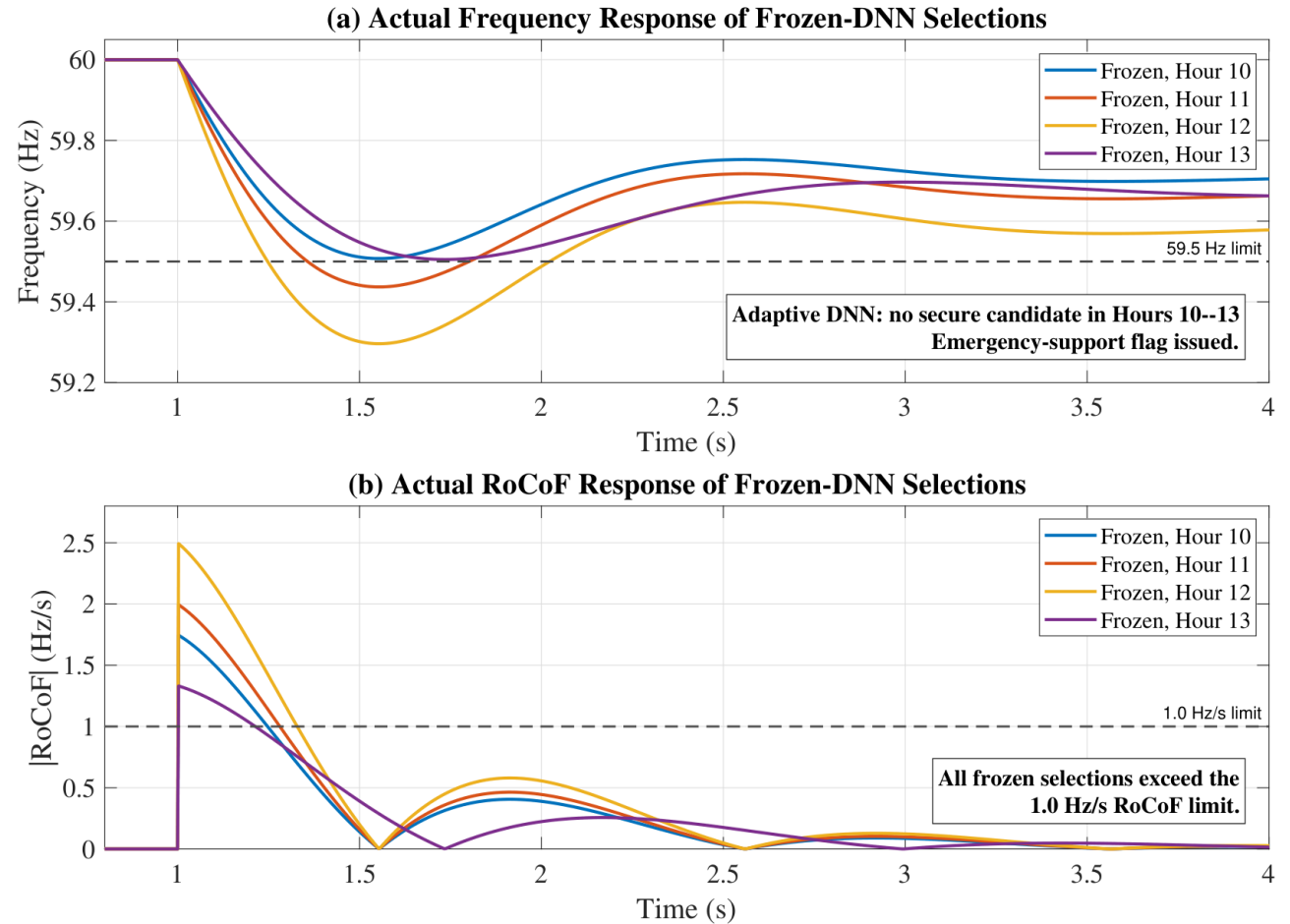
Model	Predicted secure	False secure	FSR
Fixed DNN	1,889	443	23.45%
Adaptive DNN	1,640	35	2.13%

- False-secure decisions fall from 443 to 35.
- Each FSR uses that model's predicted-secure decisions as its denominator.

Frequency Security Validation

False-secure validation of fixed VIS:

- (a) Hours 11–12 violate the 59.5 Hz nadir limit.
- (b) Hours 10–13 all exceed the 1.0 Hz/s RoCoF limit.



False security response of fixed-DNN VIS during stressed operation: (a) frequency and (b) RoCoF.

Conclusions and Future work

Conclusions

- Drift monitoring and validation make DNN-assisted VIS more reliable.
- FSR falls from 23.45% to 2.13% over 2,000 cases.

Future work

- Physics-integration for security performance guarantee.
- Integration of detailed electromagnetic-transient (EMT) models.

Thank you

Questions?