

Supplementary Information

Distributed Stability-Constrained Operation of Receiving-End Grids with Multiple Operators and High-Voltage Direct-Current Infeeds

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Supplementary Note 1. HVDC terminal and cost parameters

For buses [30, 31, 32, 33, 34, 35, 36, 37, 38], the ordered terminal parameter vectors are

$$\begin{aligned} \mathbf{P}^{\max} &= [1040, 646, 725, 652, 508, 687, 580, 564, 865] \text{ MW}, \\ \boldsymbol{\kappa} &= [0.647200, 0.326892, 0.318462, 0.171361, 0.328150, 0.324154, 0.178929, 0.002593, 0.026145], \\ \mathbf{S}^{\text{rated}} &= [1114.27, 712.26, 784.62, 698.29, 534.75, 749.65, 627.69, 616.92, 915.55] \text{ MVA}, \\ \mathbf{c}^P &= [0.075, 0.077, 0.079, 0.081, 0.083, 0.085, 0.087, 0.089, 0.091], \\ \mathbf{m}_P^0 &= [0.070, 0.066, 0.068, 0.072, 0.074, 0.064, 0.070, 0.068, 0.062], \\ \boldsymbol{\tau}_P^0 &= [0.34, 0.36, 0.35, 0.37, 0.38, 0.34, 0.36, 0.35, 0.33] \text{ s}. \end{aligned}$$

All terminals use $c_d^Q = 0.018$ and $c_d^S = 0.012$. The external-grid coefficients are $c_0^{(2)} = 8 \times 10^{-4}$ and $c_0^{(1)} = 18$. These values define the benchmark; application to a utility system requires parameters identified from HVDC station and operating data.

The nominal voltage-channel coefficients for buses 30–38 are

$$\begin{aligned} \mathbf{m}_Q^0 &= [0.025, 0.023, 0.024, 0.026, 0.027, \\ &\quad 0.022, 0.025, 0.024, 0.021], \\ \boldsymbol{\tau}_V^0 &= [0.42, 0.44, 0.43, 0.45, 0.46, \\ &\quad 0.42, 0.44, 0.43, 0.41] \text{ s}. \end{aligned}$$

Together with the $\mathbf{m}_P^0$ and $\boldsymbol{\tau}_P^0$ vectors above, these values define the four terminal parameter matrices used in the dynamic-parameter mapping and independent AC-dynamics equations in the main text.

Supplementary Note 2. Data provenance and implementation details

The transmission network, bus demands, generator limits, and quadratic generation-cost structure originate from the IEEE/New England 39-bus benchmark distributed with MATPOWER [1]. The three-operator ownership assignment, HVDC-terminal classification, P–Q coefficients, stability-model parameters, and terminal-related cost weights are benchmark assumptions introduced in this study and are reported in Supplementary Note 1 and Section 4.1 of the main text.

The renewable trajectories use the 19 January 2024 portion of the IEEE DataPort “Hybrid Energy Forecasting and Trading Competition” dataset [2]. Half-hourly wind and solar measurements are averaged to hourly resolution before normalization and capacity scaling. The load profile is generated from the 39-bus benchmark demand and the deterministic multiplier stated in Section 4.1 of the main text. The optimization uses the transformed wind, solar, and load series. Electricity-market price fields from the source dataset are not used.

The optimization and validation routines are implemented in Python with CVXPY, PYPOWER, and standard numerical linear-algebra packages [3]. Centralized and distributed comparisons share the same master network, nonlinear network model, cost coefficients, adaptive stability cuts, feasibility tolerances, and validation-model evaluator.

Supplementary Note 3. Detailed dynamic-validation statistics

Supplementary Table S1 reports the aggregate statistics associated with the dynamic-validation results shown in Fig. 4 of the main text. Each of the 24 hourly operating points uses 50 paired parameter samples for the baseline and stability-constrained schedules.

Table S1: Dynamic validation over 24 hourly periods and 50 paired parameter samples per period.

Metric	Baseline	Stability-constrained
Periods satisfying the small-disturbance limit	21/24	24/24
Worst nominal spectral abscissa (s^{-1})	−0.11555	−0.12049
Mean nominal spectral abscissa (s^{-1})	−0.13875	−0.13945
Minimum nominal damping ratio	0.33438	0.33438
Stable sampled cases	1200/1200	1200/1200
Worst sampled spectral abscissa (s^{-1})	−0.10416	−0.10857
95th-percentile sampled abscissa (s^{-1})	−0.11187	−0.11502

Supplementary references

- [1] Zimmerman, R. D., Murillo-Sanchez, C. E. & Thomas, R. J. MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education. *IEEE Transactions on Power Systems* **26**, 12–19 (2011).
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- [3] Diamond, S. & Boyd, S. CVXPY: A python-embedded modeling language for convex optimization. *Journal of Machine Learning Research* **17**, 1–5 (2016). URL <https://jmlr.org/papers/v17/15-408.html>.