Active Virtual Microgrid Forming (AVMGF) for Transmission–Distribution–Microgrid Coordination under High PV Penetration

A Computational Discovery Framework for High-Penetration Distribution Networks

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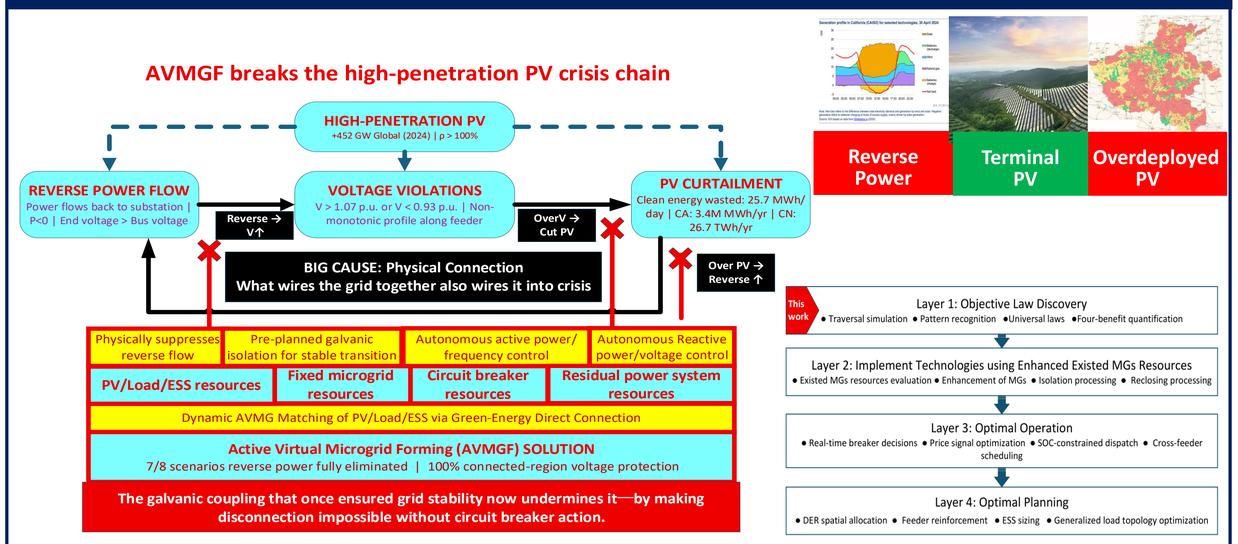
Introduction

High-penetration distribution networks face three interrelated challenges: reverse power flow, voltage violations, and renewable curtailment. We propose Active Virtual Microgrid Forming (AVMGF), leveraging existing fixed microgrids and distribution breakers with system-wide forecasts to dynamically form planned islands and later resynchronize with the host grid. A transmission–distribution–microgrid (T-D-M) benchmark is constructed; a systematic study is conducted in four phases: exhaustive simulation, enhanced control, optimized operation, and optimized planning; this poster focuses on the first phase. Across 768 time points (8 scenarios × 96 points), AVMGF suppresses reverse flow via pre-planned isolation. Formed islands achieve autonomous power balancing and voltage regulation, alleviating host-grid stress. Green Electricity Direct Connection (GEDC) achieves 40–43% additional curtailment reduction. Four findings: (1) reverse flow eliminated in 7/8 scenarios, 92.8% reduction in extreme cases; (2) connected-region voltage violations fully eliminated (100%), risk transferred within AVMGs; (3) end-zone breakers show highest activation (21.7%–27.1%), validating the near-and-far-off principle; (4) only soft automation and PV curtailment costs are incurred. Under extreme holiday conditions (high PV, low load), daily curtailment is 25.7 MWh—an acceptable trade-off for eliminating reverse flow and voltage violations. All scenarios pass thermal verification; weather-fluctuation analysis confirms robustness. Extending AVMGF into control, operation, and planning provides a novel paradigm for high-penetration networks and T-D-M coordination.

Initiation of the Study



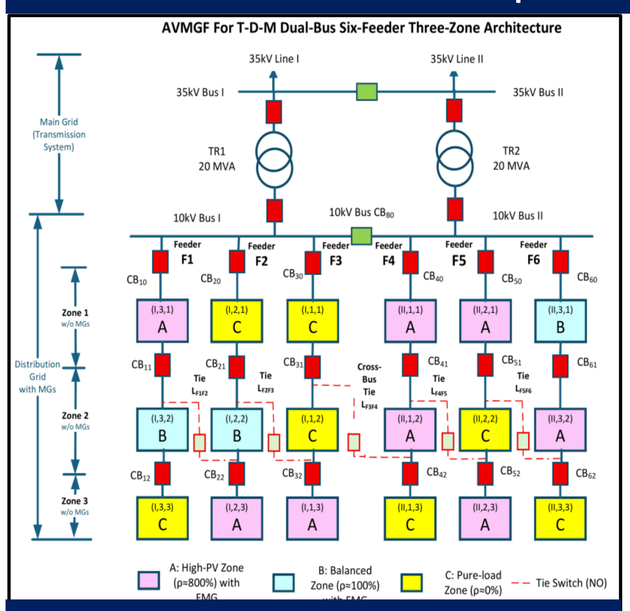
Reverse Power Flow & Oscillations & Voltage Violations

- Holiday Paradox: RES surplus occurs worldwide.
- Spain–Portugal blackout, April 28, 2025 — 15 GW lost in 5 seconds due to inverter-based resource oscillations.
- CAISO “duck curve” deepens annually; net-load drops >13 GW at noon peak hours.

Renewable Curtailment

- 2024 **China** PV curtailed 26.7 TWh (3.2%), some provinces with rates of 7%–31%.
- **CAISO curtailed** 3.4 million MWh of utility-scale wind and solar in 2024 (93% solar), up 29% year-over-year—U.S. EIA, May 2025.

A Minimum-Complete Benchmark T-D-M System

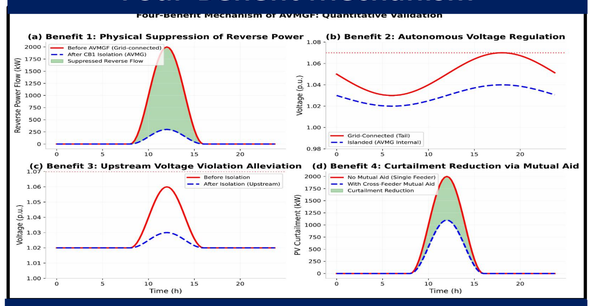


- Dual 35 kV / 10 kV substation; two **20 MVA** transformers (TR1, TR2)
- **6 radial feeders** (F1–F6), each with **3 zones**, separated by **2 sectionalizing CBs**
- **5 tie switches** including cross-bus tie **L_F3F4**
- Three generalized load modules:
  - **A**: High-PV zone (ρ ≈ 800%)
  - **B**: Balanced zone (ρ ≈ 100%)
  - **C**: Pure-load zone (ρ = 0%)
- **Thermal Stability**: All 48 feeder-scenario combinations pass Grade A–C. No Grade D.
- **F2 under S4: 445 A vs. 454 A limit → LGJ-240 upgrade justified.**
- **Weather Resilience Index (WRI)**:
  - Partly cloudy**: WRI = 0.94**
  - Clear sky: **WRI = 0.99**
- **15-minute persistence window** filters transient cloud-induced false triggers.

What is AVMGF?

- Extension of islanding from emergency restoration to normal operating conditions.
- Leverages existing sectionalizing circuit breakers (already installed on every feeder) as reconfigurable control actuators.
- Leverages existing single or multiple fixed microgrids and other locally connected resources as cores for autonomous control and operation.
- Creates galvanically isolated microgrids with boundaries computed in real time from predictive state signals (voltage / reverse power / SOC).
- Pre-balancing before breaker opening → zero transient shock.

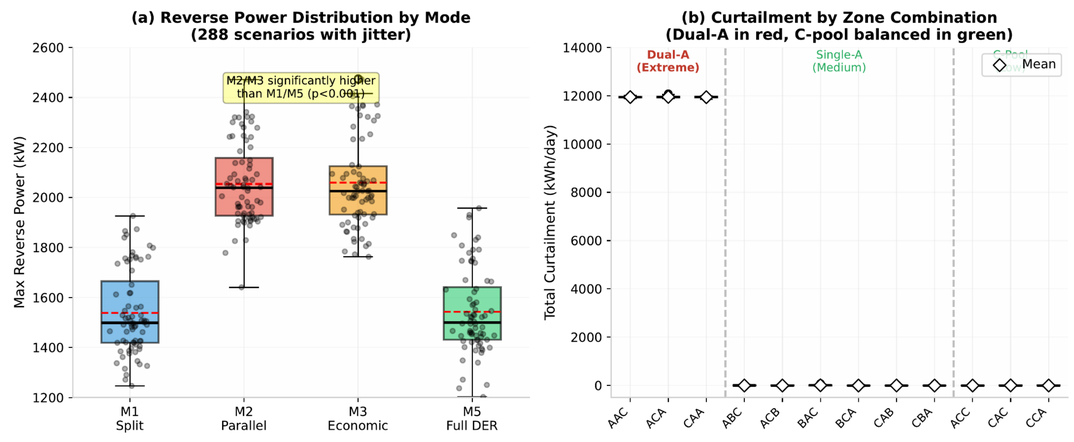
Four-Benefit Mechanism



Deterministic Six-Level Decision-Making Mechanism

L1: DER Regulation (PV curtailment + ESS charging)
L2: Sectionalizing CB Isolation (open the highest-risk zone CB)
L3: Intra-Bus Feeder Interconnection
L4: Cross-Bus Interconnection (transfer ≤ 5 MW)
L5: Bus Islanding (open CB0)
L6: Full Station Islanding (mega-AVMG)

Statistical Operation Modes of Substation in T-D-M

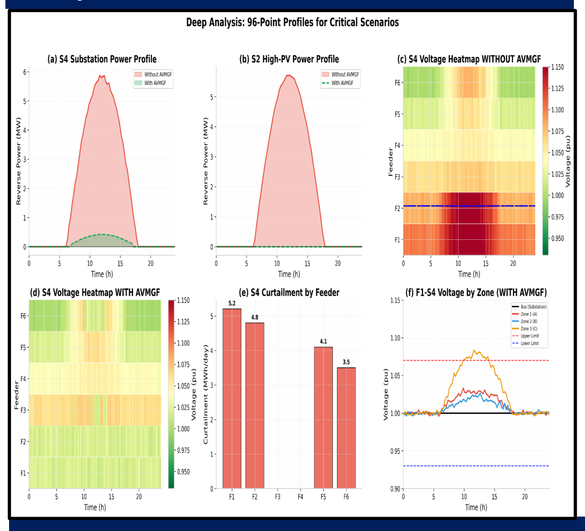


Statistical validation:8 typical scenarios × 96 time points

- **7/8** scenarios → reverse power **fully eliminated**
- **92.8%** → max reverse power cut (S4: **11.12 MW → 796 kW**)
- **100%** → voltage violations eliminated in **connected regions**
- **21.7%–27.1%** → L3 (end-zone) breaker activation frequency



W/O AVMGF for Critical Scenarios

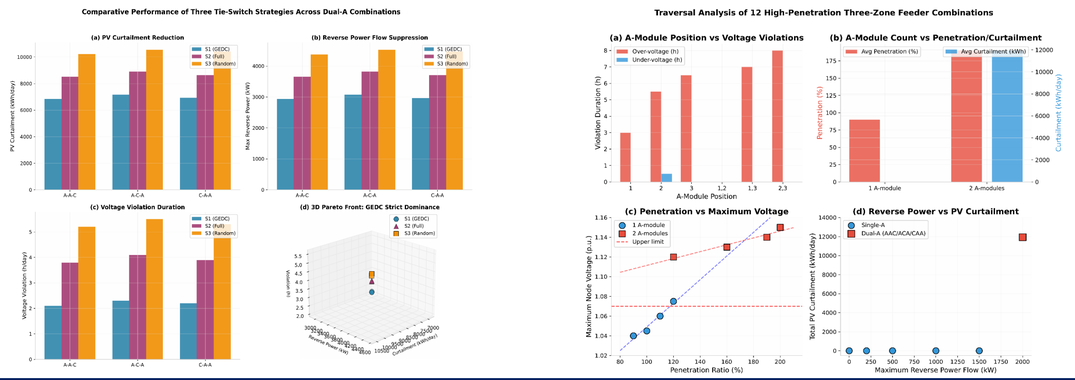


Statistical Analyses w/o AVMGF



Emergent Laws & Green Energy Direct Connection

- **A-Position Law**: A at feeder head → sharp voltage rise; A at tail → localized rise.
- **A-Count Law**: Dual-A combinations generate **11,943 kWh/day** unavoidable curtailment without AVMGF.
- **Penetration–Voltage Linear Law**: slope **2.5×10^{-4} p.u.** per percent penetration.
- **GEDC**: Connect high-PV zone (A) to nearest pure-load zone (C) via tie switch.



Conclusion

① AVMGF transforms existing protection assets into real-time topological control actuators with **near-zero hard investment**.
② Exhaustive traversal of **8 typical scenarios × 96 time points** proves physical suppression of reverse power and **100%** connected-region voltage protection.
③ GEDC cross-feeder strategy achieves **40–43% additional curtailment reduction** with strict Pareto dominance.
④ Four-phase roadmap: **Law Discovery → Enhanced Control → Optimal Operation → Optimal Planning**.

Comparison with other forms of Microgrids/VPPs

Feature	FMG/NMG	VMG/VPP	AVMGF
Boundary	Fixed	Logical only	**Dynamic + Galvanic**
Trigger	Fault	Economic	**Predictive state**
Isolation	Yes/Limited	No	**Physical suppression**
Investment	High/Medium	Low	**Near-zero (soft)**

Comparison with other forms of Microgrids/VPPs

Dimension	DMGF	AVMGF
Core philosophy	Dynamic boundary expansion/contraction	Inherited + galvanic isolation
Trigger event	Fault / outage (reactive)	Predictive state signal (proactive)
Operating condition	Emergency restoration only	Normal operation
Pre-balancing	Impossible (sudden fault)	Enabled (minutes–hours ahead)
Islanding nature	Unplanned, with transient shock	Intentional, zero transient shock
Primary objective	Resilience, black-start, recovery	Reverse power, voltage, curtailment

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