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Energy Storage Modulation for Transient Stability Control

Background

Transient stability control of power systems is based on actions that are taken automatically following a disturbance to ensure that the system remains in synchronism. Examples of such measures include the insertion of dynamic braking resistors. These methods are designed to rapidly absorb excess energy or alter the generation-demand balance at key points in the system. While these methods are often effective, they lack the ability to inject real power to compensate for a deficit. Utility-scale energy storage systems enable bidirectional modulation of real power with the bandwidth necessary to provide synchronizing torque.

Two-Area System with Storage

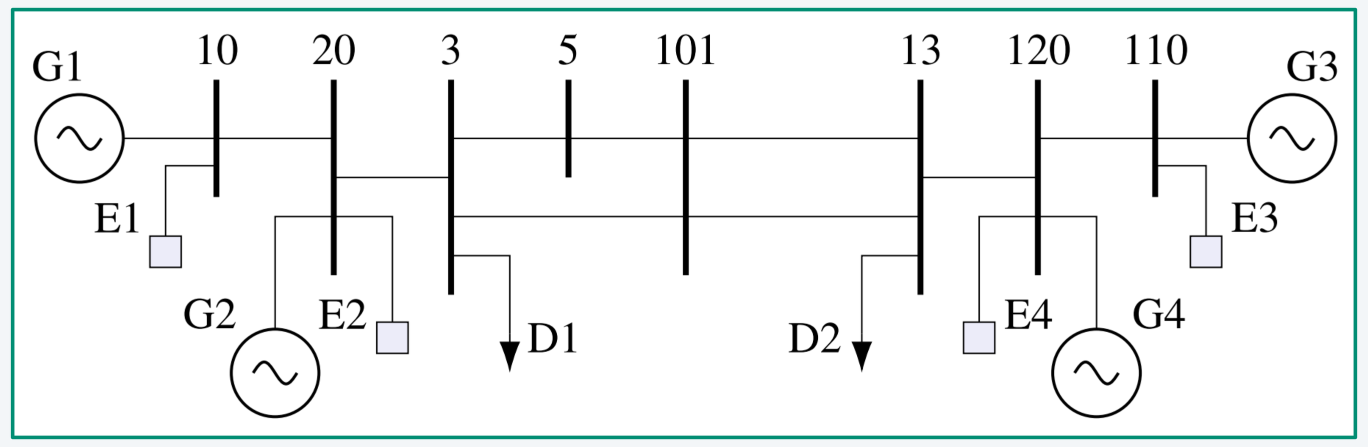

Fig. 1. Augmented two-area system with energy storage.

Tables I and II. Specifications and generation dispatch.

Index (No.)	Intercon. bus (No.)	Generator (MVA)	Energy storage (MW)	(MWh)
1	10	200	20	10
2	20	1800	180	90
3	110	200	20	10
4	120	1800	180	90

	D1	D2	G1	G2	G3	G4	Total
P_{gen} (MW)	–	–	168	1403	168	1080	2819
P_{load} (MW)	976	1765	–	–	–	–	2741

Trajectory Tracking Control

Our control approach specifies a desired angle trajectory:

$$\bar{\delta}_i(t) = \bar{\delta}(t) - \bar{\delta}(t_0) + \delta_i(t_0), \quad (1)$$

where $\bar{\delta}(t)$ is the angle of the center of inertia [1]. The control error $\Delta\zeta_i(t)$ is specified to "push" the local voltage angle toward this desired trajectory, i.e.,

$$\Delta\zeta_i(t) = \delta_i(t) - \bar{\delta}_i(t) = \omega_b \int_{t_0}^{t} \omega_i(\tau) - \overline{\omega}_i(\tau)\, d\tau. \quad (2)$$

Simulation Results

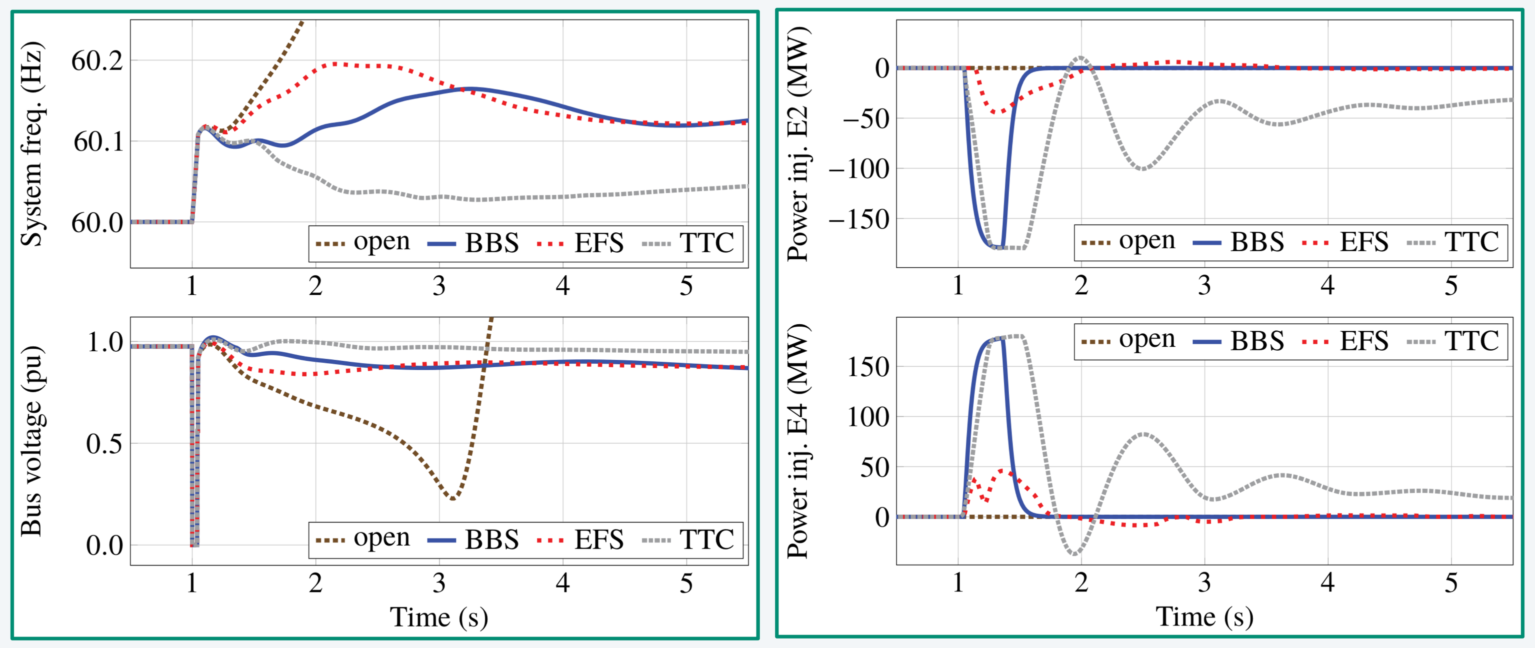

Fig. 2. System response to a 3-cycle fault near bus 5.

Koopman Operator Illustration

To overcome the inherent nonlinearity of power systems, we apply a nonlinear coordinate transformation to the original system that linearizes the dynamics [2].

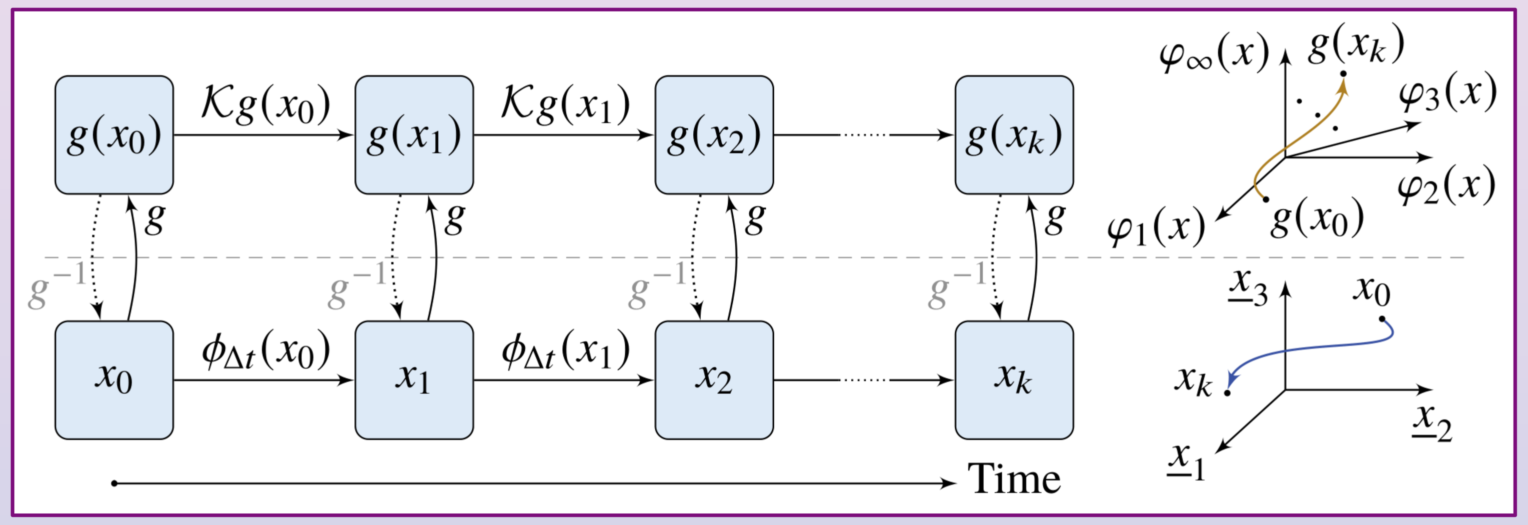

Fig. 3. Illustration of the Koopman operator framework.

Region of Attraction

Initial conditions that reside within the *region of attraction* (ROA) converge to the stable equilibrium. The estimated ROA for G2 following a fault near bus 5 is shown below. Estimates produced using brute-force simulation are shown in black.

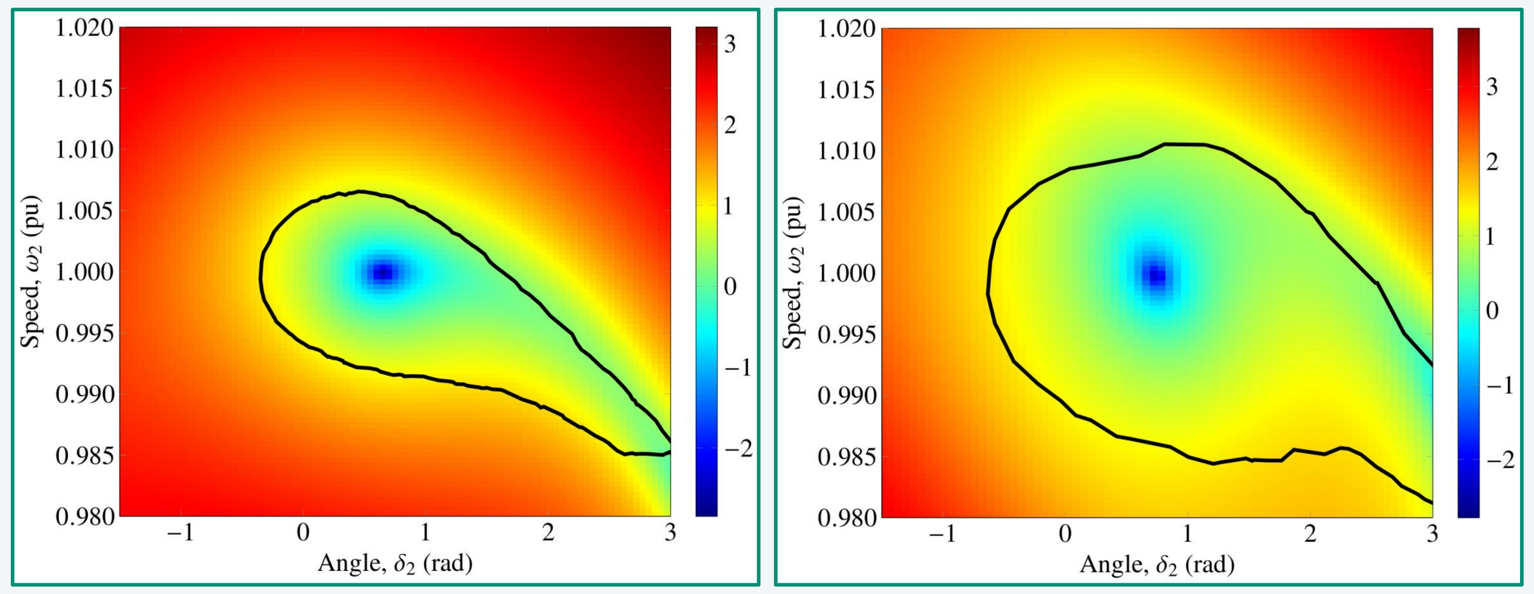

Fig. 4. Est. ROA slice for G2 in open (L) and closed loop (R).

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References

[1] R. T. Elliott, H. Choi, D. J. Trudnowski and T. Nguyen, "Real Power Modulation Strategies for Transient Stability Control," in *IEEE Access*, vol. 10, pp. 37215-37245, 2022.

[2] S. L. Brunton, B. W. Brunton, J. L. Proctor, E. Kaiser, and J. N. Kutz, "Chaos as an intermittently forced linear system," Nature Commun., vol. 8, no. 1, pp. 1–9, May 2017.

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