

The Empirical Transfer Function Estimation (ETFE) Method for Monitoring Electromechanical Mode Shape

Wide Spread Power Grid Blackout Prevention

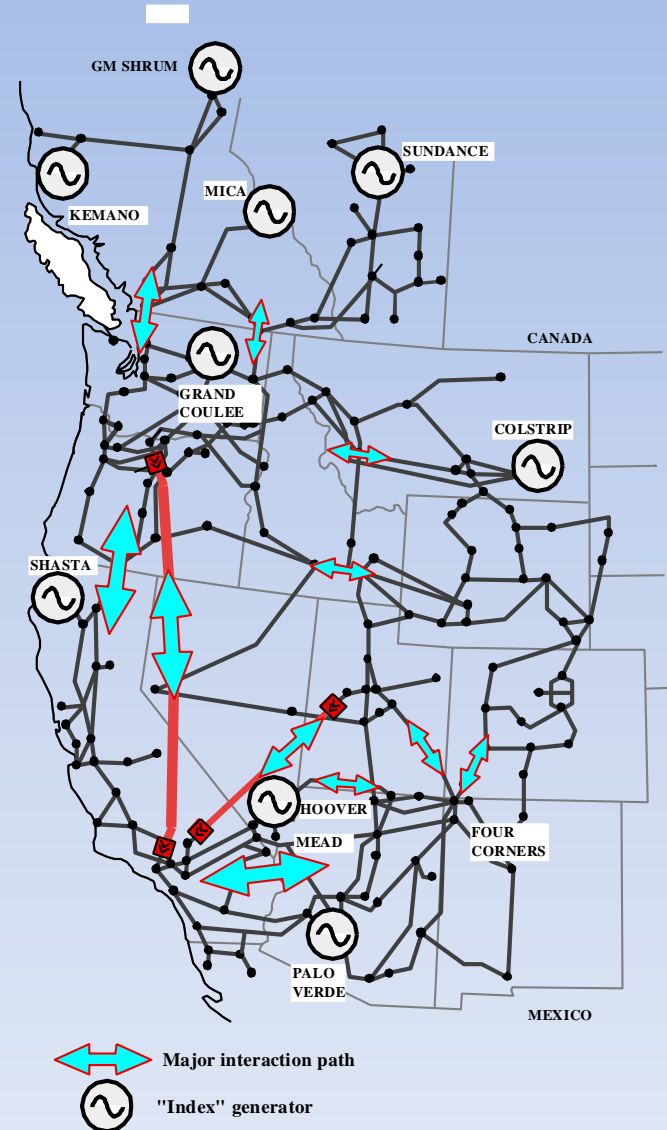
Jim Follum

Outline

- Electromechanical Modes
 - Definition
 - Importance
- Methods for Obtaining Mode Shape
- The ETFE Method
 - Fast Fourier Transform
 - Probing Signal
- Research Methodology
- Results and Analysis
- Concluding Remarks

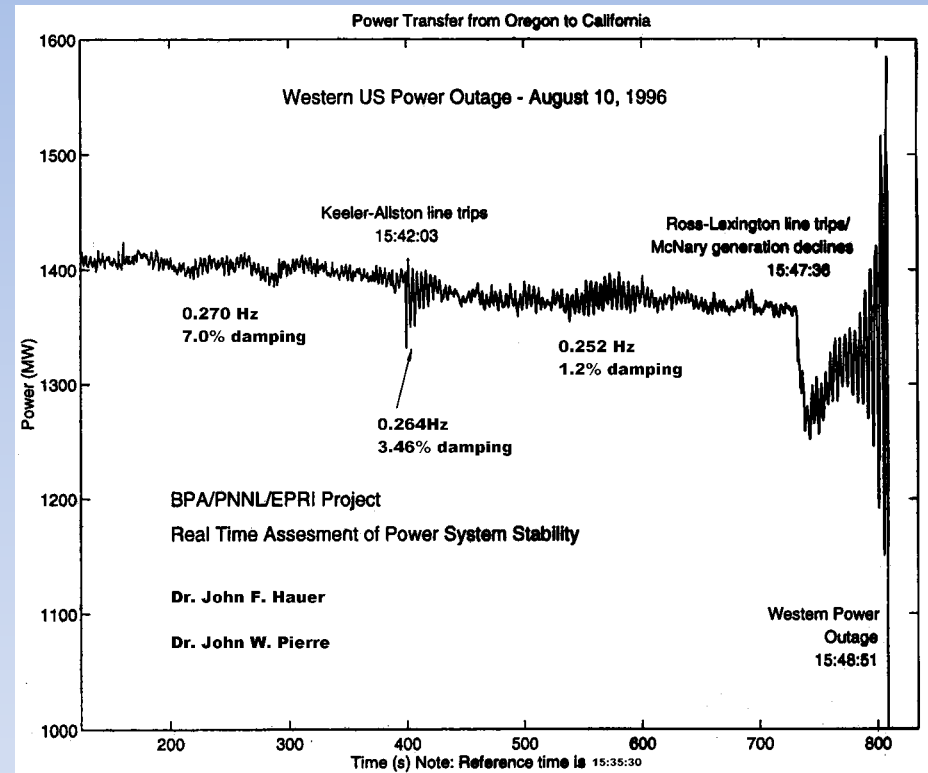
Electromechanical Modes

- Caused by generators in different parts of the power system “swinging” against each other
- Low frequency oscillations: 0.1 to 2 Hz
- Attributes of Interest:
 - Frequency
 - Damping
 - Shape
 - *Amplitude*
 - *Phase*



Importance of Electromechanical Modes

- Modes are important to power system stability
- Undamped modes cause growing oscillations resulting in cascading blackouts
- Cascading blackouts cost billions of dollars and endanger human life



Methods for Obtaining Mode Shape

- Ambient Data Collection
 - Requires no adjustment to power grid
- Brake Insertion
 - Requires insertion of 1400 MW dynamic brake
 - Prony Analysis
- Probing Signal Insertion
 - Requires insertion of a 20 MW probing signal
 - ETFE Method

Mode Shape Retrieval Methods

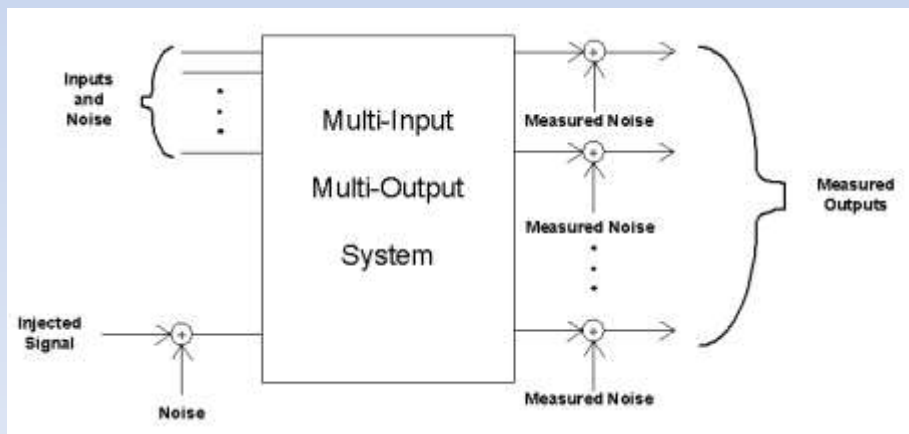
		Brake Insertion
	Probing Signal Insertion	
Ambient Collection		

Accuracy of Results

Note: The label 'System Disturbance' is positioned vertically to the left of the table.

The ETFE Method

- Uses the injection of a probing signal to increase accuracy of results
- Power grid modeled as linear system with many inputs and outputs
- Electromechanical modes are revealed as the interactions between outputs
- The ETFE quantifies these interactions



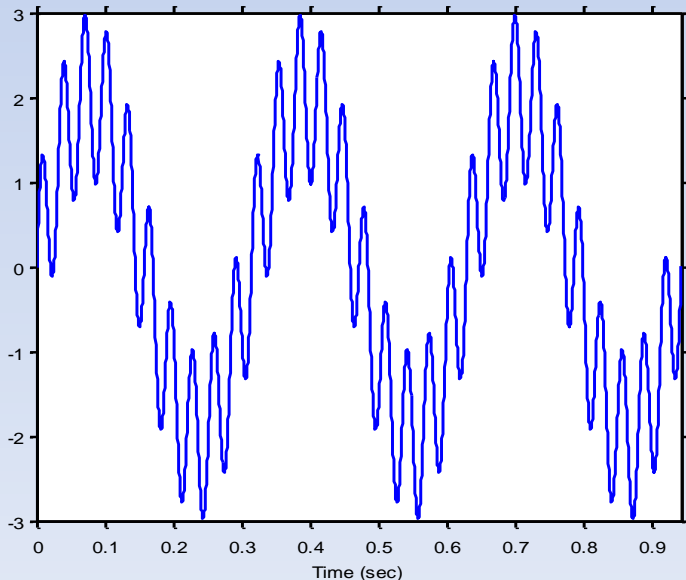
$$ETFE = \frac{FFT\{System\ Output\}}{FFT\{Reference\ Output\}}$$

The ETFE Method Cont.

The Fast Fourier Transform (FFT)

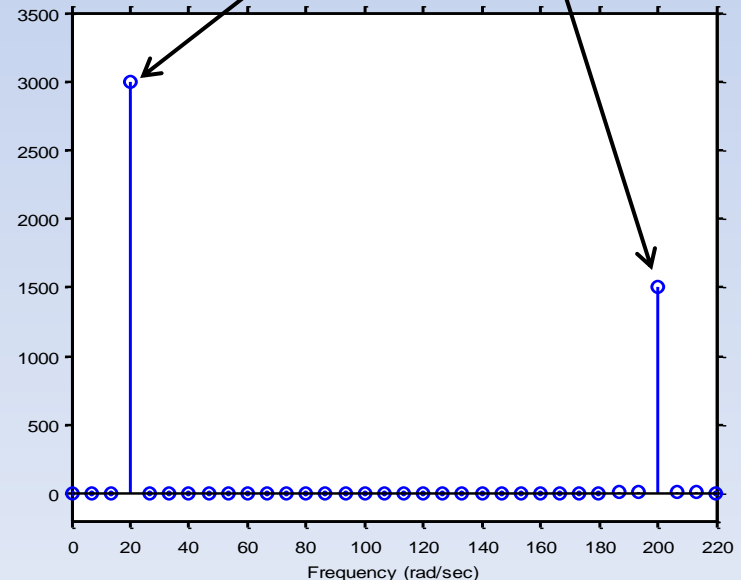
- An algorithm used to efficiently compute the Discrete Fourier Transform (DFT)
- Allows conversion from time domain to frequency domain
- DFT: $X^d[k] = \sum_{n=0}^{N-1} x[n] * e^{-j2\pi kn/N}$

$$2 \sin(20t) + \sin(200t)$$



FFT

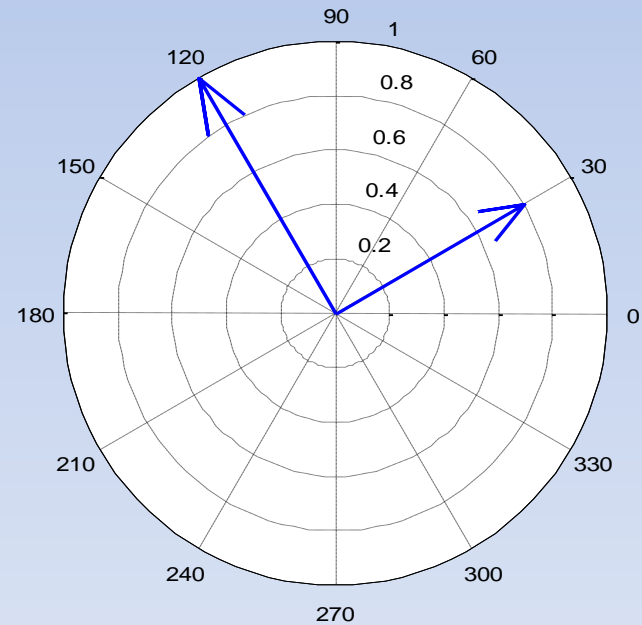
$$2 \sin(20t) + \sin(200t)$$



The ETFE Method Cont.

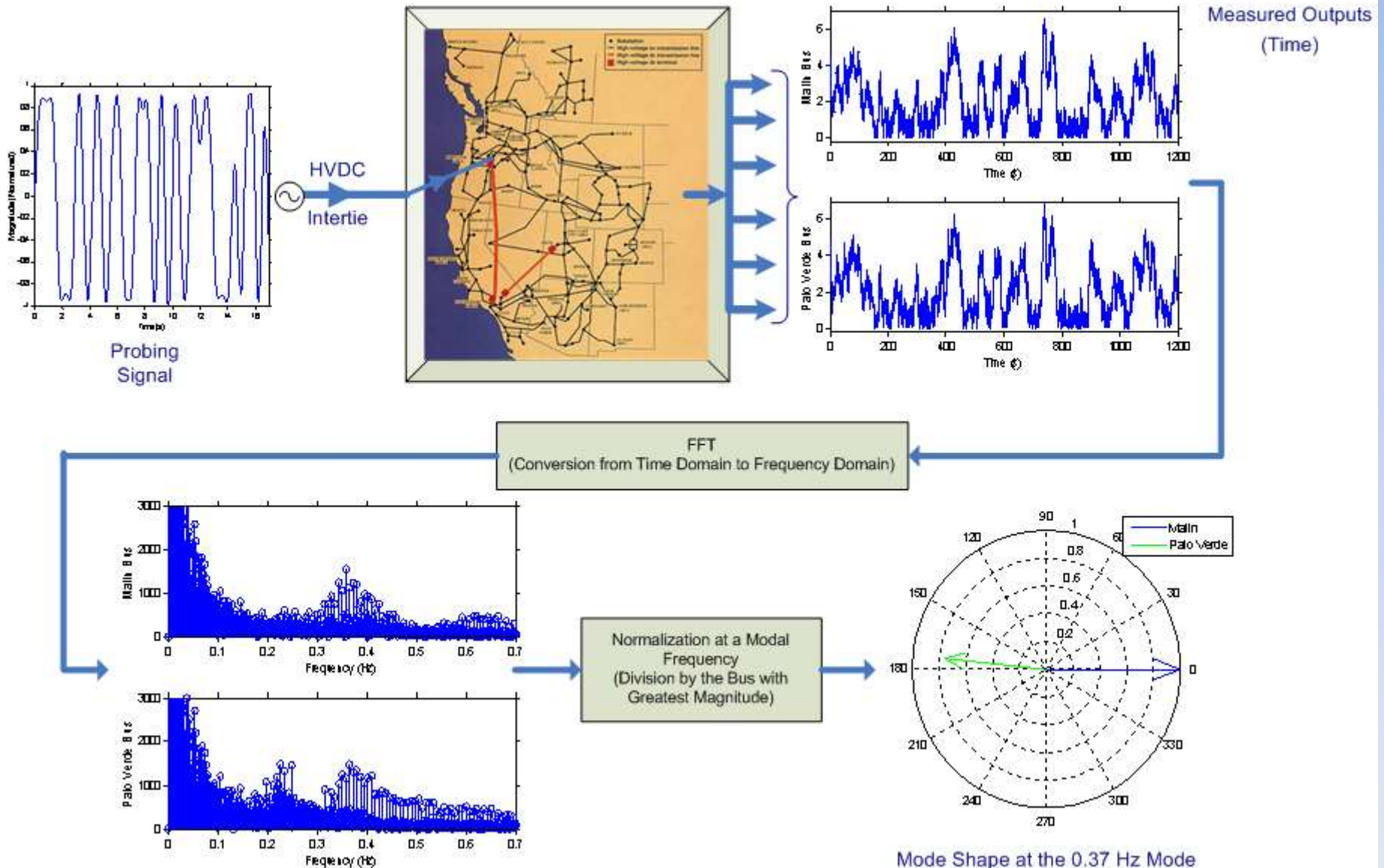
$$ETFE = \frac{FFT\{System\ Output\}}{FFT\{Reference\ Output\}}$$

- Reference output: channel with the most frequency content at the mode of interest
- ETFE comprised of complex values
- The value of the ETFE at a modal frequency provides mode shape information



Complex Value Compass Plot

The ETFE Method Cont.



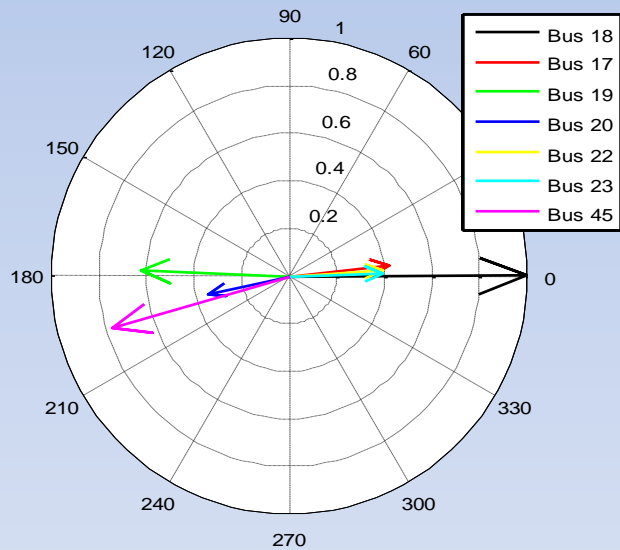
Research Methodology

- Two methods were evaluated
 - ETFE (method of interest)
 - Prony Analysis (for comparison)
- Methods were applied to two sets of data
 - Modeled System
 - 17 Machine Model
 - 1000 iteration Monty Carlo Trial
 - Real World
 - Collected in August 2008
 - Tests included both brake and probing signal insertions, allowing both Prony Analysis and the ETFE method to be performed

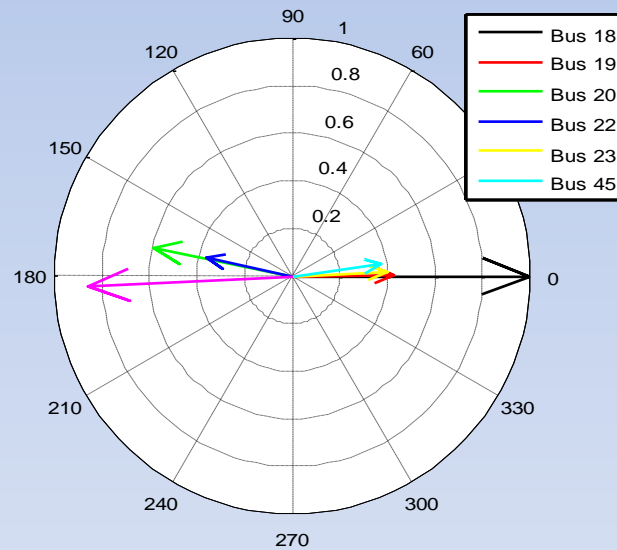
Results/Analysis

Model Results for 0.42 Hz Mode

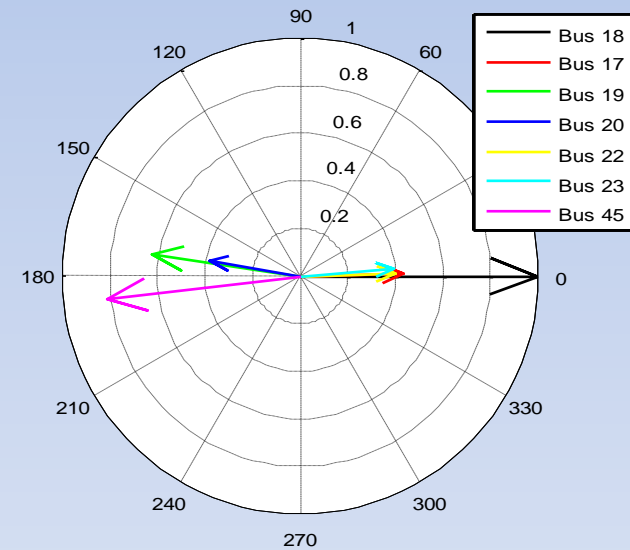
Mode Shape from ETFE Method Applied to 17 Machine Model



Actual 17 Machine Model Mode Shape

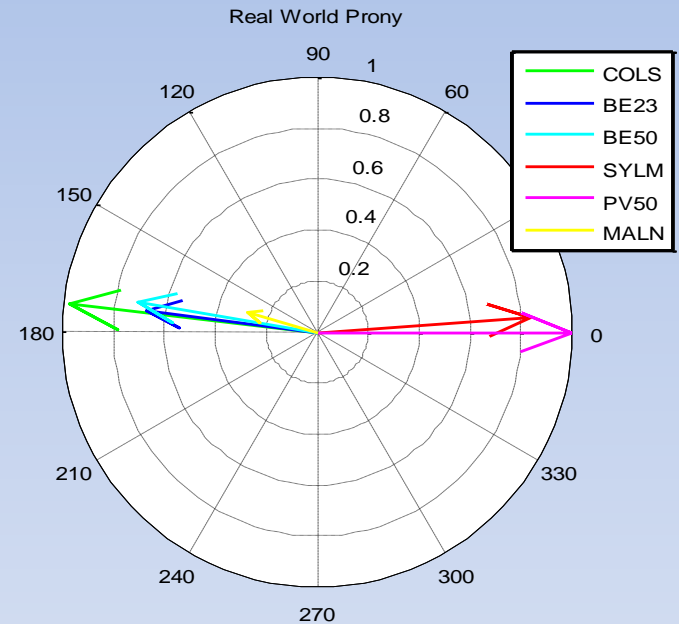
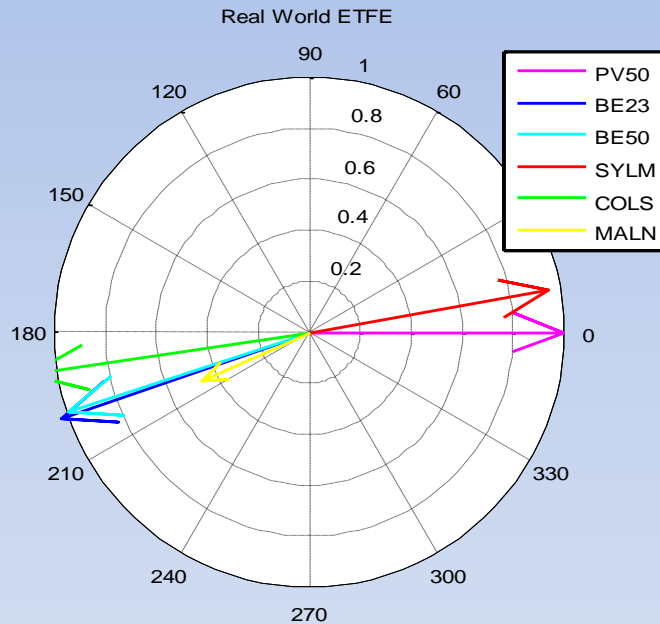


Mode Shape from Prony Analysis Applied to 17 Machine Model



Results/Analysis

Real World Results for 0.2520 Hz Mode



ETFE Results

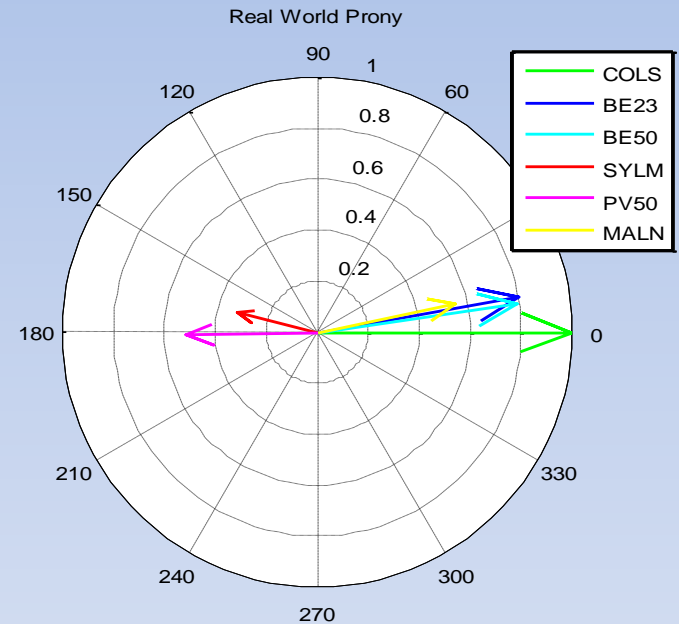
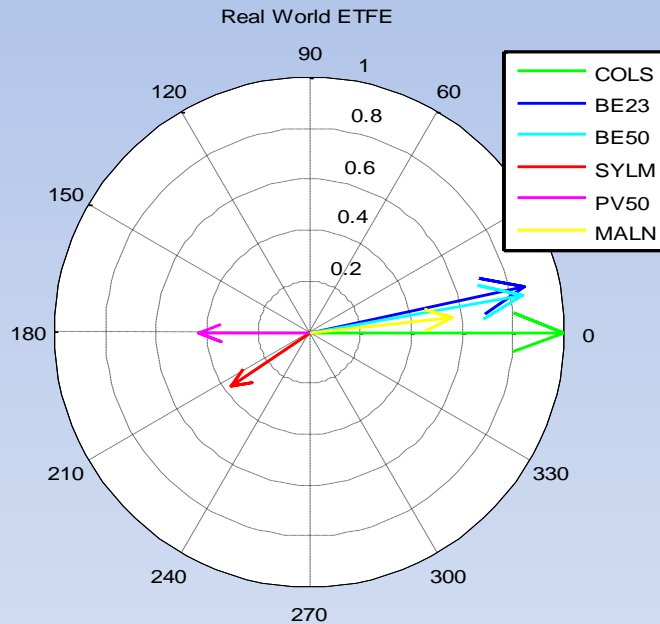
Bus	Magnitude	Phase	Equiv. Phase
MALN	0.4587	-2.7125	3.5707
BE23	1.0320	-2.8047	3.4785
BE50	0.9925	-2.8235	3.4597
SYLM	0.9516	0.1732	0.1732
PV50	1.0000	0.0000	0.0000
COLS	1.1114	-2.9888	3.2944

Prony Analysis Results

Bus	Magnitude	Phase
MALN	0.2832	2.8652
BE23	0.6744	3.0149
BE50	0.7110	2.9719
SYLM	0.8393	0.0700
PV50	1.0000	0.0000
COLS	0.9763	3.0259

Results/Analysis

Real World Results for 0.3700 Hz Mode



ETFE Results

Bus	Magnitude	Phase	Equiv. Phase
MALN	0.5671	0.1046	0.1046
BE23	0.8615	0.2063	0.2063
BE50	0.8485	0.1738	0.1738
SYLM	0.3735	-2.5277	3.7555
PV50	0.4329	-3.1354	3.1478
COLS	1.0000	0.0000	6.2832

Prony Analysis Results

Bus	Magnitude	Phase
MALN	0.5555	0.2039
BE23	0.8046	0.1681
BE50	0.7930	0.1416
SYLM	0.3241	2.9013
PV50	0.5133	3.1658
COLS	1.0000	6.2832

Conclusions About the ETFE Method

- Not as accurate as Prony analysis (higher bias)
- Accurate enough to provide system operators with valuable information
- Possesses key advantages
 - Computationally cheap
 - Requires only a small system disturbance
 - Phase measurements possessed low variance, standard deviation, and RMSE
- Should be considered a valuable tool for quickly and simply obtaining electromechanical mode shape information

Future Work

- Exploration of methods to reduce the bias of ETFE results

Questions

