GB Reduced Model

Small-Signal Stability Study — Final Report

Renewable penetration, seasonal dispatch, data-centre load growth, network outages and the black-box controller blind spot

Model: DIgSILENT PowerFactory 2026 · "GB Reduced Model", Study Case 01 (28 zones, 400 kV)

Basis: 94 eigenvalue solutions (72-case factorial matrix + 22 development-ladder solves); ~120 solves executed in total including baseline and diagnostic runs

11 July 2026 · Prepared with Claude (PowerFactory MCP automation) for S. Sommerville

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Executive summary

This study uses eigenvalue (small-signal) analysis to map the oscillatory stability of a 28-zone reduced model of the GB transmission system across the operating space that the energy transition is creating: higher renewable penetration, seasonal extremes of demand and commitment, large new northern loads representing data-centre build-out, transmission outages, and — critically — the partial observability of vendor converter controls. The evidence base is a 72-case factorial matrix (season × wind × data-centre load × outage × controller visibility) built on four targeted experiments.

Five findings:

- **One mode governs winter security.** The system-wide critical mode is a 0.60 Hz swing anchored on the southern gas fleet (epicentre Zone 04), which becomes a coherent Scotland-versus-England inter-area oscillation under stress. Its damping is set less by boundary flow direction than by how hard the southern gas units are driven.
- **Winter renewable growth erodes it.** Replacing gas output with wind MW-for-MW takes the mode from 3.66% to 2.30% damping over nine percentage points of penetration; the worst single circuit (Line 13-16) alone halves the base margin to 1.76%.
- **The binding credible case is low wind plus Scottish data centres — and it is invisible to static analysis.** With Scottish wind at 30% and +4 GW of data-centre demand, the mode is outright unstable (−0.11% at 0.59 Hz) at an operating point where the load flow converges with healthy voltages (Vmin 0.974) and no thermal violation (worst circuit 64%). Of the 36 matrix dispatches, 1 is unstable, 4 more sit below 2% damping and 25 sit between 2% and 5%.
- **Summer minimum changes the physics, and load growth changes it back.** At half demand the classical fleet decommits to 2–3 units and the electromechanical mode family retires with it (no mode below ~12.7%, the floor set by a 5.6 Hz converter-coupled cluster). But data-centre growth re-commits classical units and resurrects the 0.65 Hz mode: 12.7% → 6.8% → 3.2% at +2/+4 GW.
- **Black-boxed controllers corrupt the assessment.** Excluding the renewable REEC/REGC blocks from the linearisation — as encrypted vendor models force in practice — deletes roughly 400 states, reads optimistically in 35 of 36 paired dispatches (up to 13% of the true margin), and at high penetration misidentifies which mode is critical. The unstable data-centre case reads as essentially marginal-but-stable when blind.

The recommendations follow directly: season-aware operating envelopes and dispatch-aware contingency lists; small-signal screening (under low-renewable dispatch) for large-load connections, with firming arrangements in the connection agreement; PSS retuning on the named participating units; HVDC/IBR power-oscillation damping on the Western Link and Scottish wind; boundary reinforcement; and model-transparency requirements so that the analysis that certifies stability can actually see the plant that provides it.

1. Introduction and objectives

Eigenvalue analysis linearises the differential-algebraic model of a power system about a converged load flow and computes the eigenvalues $\lambda = \sigma \pm j\omega$ of the state matrix. Each complex pair is an oscillatory mode of frequency $f = \omega/2\pi$ and damping ratio $\zeta = -\sigma/|\lambda|$; a mode with $\sigma > 0$ grows without bound at small signal, and modes with ζ below roughly 5% are conventionally treated as watch items, below 3% as remedial-action items. Unlike time-domain simulation, the eigenvalue view is exhaustive: every mode is found, whether or not a chosen disturbance happens to excite it — which makes it the natural instrument for the questions asked here.

The study set out to answer, on a credible GB-shaped test system:

- How does rising renewable penetration (displacing synchronous plant) move the critical modes, in winter and at summer minimum?
- Can plausible new load patterns — a Scottish data-centre build-out — create instability, and under what supply conditions?
- Do high-penetration dispatches create genuinely new oscillatory modes, or promote previously comfortable ones into risk?
- How wrong is an eigenvalue study when the renewable controllers are black boxes it cannot linearise — the everyday condition of real interconnection studies?

All analysis was performed in DIgSILENT PowerFactory 2026 on the “GB Reduced Model” project, driven end-to-end through scripted automation (MCP + in-process ComPython batches), with every dispatch built programmatically and every result archived for reproduction.

2. The model

2.1 Network and fleet

Property	Value
Zones / structure	28 zones (Zone 01–28), one 5-busbar 400 kV substation each; zones internally single-node
Buses / circuits	1,412 terminals; 46 × 400 kV circuits (44 inter-zone corridors + 2 Western Link AC stubs)
Voltage levels	400 / 56.5 / 33 kV
Synchronous machines	174 ElmSym — one aggregated unit per fuel type per zone (Gas, Nuclear, Biomass, Hydro, Pump storage, Others) + 6 synchronous condensers
Converter plant	152 ElmGenstat — Wind, Solar, Battery, Hydrogen, Marine per zone + 12 HVDC terminals; 29 SVCs
Demand (winter base)	46,642 MW (56 loads, constant-P); generation ≈ 48.0 GW; slack Z21 Nuclear ≈ 1.94 GW
Installed capacity	≈ 109.7 GW nameplate, incl. 16.2 GW Marine + 2.7 GW Hydrogen future placeholders at zero output
Geography	Zone numbering runs broadly south → north; Zones 24–28 are Scotland (anchored by interconnector landing points: Moyle, NSL, Western Link)

2.2 Generation mix at the study operating point

Type	Installed (MW)	Output (MW)	Dispatch
Gas	33,284	24,209	73%
Wind	32,920	14,197	43%
Nuclear	9,166	5,074	55% (≈4 GW offline: Z01, Z18)
Biomass	3,633	2,482	68%
Hydro	1,206	1,166	97%

Type	Installed (MW)	Output (MW)	Dispatch
Others (thermal)	4,150	815	20%
Battery storage	3,609	779	22%
Pumped storage	668	490	73%
Solar	2,209	90	4%
Marine / Hydrogen	16,180 / 2,660	0	future placeholders

The mix is gas-and-wind dominated (≈33 GW installed each) with Hinkley-era nuclear — a decarbonised near-future scenario rather than the present system. The only active HVDC flow at base is the embedded Western Link (Z25 Scotland → Z18 North Wales, ≈2.2 GW); the ten external interconnectors (≈10.7 GW) are parked at zero exchange.

2.3 Controller architecture — and the observability trap

Every synchronous machine carries a composite frame with AVR (avr_AVR_wPSSinput, gain ≈50), governor (gov_GOV, 4% droop equivalent R = 0.25) and stabiliser (pss_PSS1A, Ks = 0.15) models; the converter fleet uses WECC generic models (REEC_C/REEC_D electrical controls and REGC_A/REGC_C generator-converters); 29 SVCs run an RSVC controller.

A methodological trap was uncovered and is worth recording: a controller is excluded from the eigenvalue calculation by either of two independent switches — its own in-service flag, *or* the load-flow command's Advanced Options → Simulation "Models Considered / Ignored" list. Because the modal analysis linearises about that load flow, a model left in "Ignored" contributes nothing to the state space even when its device flag says in-service. With the synchronous controls ignored, the model solves 981 states and toggling those controllers changes nothing; with both switches cleared it solves 1,335 states and the AVR visibly de-damps the critical mode. All results in this report have both switches cleared.

3. Methodology

3.1 Workflow

- Each case: reset to the authoritative base state → construct dispatch programmatically → apply outage (if any) → set controller visibility → calculate initial conditions (ComInc) → solve the full eigenvalue problem (ComMod) → archive the complete spectrum and load-flow metrics.
- All batches ran server-side inside PowerFactory's Python (in-process ComPython), with incremental result dumps and resume-on-restart capability; the desktop monitoring GUI was kept open throughout.
- Roughly 120 eigenvalue solutions were executed in total; the reported dataset comprises the 72-case matrix plus 22 development-ladder solves.

3.2 Dispatch construction rules

Axis	Construction
Winter (peak)	Base 46.6 GW demand. Penetration ladder: wind/solar raised headroom-proportionally; gas displaced MW-for-MW in merit order, decommitting whole units below 15% minimum stable generation.
Summer minimum	Demand ×0.5 (23.3 GW). Wind/solar at ×0.8 (normal) or ×0.3 (low) of winter MW. Nuclear/hydro/storage must-run. Classical fleet (gas, biomass, others) unit-committed largest-first to (load + DC) ×1.05 net of must-run, 600 MW slack reserve — 2 to 8 of 35 classical units survive depending on case.
Low wind (winter)	Scottish wind (Z24–28) ×0.3; lost energy replaced by southern gas uplift, headroom-proportional.
Data centres	Constant-P load at 0.99 PF added 40% / 40% / 20% across Zones 24 / 25 / 26 (central-belt siting), balanced by southern gas uplift (winter) or absorbed into the commitment target (summer).
Outages	Applied after dispatch (market schedules, then the circuit trips): intact; Line 13-16 (worst internal N-1); Line 22-24 (Scotland–England boundary tie).

Axis	Construction
Black-box emulation	The 112 REEC/REGC controller blocks belonging to wind, solar and battery plant flagged out of the linearisation at an identical operating point — reproducing what an eigenvalue study sees when vendor controllers are encrypted. HVDC and SVC controllers remain visible. The units still inject identical power; only the analysis loses sight of their dynamics.

3.3 Mode-population analytics

Beyond the single least-damped mode, every oscillatory mode in the 0.05–3 Hz window was banded by damping and matched case-to-case against winter base by nearest-neighbour in (frequency, damping) space (tolerances 0.06 Hz / 3.5 points). Modes with no counterpart are genuinely new — arising from changed commitment, dispatch and converter loading (per-zone aggregation fixes the controller population, so new modes cannot come from new plant).

3.4 Quality assurance

- Regression anchors: every matrix cell that duplicates a ladder case reproduces it exactly (e.g. winter base 3.66%; Line 13-16 out 1.76%; low-wind +4 GW DC −0.11%; summer ×0.8 commitment target 6,651 MW / 2 units).
- **A state-corruption incident was caught and corrected during the matrix runs:** a batch dying mid-run (API session drop) left a dirty dispatch which a resumed script initially inherited as its baseline, corrupting one winter cell and the first summer attempt (symptom: commitment target 12,249 MW where the validated value is 6,651 MW, and spurious instabilities). The batch driver was rebuilt to force-restore the model from authoritative snapshot files before taking any baseline; all affected cases were scrubbed and re-solved cleanly. Every number in this report traces to a verified-base solve.
- The model was restored and verified after the final batch: 46,642 MW load, 48,049 MW generation, zero circuits out, slack 1,942 MW, boundary circuit L22-24 at 51.9% — identical to the starting state.

4. Baseline characterisation

With all controllers in service and considered, the base winter operating point solves 1,335 states: 0 right-half-plane eigenvalues (small-signal stable), critical mode 0.604 Hz at ζ = 3.66% ($\sigma = -0.139\ s^{-1}$), a well-damped local-mode population at 10–13%, and a 5.5–5.8 Hz cluster at ~12.7–13.4% associated with excitation and converter control interactions.

4.1 The critical mode: identity and mechanism

Participation-factor analysis places the mode on the Zone-04 gas machine (the largest southern synchronous unit, 2,226 MW dispatch) with the southern converter fleet (battery and HVDC REGC blocks across Z01–Z13) swinging coherently with it. The machine AVRs appear in anti-phase to the rotor states (≈ −177°): the excitation response injects negative damping torque, and the PSS1A as tuned (Ks = 0.15, output limits ±0.05) is too weak to compensate — the classic high-gain-AVR / weak-PSS signature and a direct tuning target.

Under stress the mode's shape expands into a genuine inter-area swing. At +15% North→South transfer with a boundary tie out, England (Z01–16, phases ≈ 0–11°) swings coherently against Scotland (Z24–28, ≈ −72° to −87°), with the Zone-23 offshore hub in anti-phase:

Group	Zones (participation, phase)	Interpretation
England	Z04 8.84 @ 0° · Z03 2.82 @ 5° · Z02 1.25 @ 4° · Z13 1.08 @ 6° · Z12 1.04 @ 6° · Z05 1.01 @ 3° · Z01 0.99 @ 3° · Z16 0.68 @ 10°	Coherent southern group anchored on Z04 gas
Scotland	Z28 2.11 @ −80° · Z26 1.86 @ −84° · Z25 1.64 @ −87° · Z27 1.40 @ −80° · Z24 1.22 @ −72°	Coherent northern group, ~80° behind England
Anti-phase	Z23 0.34 @ −179°	Humber offshore hub

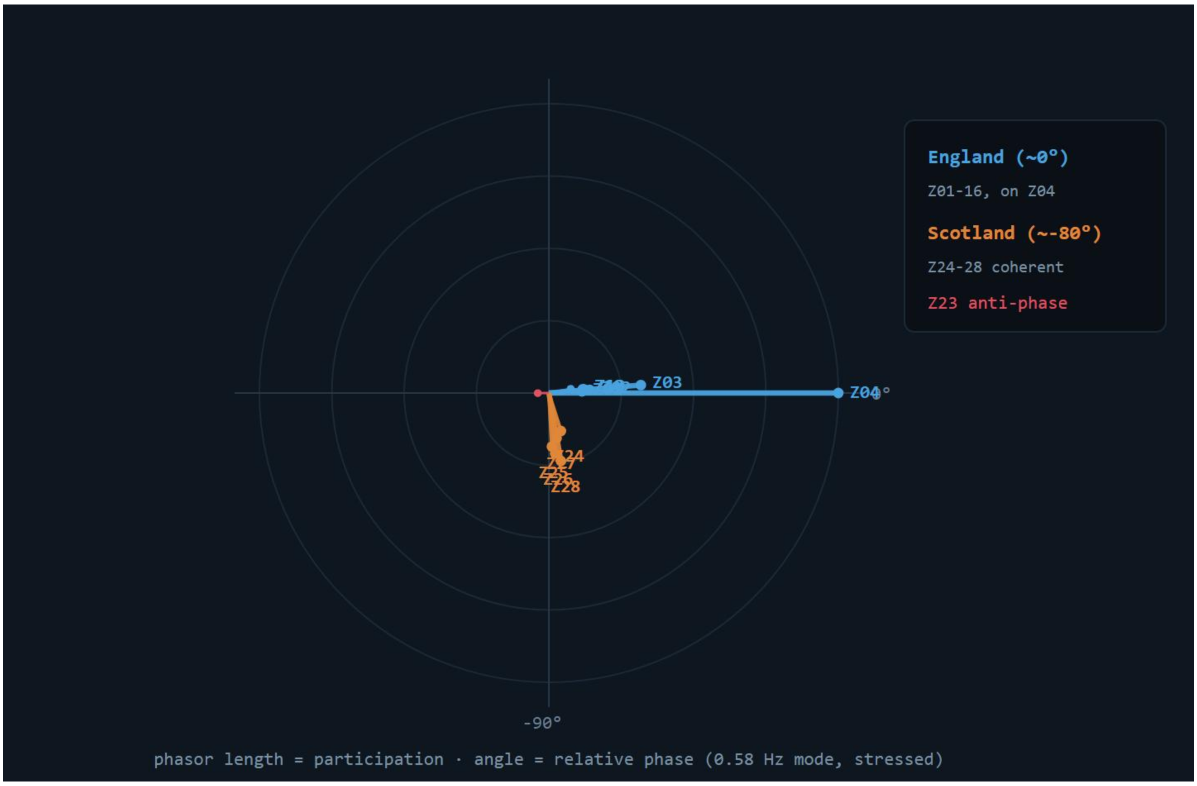

Figure 1 — Mode-shape phasors of the critical mode at the stressed operating point (0.58 Hz): England (~0°) versus Scotland (~−80°).

4.2 Sensitivity to single outages and transfer

Re-solving the eigenvalues under each relevant N-1 shows strongly non-uniform sensitivity. Outages that weaken the corridors feeding Zone 04 cut the margin roughly in half; outages elsewhere barely register;

and islanding Zone 04 (Line 04-05, its radial feed) removes the problem mode altogether — confirming the epicentre.

Contingency (winter base)	Critical mode	Damping
Intact	0.604 Hz	3.66%
Line 13-16 out	0.554 Hz	**1.76%**
Line 05-06 out	0.558 Hz	2.42%
Line 05-14 out	0.560 Hz	2.57%
Line 01-05 out	0.602 Hz	3.20%
Line 20-21 out	0.603 Hz	3.62%
Line 09-13 out (worst thermal N-1)	0.595 Hz	3.64%
Line 08-09 out	0.602 Hz	3.66%
Line 04-05 out (islands Zone 04)	0.671 Hz	9.54%

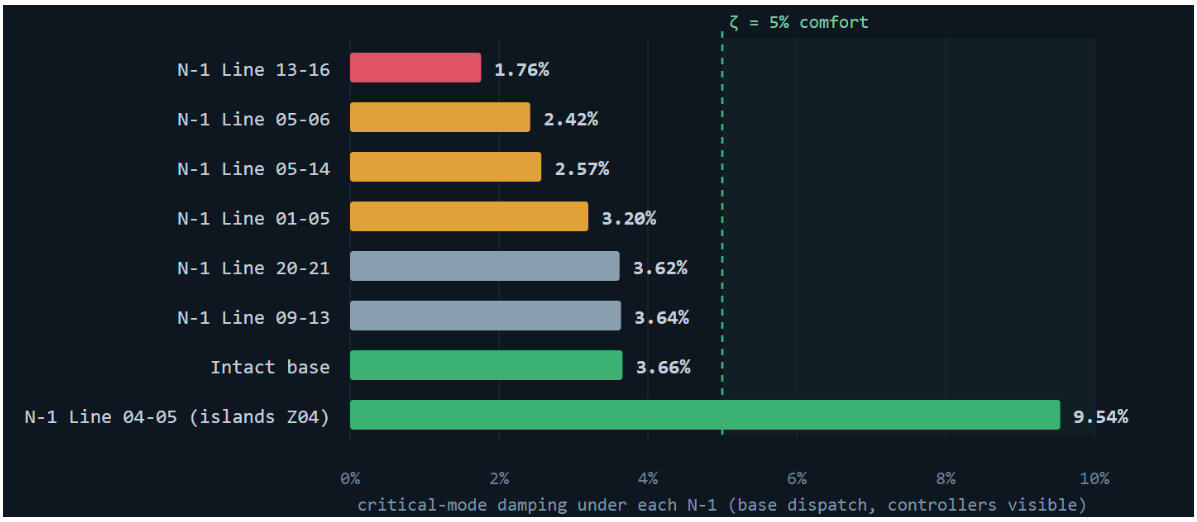

Figure 2 — Critical-mode damping under single-circuit outages, winter base dispatch.

Raising North→South transfer erodes the mode directly and simultaneously drives the boundary toward its static limit: at +15% (Scotland ×1.15, England ×0.85) damping halves to 2.01% with Line 22-24 at 94% loading; at +30%, and equally on loss of the loaded tie, the load flow no longer converges. The oscillatory and static ceilings arrive together on the same boundary.

5. Experiment 1 — winter penetration ladder

Four operating points at full demand. Each step adds ~1.5 GW of wind/solar and removes the same energy from gas in merit order with whole-unit decommitment — so the ladder removes real machines, inertia and synchronising torque, not merely re-scaled outputs.

Case	Penetration	Sync units	Inertia (GVA·s)	True ζ (f)	Black-box ζ	Error
P0 · base	28.8%	55	287	3.66% (0.60 Hz)	3.82%	+0.16
P1 · +1.5 GW wind	31.8%	48	276	3.54% (0.60 Hz)	3.74%	+0.20
P2 · +3.0 GW wind	34.8%	46	265	3.27% (0.60 Hz)	3.55%	+0.28
P3 · +4.5 GW wind	37.6%	44	251	**2.30% (0.60 Hz)**	2.59%	+0.29

The erosion is nonlinear: P0→P2 costs ~0.4 points of damping, P2→P3 alone ~1.0 point, because three mechanisms compound on the same mode — lost inertia (11 units off), lost synchronising support in the mode's epicentre zones, and rising boundary loading (L22-24 from 52% to 77%) as much of the added wind is northern.

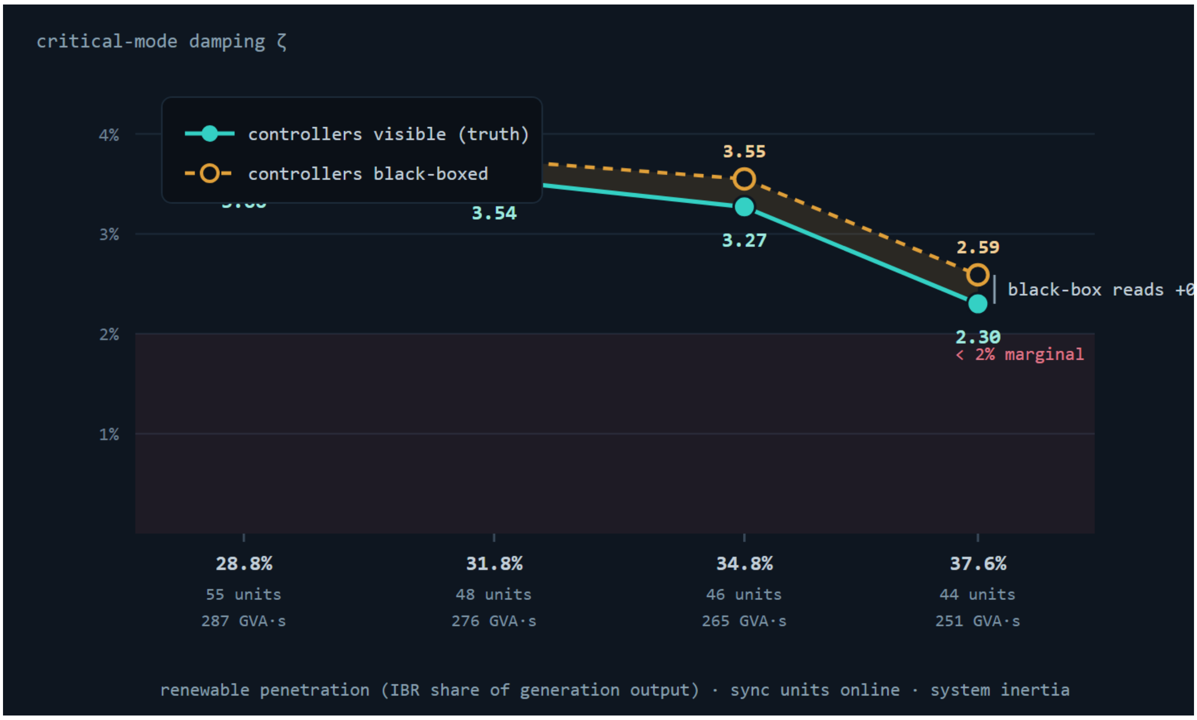

Figure 3 — Critical-mode damping vs renewable penetration at winter peak; the shaded band is the black-box optimism.

6. Experiment 2 — the black-box blind spot

Real wind, solar and battery controllers are usually delivered as encrypted, compiled vendor models: time-domain simulation runs them, but a linearisation cannot see inside, so an eigenvalue study effectively treats the plant as constant-PQ injection. Emulating that here (112 REEC/REGC blocks removed from the linearisation at identical operating points) quantifies the resulting error:

- State space: 1,342 → 930 states at P0 (≈410 states invisible); the electromechanical-band mode count falls from 175 to 152.
- Winter bias: the blind study reads the critical margin optimistically at every level — +0.16 / +0.20 / +0.28 / +0.29 points at P0–P3, i.e. roughly 4% growing to 13% of the true remaining margin, largest exactly when the margin is smallest.
- Mechanism: the visible model shows the converter controls participating in (and slightly de-damping) the critical mode; hide them and that contribution vanishes from the state matrix, so the mode looks healthier than it is.

- **At high penetration the failure changes kind.** At the summer operating points (46–56% penetration) the true least-damped mode is a 5.56 Hz converter-coupled cluster: the 4.5–6.5 Hz band holds 38 modes in the full model and 8 in the blind one, and the critical mode is among the missing. The blind study names a 1.12 Hz mode as critical instead — the number it reports is nearly right, the phenomenon is wrong, and a damping controller specified from it would target the wrong mode.

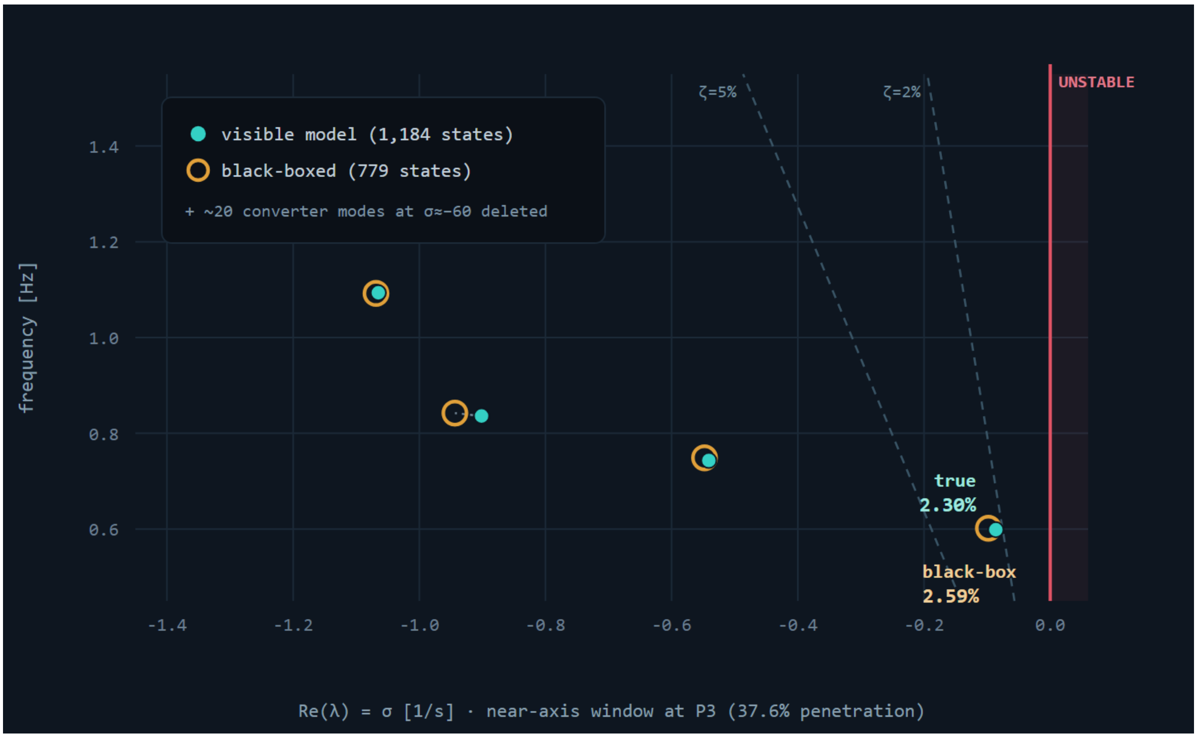

Figure 4 — The same operating point (winter P3) seen by the full and black-boxed analyses: near-axis modes shift optimistically; ~20 fast converter modes are deleted outright.

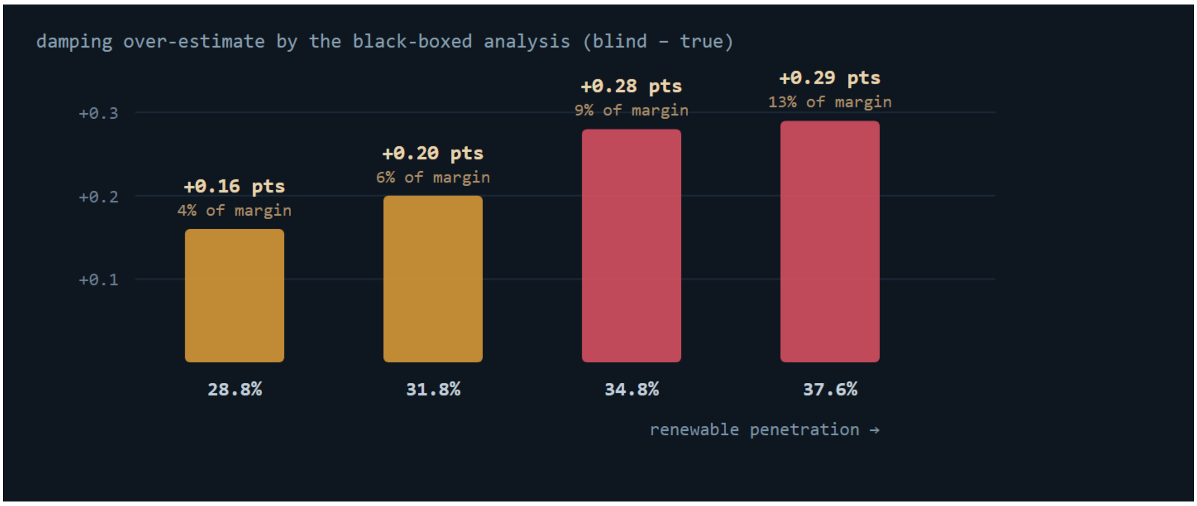

Figure 5 — Growth of the black-box damping over-estimate across the winter ladder, absolute and as a share of the true margin.

Across the full 72-case matrix the bias is optimistic in 35 of 36 paired dispatches; the single exception (winter, low wind, +4 GW DC, boundary tie out — the most extreme surviving dispatch) flips pessimistic (blind 2.61% vs true 3.21%). The direction of the error is therefore system- and dispatch-dependent — but its presence is not.

7. Experiment 3 — summer minimum and the mode-class shift

Demand halved to 23.3 GW; wind held at winter MW ×0.6/0.8/1.0 (wind does not follow demand — which is precisely why summer minimum is the binding condition); nuclear, hydro and storage must-run; classical fleet unit-committed largest-first. Only 2–3 of 35 classical units survive; inertia falls to 117–136 GVA·s (roughly half of winter); penetration reaches 36–56%.

Case	Wind	Penetration	Sync units	Inertia (GVA·s)	Critical mode
SP0	×0.6	35.9%	23	136	4.50% @ 0.66 Hz
SP1	×0.8	46.2%	22	117	12.72% @ 5.59 Hz
SP2	×1.0	56.5%	22	117	12.65% @ 5.56 Hz

At SP0 the familiar electromechanical mode survives (Zone-04 gas still part-loaded, 0.66 Hz at 4.50%). At SP1 that unit decommits and the entire swing-mode family retires with the machines that create it: no oscillatory mode remains below ~12.65%, and the system floor is set by the 5.6 Hz converter-coupled cluster — a different class of dynamics. The modal picture genuinely improves; the system is not thereby safer: inertia has halved (frequency containment and RoCoF degrade — non-modal quantities), and the new floor is exactly the class a black-boxed study cannot see, near the credibility limit of RMS phasor modelling itself.

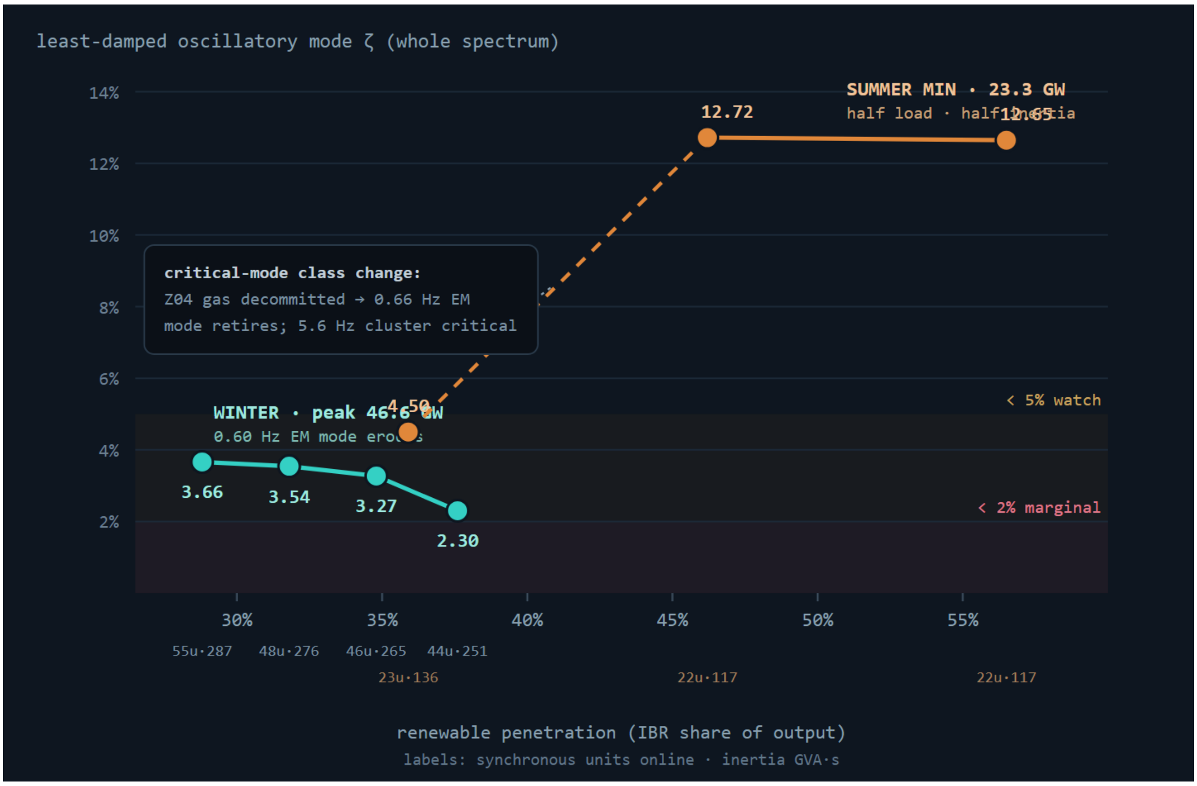

Figure 6 — Winter and summer penetration ladders on one axis: erosion versus retirement of the electromechanical mode class.

8. Experiment 4 — Scottish data-centre build-out

Up to 4 GW of constant-power load (0.99 PF) added across the Scottish central belt (40/40/20 over Z24/Z25/Z26) at winter demand, under a normal and a low-wind day, with the balance met the way the market would meet it — southern gas re-dispatch within headroom.

DC load	Normal wind: ζ (boundary)	Low wind: ζ (boundary)
0	3.66% (52% export)	2.14% (0.4 GW import)
+1 GW	3.40% (38%)	1.60% (1.0 GW import)
+2 GW	3.05% (24%)	**1.01% (1.5 GW import)**
+4 GW	2.18% (flow reversed)	**UNSTABLE −0.11% (2.5 GW import)**

Three findings:

- **A refuted intuition.** Data-centre load does de-stress the Scotland–England boundary exactly as expected (52% → 10% → reversed to import) — but the mode erodes anyway, because its participation sits on the southern gas fleet and every GW of DC (or of lost wind) is served by loading precisely those machines. Who supplies the energy matters more than which way the boundary flows.
- **The compound case crosses zero.** Low wind alone halves the margin; each GW of DC then costs ≈0.5 points; the instability threshold interpolates to ≈+3.5 GW and +4 GW is a growing 0.59 Hz oscillation.
- **Static analysis gives no warning.** At the unstable point the load flow converges with Vmin 0.974 pu and the worst circuit at 64% — thermally and voltage-wise unremarkable. Only the eigenvalues see the problem. This is the cleanest possible argument for small-signal screening of large-load connections.

The benign version exists: on the windy day (or with firm local supply — storage, wind-following flexibility, curtailment contracts) the same data centres relax the boundary and absorb otherwise-curtailed wind. The stability question for Scottish data centres is really the question of what firms them on low-wind days.

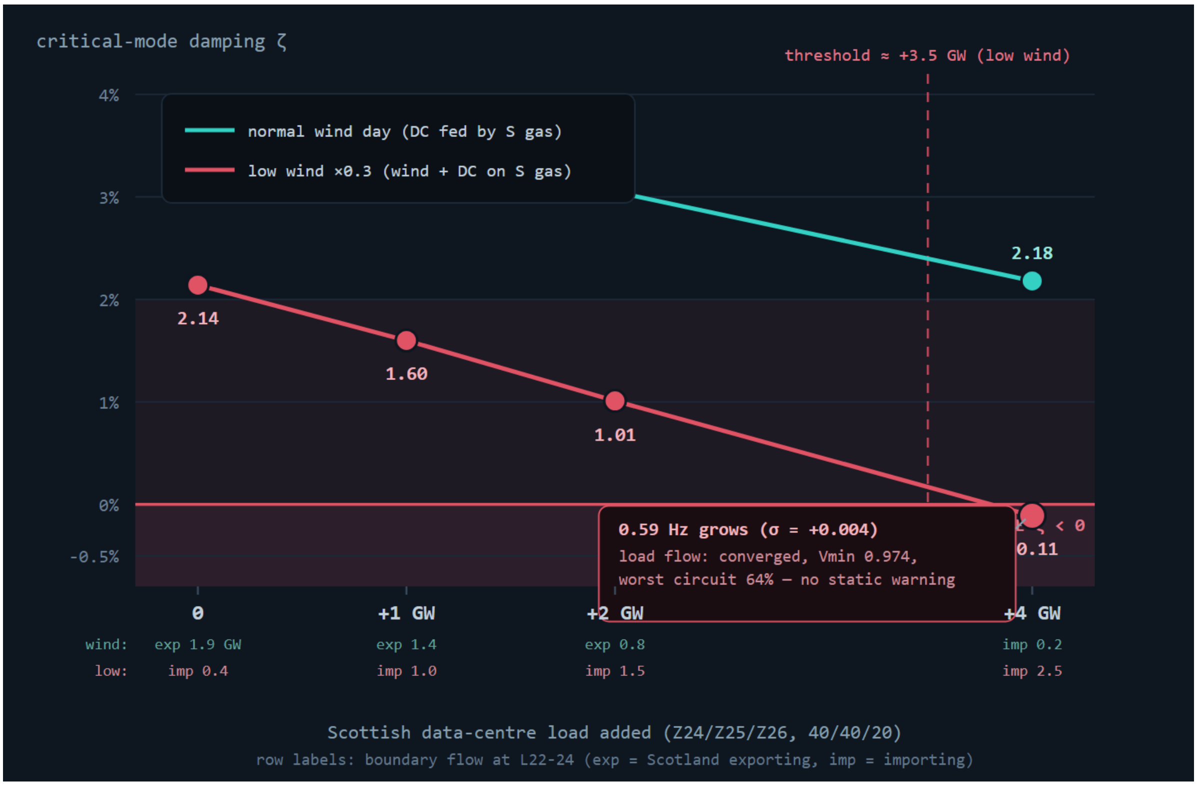

Figure 7 — Critical-mode damping vs Scottish data-centre load under normal and low wind; the low-wind curve crosses into instability at +4 GW.

9. The 72-case factorial matrix

The four experiments define the axes; the matrix solves every combination — season (2) × wind (2) × data-centre load (3) × outage (3) × controller visibility (2) — with dispatch rebuilt market-realistically per case. All 72 solves converged; the severity map below shows the true (visible-model) critical damping with the black-boxed reading alongside.

Figure 8 — The severity matrix: true critical damping per case (bb = black-boxed reading). Winter degrades toward the low-wind + DC corner; summer sits higher but data-centre growth pulls it back toward winter-like behaviour.

9.1 Winter results

Wind	DC load	Outage	True ζ	f (Hz)	Black-box ζ	Δ (bb–true)
Normal wind	+0 GW	Intact	3.66%	0.604	3.82%	+0.16
Normal wind	+0 GW	Line 13-16 out	**1.76%**	0.554	1.89%	+0.13
Normal wind	+0 GW	Line 22-24 out	3.50%	0.566	3.55%	+0.05
Normal wind	+2 GW	Intact	3.05%	0.604	3.20%	+0.15
Normal wind	+2 GW	Line 13-16 out	2.33%	0.564	2.49%	+0.16

Wind	DC load	Outage	True ζ	f (Hz)	Black-box ζ	Δ (bb−true)
Normal wind	+2 GW	Line 22-24 out	3.99%	0.582	4.16%	+0.17
Normal wind	+4 GW	Intact	2.18%	0.602	2.32%	+0.14
Normal wind	+4 GW	Line 13-16 out	2.07%	0.570	2.24%	+0.17
Normal wind	+4 GW	Line 22-24 out	3.72%	0.582	3.84%	+0.12
Low wind (Scot ×0.3)	+0 GW	Intact	2.14%	0.602	2.26%	+0.12
Low wind (Scot ×0.3)	+0 GW	Line 13-16 out	2.28%	0.576	2.43%	+0.15
Low wind (Scot ×0.3)	+0 GW	Line 22-24 out	4.01%	0.583	4.10%	+0.09
Low wind (Scot ×0.3)	+2 GW	Intact	**1.01%**	0.599	1.12%	+0.11
Low wind (Scot ×0.3)	+2 GW	Line 13-16 out	**1.48%**	0.577	1.64%	+0.16
Low wind (Scot ×0.3)	+2 GW	Line 22-24 out	3.49%	0.580	3.56%	+0.07
Low wind (Scot ×0.3)	+4 GW	Intact	**-0.11%**	0.595	0.00%	+0.11
Low wind (Scot ×0.3)	+4 GW	Line 13-16 out	**0.58%**	0.576	0.74%	+0.16
Low wind (Scot ×0.3)	+4 GW	Line 22-24 out	3.21%	0.573	2.61%	-0.60

9.2 Summer results

Wind	DC load	Outage	True ζ	f (Hz)	Black-box ζ	Δ (bb−true)
Wind ×0.8	+0 GW	Intact	12.72%	5.589	12.98%	+0.26
Wind ×0.8	+0 GW	Line 13-16 out	12.65%	5.557	13.13%	+0.48
Wind ×0.8	+0 GW	Line 22-24 out	12.61%	5.539	12.70%	+0.09
Wind ×0.8	+2 GW	Intact	6.83%	0.669	6.98%	+0.15
Wind ×0.8	+2 GW	Line 13-16 out	5.80%	0.653	5.95%	+0.15
Wind ×0.8	+2 GW	Line 22-24 out	6.97%	0.665	7.13%	+0.16
Wind ×0.8	+4 GW	Intact	3.24%	0.650	3.38%	+0.14
Wind ×0.8	+4 GW	Line 13-16 out	2.90%	0.639	3.05%	+0.15
Wind ×0.8	+4 GW	Line 22-24 out	3.44%	0.647	3.58%	+0.14
Wind ×0.3	+0 GW	Intact	3.34%	0.647	3.39%	+0.05
Wind ×0.3	+0 GW	Line 13-16 out	3.03%	0.635	3.08%	+0.05
Wind ×0.3	+0 GW	Line 22-24 out	3.51%	0.645	3.56%	+0.05
Wind ×0.3	+2 GW	Intact	3.30%	0.646	3.35%	+0.05
Wind ×0.3	+2 GW	Line 13-16 out	3.09%	0.636	3.14%	+0.05
Wind ×0.3	+2 GW	Line 22-24 out	3.50%	0.644	3.55%	+0.05
Wind ×0.3	+4 GW	Intact	3.38%	0.647	3.43%	+0.05
Wind ×0.3	+4 GW	Line 13-16 out	3.29%	0.637	3.33%	+0.04
Wind ×0.3	+4 GW	Line 22-24 out	3.67%	0.643	3.72%	+0.05

9.3 League table — the ten worst operating points

#	Operating point	True ζ	f (Hz)	Black-box ζ
1	Winter, low wind, +4 GW DC	**-0.11%**	0.595	0.00%
2	Winter, low wind, +4 GW DC, Line 13-16 out	**0.58%**	0.576	0.74%
3	Winter, low wind, +2 GW DC	**1.01%**	0.599	1.12%
4	Winter, low wind, +2 GW DC, Line 13-16 out	**1.48%**	0.577	1.64%
5	Winter, normal wind, Line 13-16 out	**1.76%**	0.554	1.89%
6	Winter, normal wind, +4 GW DC, Line 13-16 out	2.07%	0.570	2.24%
7	Winter, low wind	2.14%	0.602	2.26%

#	Operating point	True ζ	f (Hz)	Black-box ζ
8	Winter, normal wind, +4 GW DC	2.18%	0.602	2.32%
9	Winter, low wind, Line 13-16 out	2.28%	0.576	2.43%
10	Winter, normal wind, +2 GW DC, Line 13-16 out	2.33%	0.564	2.49%

9.4 Cross-cutting findings

- **The binding contingency depends on the dispatch.** At normal wind the binding N-1 is the internal corridor Line 13-16. Under low wind, losing the boundary tie Line 22-24 improves damping (2.14% → 4.01% at DC0; 1.01% → 3.49% at DC2; even the unstable DC4 case recovers to 3.21%) because it severs the import path that loads the southern fleet — while leaving the remaining tie Line 21-24 at 97% carrying 5.2 GW: oscillatory relief bought at the price of static exhaustion. Security assessment against a fixed worst-contingency list misses this entirely.
- **How the load is served matters more than how much.** Summer meets data-centre growth by committing additional part-loaded units (2→3→4 at normal wind; 5→7→8 at low wind) and damping holds ≈3.2–3.7% even in the worst corner. Winter meets the identical stress by pushing already-committed southern gas toward its limits, and the same wind+DC combination collapses to instability. Same stressors, opposite outcomes, distinguished only by the dispatch mechanism.
- **Commitment feedback resurrects retired physics.** Summer DC growth re-commits classical units and brings the electromechanical mode class back: the floor falls from 12.72% @ 5.6 Hz (DC0) through 6.83% @ 0.67 Hz (+2 GW) to 3.24% @ 0.65 Hz (+4 GW). Load growth changes not just flows but which physics exists on the system.
- **The black-box error is universal in presence, variable in kind.** Optimistic in 35 of 36 paired dispatches (one extreme case flips pessimistic); wrong about which mode is critical in 2 (the high-penetration summer dispatches); and it reads the one genuinely unstable dispatch as essentially marginal.

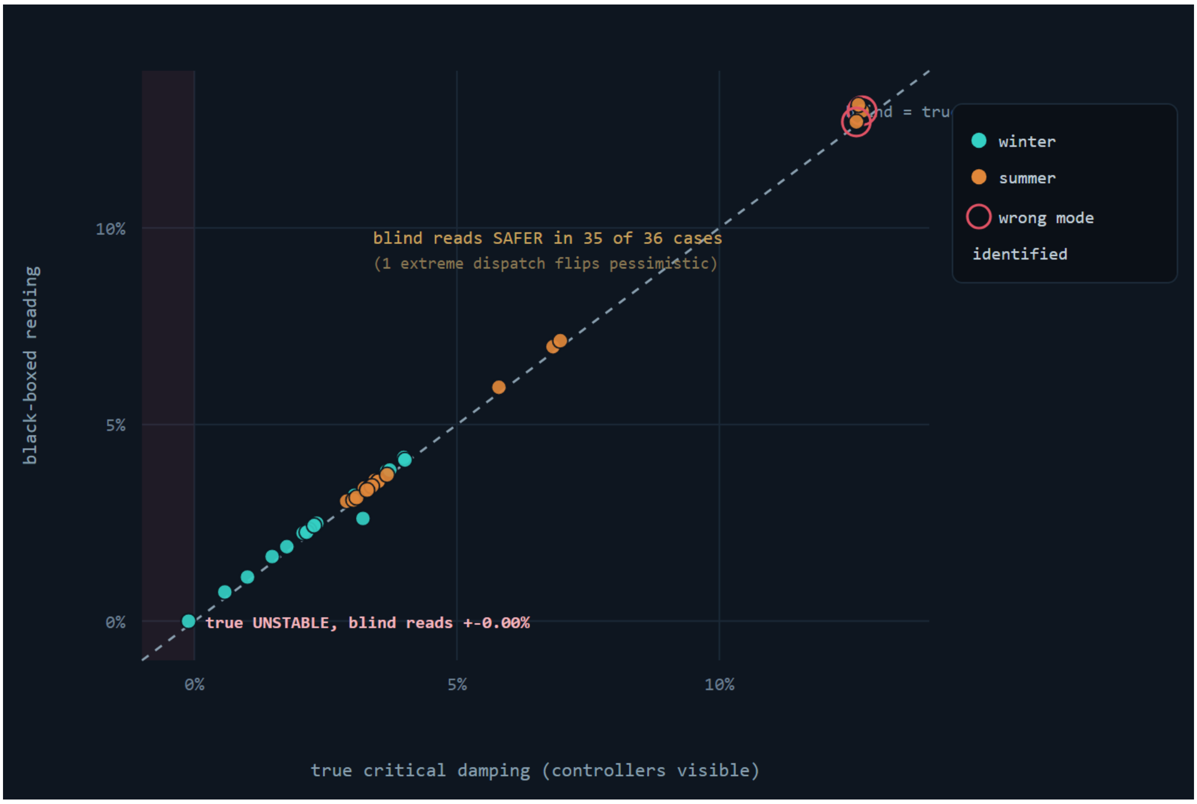

Figure 9 — Black-boxed vs true critical damping across all 36 paired dispatches. Points above the diagonal are optimistic readings; ringed points misidentify the critical mode.

10. New modes and borderline promotion

Do high-penetration dispatches create new oscillatory modes, or promote previously comfortable ones into risk? Matching every spectrum against winter base answers empirically:

Case	Modes in window	<2%	2–5%	5–10%	New modes (ζ<35%)
P0 (base)	210	0	1	0	0
P1	179	0	1	0	0
P2	171	0	1	0	0
P3	163	0	1	0	1 (1.25 Hz @ 30%)
SP0	91	0	1	0	1 (0.90 Hz @ 30%)
SP1	90	0	0	0	2 (1.13 Hz @ 25%; 0.91 @ 30%)
SP2	91	0	0	0	3 (1.24 @ 22%; 1.13 @ 25%; 0.95 @ 29%)

- New modes: yes — a handful of converter-and-commitment-driven arrivals in the 0.9–1.3 Hz range — but all arrive well-damped (≥22%). The significant change is the critical class shifting (electromechanical → converter-coupled), not a new unstable arrival.
- Borderline promotion: none in the penetration ladders — no mode crosses into <5% that was not already the critical one, and the 1.37 Hz cluster improves in summer (10.9% → 15.1%). But the data-centre experiment demonstrates the promotion mechanism is real: the same "comfortable" 3.66% mode is driven through zero by a plausible, previously unstudied operating point. No new physics — just a dispatch nobody checked.
- Instability was found in exactly 1 of the 36 visible matrix dispatches, and it is invisible to static analysis.

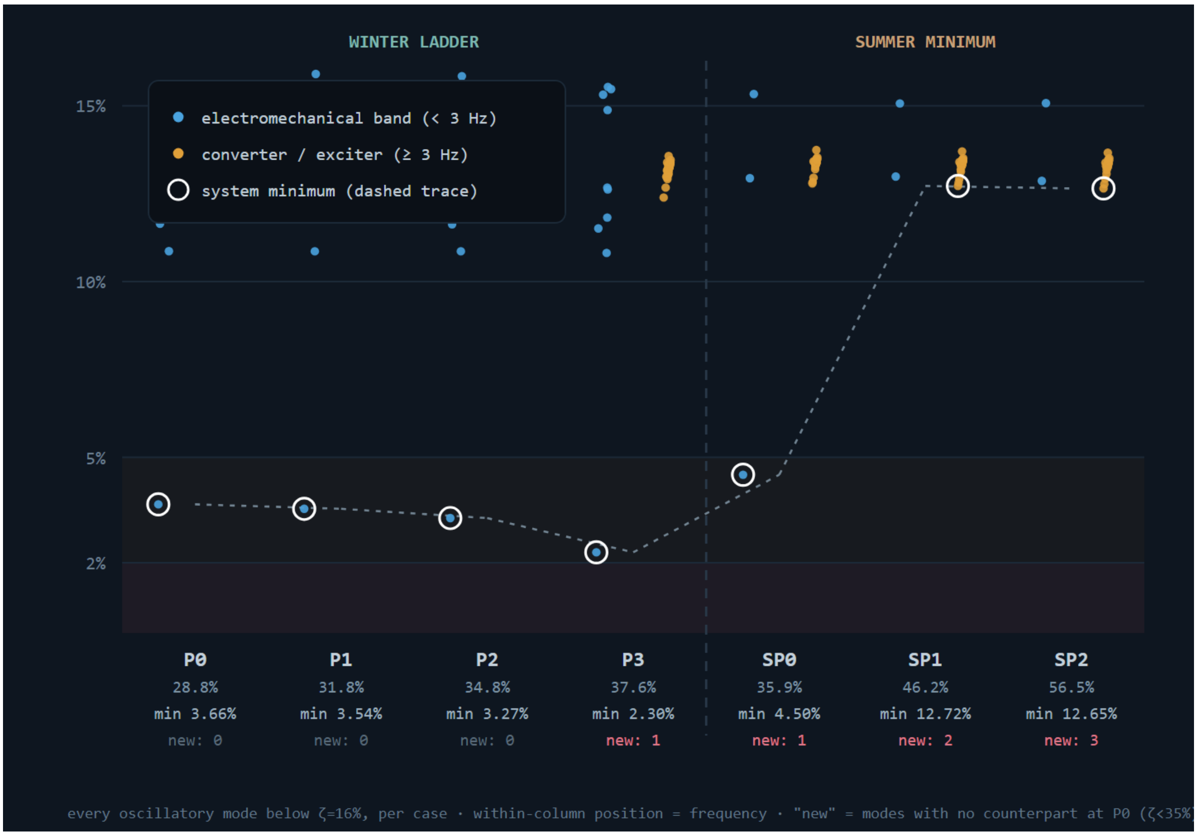

Figure 10 — The mode population below ζ = 16% per case: winter's lone eroding critical mode versus summer's thinned population and raised floor.

11. Scope and limitations

- RMS phasor eigenvalues cannot represent sub-synchronous control interactions, PLL weak-grid instability or other fast converter phenomena; the 5.6 Hz cluster marks the frontier of credibility, and EMT analysis is the right tool beyond it. “No mode below 12.65%” at summer minimum is a statement about what phasor-domain analysis can see — not a clean bill of health.

- Frequency stability (RoCoF, containment after an infeed loss) is not an eigenvalue property; it unambiguously worsens as inertia halves at summer minimum and needs its own assessment.
- One aggregated machine per fuel per zone understates the diversity of real multi-vendor converter interactions and intra-zonal dynamics; the 5-busbar zone substations are electrically single nodes.
- Data-centre load is modelled as constant-P at 0.99 PF; the fast power-electronic load dynamics of real facilities (and their ride-through behaviour) are a further, unmodelled layer.
- Dispatch construction is deliberately simple and rule-based (merit order, headroom-proportional, largest-first commitment). It is defensible and reproducible, but a production study would use market-model dispatches.
- Damping ratios are quoted to two decimals for traceability; given initialisation residuals on the WECC models, differences below ~0.1 point should not be over-interpreted.

12. Conclusions and recommendations

Conclusions:

- The GB reduced model's oscillatory security is governed by a single 0.60 Hz mode whose fate is set by how hard the southern gas fleet runs. Winter renewable growth, low-wind re-dispatch and Scottish load growth all act on it through that one mechanism, and their effects compound approximately linearly until instability (or static collapse) intervenes.
- The most dangerous credible operating point found — low wind plus 4 GW of Scottish data centres — is small-signal unstable while passing every static check. Eigenvalue analysis is the only tool in the standard planning toolbox that sees it.
- At summer minimum the electromechanical risk retires with the decommitted fleet, the floor rises to ~12.7%, and the critical dynamics change class to converter-coupled — but load growth reverses this by re-committing classical plant.
- Black-boxing the renewable controllers biases the assessment optimistically almost everywhere, by up to 13% of the true margin, and at high penetration it misidentifies the critical phenomenon altogether.

Recommendations:

Domain	Recommendation	Basis
Analysis	Require linearisable (e.g. WECC-generic) controller equivalents in connection agreements; treat black-box-only submissions as a stability-assessment gap.	35/36 optimistic readings; wrong critical mode at 46–56% penetration; unstable case read as stable.
Planning	Add small-signal screening under low-renewable dispatch to large-load (data-centre) connection studies; place firming arrangements — storage, wind-following flexibility, curtailment contracts — in the connection agreement.	+4 GW Scottish DC unstable at −0.11% while the load flow shows a healthy network; threshold ≈ +3.5 GW.
Operations	Make operating envelopes season-aware and contingency lists dispatch-aware: winter binds on the 0.60 Hz mode (hold $\zeta > 2$–5%); summer binds on inertia/RoCoF and converter-interaction screening; the binding N-1 flips with wind level.	Line 13-16 binding at normal wind; Line 22-24 outage helpful at low wind but leaves L21-24 at 97%.
Machines	Retune the PSS on the participating units (Z04 gas; boundary plant Z21/Z24/Z25 nuclear, Z28) — the AVRs currently de-damp the mode and the stabilisers are under-gained.	AVR anti-phase participation; base margin AVR-limited at 3.66%.
Converters	Implement power-oscillation damping on the Western Link and/or the participating Scottish wind converters.	The link bridges the two swing groups; converters dominate high-IBR dispatches — they are the damping resource.
Network	Reinforce the Scotland–England boundary (third circuit or series compensation).	L22-24/L21-24 bind the static limits and shape the mode; reinforcement raises both ceilings.

Appendix A — full matrix results

All 36 dispatches, visible and black-boxed. ζ = damping of the least-damped oscillatory mode; f = its frequency; Δ = black-box minus true.

Wind	DC load	Outage	True ζ	f (Hz)	Black-box ζ	Δ (bb−true)
Normal wind	+0 GW	Intact	3.66%	0.604	3.82%	+0.16
Normal wind	+0 GW	Line 13-16 out	**1.76%**	0.554	1.89%	+0.13
Normal wind	+0 GW	Line 22-24 out	3.50%	0.566	3.55%	+0.05
Normal wind	+2 GW	Intact	3.05%	0.604	3.20%	+0.15
Normal wind	+2 GW	Line 13-16 out	2.33%	0.564	2.49%	+0.16
Normal wind	+2 GW	Line 22-24 out	3.99%	0.582	4.16%	+0.17
Normal wind	+4 GW	Intact	2.18%	0.602	2.32%	+0.14
Normal wind	+4 GW	Line 13-16 out	2.07%	0.570	2.24%	+0.17
Normal wind	+4 GW	Line 22-24 out	3.72%	0.582	3.84%	+0.12
Low wind (Scot ×0.3)	+0 GW	Intact	2.14%	0.602	2.26%	+0.12
Low wind (Scot ×0.3)	+0 GW	Line 13-16 out	2.28%	0.576	2.43%	+0.15
Low wind (Scot ×0.3)	+0 GW	Line 22-24 out	4.01%	0.583	4.10%	+0.09
Low wind (Scot ×0.3)	+2 GW	Intact	**1.01%**	0.599	1.12%	+0.11
Low wind (Scot ×0.3)	+2 GW	Line 13-16 out	**1.48%**	0.577	1.64%	+0.16
Low wind (Scot ×0.3)	+2 GW	Line 22-24 out	3.49%	0.580	3.56%	+0.07
Low wind (Scot ×0.3)	+4 GW	Intact	**-0.11%**	0.595	0.00%	+0.11
Low wind (Scot ×0.3)	+4 GW	Line 13-16 out	**0.58%**	0.576	0.74%	+0.16
Low wind (Scot ×0.3)	+4 GW	Line 22-24 out	3.21%	0.573	2.61%	-0.60

Winter (above); summer (below).

Wind	DC load	Outage	True ζ	f (Hz)	Black-box ζ	Δ (bb−true)
Wind ×0.8	+0 GW	Intact	12.72%	5.589	12.98%	+0.26
Wind ×0.8	+0 GW	Line 13-16 out	12.65%	5.557	13.13%	+0.48
Wind ×0.8	+0 GW	Line 22-24 out	12.61%	5.539	12.70%	+0.09
Wind ×0.8	+2 GW	Intact	6.83%	0.669	6.98%	+0.15
Wind ×0.8	+2 GW	Line 13-16 out	5.80%	0.653	5.95%	+0.15
Wind ×0.8	+2 GW	Line 22-24 out	6.97%	0.665	7.13%	+0.16
Wind ×0.8	+4 GW	Intact	3.24%	0.650	3.38%	+0.14
Wind ×0.8	+4 GW	Line 13-16 out	2.90%	0.639	3.05%	+0.15
Wind ×0.8	+4 GW	Line 22-24 out	3.44%	0.647	3.58%	+0.14
Wind ×0.3	+0 GW	Intact	3.34%	0.647	3.39%	+0.05
Wind ×0.3	+0 GW	Line 13-16 out	3.03%	0.635	3.08%	+0.05
Wind ×0.3	+0 GW	Line 22-24 out	3.51%	0.645	3.56%	+0.05
Wind ×0.3	+2 GW	Intact	3.30%	0.646	3.35%	+0.05
Wind ×0.3	+2 GW	Line 13-16 out	3.09%	0.636	3.14%	+0.05
Wind ×0.3	+2 GW	Line 22-24 out	3.50%	0.644	3.55%	+0.05
Wind ×0.3	+4 GW	Intact	3.38%	0.647	3.43%	+0.05
Wind ×0.3	+4 GW	Line 13-16 out	3.29%	0.637	3.33%	+0.04
Wind ×0.3	+4 GW	Line 22-24 out	3.67%	0.643	3.72%	+0.05

Appendix B — data and reproducibility

All inputs, scripts and results are archived under C:\Users\steve\pf_scratch\ :

Artefact	File(s)
Matrix driver (resumable, self-healing base restore)	pen_matrix.py + matrix_phase.txt
Matrix results / spectra	pen_matrix.json · eig_M_<case>.json (72 spectra)
Experiment ladders	pen_study.py/.json (winter) · pen_summer.py/.json · pen_dc.py/.json · pen_eig_*.json
Baseline & diagnostics	ctrl_considered.json · cont_modal.json · ns_stress2.json · ns_shape.json · mode_population.py/.json
Authoritative base snapshots	dc_snapshot.json (dispatch + loads) · summer_snapshot.json (commitment)
Report generators	gen_report2–5.py (interactive HTML) · generate_docx.js (this document) · figs_png/ (10 figures)
Interactive report (all figures, shareable)	https://claude.ai/code/artifact/cf83ef52-3883-4f59-8d5d-5ad6aca9f738

Model state after the study: restored and verified against base (load 46,642 MW; generation 48,049 MW; no outages; slack 1,942 MW; L22-24 at 51.9%).