Distributed Artificial Intelligence Based Controller for Power Quality Enhancement in Renewable Based Microgrids

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Introduction

Context. Converter-interfaced DGs enable flexible microgrids (MGs) but intensify power-quality (PQ) concerns—harmonics, unbalance, and voltage/frequency deviations—requiring compliance with international limits [1, 2, 3].
Limitations of conventional mitigation. Filters, custom power devices (D-STATCOM/UPQC), and fixed-parameter controllers can address specific disturbances but scale poorly, need careful retuning, and incur cost/complexity [4, 5].
Control background. Primary droop control achieves decentralized power sharing but has steady-state offsets and lacks explicit harmonic suppression [6].
Rationale for DAI. Distributed AI (multi-agent RL/learning-based secondary control) offers adaptive, cooperative compensation with no single point of failure and reduced modeling dependence [7, 8, 9].
This work. A hierarchical scheme is proposed: droop-based primary control augmented by a distributed AI (MADDPG) secondary layer that injects bounded v_{dq}^{inj} to suppress harmonics and restore $V{-}f$ under operating uncertainty.

Control Architecture

Primary Droop Control.

$$f = f_0 - m_P(P - P_0), \qquad V = V_0 - n_Q(Q - Q_0).$$

Distributed AI (DAI) Layer.

$$v_{d,i}^{ref} = v_{d,i}^{droop} + v_{d,i}^{inj}, \qquad v_{q,i}^{ref} = v_{q,i}^{droop} + v_{q,i}^{inj},$$

where $v_{dq,i}^{inj}$ minimizes PQ distortions and offsets.

Learning Model. Each agent observes $o_i = [V_1, \{V_h\}, \mathrm{THD}, P, Q]_i$ and outputs $a_i = [v_{d,i}^{inj}, v_{q,i}^{inj}]$ to maximize

$$R_i = -w_h \mathrm{THD}_i - w_v|V_i - V_{\mathrm{nom}}| - w_f|f_i - f_{\mathrm{nom}}|.$$

Consensus Coordination.

$$\dot{\xi}_{f,i} = k_{if}(f_{\mathrm{nom}} - f_i) - k_{cf}\sum_{j\in\mathcal{N}_i}(f_i - f_j),$$

$$\dot{\xi}_{v,i} = k_{iv}(V_{\mathrm{nom}} - V_{d,i}) - k_{cv}\sum_{j\in\mathcal{N}_i}(V_{d,i} - V_{d,j}),$$

providing $\Delta\omega_i = \xi_{f,i}$ and $\Delta V_{d,i} = \xi_{v,i}$ without central supervision.

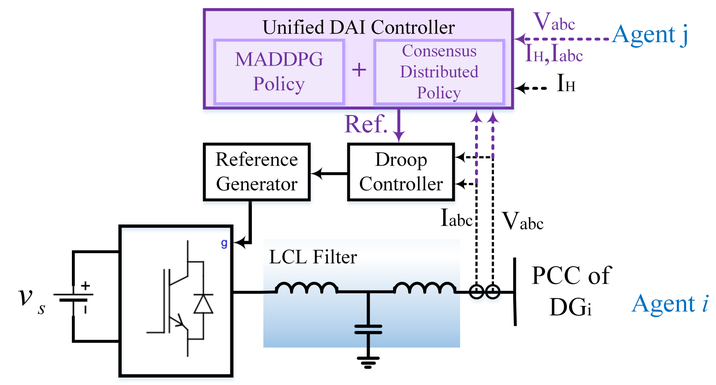

Figure: Hierarchical droop–DAI control for PQ enhancement.

System and Stability Analysis

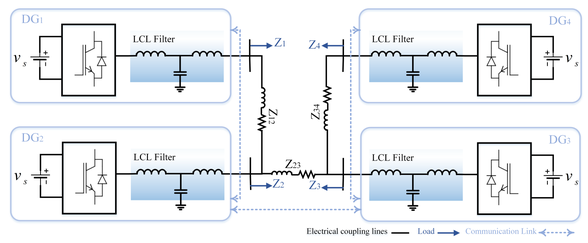

Figure: The MG Configuration.

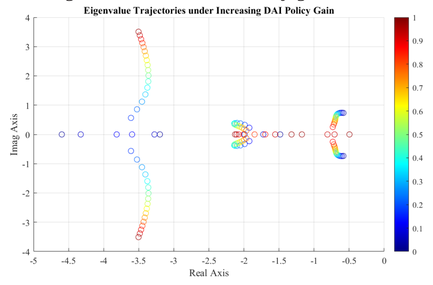

Figure: Eigenvalue migration.

Conclusion

A distributed AI based hierarchical controller has been developed for PQ enhancement in inverter-dominated MGs. The structure integrates droop-based primary regulation with multi-agent reinforcement learning driven secondary compensation.
Key findings:

- Suppresses harmonics and restores voltage and frequency without centralized supervision.
- Faster steady-state recovery and lower communication overhead than conventional secondary or centralized AI control.
- Maintains stability under communication latency and parameter variations through consensus-based adaptation.
- Scalable and cooperative PQ control suitable for large renewable-integrated MGs.

Future work. Ongoing research extends this DAI framework toward real-time experimental validation with hardware-in-the-loop integration in addition to considering other PQ issues.

Results

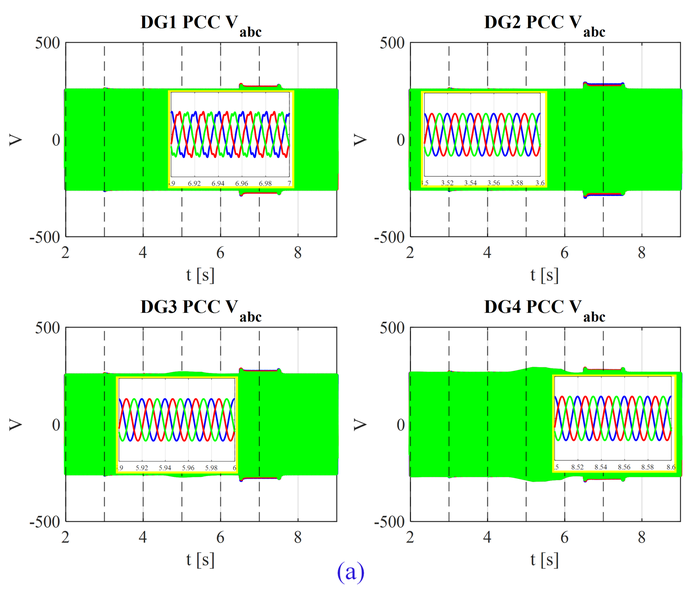

Figure: PCC phase voltages (a) Droop, (b) DAI.

Results

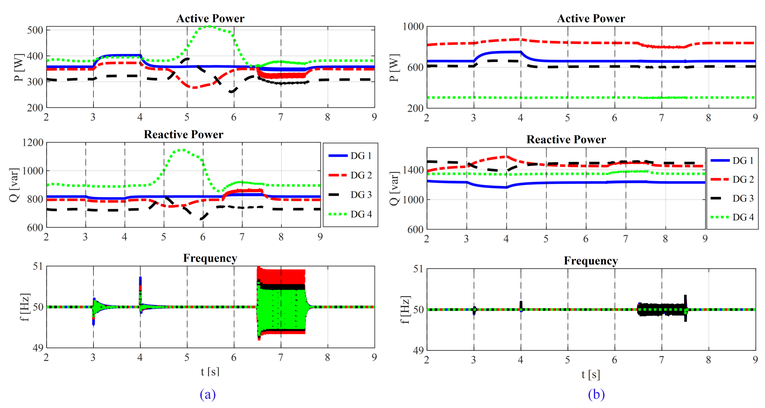

Figure: Active/reactive power and frequency (a) Droop, (b) DAI.

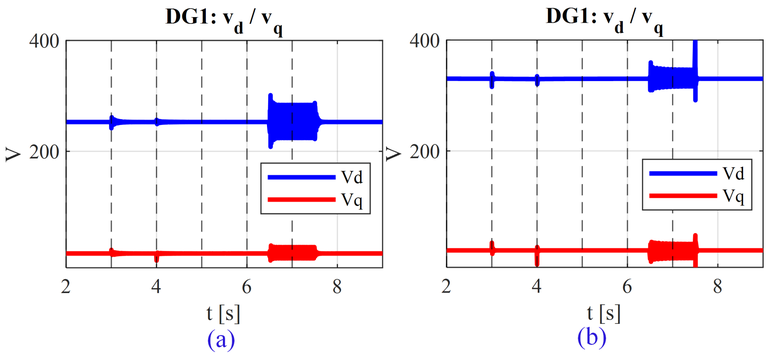

Figure: dq–axis voltages of DG_1 (a) Droop, (b) DAI.

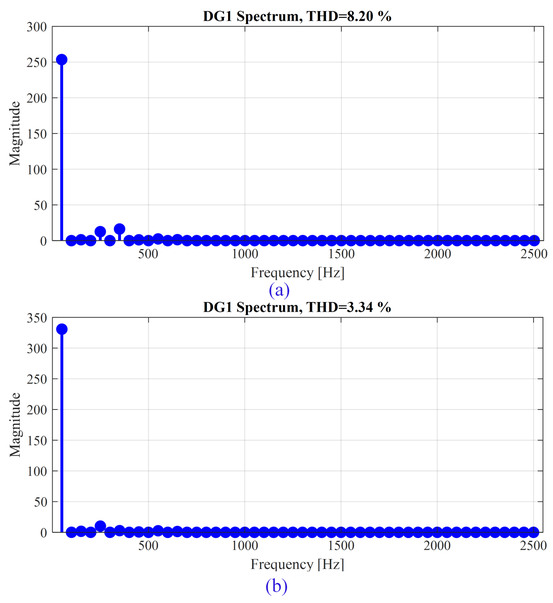

Figure: Voltage spectrum and THD of DG_1 (a) Droop, (b) DAI..

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Acknowledgements

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