Distributed AI-Based Voltage Regulation in Microgrids: Performance and Operational Trade-Offs

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Why this matters

- High DER penetration makes voltage regulation harder in inverter-dominated microgrids and active distribution feeders.
- Local droop or Volt-VAR control is fast, but weakly coordinated under stressed feeder conditions.
- Centralized optimization can coordinate globally, but requires extensive observability, communication, and computation.
- DAI is investigated as a scalable middle ground between purely local and fully centralized control.

Research objective

- Evaluating DAI-based voltage regulation for inverter-dominated, DER-rich microgrids and active distribution feeders.
- Comparing two DAI formulations that use local measurements and sparse neighbor information to improve voltage regulation, reduce unnecessary control effort, and preserve inverter capability constraints under stressed operating and communication conditions.

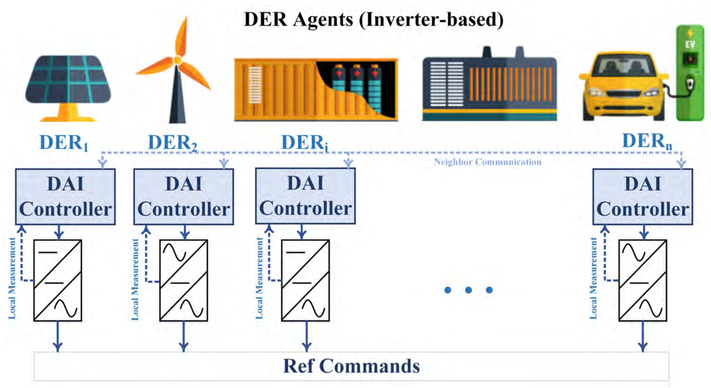

Figure 1: Conceptual distributed DAI control architecture for inverter-based DER agents.

Two DAI structures

1. Imitation-learning DAI

- Trains an MLP policy to reproduce a distributed Volt-VAR expert controller.
- Uses local voltage/power measurements and neighbor-averaged scalar information.
- Executes locally at each inverter without centralized optimization.
- Main contribution: preserves distributed Volt-VAR behavior while producing smoother reactive-power trajectories.

2. Hybrid DAI

- Combines sensitivity-based least-squares coordination with RL refinement.
- Computes feasible active- and reactive-power adjustments for voltage regulation.
- Projects control actions onto inverter capability limits.
- Main contribution: shifts DER-bus voltages closer to 1.0 pu while limiting active-power curtailment.

Operational trade-offs

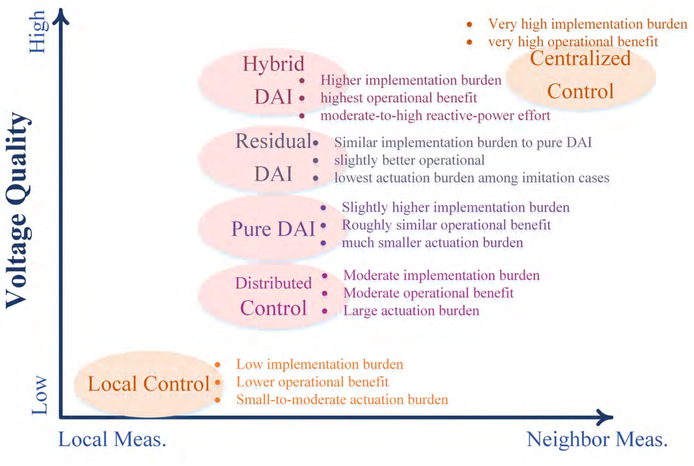

Figure 2: Qualitative comparison of controllers and operational trade-offs..

Main findings

- The imitation-learning DAI controller reproduces the behavior of distributed Volt-VAR control using local and neighbor-averaged measurements, while substantially improving reactive-power actuation smoothness.
- The residual DAI formulation is operationally useful because it corrects, rather than replaces, the rule-based distributed controller; therefore, it preserves interpretability while reducing unnecessary control fluctuations.
- The hybrid DAI framework improves voltage centering by combining sensitivity-based coordination with bounded learning-based refinement, while maintaining inverter capability constraints.
- The results show that DAI is not simply a replacement for conventional control; its main value is in coordinating local agents under sparse communication while managing the trade-off between voltage quality, control effort, and implementation complexity.

Acknowledgment

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DAI control architectures

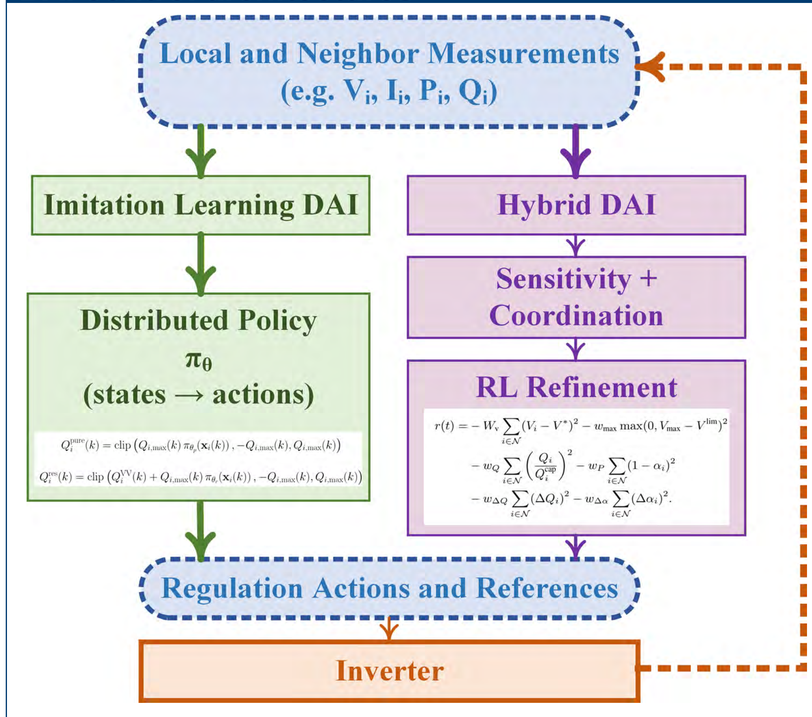


Figure 3: Distributed DAI control architectures: the imitation-learning and hybrid DAI.

Test system and communication structure

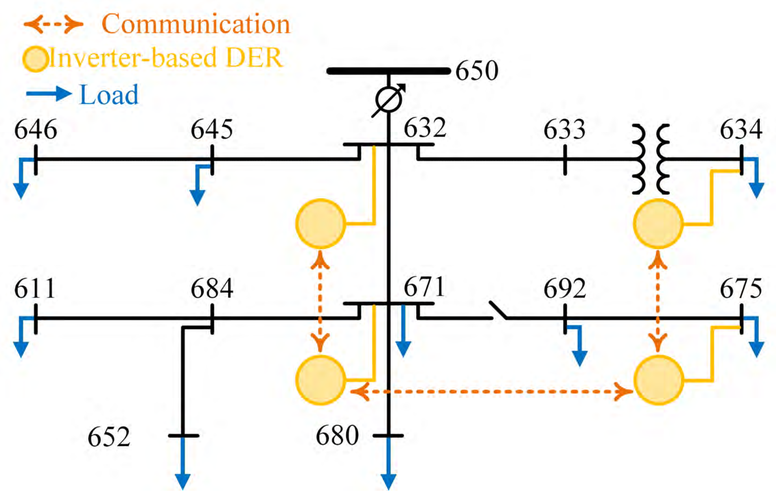


Figure 4: IEEE 13-bus feeder with four inverter-based DER agents and sparse neighbor communication links.

Hybrid DAI results

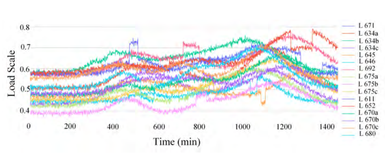


Figure 5: Load demand profiles.

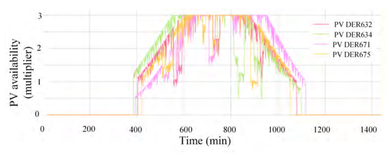


Figure 6: PV generation availability profiles.

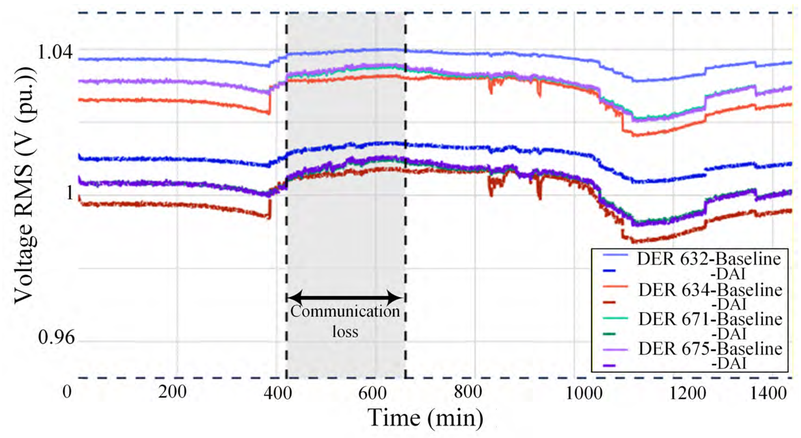


Figure 7: DER RMS voltage profiles.

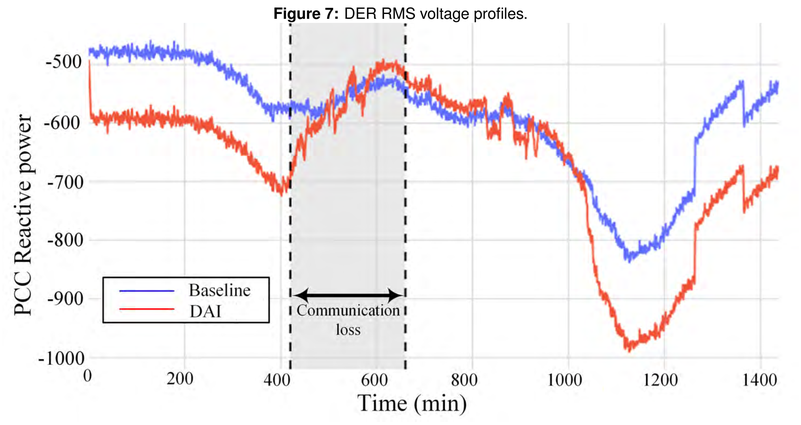


Figure 8: PCC reactive power.

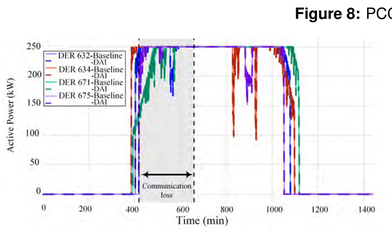


Figure 9: DER active power injection.

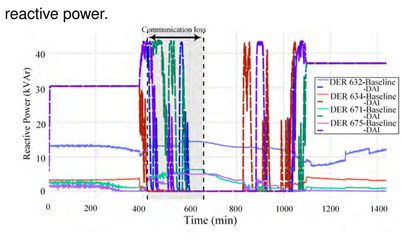
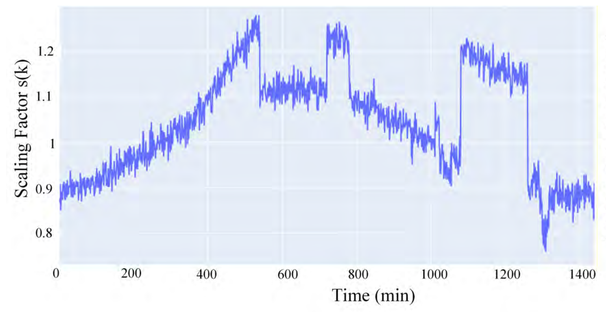


Figure 10: DER reactive power injection.

Future work

- Grid-aware DAI coordination at system level.
- Integration with higher-level control layers.
- Coordination with legacy voltage-regulation devices.
- Real-time, HIL, and hardware validation.

Imitation-learning DAI results



Bus	P_{Load} (kW)	Q_{Load} (kvar)
611	170	80
634	400	290
645	170	125
646	230	132
652	128	86
680	200	116
671	1155	660
675	843	462
692	170	151

Figure 11: Synthetic 24-h load variation.

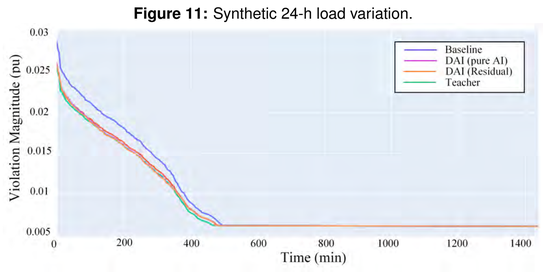


Figure 12: Voltage violation behavior.

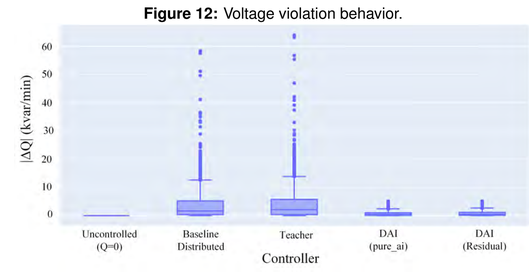


Figure 13: Q smoothness comparison.

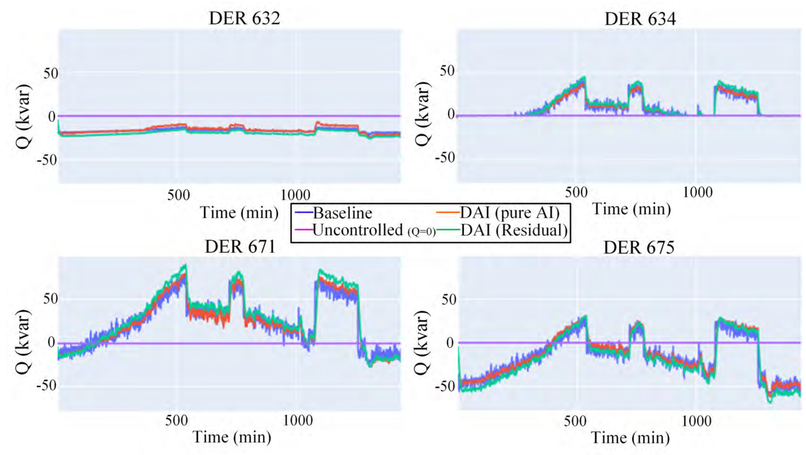


Figure 14: Reactive power output trajectories at inverter buses.

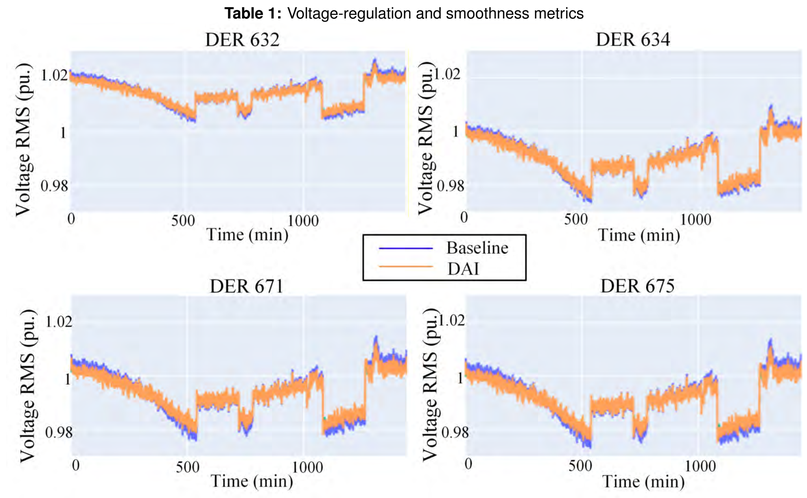


Figure 7: RMS voltage comparison.

Table 1: Voltage-regulation and smoothness metrics

Metric	Unctrl.	Base.	Teach.	Pure	Resid.
Mean viol. (pu)	0.0094	0.0089	0.0088	0.0088	0.0088
P95 viol. (pu)	0.0222	0.0201	0.0198	0.0200	0.0199
Max viol. (pu)	0.0289	0.0261	0.0258	0.0261	0.0259
Worst $V_{\min}$ (pu)	0.9271	0.9298	0.9302	0.9299	0.9301
Worst $V_{\max}$ (pu)	1.0562	1.0561	1.0561	1.0561	1.0561
RMS(ΔQ)	–	5.3345	6.2050	1.3019	1.2502

Operational interpretation

- The imitation-learning DAI does not aim to outperform the expert Volt-VAR controller in voltage violation magnitude; its main operational benefit is smoother inverter reactive-power actuation.
- The residual DAI structure is more conservative than pure policy replacement because it corrects the distributed Volt–VAR command instead of fully replacing it.
- The hybrid DAI improves voltage centering by combining sensitivity-based coordination with bounded learning-based correction.
- The dominant control mechanism is coordinated reactive-power support, while active-power curtailment remains a secondary corrective action.
- The overall trade-off is therefore between voltage-centering quality, inverter actuation burden, communication dependence, and implementation complexity.