Propagation of Power System Disturbances and Effects of Local Loading and Inertia

Jason Bank and Andrew Arana

NASPI Working Group Meeting

October 16, 2008

FNET

Virginia Tech
Invent the Future

Introduction

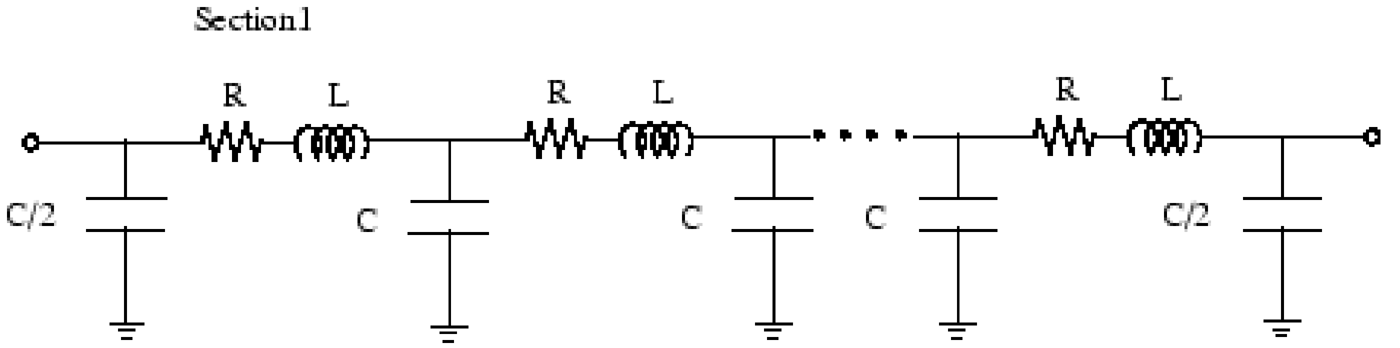
- Electromechanical propagation delays have been measured in both PMU and FNET data.
- Significant variations in propagation speed have been noticed.
- Understanding disturbance propagation is necessary for accurate event triangulation and other post-disturbance analyses.
- A better understanding of electromechanical disturbance propagation is needed for these studies

Types of Propagation

- Electromagnetic wave propagation: V,I experience a delay along transmission lines due to RLC time constants.

- Electromechanical wave propagation: ***f*** and δ experience a delay along transmission lines due to machine inertia.

Electromagnetic Propagation



$$V(t,x) = \sqrt{2}A_1 e^{\alpha x}\cos(wt + \beta x) + \sqrt{2}A_1 e^{-\alpha x}\cos(wt - \beta x)$$

$$v = \frac{1}{\sqrt{LC}}, \quad \textit{when losses are neglected}$$

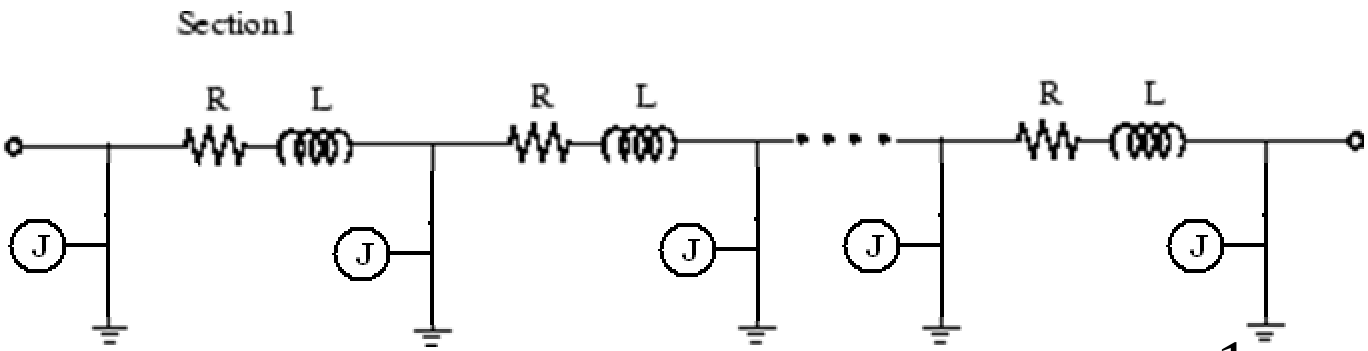
When the internal flux linkage of the conductor is neglected: $v \approx \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \approx 3\times 10^8 m/s$

Typically speeds from 250,000 – 295,000 km/s

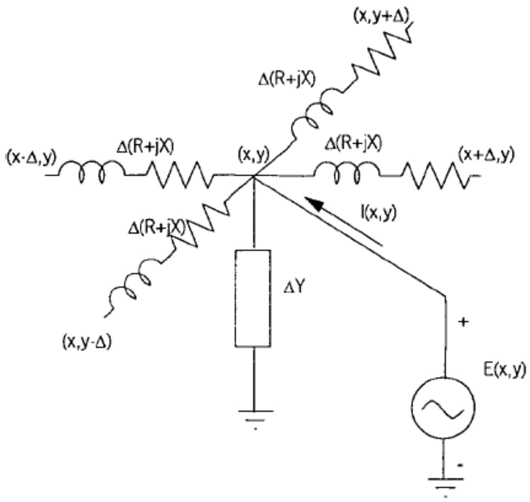
FNET

VirginiaTech Invent the Future

Electromechanical Propagation



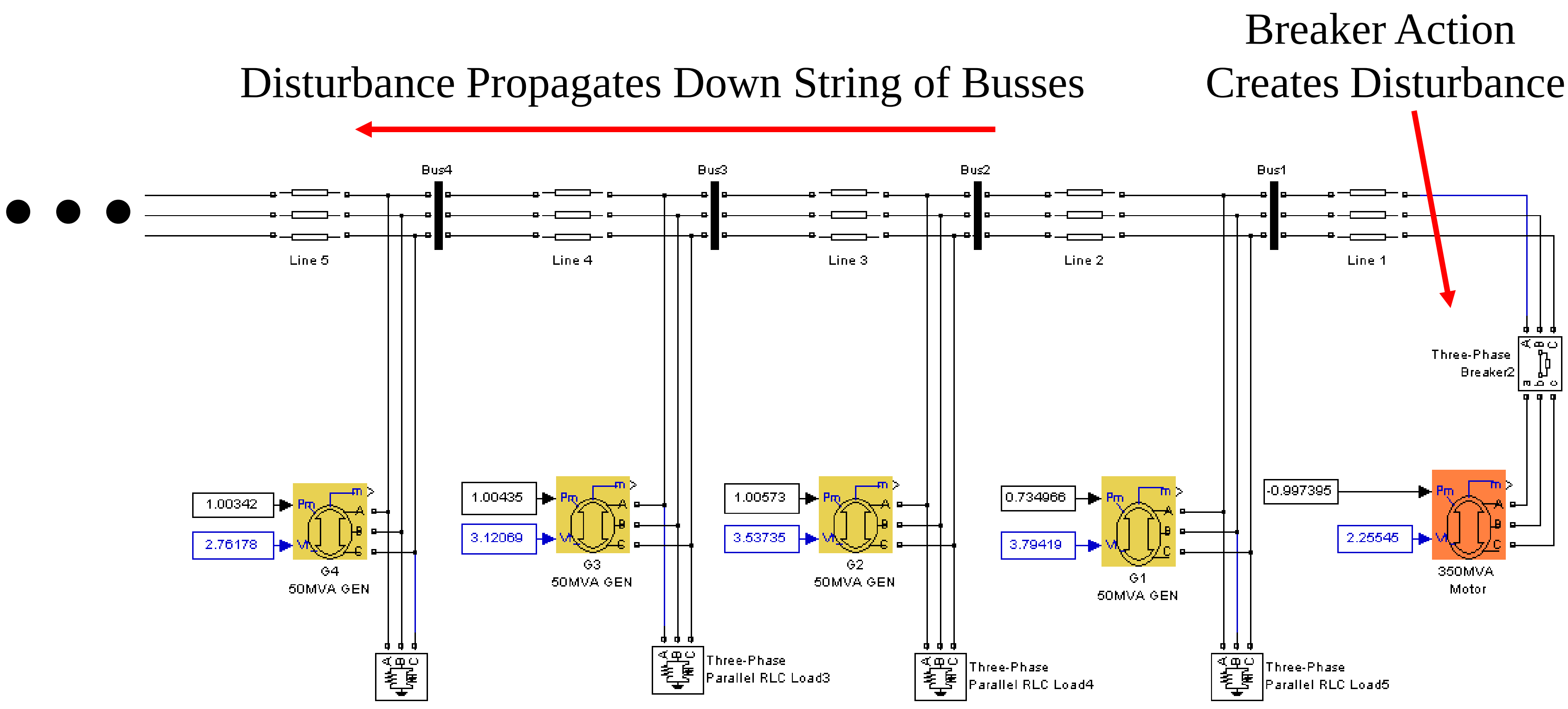
$$v = \frac{1}{\sqrt{J\omega_s X}} \quad (R = 0)$$



$$v = \frac{\omega V^2 \sin\delta}{2h|z|}$$

Calculated and observed speeds of 500km/s

Test System

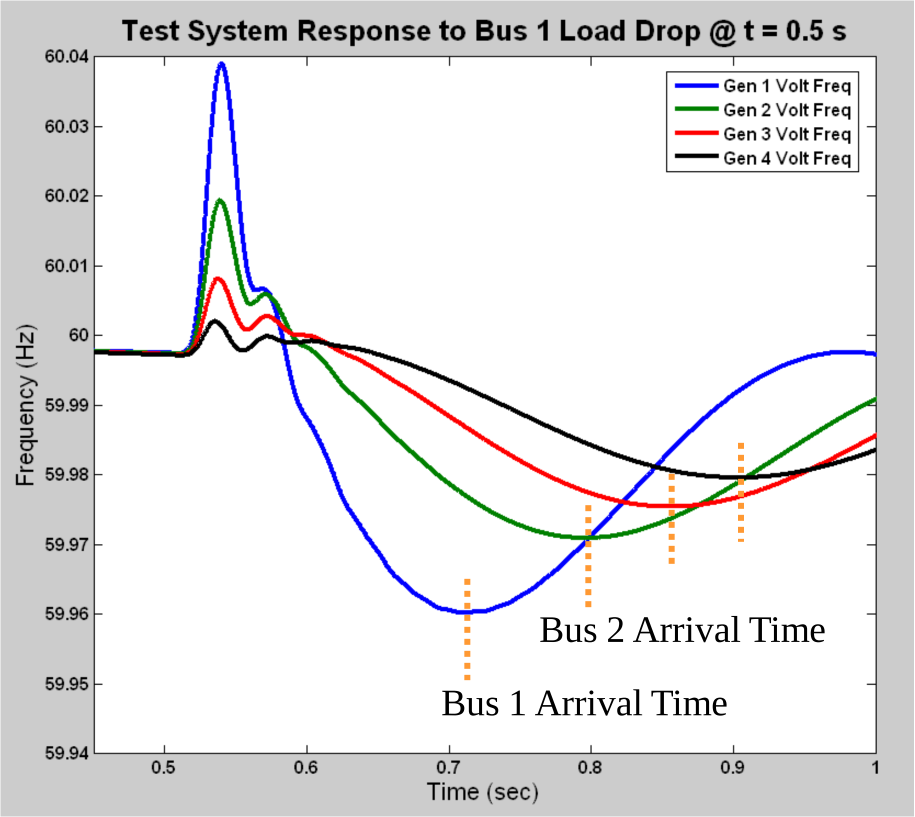


FNET

Virginia Tech
Invent the Future

Measurement of Propagation Delay

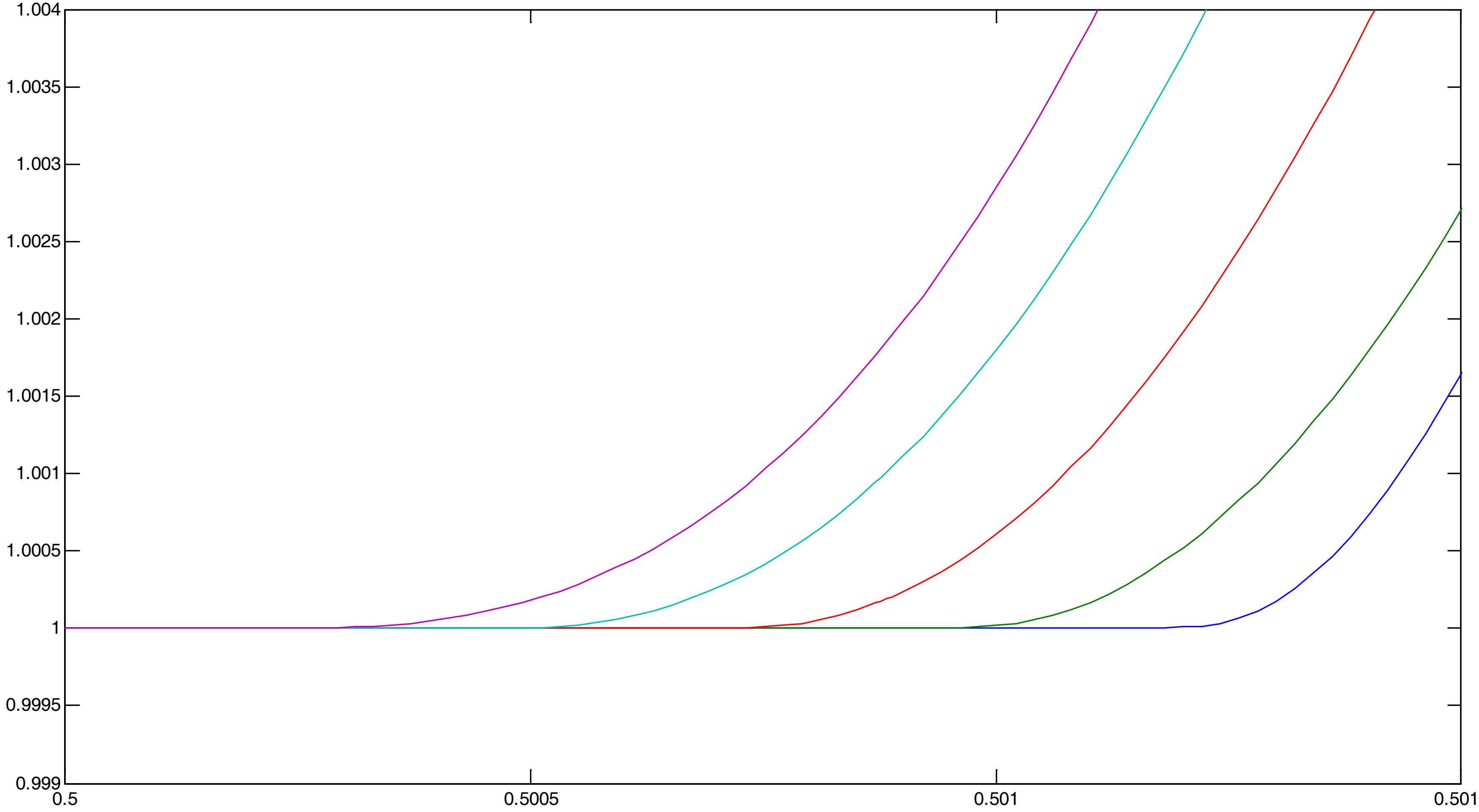
- The disturbance arrival time at a bus was defined as the time at which the first minimum was observed in the transient response of voltage frequency (measured at terminals of generator)



FNET

VirginiaTech
Invent the Future

Electromagnetic Delays



FNET

VirginiaTech
Invent the Future

Comparison of Calculated and Measured Electromagnetic Delays

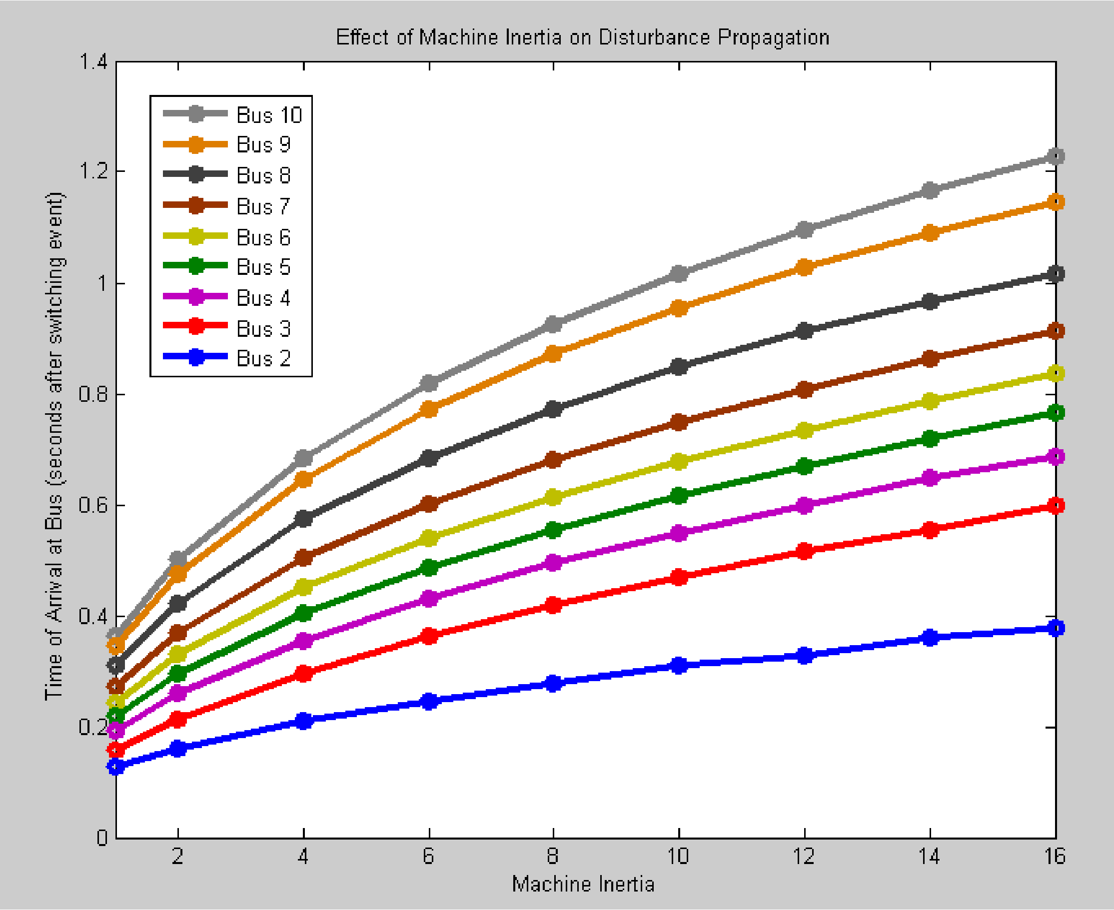
$$v = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.0013*8.9414*10^{-9}}} = 2.93*10^{5}\,km/s$$

$$Delay = \frac{70}{2.93*10^{5}} = 0.239ms$$

Measured Delays (ms): ~0.24ms

Machine Inertia

- For these tests the machine inertias were steadily increased to observe the effects on disturbance propagation

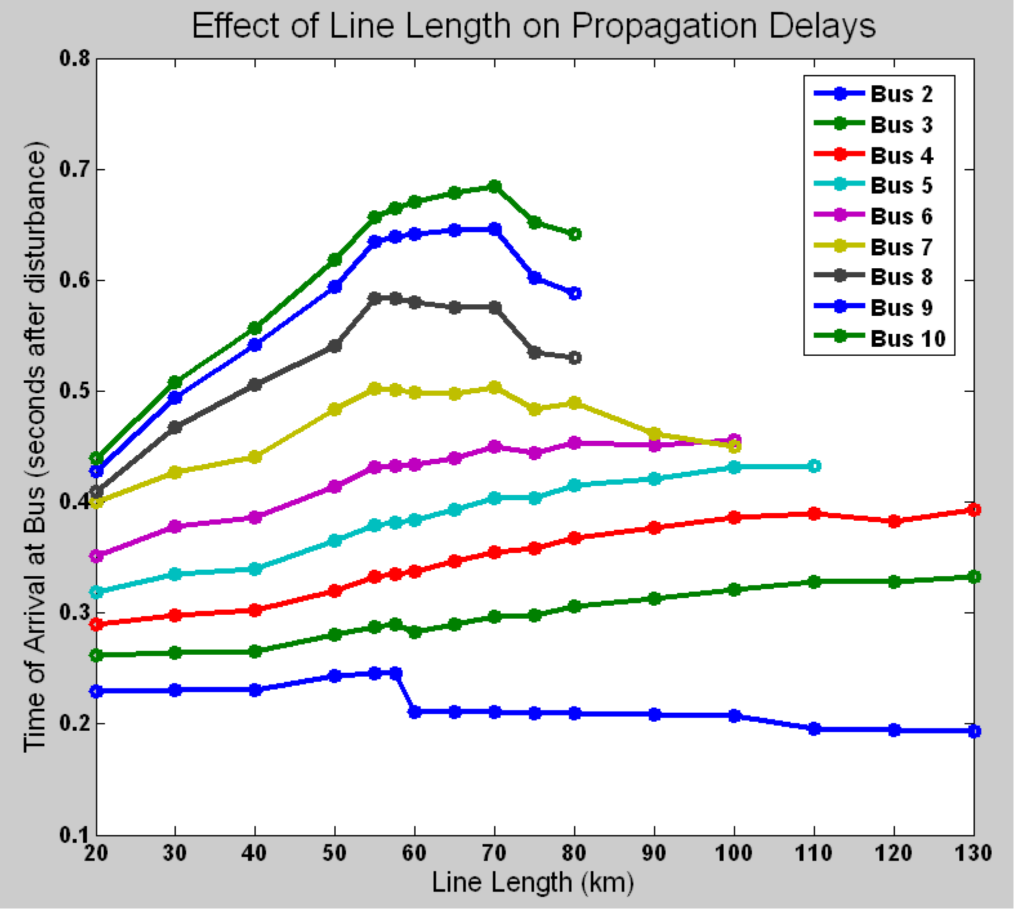


FNET

VirginiaTech
Invent the Future

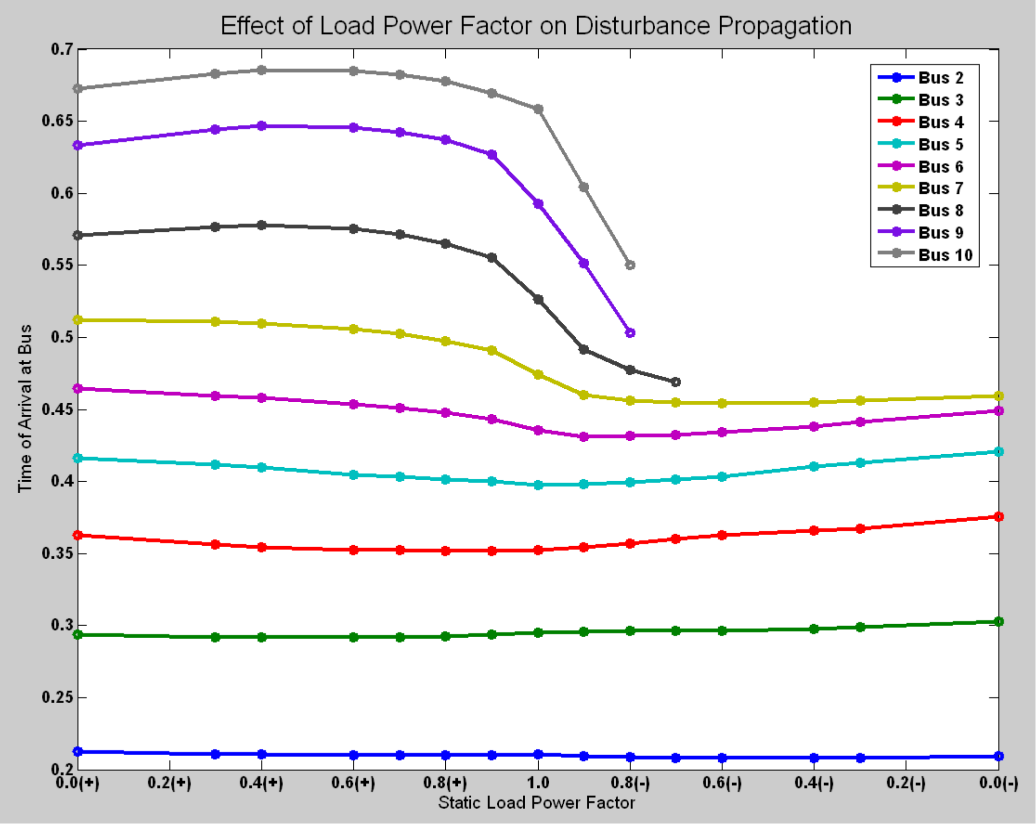
Line Length

- For these tests the transmission line lengths were steadily increased to observe the effects on disturbance propagation



Static Load Power Factor

- For these tests the power factors of the static loads at each bus were varied (holding apparent power constant) to observe the effects on disturbance propagation



FNET

VirginiaTech
Invent the Future

Conclusions

- Propagation delays are proportional to the square root of the inertia.
- Increasing line length (and thus impedance) causes progressively larger delays between adjacent busses
- Inductive static loads have little effect on the disturbance propagation time
- Capacitive loads effectively reduce the propagation time by increasing the reactive power flow, this effect is more prominent for lines with lighter loading
- Variations in inertia, line length, and loading can be used to explain observed variations in speed in real systems.