Unified Tensor Systems

Regime-Aware Spectral Acceleration of Nonlinear Stability Analysis

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57,946× faster than RK4 time-domain integration

IEEE 39-bus New England System — <2.73% deviation from reference — Patent Pending

The Problem

Modern power systems rely on time-domain integration for stability assessment. Critical clearing time (CCT) estimation — determining the maximum fault duration before a generator loses synchronism — is the central bottleneck in N-1 contingency screening.

A 500-bus system with 50 generators and 500 contingencies requires **25,000 CCT computations.** The standard RK4 binary-search method demands approximately 13 iterations×3,000 steps×4 evaluations = 156,000 ODE evaluations per CCT. At 0.1 ms per evaluation, a full N-1 screen takes **over four hours.**

Real-time contingency analysis, energy market operation, and remedial action schemes all require orders-of-magnitude improvement.

The Breakthrough

We replace brute-force time integration with a **spectral regime classification pipeline:**

1. Linearize local dynamics via Modified Nodal Analysis (MNA)
2. Construct a Koopman operator approximation (EDMD)
3. Identify *locally commutative* (LCA) stability regions
4. Detect regime transition boundaries spectrally
5. Compute CCT analytically from regime geometry

Rather than simulating trajectories step-by-step, the method identifies the **structural stability manifold directly.** The architecture is domain-agnostic: any system expressible as

$$C\dot{x} + Gx + h(x) = u(t)$$

can be analyzed with the same pipeline.

Validation

Benchmark	IEEE 39-bus New England System
Generators	10
Speedup	**57,946**× over RK4
Max error	<**2.73%** deviation
Damping	$\zeta = 0.00$–0.20 (full realistic range)
Cross-val	$\binom{10}{2} = 45$ generator subsets
Stability	$a = 1.51 \pm 0.01$ (2.3% range)
Test suite	2,239 automated tests passing

The correction parameter $a = 1.51$ is stable across all cross-validation splits, indicating a **structural property** of the system rather than a fitting artifact.

Platform Architecture

The core engine comprises four layers:

- **MNA linearization** — system equations to matrix form
- **Koopman spectral estimator** — EDMD-based operator construction
- **Regime classifier** — LCA / transition / nonabelian detection
- **Stability manifold mapper** — analytic threshold extraction

A multi-objective optimization interface enables simultaneous targeting of stability margins, component cost, and regime robustness (Pareto front, Monte Carlo basin analysis).

Applications

Power Systems

- Real-time N-1 contingency screening
- Renewable integration stability envelopes
- Inverter-grid interaction analysis

Power Electronics

- Converter stability margins
- Switching regime detection

Multiphysics Simulation

- Accelerated PDE stability screening
- Structural and thermal transition analysis

Competitive Advantage

	Approach
Traditional	Time-domain integration, brute-force iteration
Ours	Spectral regime classification, analytic thresholds
	Advantage
Speed	Orders-of-magnitude acceleration
Insight	Structural interpretability of stability boundaries
Scale	Suitable for large networks and real-time integration

Intellectual Property

A provisional patent has been filed covering:

- Regime classification via Koopman spectral geometry
- Detection of locally commutative (LCA) stability regions
- Computation of stability-critical transitions from spectral signatures
- Application to nonlinear dynamical networks

Additional filings planned for cross-domain regime mapping and multi-network spectral optimization.

Vision

To become the **foundational acceleration layer** for stability-critical simulation in power systems and nonlinear dynamical infrastructure — enabling real-time contingency analysis at scales previously impossible.

For collaboration, licensing, or pilot deployments:
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