PSERC

A Zero-Reflection Controller for Electromechanical Disturbances in Power Networks

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Acknowledgements

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Architectures for Secure and Robust Distributed Infrastructures

Approach

- Use a continuum model to gain insight for the design of generator controls.

- Focus on traveling waves and impedance-matching controllers.

Background - general

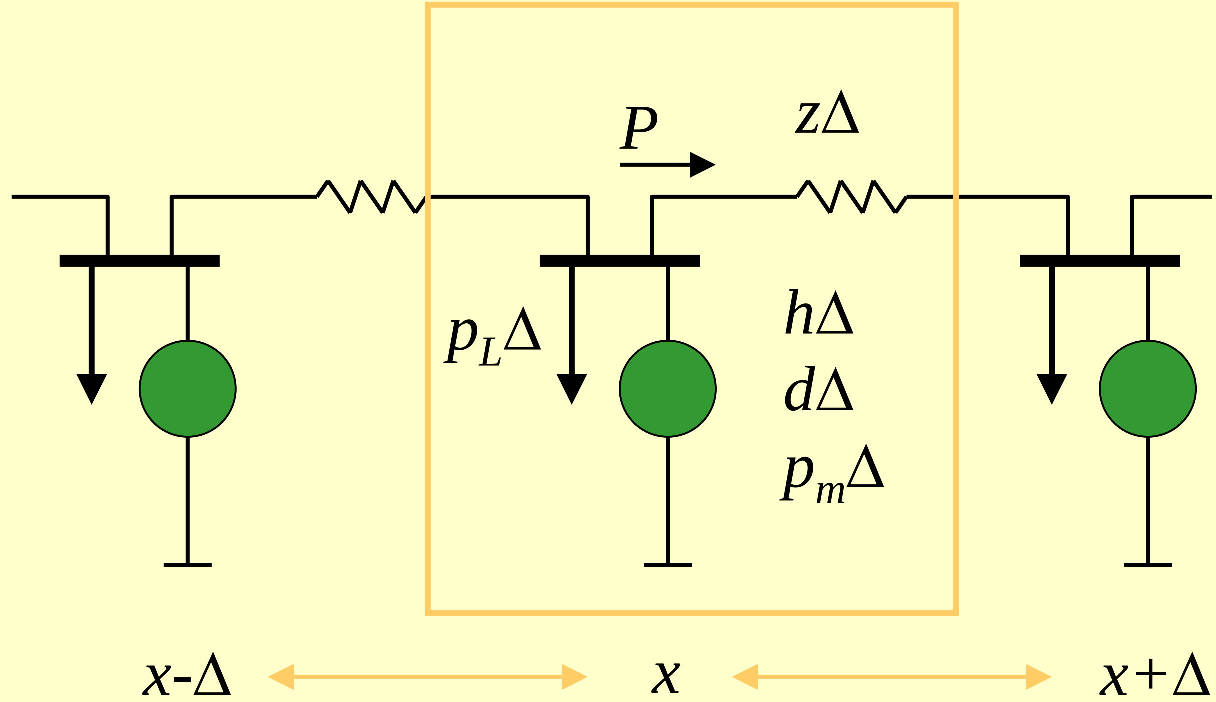
- Power System Models - ODEs, DAEs
- Analysis – simulation, modal analysis, energy methods.
- Control – modal approach.

Background – continuum model

Distributed model, PDE description, electromechanical wave behavior.

- Semlyen (1974) Introduced model, traveling waves, standing waves, parallels to EM.
- Thorp et al. (1998) Develop model to study traveling waves observed in phasor measurements.
- Our work (2002) Controls to eliminate traveling waves.

A Power System Model



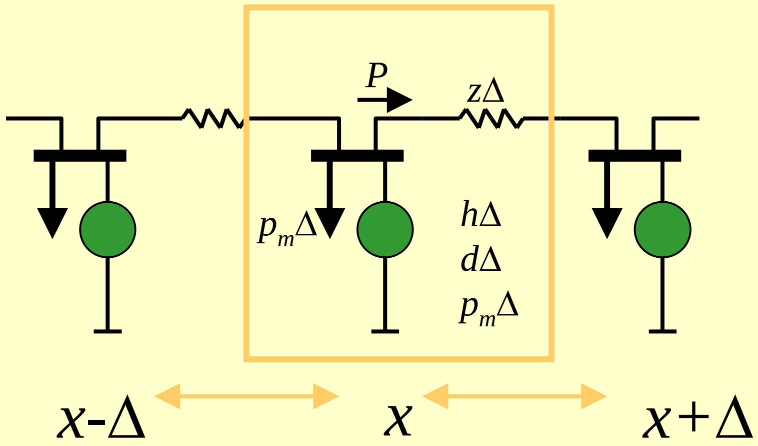
Distributed parameters:

- z impedance per unit length
- h inertia per unit length
- d damping per unit length

Denote

$z^{-1} = g - j\,b$

A Power System Model



$$\frac{2h\Delta}{\omega_s}\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = p_g\Delta - d\Delta\frac{\mathrm{d}\delta}{\mathrm{d}t}$$

$$-\frac{E^2 b}{\Delta}\left(\sin(\delta(x)-\delta(x-\Delta)) + \sin(\delta(x)-\delta(x+\Delta))\right)$$

$$-\frac{E^2 g}{\Delta}\left(2 - \cos(\delta(x)-\delta(x-\Delta)) - \cos(\delta(x)-\delta(x+\Delta))\right)$$

(Swing Equation Model)

Neglect *g*, *d*, and examine the limit as $\Delta \to 0$

$$\frac{2h}{\omega_s}\frac{\partial\omega}{\partial t} = p_g - \frac{\partial P}{\partial x}$$

Continuum Model

$$\frac{2h}{\omega_s}\frac{\partial\omega}{\partial t} = p_g - \frac{\partial P}{\partial x}$$

where

$$P = -E^2 b \frac{\partial\delta}{\partial x}$$

differentiate w.r.t. time

$$\frac{\partial P}{\partial t} = -E^2 b \frac{\partial\omega}{\partial x}$$

Telegrapher's Equation
(we'll use later)

Continuum Model

$$\frac{2h}{\omega_s}\frac{\partial\omega}{\partial t} = p_g - \frac{\partial P}{\partial x}$$

where

$$P = -E^2 b \frac{\partial\delta}{\partial x}$$

combine

$$\frac{2h}{\omega_s}\frac{\partial^2\delta}{\partial t^2} = p_g - E^2 b \frac{\partial^2\delta}{\partial x^2}$$

linear undamped wave equation

(a more detailed nonlinear model is found in Thorp et al.)

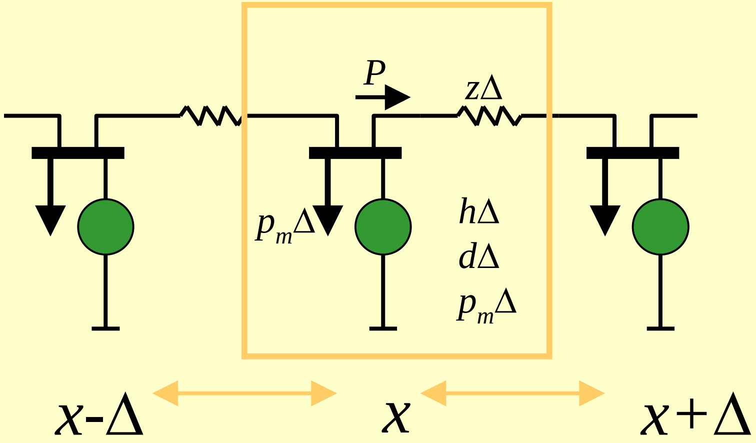
Continuum Model - Higher Dimensions

$$\frac{2h}{\omega_s}\frac{\partial^2 \delta}{\partial t^2} = p_g - E^2 b \nabla^2 \delta$$

Same equation, parameters have different units.

Does the original discrete model exhibit wave-like behavior?

A Power System Model



$$\frac{d\delta_k}{dt} = \omega_k \qquad \forall k$$

$$\frac{2H}{\omega_s}\frac{d\omega_k}{dt} = p_k - 0.01\omega_k$$
$$-6\left(\sin(\delta_k - \delta_{k-1}) + \sin(\delta_k - \delta_{k+1})\right)$$
$$-\left(2 - \cos(\delta_k - \delta_{k-1}) - \cos(\delta_k - \delta_{k+1})\right) \qquad 2 \le k \le 63$$

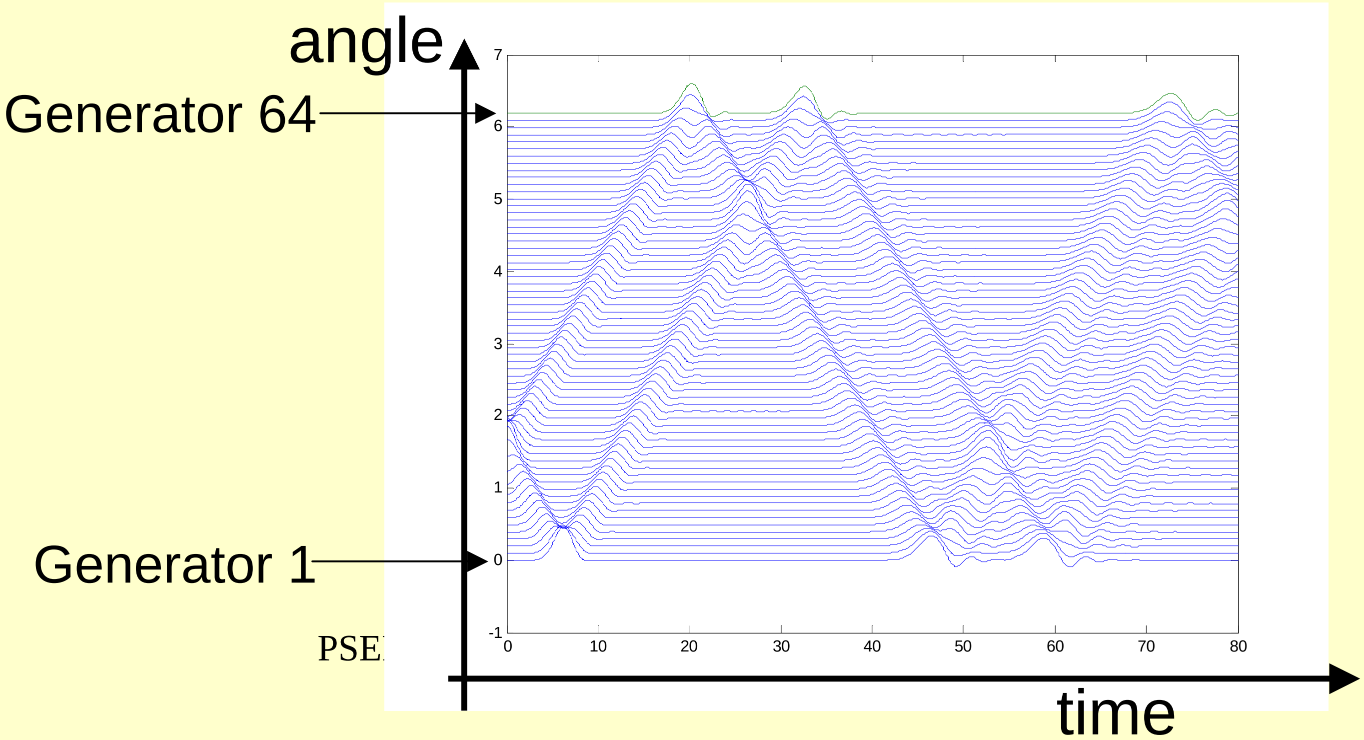
$$\frac{2H}{\omega_s}\frac{d\omega_1}{dt} = p_1 - 0.01\omega_1$$
$$-6\sin(\delta_1 - \delta_2) - \left(1 - \cos(\delta_1 - \delta_2)\right) \qquad k = 1$$

$$\frac{2H}{\omega_s}\frac{d\omega_{64}}{dt} = p_{64} - 0.01\omega_{64}$$
$$-6\sin(\delta_{64} - \delta_{63}) - \left(1 - \cos(\delta_{64} - \delta_{63})\right) \qquad k = 64$$

Initial Conditions and Disturbance

- Initial conditions: angle varies by 2π over the string of generators.

- Gaussian pulse perturbation: $\tilde{\delta}_k = \frac{1}{2} e^{-0.1(k-15.5)^2}$



Continuum Model - Characteristic Impedance

Forward traveling wave

$$P^+ = P\left(t - \frac{x}{v}\right) = P(y)$$

$$\omega^+ = \omega\left(t - \frac{x}{v}\right) = \omega(y)$$

$$\frac{\partial P}{\partial t} = -E^2 b \frac{\partial \omega}{\partial x}$$

$$\frac{\partial P^+}{\partial y} = \frac{E^2 b}{v} \frac{\partial \omega^+}{\partial y}$$

$$P^+ = \frac{E^2 b}{v} \omega^+$$

P^+ and ω^+ are in constant proportion in the traveling wave.

Continuum Model - Characteristic Impedance

Forward traveling wave

$$P^+ = \frac{E^2 b}{v}\omega^+$$

Characteristic Impedance

$$C_o = \frac{\omega^+}{P^+} = \frac{v}{E^2 b} = \sqrt{\left(\frac{\omega_s}{2h}\right)\frac{1}{E^2 b}}$$

Reflection Coefficients

Terminating the string of generators such that frequency and power are in constant proportion, $C=\omega/P$, leads to the Following Reflection Coefficient:

$$R = \frac{C - C_o}{C + C_o}$$

$R = 1$ positive reflection (in frequency)

$C \rightarrow \infty$, open ended, negative reflection in power

$R = -1$ negative reflection (in frequency)

$C=0$, infinite bus, angle and frequency are fixed.

$R = 0$ no reflection

A Zero Reflection Controller

Terminate the string of generators with the characteristic impedance.

Imposed Generator Control Objective: $\tilde{P}_{end} = \frac{\omega}{C_o}$

deviations from nominal values

Generator Model

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega$$

$$\frac{2H}{\omega_s}\frac{\mathrm{d}\omega}{\mathrm{d}t} = p_g + P_{end} - D\omega$$

Using p_g as the input, the control objective cannot be achieved… *at least not exactly…*

A Zero Reflection Controller

Generator Model

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega$$

$$\frac{2H}{\omega_s}\frac{\mathrm{d}\omega}{\mathrm{d}t} = p_g + P_{end} - D\omega$$

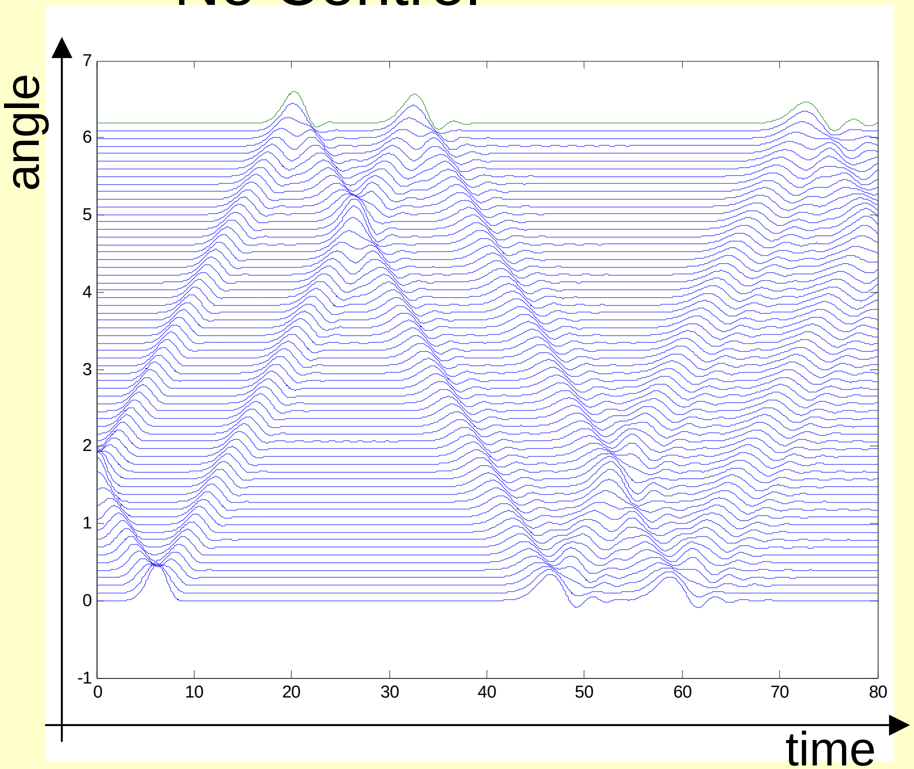
Try the following feedback control

$$\tilde{p}_g = K\left(\tilde{P}_{end} - \frac{\omega}{C_o}\right) - \tilde{P}_{end} + D\omega$$

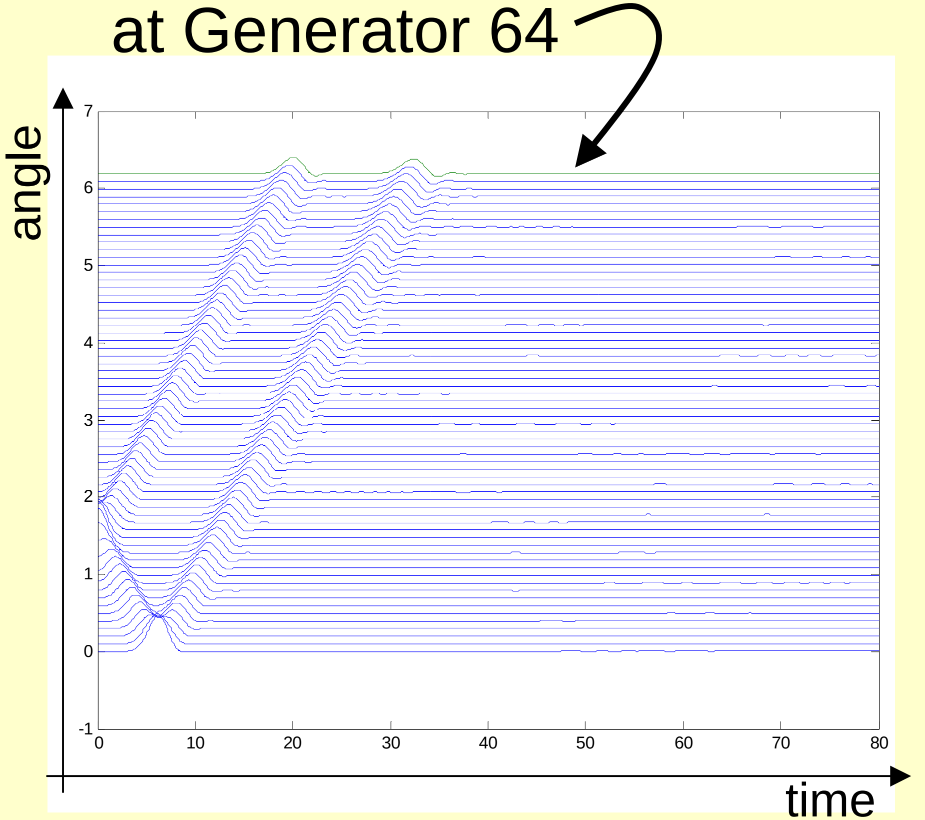
control objective

Results - 1D Case

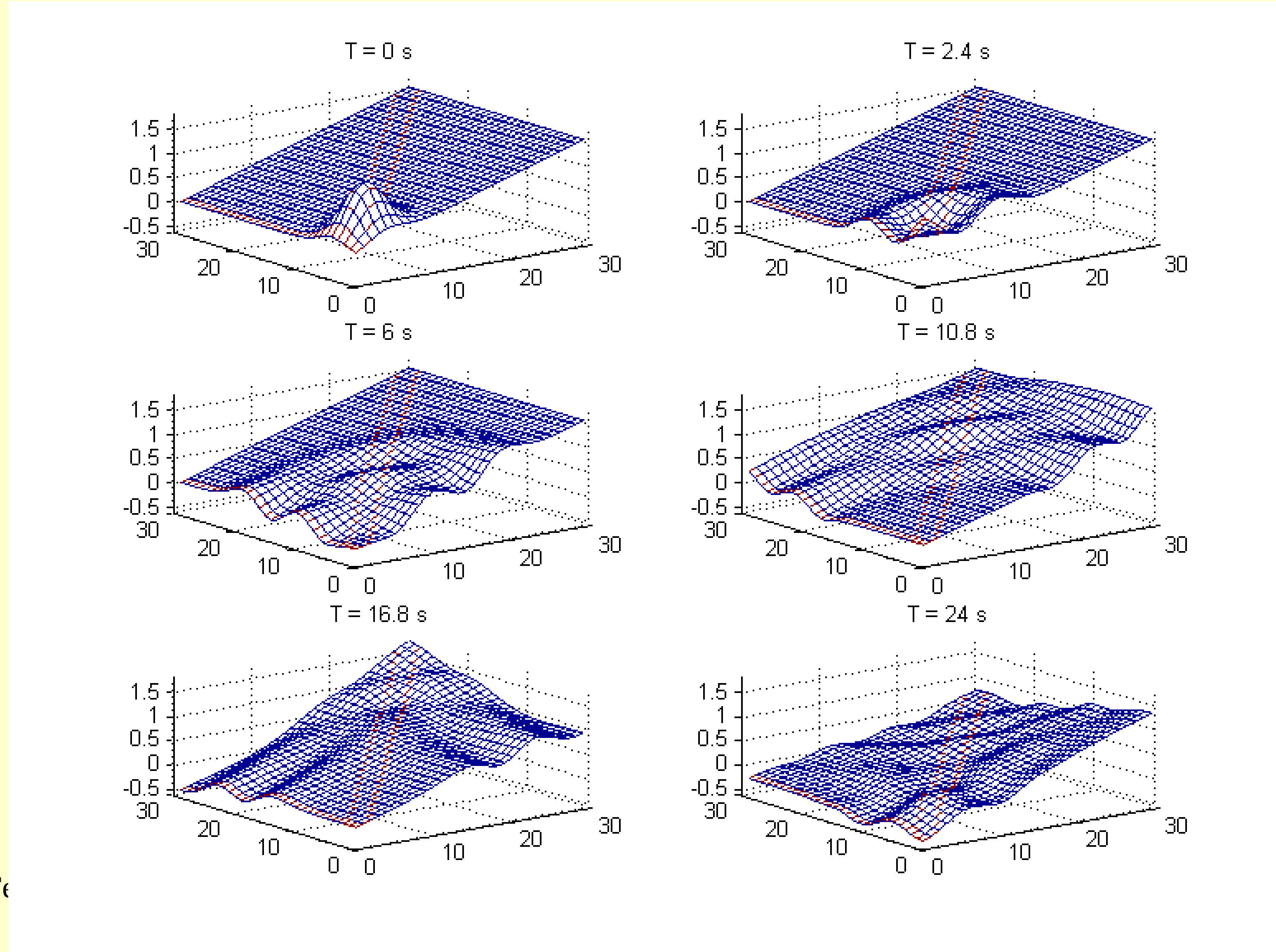
No Control



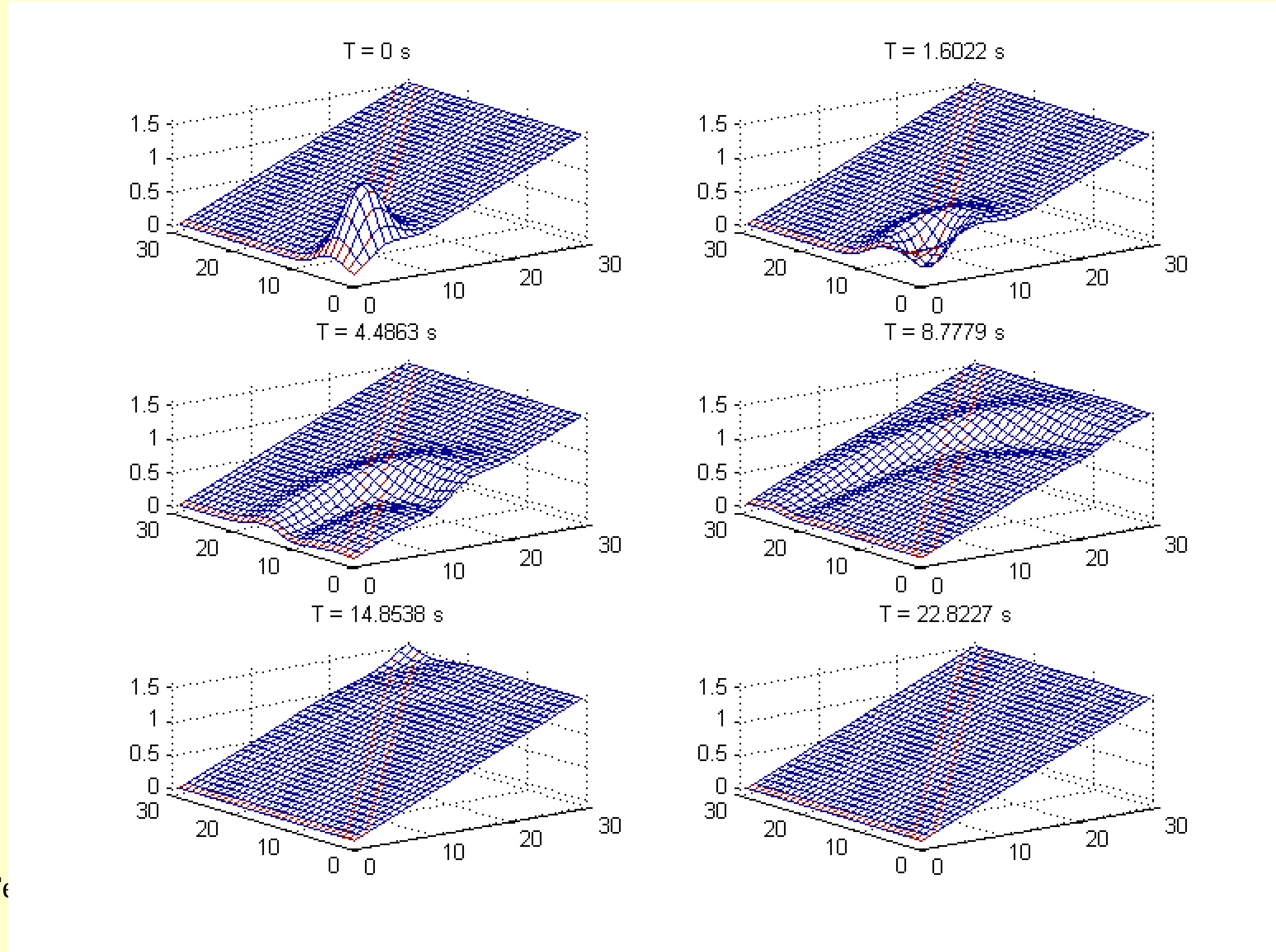
Zero-Reflection Controller
at Generator 64



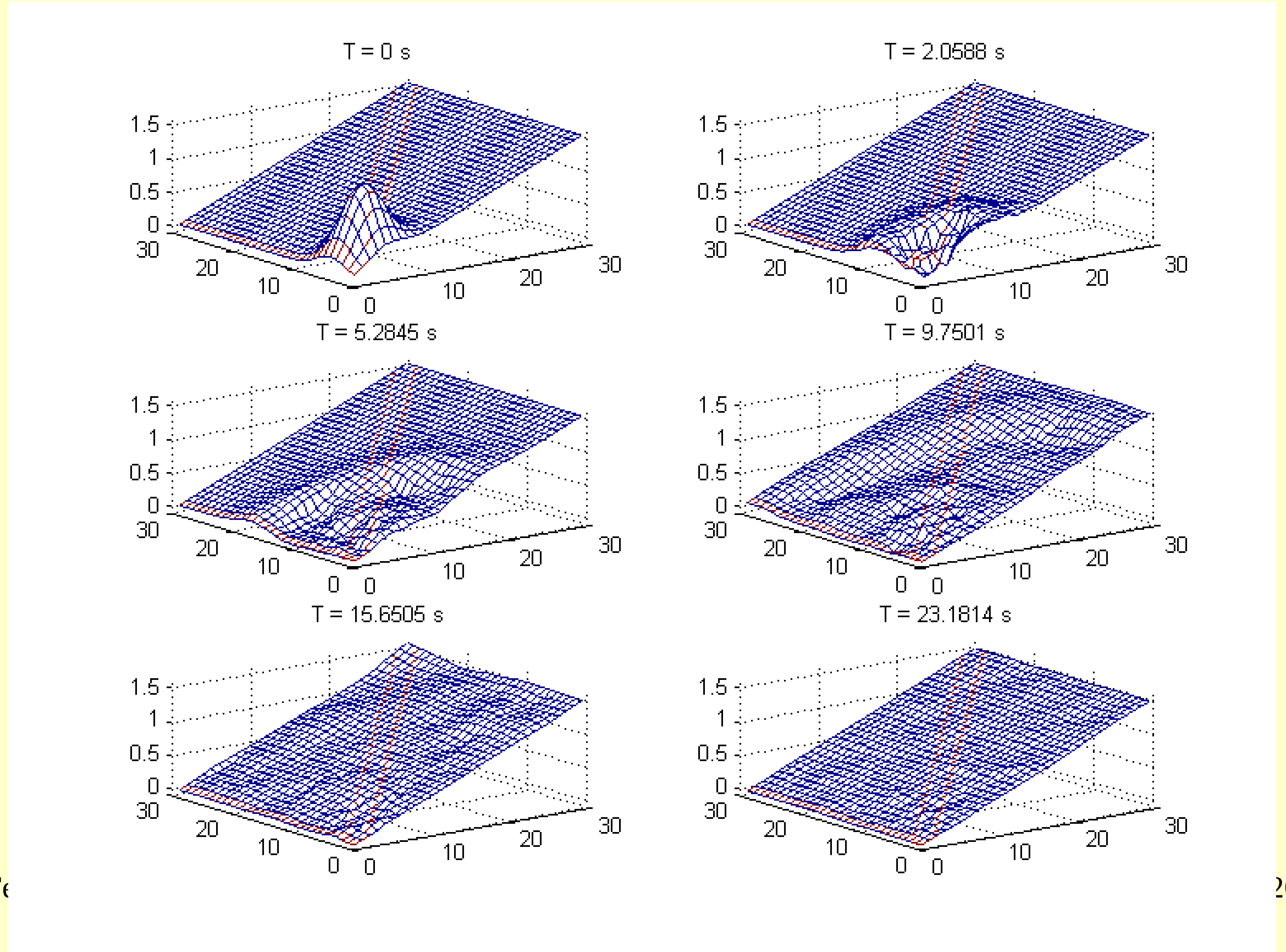
2D Grid / no control



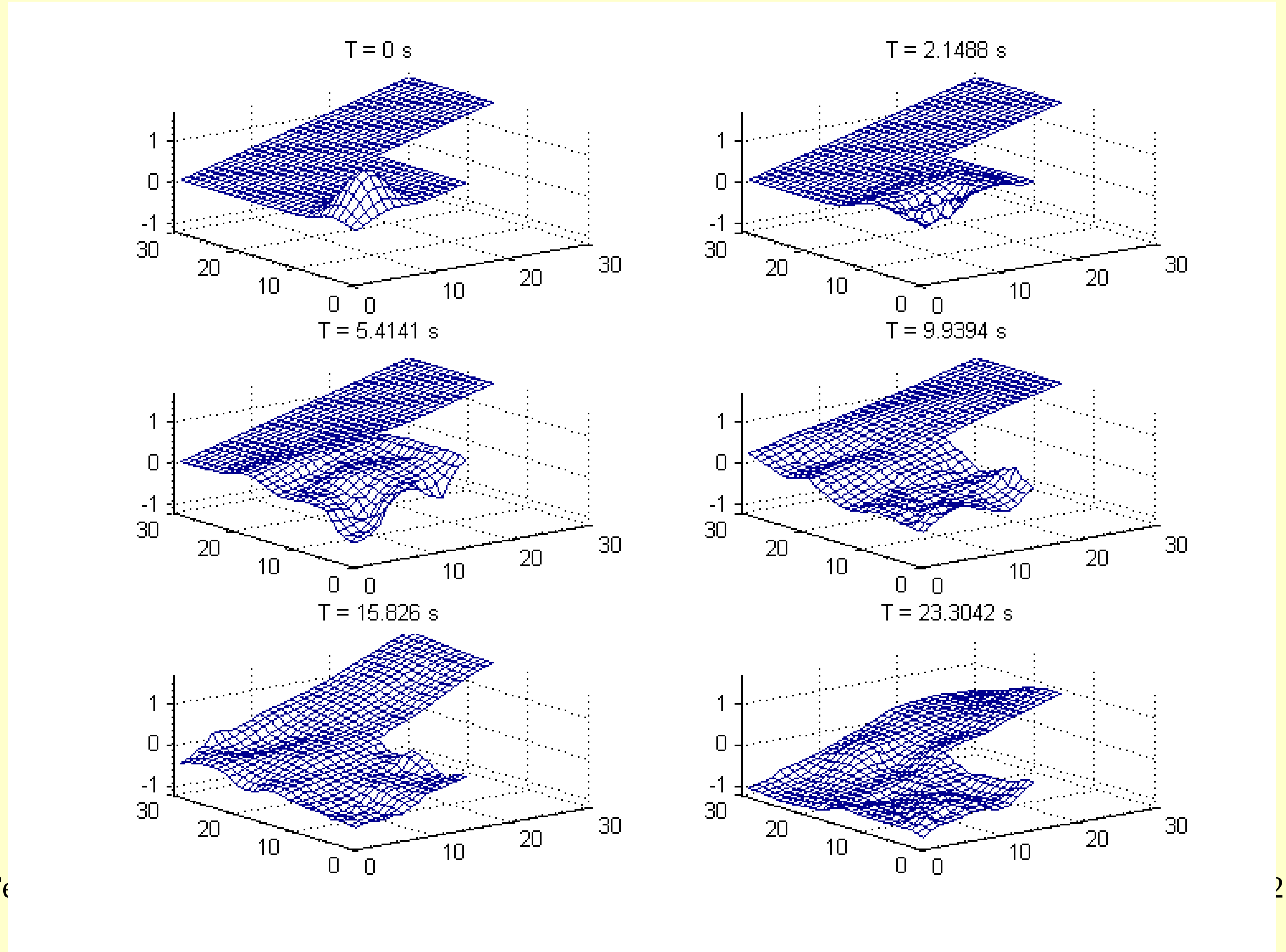
2D Grid / Zero Reflection Controller



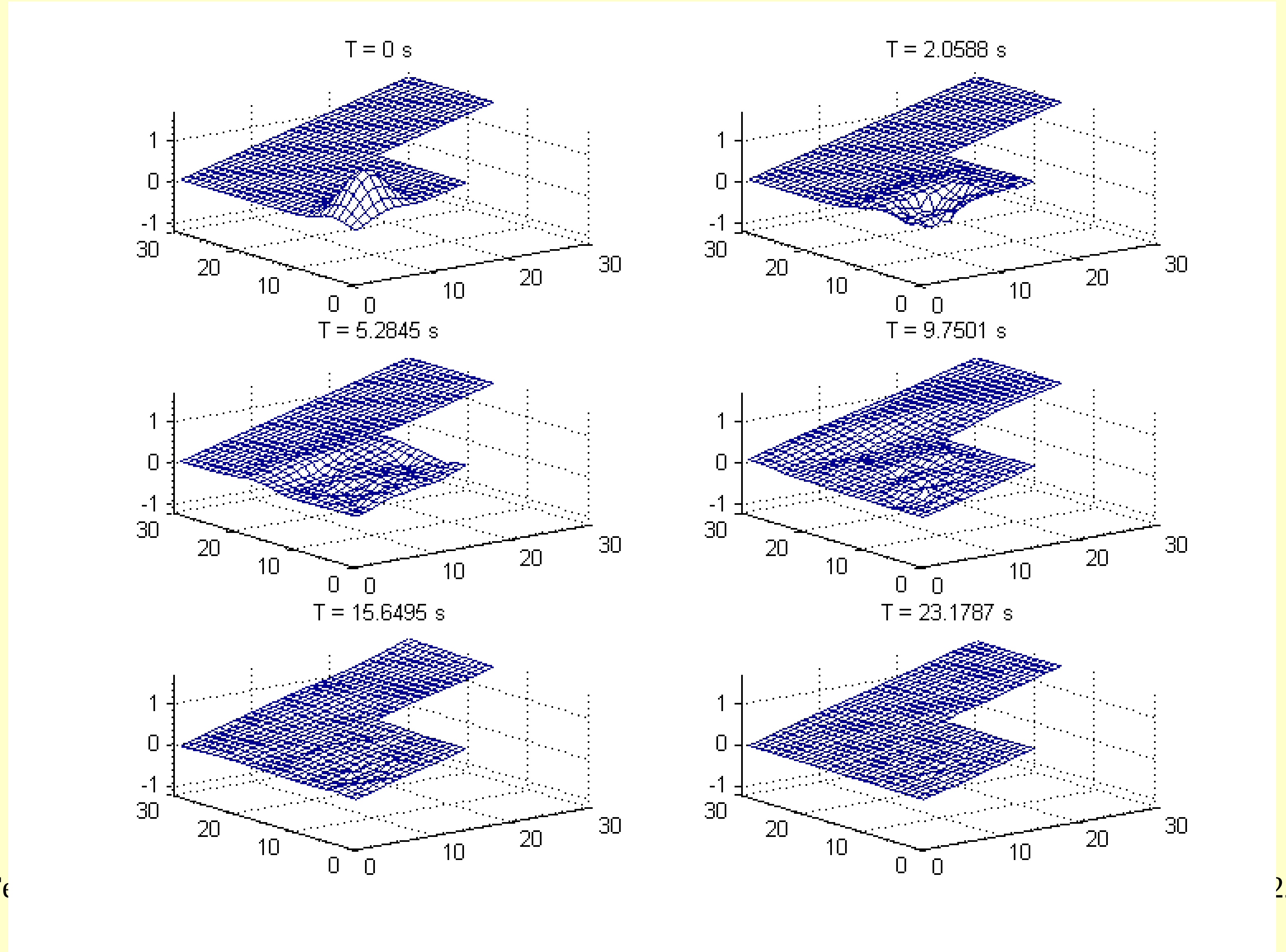
2D Grid / Zero Reflection Controller Perturbed Parameters ±90%



L-Shaped Grid / No Control



L-Shaped Grid / Zero Reflection Controller Perturbed Parameters ±90%



Conclusions

- Conceptual Contributions:
  - Traveling waves → eliminate reflections.
  - Place controllers where reflections are expected.
  - Controller uses deviations in both power and frequency as inputs.

- Future Work: *lots!*

  more realistic models, realistic assessment, irregular topologies, other control opportunities, and more.