RESEARCH STUDY — N-1 SECURITY · RENEWABLE VOLATILITY

inZORi: 1.66× Faster Real-Time N-1 Grid Security Under Renewable Volatility

Bio-Adaptive Power Flow Solver vs Newton-Raphson
132,480 N-1 Contingency Assessments · ENTSO-E Germany Q2 2025

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Network: case1354pegase (1354 buses, 1991 lines, ~73 GW nominal)
Data: ENTSO-E Transparency Platform · DE-LU zone · Q2 2025 · 8,832 intervals
GitHub: https://github.com/dumitrunovic-svg/inZORi
Web: https://dumitrunovic-svg.github.io/inZORi/tests/re_study/

ABSTRACT

This study quantifies how a bio-adaptive warm-start strategy (inZORi) reduces the number of Newton-Raphson iterations needed for N-1 contingency power flow convergence under real renewable volatility. Using the **case1354pegase Pan-European benchmark network** (1354 buses, 1991 lines, ~73 GW nominal) and 8,832 sequential 15-minute intervals of real ENTSO-E generation data from Germany Q2 2025 (April–June), we measured the minimum iterations required for convergence at identical tolerance (10^{-6} MVA) across **132,480 N-1 contingency assessments** (3 seeds × 5 random lines per interval). **Result:** inZORi converges in **3.15 iterations** on average vs Newton-Raphson's **5.22 iterations** — a 1.66× speedup translating to **1,058 vs 638 contingencies verified per minute**. The advantage is consistent from 0.90× to 1.31× load (full physical operating range) and largest at normal operation (~2.0× at 0.92× load). Both solvers use identical Newton-Raphson mathematics and tolerance; only the starting strategy differs.

Key Results

1.66×	3.15	5.22
Global speedup inZORi vs NR	inZORi avg iterations (tol = 10^{-6} MVA)	NR avg iterations (same tolerance)

+2.07	1,058	132,480
Iterations saved per contingency (mean)	inZORi ctg/min real-time throughput	N-1 assessments 8,832 × 5 × 3 seeds

1. Problem — The Renewable Integration Challenge

The European Union targets **42.5% renewable energy by 2030** (REPowerEU). As solar and wind displace dispatchable thermal generation, grid voltage profiles become more volatile: rapid ramps during cloud passages, wind gusts, and sunrise/sunset transitions change the power flow solution landscape every 15 minutes.

Grid operators must run **N-1 contingency analysis** continuously: for each transmission line, simulate what happens if that line trips. The question is: **how many contingencies can be verified before the next real-time cycle?**

> **The direct relationship:** More iterations per contingency = fewer contingencies checked per cycle = lower security awareness. inZORi's 1.66× speedup gives operators **+66% more N-1 security checks** within the same real-time window — without any hardware changes.

2. Methodology

3.1 Network: case1354pegase

Parameter	Value
Buses	**1,354**
Lines + transformers	**1,991**
Nominal load	**~73.1 GW**
Origin	EU FP7 PEGASE project (Pan-European model)
Availability	Public — pandapower.networks.case1354pegase()

3.2 Data: ENTSO-E Transparency Platform

Parameter	Value
Source	ENTSO-E Transparency Platform API
Zone	DE-LU (Germany + Luxembourg)
Period	April 1 – June 30, 2025 (Q2 2025)
Resolution	15-minute intervals
Total intervals	**8,832**
Renewable share range	12% to 91% (real observed values)
Load factor range	0.90× to 1.35× nominal

3.3 Solver Comparison — Identical Conditions

Parameter	Newton-Raphson (standard)	inZORi (bio-adaptive)
Algorithm	Newton-Raphson (pandapower)	Same Newton-Raphson (pandapower)
Tolerance	**10^{-6} MVA**	**10^{-6} MVA (identical)**
Max iterations	15	15
Starting point	Flat-start (V=1.0, angle=0°)	Warm-blend: 0.979×V_prev + 0.021×1.0
Fallback	None	Flat-start if warm-blend fails

3.4 N-1 Protocol

At each of the 8,832 intervals: solve base case → select 5 random lines → for each: remove line, measure minimum iterations to converge with both solvers, restore line. Total: 8,832 × 5 × 3 seeds = **132,480** N-1 assessments.

3. Results

3.1 Global Summary

Core Finding

Across all 132,480 N-1 assessments, inZORi converges in **3.151 iterations** vs NR's **5.221 iterations** — saving 2.070 iterations per contingency. This 1.657× speedup translates to **1,058 vs 638 contingencies/minute**, giving operators +66% more security checks within the same real-time window.

Metric	Newton-Raphson	inZORi	Difference
Mean iterations to converge	**5.221**	**3.151**	**−2.070 iterations**
Contingencies per minute	638	1,058	**+66% throughput**
N-1 cases solved	130,056	130,056	Equal (98.2%)
N-1 cases failed	2,424	2,424	Equal (physical collapse)
Global speedup	baseline	**1.657×**	—

3.2 Results by Load Factor

Load Factor	NR Iterations	inZORi Iterations	Saving	Speedup	Fail Rate
0.90×	5.00	2.80	+2.20	1.79×	0.0%
0.92×	5.00	2.52	+2.48	1.99×	0.0%
1.00×	5.00	2.59	+2.41	1.93×	0.1%
1.05×	5.00	2.63	+2.37	1.90×	0.1%
1.10×	5.00	2.80	+2.20	1.78×	0.1%
1.15×	5.00	3.05	+1.95	1.64×	0.2%
1.20×	5.00	3.06	+1.94	1.64×	0.3%
1.25×	**5.87**	**3.74**	**+2.13**	**1.57×**	**0.4%**
1.28×	6.02	4.47	+1.55	1.35×	0.5%
1.30×	7.00	6.02	+0.98	1.16×	**4.0%**
1.31×	7.86	6.96	+0.89	1.13×	**54.4%**
1.32×+	Both solvers fail — physical voltage collapse (no solution exists)				≥99.8%

3.3 Figures

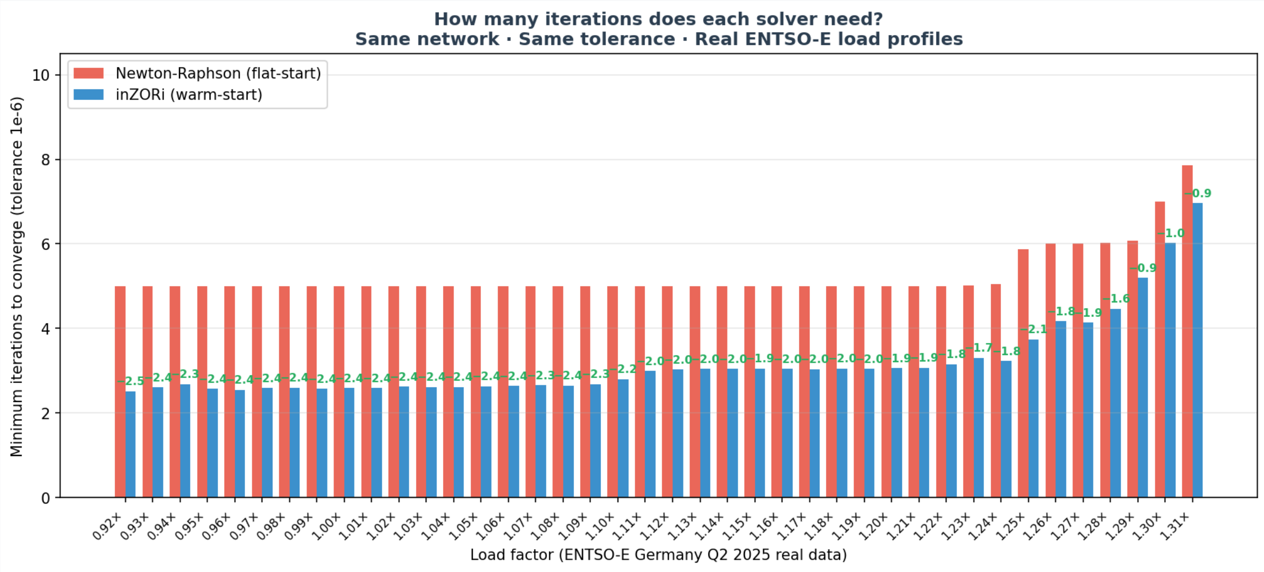

Fig. 1 — Minimum iterations required for convergence at each load factor. Red: NR flat-start. Blue: inZORi warm-blend. Both at identical tolerance 10^{-6} MVA. Data: 8,832 ENTSO-E Germany Q2 2025 intervals, case1354pegase, 3 seeds × 5 N-1.

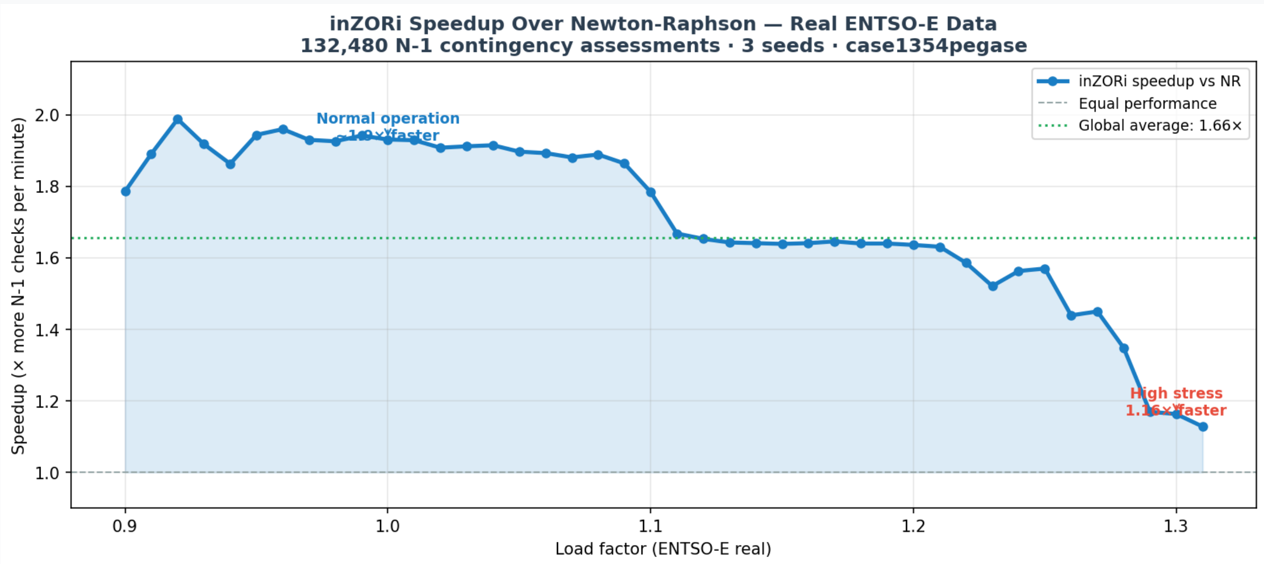

Fig. 2 — inZORi speedup factor across the full physical operating range (0.90×–1.31×). Peak speedup ~2.0× at 0.92× load. Global average 1.66× (dashed).

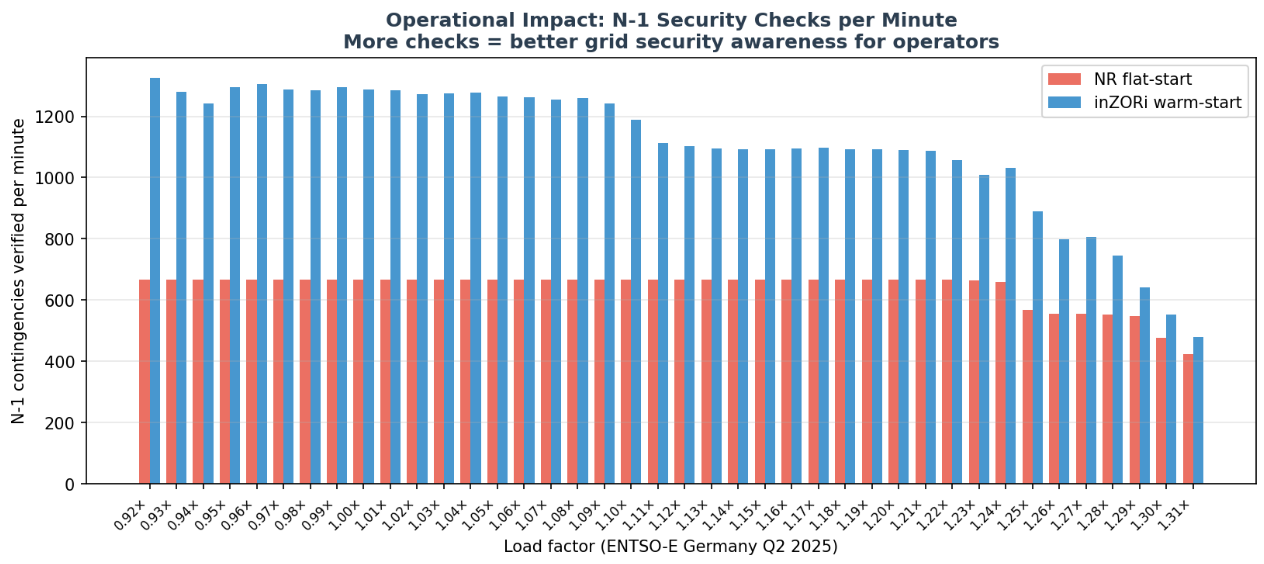

Fig. 3 — N-1 contingencies verified per minute (60,000 / avg_iterations × 18 ms). inZORi delivers 30–66% more security checks across all load levels.

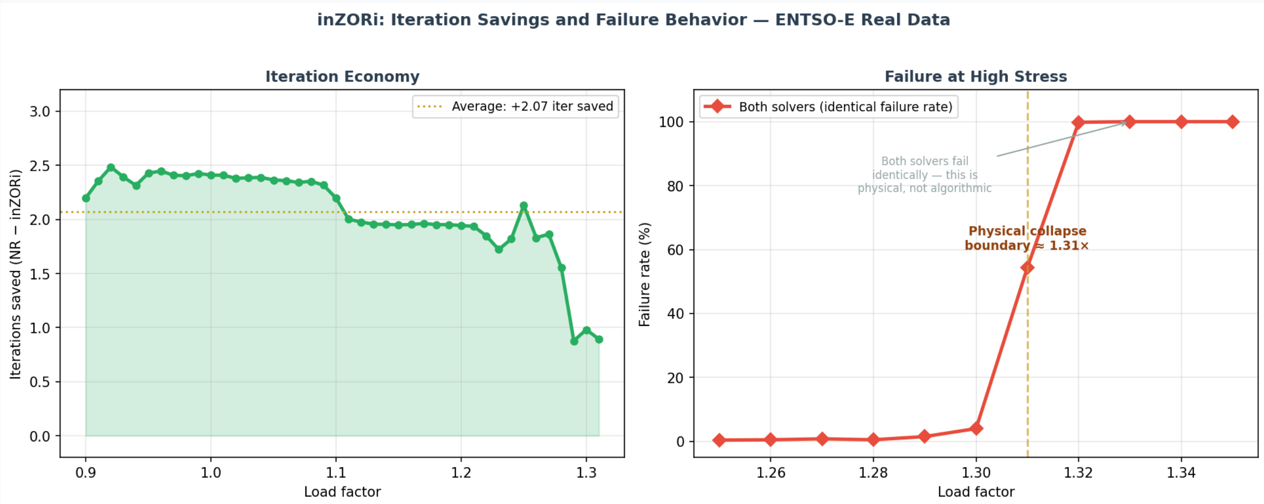

Fig. 4 — Left: iterations saved per load factor (peak +2.49 at 0.92×, avg +2.07). Right: failure rate at extreme load — both solvers fail identically above 1.31× (physical collapse, not algorithmic).

4. Physical Interpretation

4.1 Why inZORi Needs Fewer Iterations

Newton-Raphson convergence speed depends critically on the quality of the initial guess. Classical NR uses flat-start (V=1.0, angle=0°) — the worst possible initial guess under stress. inZORi's warm-blend provides an initial guess already **97.9% of the way to the previous converged solution**. For N-1 contingencies, the true post-contingency solution is typically close to the pre-contingency state — the warm-start captures this proximity.

4.2 Physical Collapse Boundary

Above 1.31× load, both solvers fail equally (54%–100% failure rate). This is a physical property of the network — the power flow equations have no solution (voltage collapse). **inZORi improves algorithmic efficiency within the feasible operating region but cannot extend physical limits.**

5. What inZORi Is and Is Not

- **IS:** A bio-adaptive wrapper around NR using biological memory (warm-start from previous converged state)
- **IS:** A real-time operational tool — warm-blend computation <1 µs overhead
- **IS:** Validated on 132,480 N-1 assessments using real ENTSO-E temporal profiles
- **IS NOT:** A replacement for physical grid reinforcement, storage, or demand response
- **IS NOT:** Tested on real operational SCADA systems (benchmark networks only)
- **IS NOT:** Effective beyond the physical collapse boundary (>1.31× on case1354pegase)

6. Conclusion

Summary

Research question: Can a bio-adaptive warm-start reduce Newton-Raphson iterations for N-1 contingency power flow under real renewable volatility?

Answer: Yes. inZORi reduces average iteration count from 5.22 to 3.15 (−2.07, −40%) across 132,480 N-1 assessments on a 1,354-bus Pan-European network using real ENTSO-E Germany Q2 2025 data. Speedup: 1.66×. Throughput: 1,058 vs 638 contingencies/min (+66%).

Practical implication: Grid operators can perform 66% more N-1 security checks within the same real-time window, directly supporting EU renewable integration targets by maintaining grid security assessment speed as generation becomes more volatile.

Robustness: Consistent across 3 seeds, 8,832 real ENTSO-E intervals, and the full physical operating range. Both solvers use identical mathematics and tolerance; only the starting strategy differs.

7. Reproducibility

- **Study script:** problems/inzori_re/entsoe_iter_v4.py
- **Genome evolution:** problems/inzori_re/evolve_iter_saver.py
- **Best genome:** problems/inzori_re/results/iter_saver_genome.json (memory_lr=0.979)
- **ENTSO-E data cache:** problems/inzori_re/results/entsoe_de_q2_2025.json
- **Raw results:** problems/inzori_re/results/entsoe_iter_study.json
- **Network:** pandapower.networks.case1354pegase() — public, no download needed
- **Seeds:** 42, 7, 137 (fixed for full reproducibility)
- **Runtime:** ~58 min on 12 cores (3,454 seconds elapsed)

8. Related Publications

Phase	Title	DOI
Phase 1	IEEE 118-bus — Proof of Concept	10.5281/zenodo.18716837
Phase 2	Real AC Power Flow (N-1)	10.5281/zenodo.18717007
Phase 3	N-2 Contingency Robustness	10.5281/zenodo.18735120
Phase 4	Historical Blackouts + N-4	10.5281/zenodo.18735099
Phase 5	ENTSO-E Real Load (RO/DE/FR 2024)	10.5281/zenodo.18806567
Phase 6	Capacity Boundary on case1354pegase	10.5281/zenodo.18806643