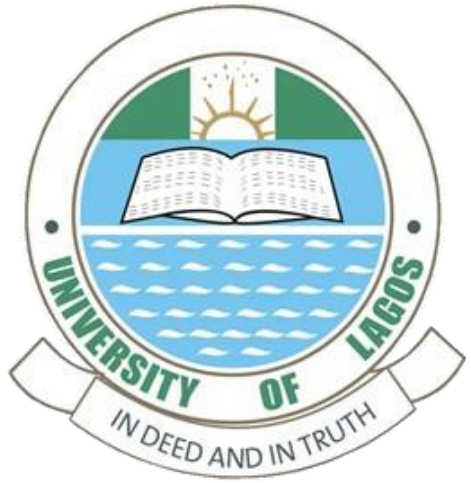
OPTIMISED ADAPTIVE PROTECTION COORDINATION OF A CAMPUS RING NETWORK USING STANDARD OVERCURRENT RELAYS

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116 Grid Collapses Leave UNILAG Reliant on Backup Power and Fixed, Non-Directional Relay Settings

Why It Matters

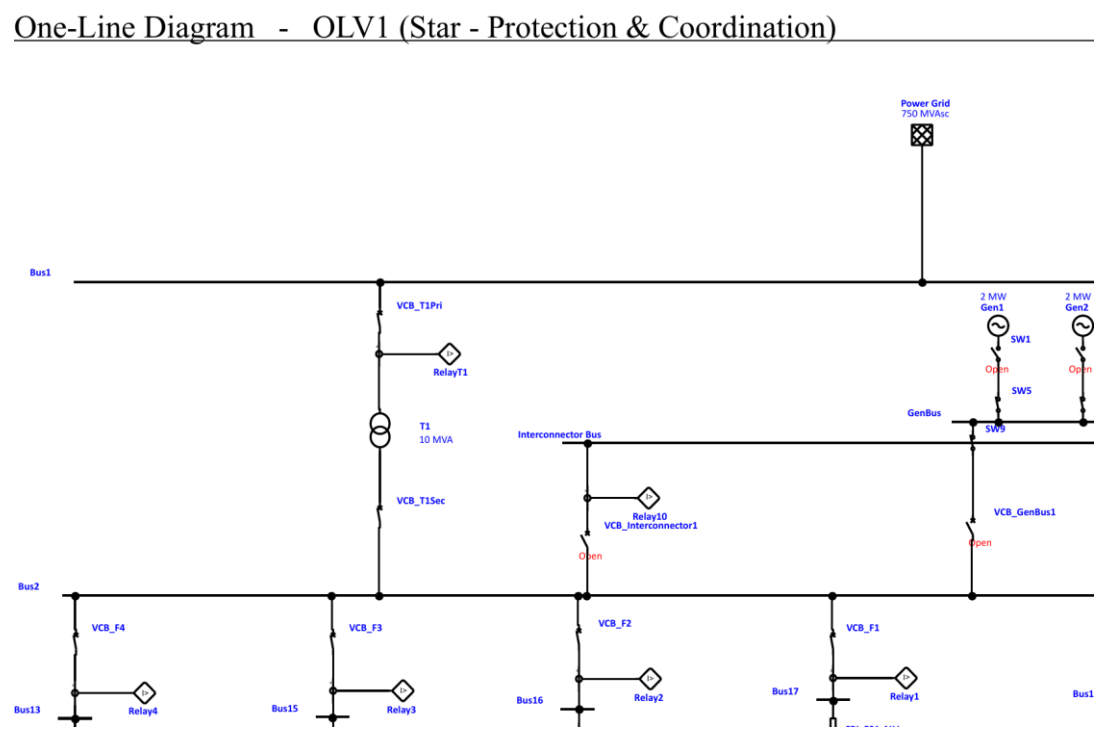
- **116 national grid collapses** between 2015 and 2026.
- Outages drain an estimated **5% to 7% of GDP** every year.
- The campus leans on **diesel backup**; solar is under consideration.
- **13 standard relays** protect the 11 kV ring; none is directional.

What Existing Work Leaves Open

- Metaheuristics solve relay coordination well (Gupta & Deep, 2020; Sadeghi et al., 2024).
- Adaptive protection is studied for microgrids, multi-DG and networked systems (Kumari & Naick, 2024; Okelola et al., 2025; Kim et al., 2023).
- The usual fix, directional relays, needs substantial capital.

THE GAP: no paper found handles grid-connected, tie-closed and islanded operation simultaneously for a real campus ring with existing non-directional relays and a fuse-selectivity time floor.

Island Mode Cuts Fault Current by About 45% Across Three Operating Topologies of the 11 kV Ring



1 **Grid-Connected**

33 kV utility supply, bus-tie open.

2 **Tie-Closed**

Relay10 joins the fault path: a three-relay chain.

3 **Islanded**

Diesel generators feed six feeders; fault current falls 44.6% (14,028 A to 7,770 A).

AIM: select scenario-specific Time Dial Settings for the existing non-directional relays in software, so faults are isolated selectively in every mode without replacing hardware.

Site Audits of 56 Transformers and Python OSRM Routing Built the Campus Network Model

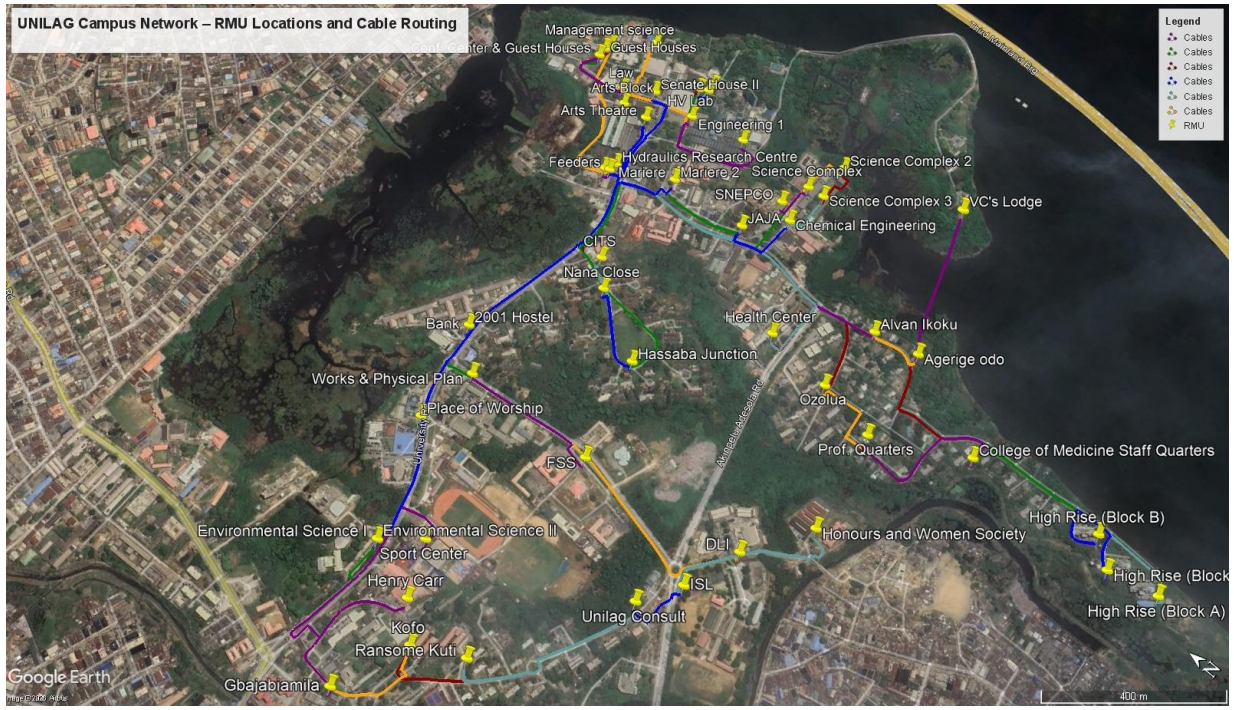


Figure 1. RMU locations and feeder cable routing.

56
distribution transformers

39,520
kVA installed

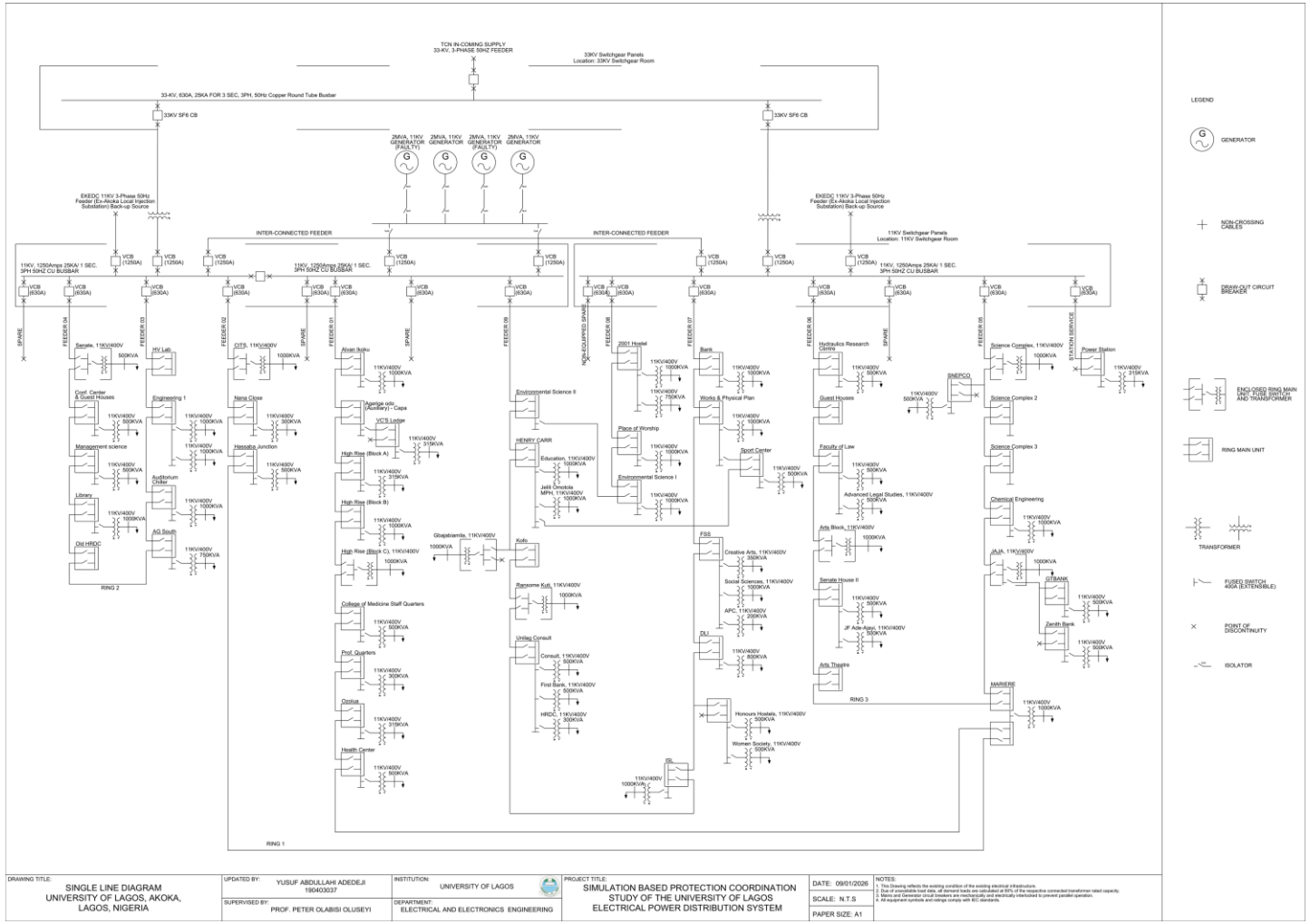
13
overcurrent relays

Five-Step Workflow

1. **Audit:** equipment specifications and datasheets from the campus service area.
2. **Allocate:** loads via IEC utilisation and simultaneity factors.
3. **Route:** Google Earth, Python, OSRM and Haversine distances.
4. **Model and Simulation:** ETAP for load-flow and short-circuit studies which serves as data for training the Metaheuristics.
5. **Validate:** ETAP Star time-current curves.

Cable heuristic: $D_{real} = 1.02 \times D_{computed} + 8$ m, used to compute realistic cable impedances.

The AutoCAD Single-Line Diagram Reconciles 10 Feeder Relays, Split 11 kV Busbars and Backup Generation



- **Redrawn in AutoCAD** from site audits and reconciled with nameplates.
- **10 feeder relays** (Relay1 to 9, RelayFService), 2 incomers and the Relay10 interconnector.
- **4 × 2 MVA**, 11 kV generators on the generation bus.
- Split 11 kV busbars joined by the **interconnected feeder**.

Baseline Incomers Are Set Faster (TDS 0.06) Than Feeders (0.10), and Island Faults Cut Current by 45%

Relay	CT Primary (A)	I_pickup (A)	Baseline TDS	I_f Grid (A)	I_f Tie (A)	I_f Island (A)
RelayT1	400	320	0.06	15,046	15,046	0 (inactive)
RelayT2	400	320	0.06	15,046	15,046	0 (inactive)
Relay10	600	300	0.10	0 (inactive)	15,046	**7,885**
Relay4	200	100	0.10	14,028	14,028	**7,770**
Relay3	200	100	0.10	13,232	13,232	0 (inactive)
Relay2	200	100	0.10	14,012	14,012	**7,766**
Relay1	200	100	0.10	12,763	12,763	**7,371**
Relay9	200	100	0.10	11,979	11,979	0 (inactive)
Relay8	200	100	0.10	13,253	13,253	**7,529**
Relay7	200	100	0.10	13,253	13,253	**7,529**
Relay6	200	100	0.10	14,922	14,922	0 (inactive)
Relay5	200	100	0.10	13,156	13,156	0 (inactive)
RelayFService	200	100	0.10	14,977	14,977	**8,050**

Blue: island-mode fault current, about 45% lower (e.g. Relay4: 14,028 A to 7,770 A).

Coordination Is Posed as Minimising Relay Time Across 13 Relays Under 29 Safety Constraints

Equations

$$t_i = \mathrm{TDS}_i \times \left(\frac{0.14}{(PSM_i)^{0.02} - 1} \right)$$

Eq. 2: Normal Inverse, TDS is the only variable

$$\min \; PI_{S_k}(x) = \sum_{i \in R(S_k)} t_i$$

Eq. 3: sum of active relay times

$$F_s(x) = PI_s(x) + \lambda \sum_{n \in C_s} \max(0, -g_n(x))$$

Eq. 6: penalised fitness

29 Constraints

19 CTI pairs: backup minus primary ≥ 0.3 s.

10 fuse floors: t ≥ 0.16 s keeps selectivity with RMU fuses (0.01 s pre-arcing + 0.15 s margin).

Bounds: 0.05 ≤ TDS ≤ 1.00.

GWO

Standard variant; leaders α, β, δ guide the pack. 300 iterations, λ = 100,000.

ARO

Enhanced: opposition-based start, Levy flight, restart of worst 70% after 25 stalls. 300 iterations, λ = 10,000.

SMA

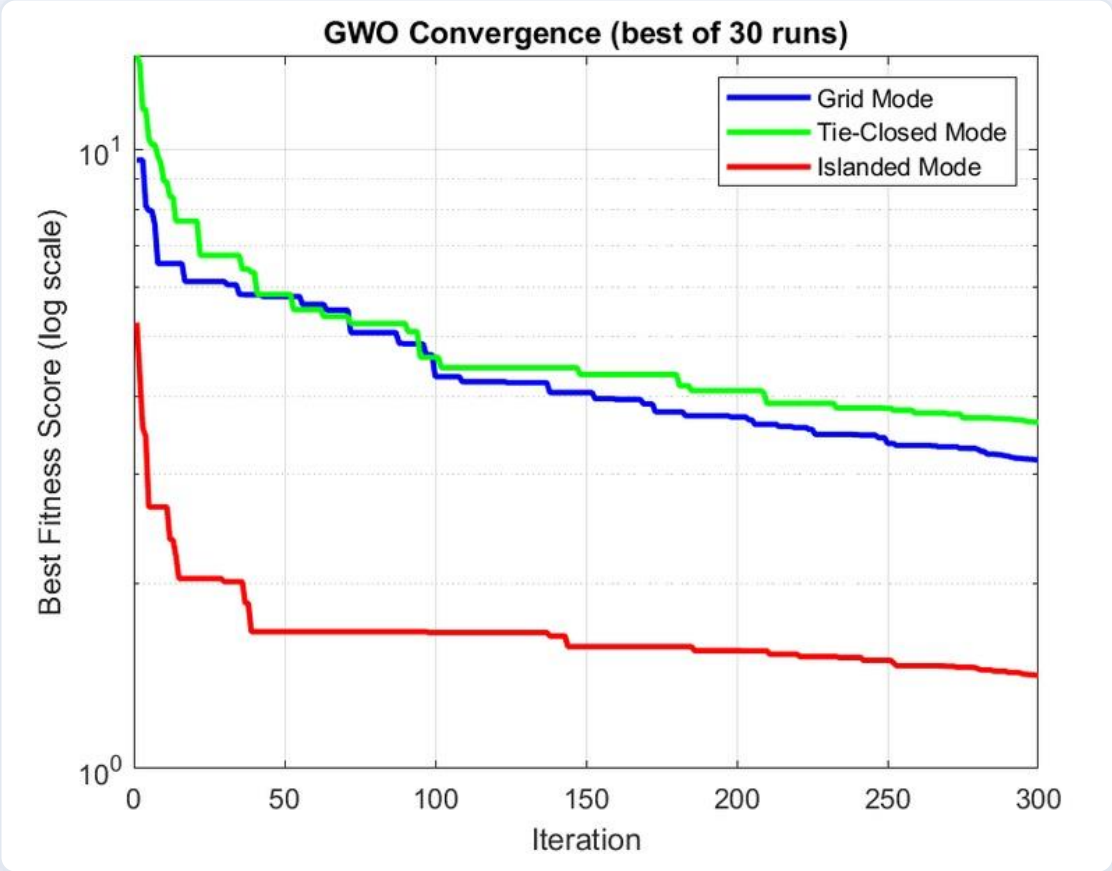
Enhanced: same three, restart after 10 stalls, damped amplitude. 500 iterations, λ = 10,000.

GWO Is the Most Consistent (Std Dev 0.0339 s) and Lands Within About 3% of the Exact Optimum

Algorithm	Scenario	Best (s)	Mean (s)	Std Dev (s)	Worst (s)
GWO	Grid	3.1634	3.2131	0.0339	3.2812
GWO	Tie-Closed	3.6383	3.6902	0.0361	3.7812
GWO	Islanded	1.4216	1.4233	0.0010	1.4258
ARO	Grid	3.1403	3.6351	0.3778	4.4089
ARO	Tie-Closed	3.5979	3.9729	0.3202	4.5200
ARO	Islanded	1.4211	1.4212	0.0003	1.4227
SMA	Grid	3.3531	3.5844	0.1242	3.7995
SMA	Tie-Closed	3.7035	4.1035	0.1544	4.4654
SMA	Islanded	1.4212	1.4231	0.0017	1.4264

Exact linear-programming optimum: GWO mean PI is about 3% above it in Grid and Tie-Closed, against 11% to 16% for ARO and SMA. All runs were 100% CTI-feasible.

GWO Converges in Two Phases and Lands on Nearly the Same Solution in Every One of 30 Runs



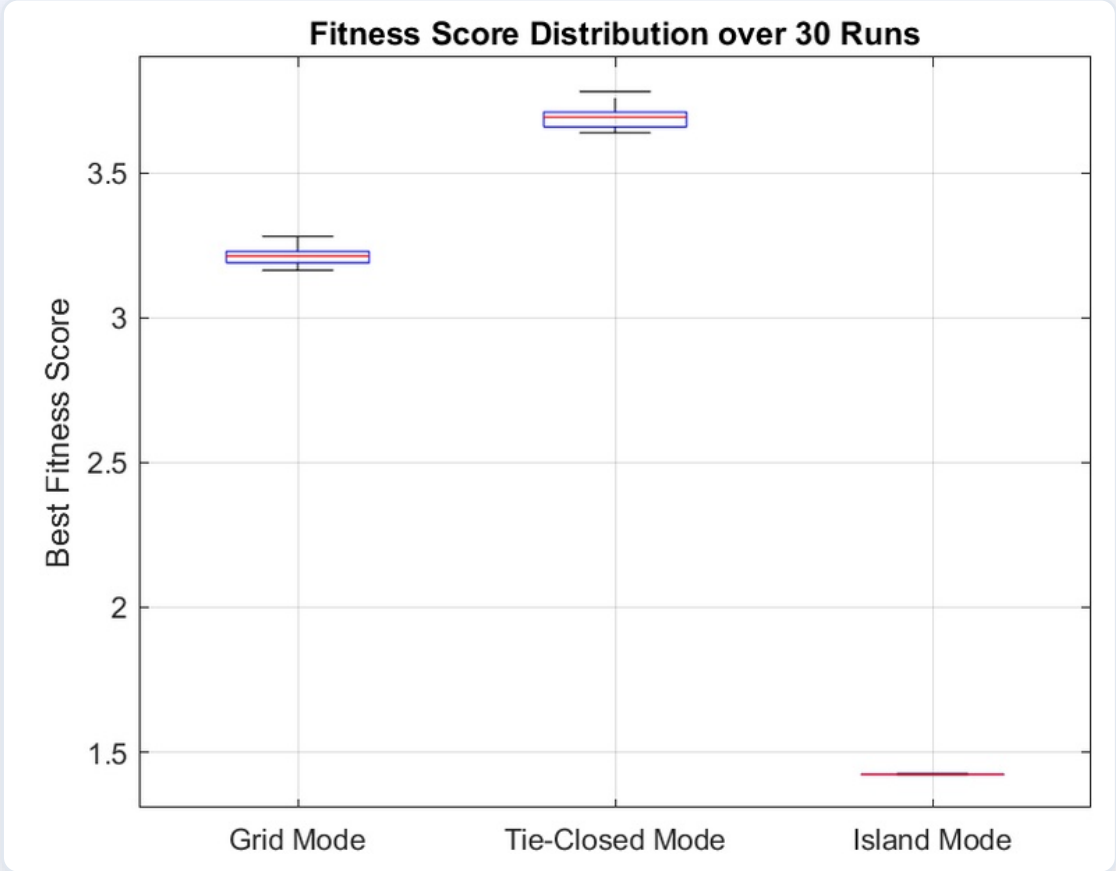
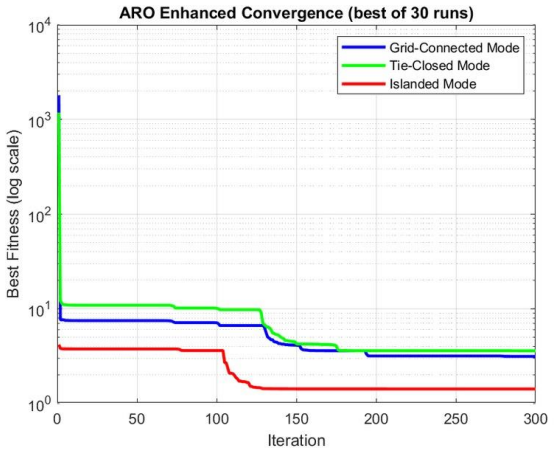
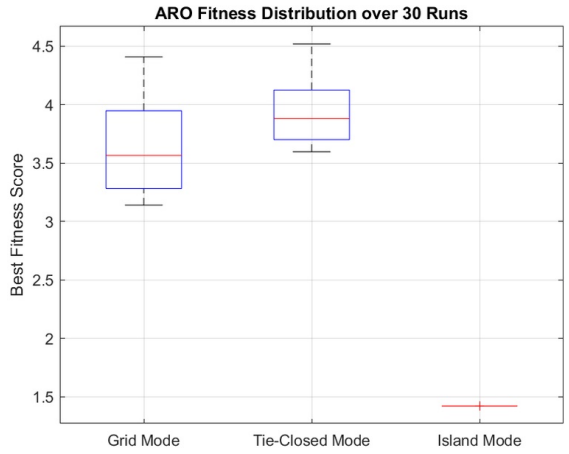


Figure 3: a steep drop in the first 20 to 50 iterations, then slow refinement; Std Dev 0.0339 s in Grid mode.

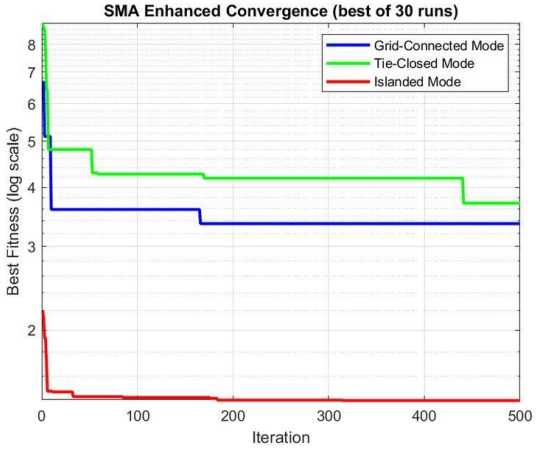
ARO and SMA Enhancements Trade Consistency for Restart Jumps and Incomplete Convergence

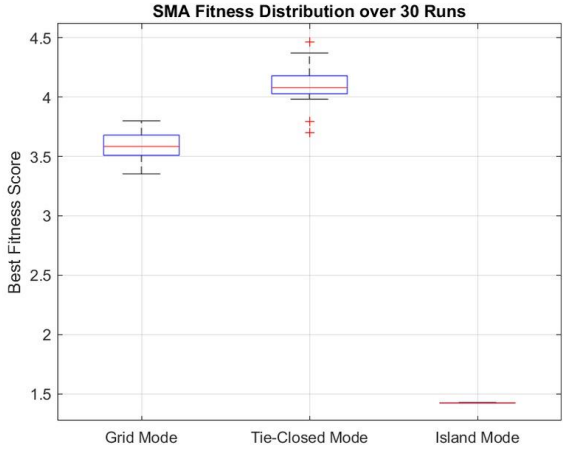




ARO (Figure 4)

Restart events cause sharp drops that sometimes find a better basin: lowest best Grid PI (3.1403 s) but the widest spread (Std Dev 0.3778 s, worst 4.4089 s).





SMA (Figure 5)

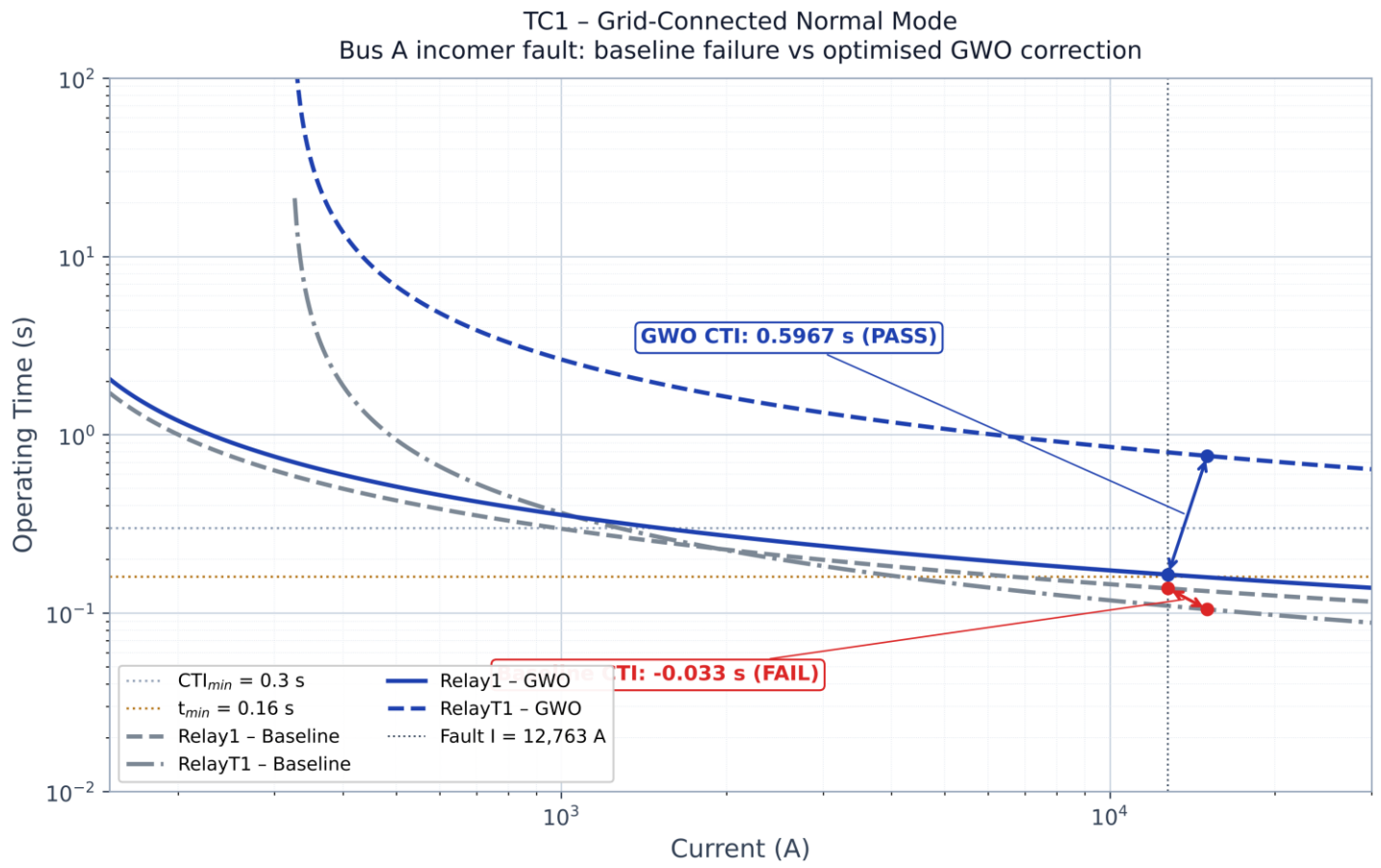
Smooth descent to a higher final value (best Grid 3.3531 s). That best run is not fully converged (RelayFService 0.1682 vs about 0.12). Std Dev 0.1242 s.

Adaptive Setting Groups Raise Incomers to About 0.435 and Step Island Feeders Down to About 0.104

Relay	GWO Grid	GWO Tie	GWO Island	ARO Grid	ARO Tie	ARO Island	SMA Grid	SMA Tie	SMA Island
RelayT1	**0.4352**	**0.4355**	N/A	0.4351	0.4349	N/A	0.4872	0.4869	N/A
RelayT2	**0.4352**	**0.4352**	N/A	0.4363	0.4351	N/A	0.4781	0.4379	N/A
Relay10	N/A	0.2681	0.2222	N/A	0.2679	0.2221	N/A	0.2699	0.2221
Relay4	0.1191	0.1190	0.1040	0.1192	0.1190	0.1041	0.1189	0.1189	0.1041
Relay3	0.1185	0.1250	N/A	0.1203	0.1174	N/A	0.1174	0.1174	N/A
Relay2	0.1229	0.1204	0.1042	0.1195	0.1233	0.1040	0.1189	0.1189	0.1040
Relay1	0.1196	0.1196	0.1027	0.1165	0.1188	0.1027	0.1165	0.1165	0.1027
Relay9	0.1185	0.1154	N/A	0.1151	0.1161	N/A	0.1149	0.1296	N/A
Relay8	0.1218	0.1196	0.1033	0.1175	0.1175	0.1033	0.1175	0.1175	0.1033
Relay7	0.1240	0.1244	0.1034	0.1206	0.1175	0.1033	0.1175	0.1175	0.1033
Relay6	0.1208	0.1210	N/A	0.1220	0.1206	N/A	0.1205	0.1205	N/A
Relay5	0.1205	0.1265	N/A	0.1189	0.1185	N/A	0.1173	0.1173	N/A
RelayFService	0.1233	0.1281	0.1049	0.1212	0.1218	0.1049	0.1682	0.1205	0.1049

Shaded columns are the GWO setting groups: Grid, Tie-Closed and Island. N/A = relay inactive in that scenario.

TC1: GWO Removes the -33 ms Incomer Inversion and Restores a 0.5967 s Margin

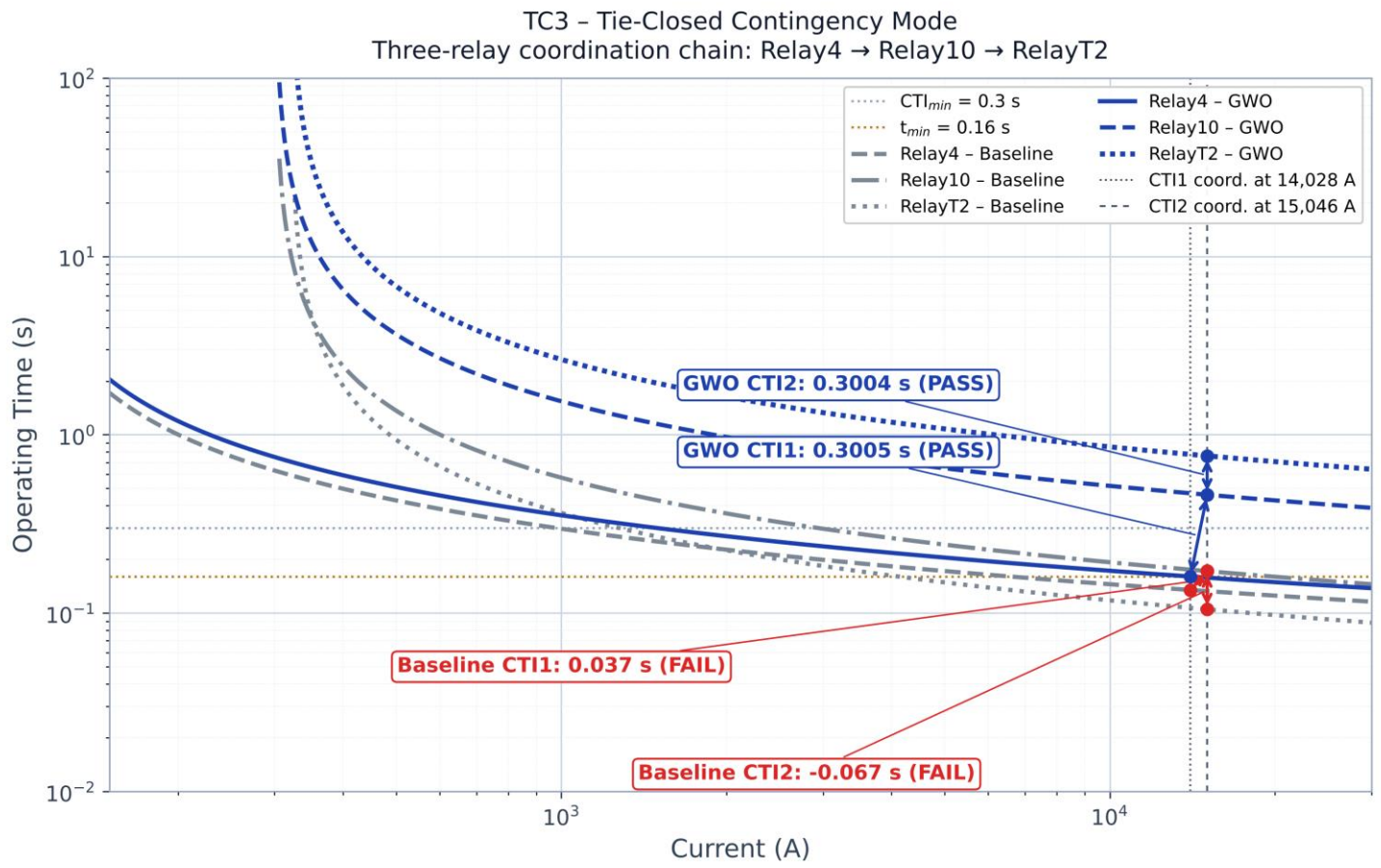


Scenario: Bolted fault at the Bus A incomer busbar: 12,763 A at Relay1, 15,046 A at RelayT1.

Baseline FAILS (-0.033 s). RelayT1 operates 33 ms before Relay1.

GWO PASSES (0.5967 s). TDS 0.4352 and 0.1196; above 0.3 s owing to the tie boundary pairs.

TC3: GWO Restores Both Margins of the Three-Relay Tie-Closed Chain to About 0.3 s

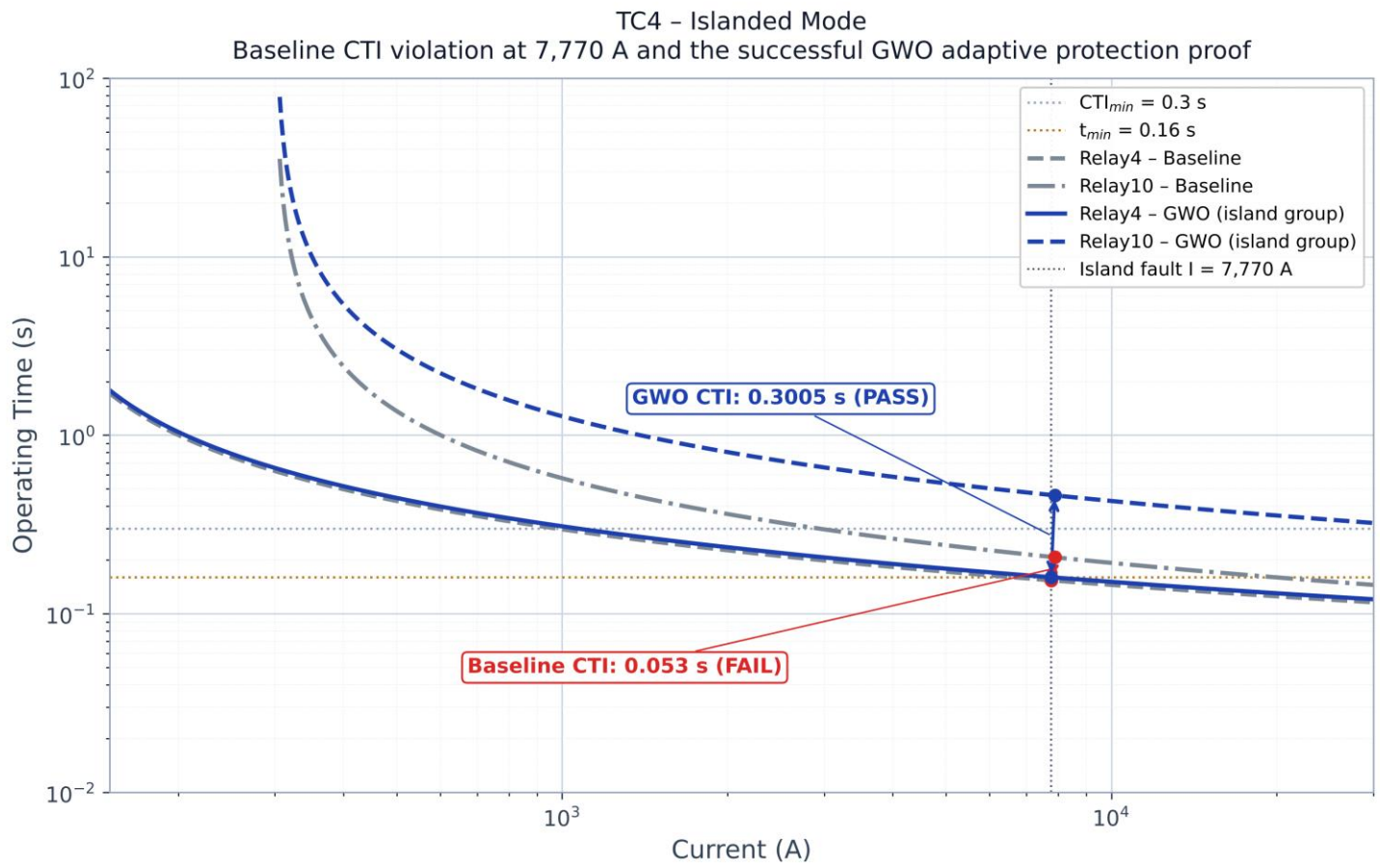


Scenario: Fault at the Relay4 feeder bus with the tie closed: Relay4, Relay10, then RelayT2.

Baseline FAILS twice.
CTI1 = 0.037 s and
CTI2 = −0.067 s.

GWO PASSES both.
CTI1 = 0.3005 s and
CTI2 = 0.3004 s, essentially on the 0.3 s boundary.

TC4: The Island-Mode Setting Group Restores a 0.3005 s Margin After the 45% Current Drop



Scenario: Relay4 fault in island mode: fault current falls to 7,770 A, a 44.6% reduction from Scenario 1.

Baseline FAILS (0.053 s). The fixed margin collapses.

GWO PASSES (0.3005 s). The island-mode setting group restores the margin.

Switching Settings Groups on Existing Relays Avoids a $21,450 Directional-Relay Upgrade

Cost-Benefit

Hardware: about $1,650 per SEL-751, so $21,450 for 13 relays, excluding PTs, communication links and panel work.

Software: reuses relays, CTs and switchgear; cost is the model and settings loading. Needs relays with multiple setting groups.



Conclusions

Baseline fails: inversion of -0.033 s on grid faults; short of margin in tie-closed and island modes.

All three algorithms restore at least 0.3 s in every scenario.

GWO: most consistent, about 3% above optimum. ARO: lowest best run, higher variance.

Next Steps

Reinforcement learning: improve the scheme with RL, planned for a follow-up paper.

Repeat the study whenever the network changes.

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