Modeling Dynamic Response of Inverter-Based Resources Using Waveform Measurements

NASPI April Meeting (April 4, 2023)

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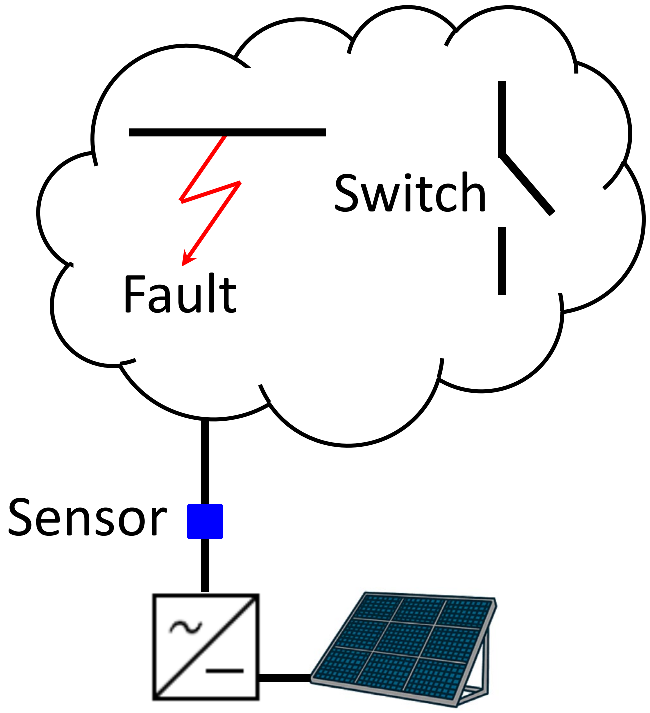
Associate Director, Winston Chung Global Energy Center

Acknowledgement: Fatemeh Ahmadi (Ph.D. Student)

Dynamic Response of Inverter-Based Resources

Grid Disturbances



Inverter-Based Resource (IBR)

Dynamic Response of Inverter-Based Resources

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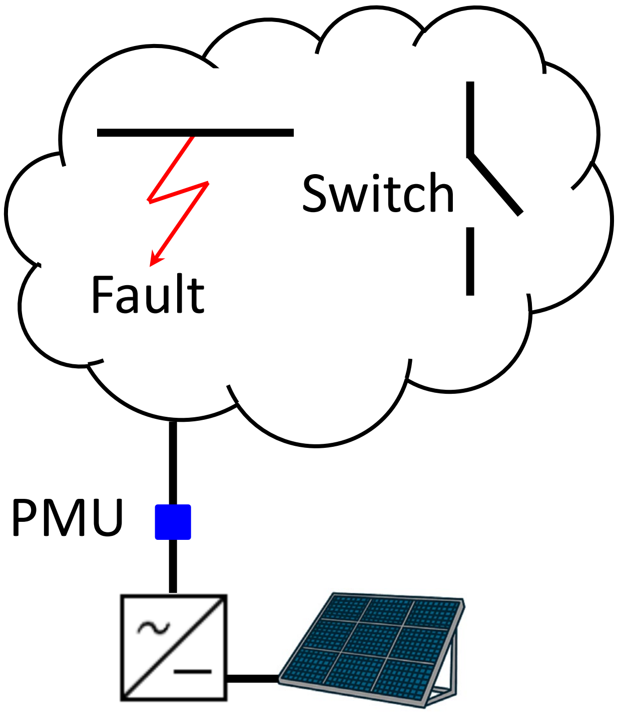
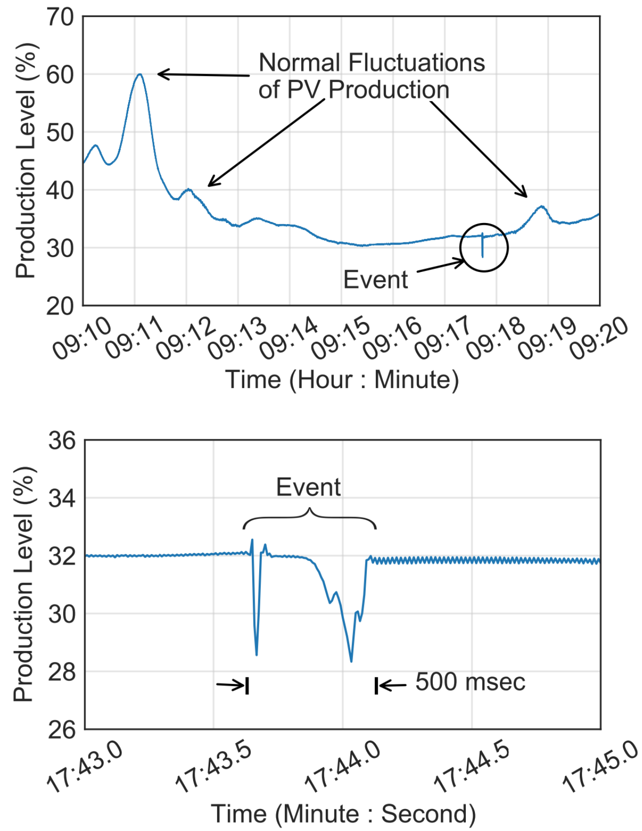


Inverter-Based Resource (IBR)

- Phasor-Level Dynamics [1]



[1] P. Khaledian and H. Mohsenian-Rad, "Automated Event Region Identification and its Data-Driven Applications in Behind-the-Meter Solar Farms Based on Micro-PMU Measurements," in *IEEE Trans. on Smart Grid*, May 2021.

Dynamic Response of Inverter-Based Resources

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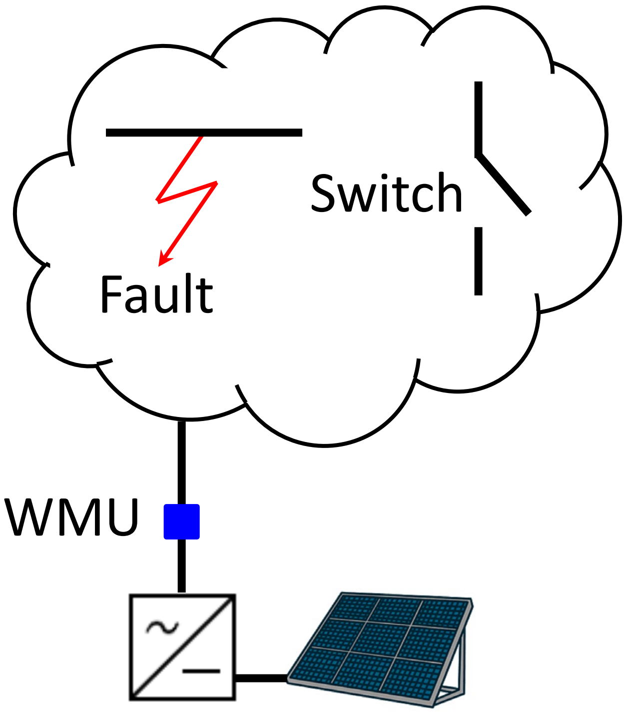
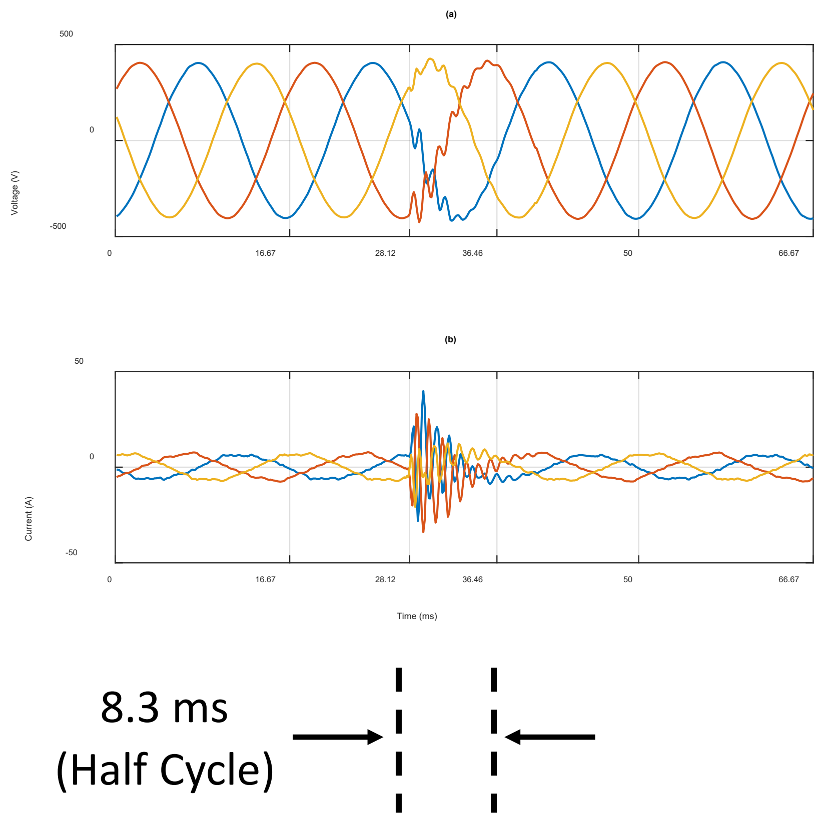


Inverter-Based Resource (IBR)

- Waveform-Level Dynamics [2]



[2] F. Ahmadi and H. Mohsenian-Rad, "Data-Driven Models for Sub-Cycle Dynamic Response of Inverter-Based Resources Using WMU Measurements," Submitted to *an IEEE Journal* (Under Review), January 2023.

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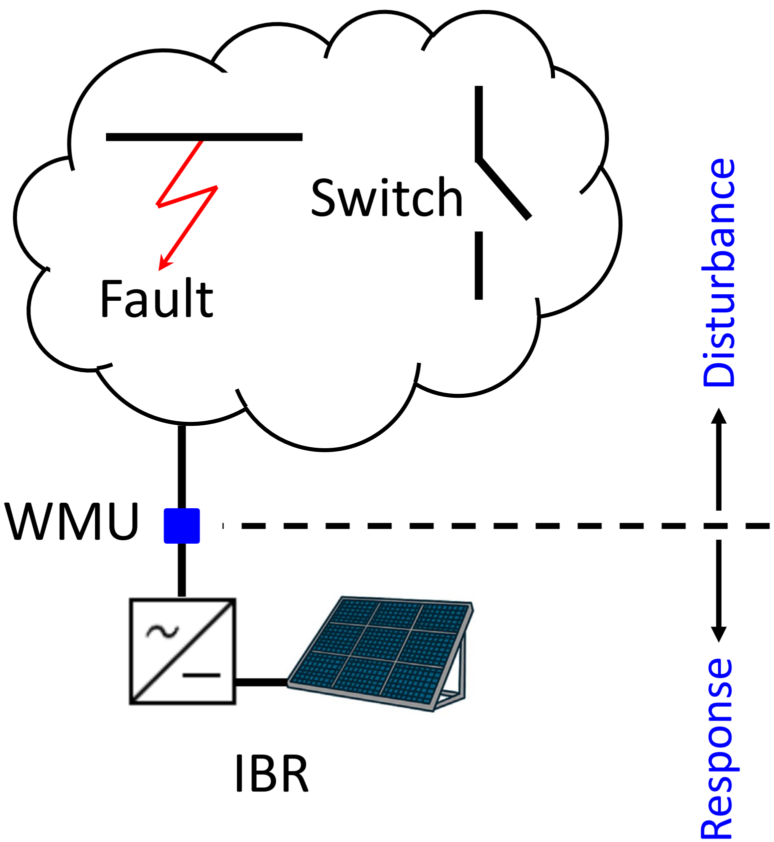

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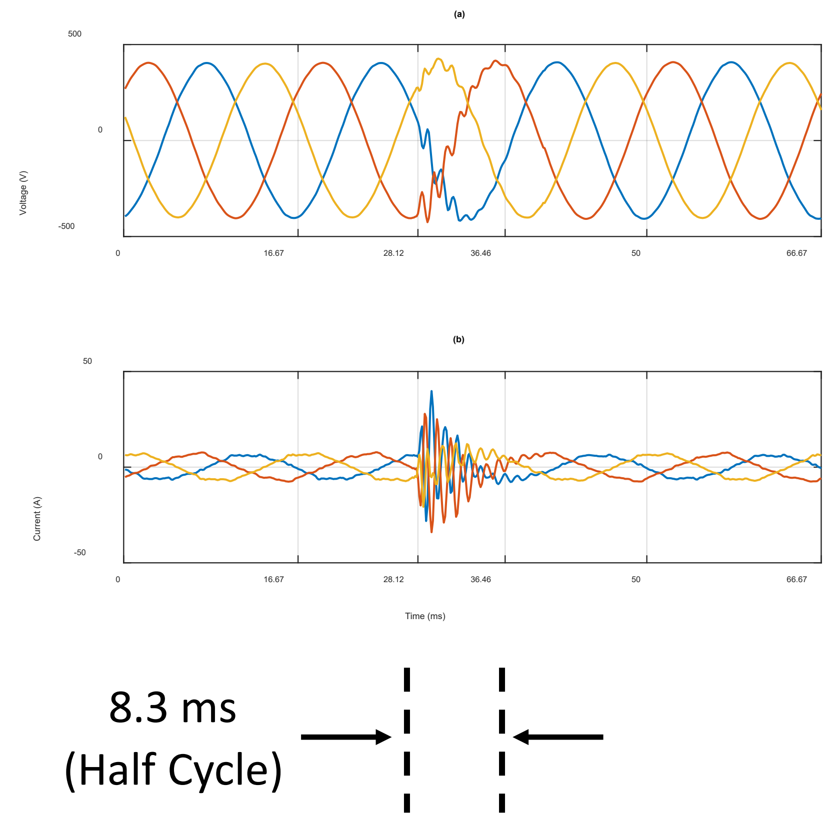

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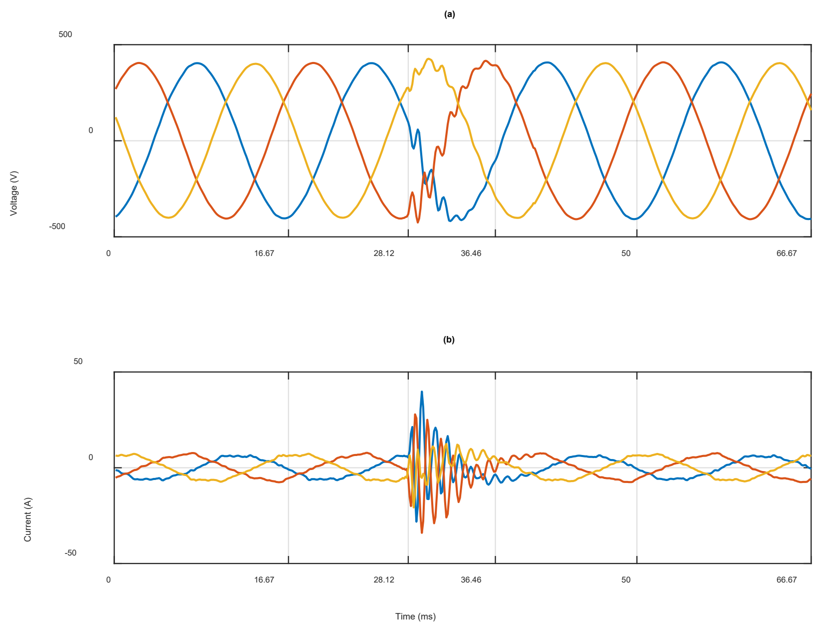
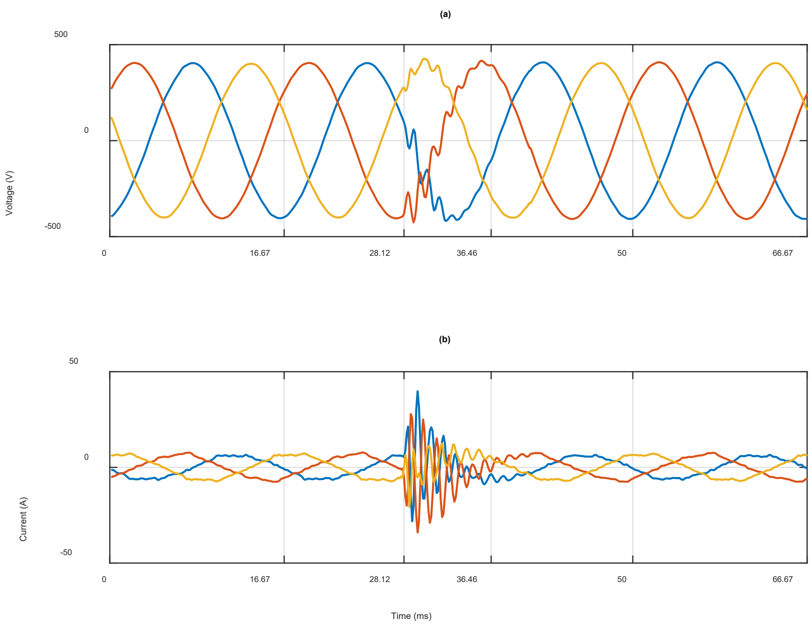
Dynamic Response of Inverter-Based Resources

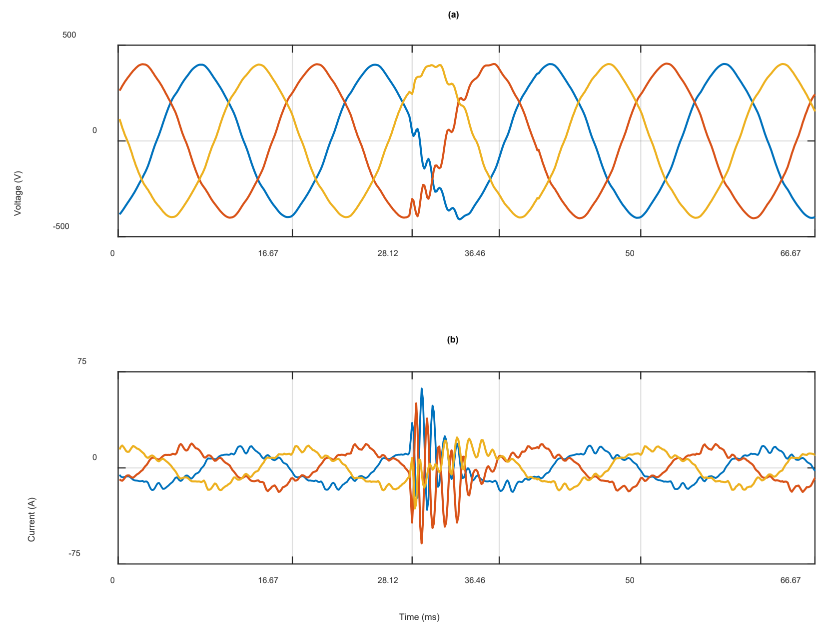
- **Q**: How do we know that this is a “Response” and not the “Cause”?



IBR 1 / WMU 1

- **Q**: How do we know that this is a “Response” and not the “Cause”?





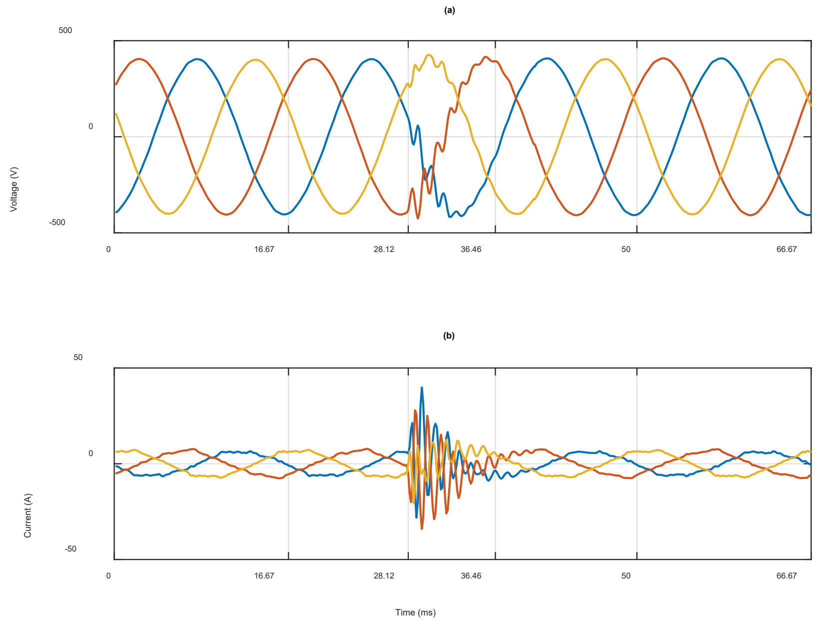
Synchro-Waveforms

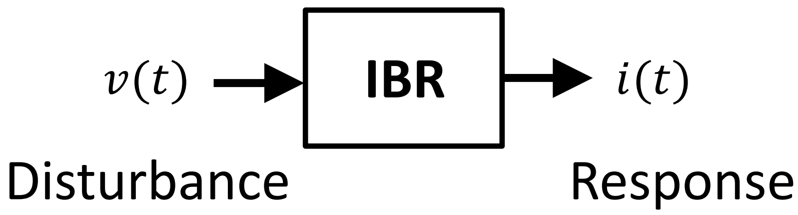
IBR 1 / WMU 1 ⟷ IBR 2 / WMU 2

Different Feeders, Similar Inverters, Different Sizes

Modeling Dynamic Response of IBRs

- **Q**: How can we **model** the IBR's sub-cycle dynamic response?





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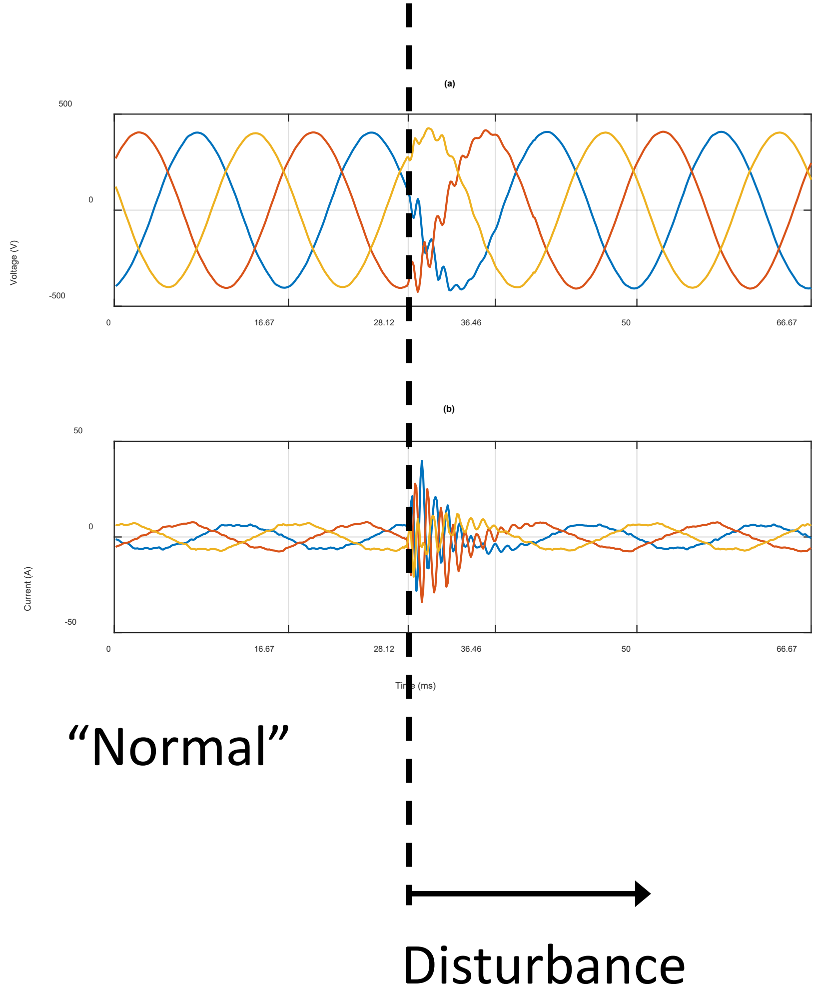
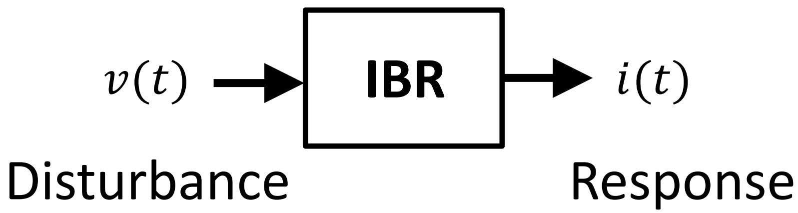


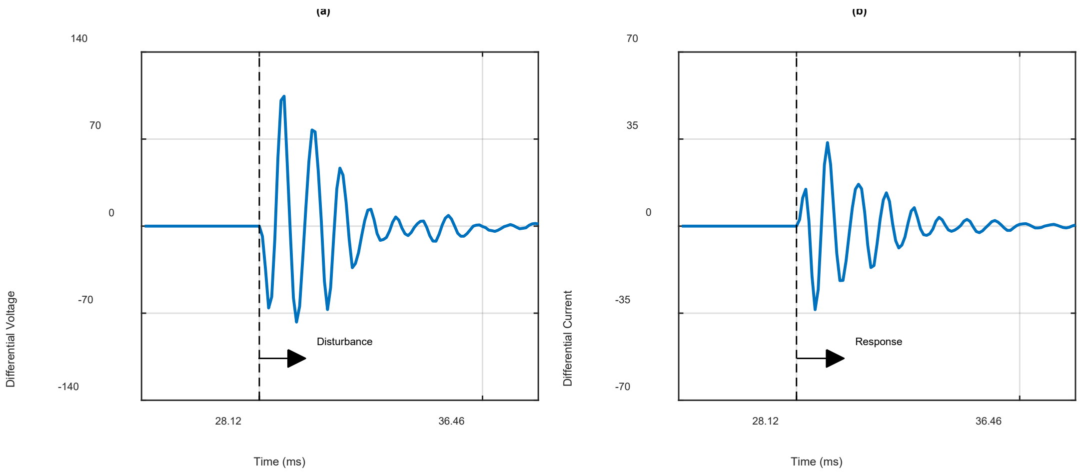


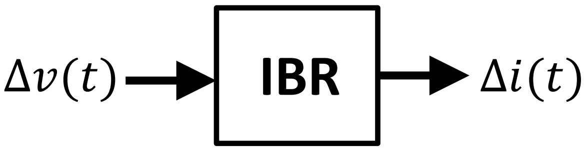
Differential Waveform Dynamics

- We use Differential Waveform to obtain the model:

$$\Delta x(t) = x(t) - x_{\text{ref}}(x)$$

Normal (e.g., Pre-Disturbance Cycle)





(Half Cycle)

Data-Driven Approach

- Field Data Set:
  - PV Unit: 480 V / 100 kW
  - Six Months of WMU Data

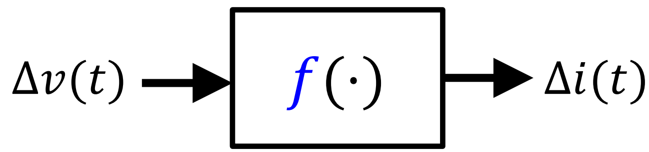
63 Disturbances (Differential Voltage and Current Waveforms)

→ 42 **Training** Data (Two Third)

→ 21 **Test** Data (One Third)

Data-Driven Approach

- **Option 1**: Single Model



Train $f(\cdot)$ to reach the best match between *all 42 pairs* of training data:

$$e_1(t) = \Delta i_1(t) - f(\Delta v_1(t))$$

$$e_1(t) = \Delta i_1(t) - f(\Delta v_1(t))$$

(Same Model)

$$\vdots$$

$$e_{42}(t) = \Delta i_{42}(t) - f(\Delta v_{42}(t))$$

Data-Driven Approach

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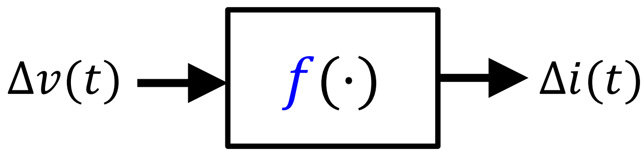

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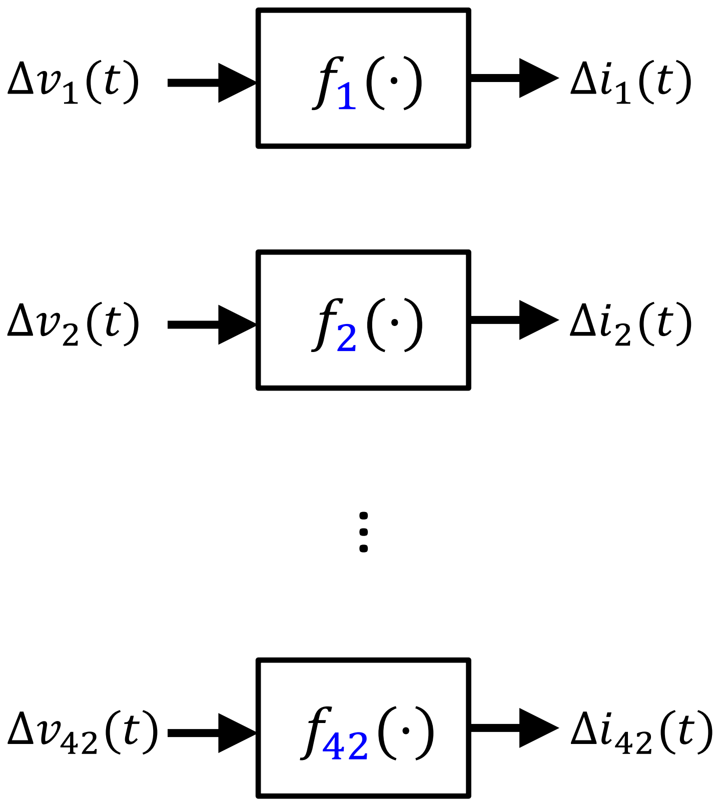
$$e_{42}(t) = \Delta i_{42}(t) - f(\Delta v_{42}(t))$$

Poor Performance!

Data-Driven Approach

- **Option 2**: Multiple Models



Data-Driven Approach

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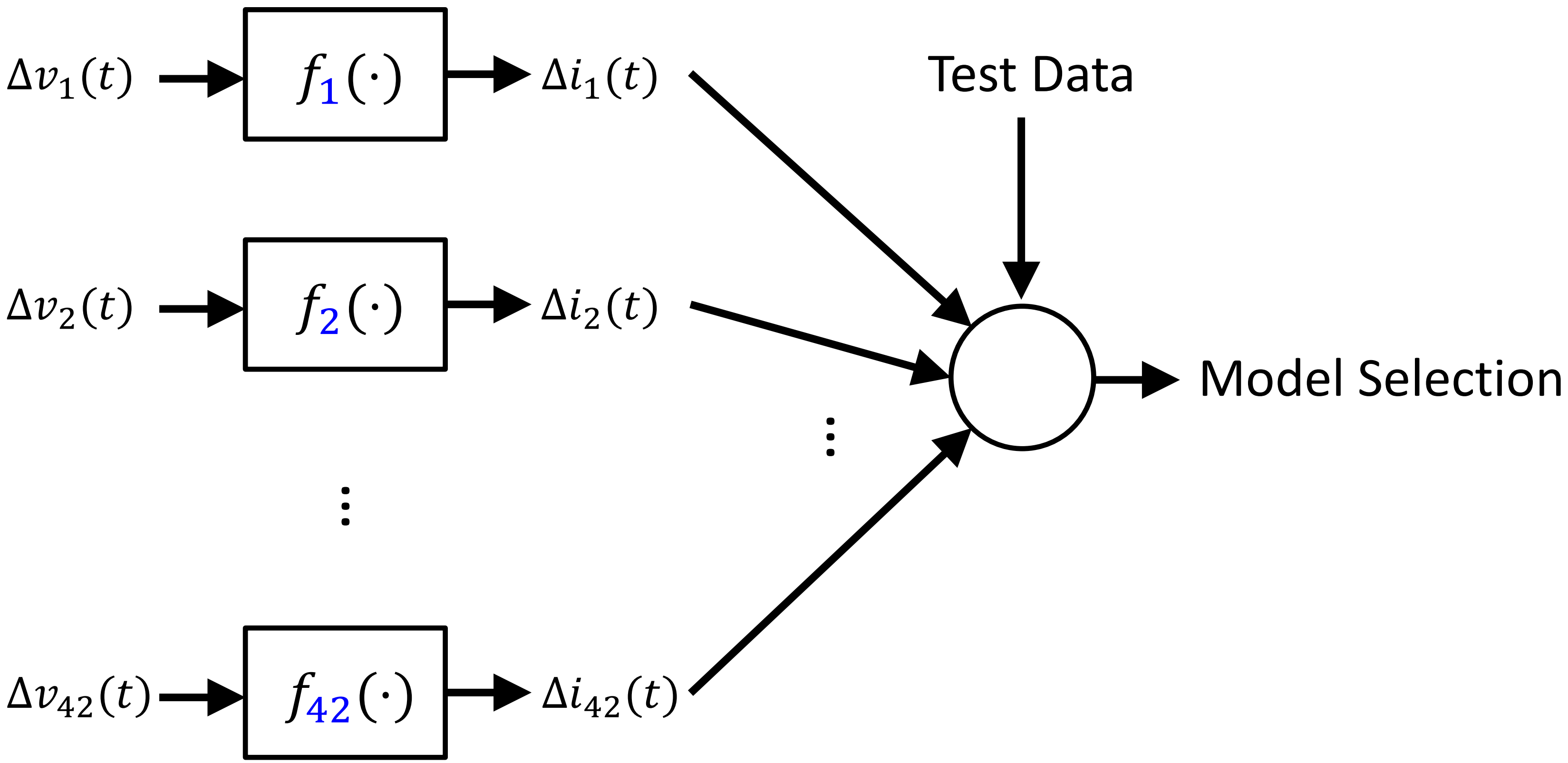

Data-Driven Approach

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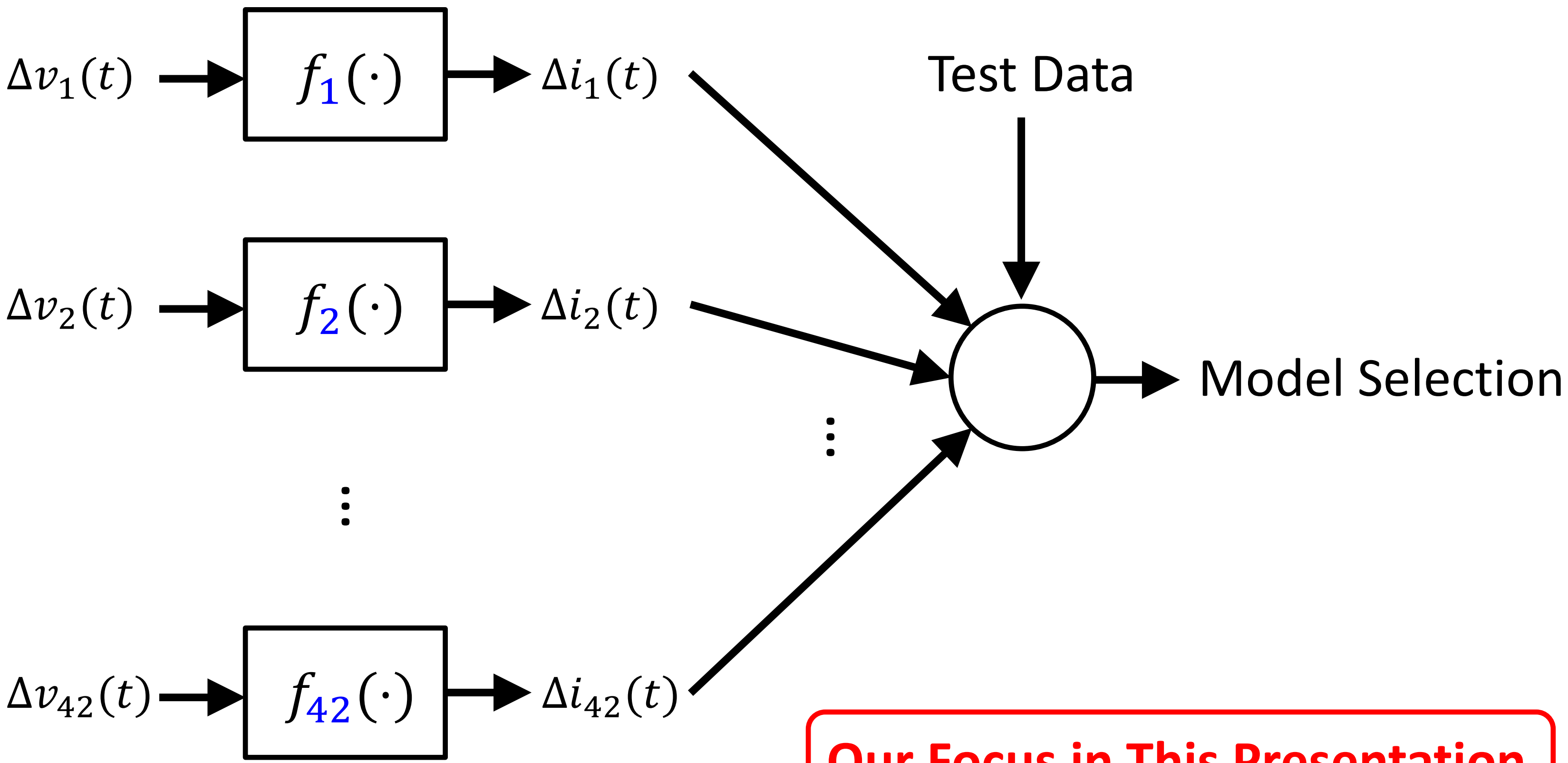
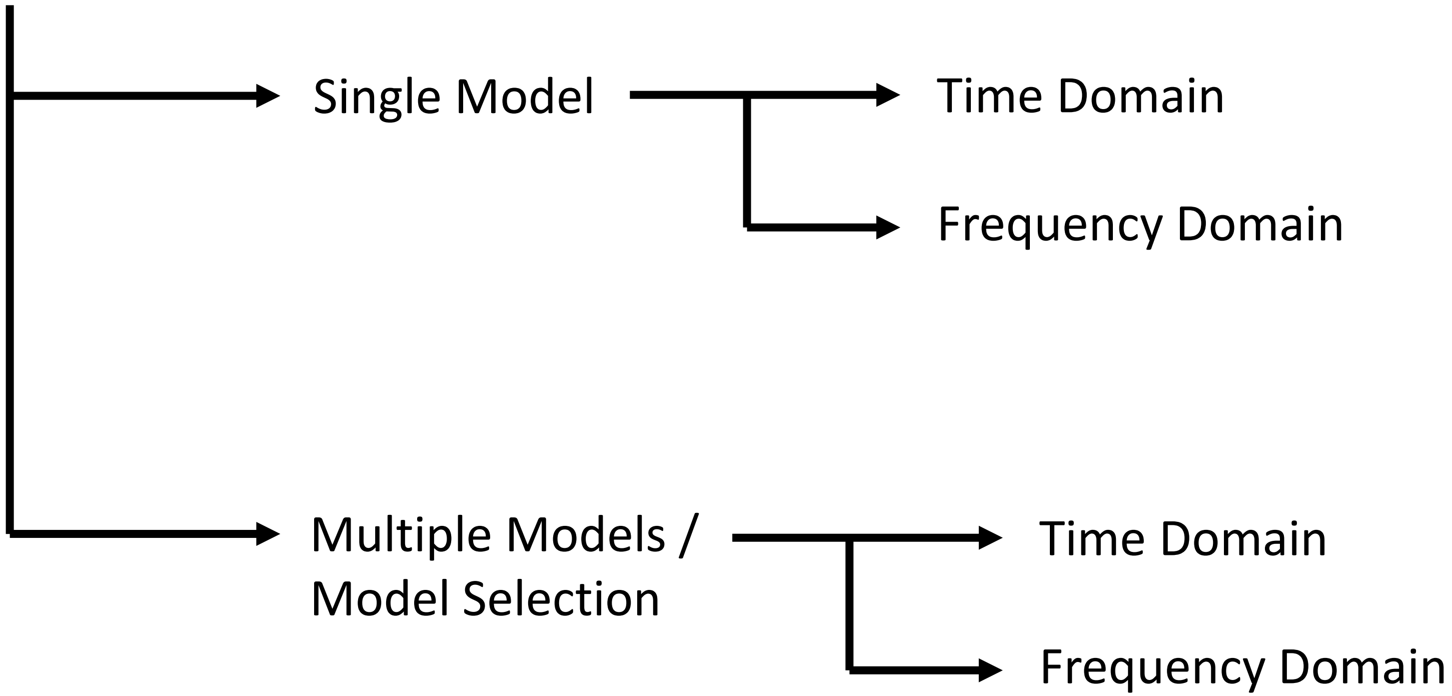


Our Focus in This Presentation

Data-Driven Approach

- Summary of Options[2]:



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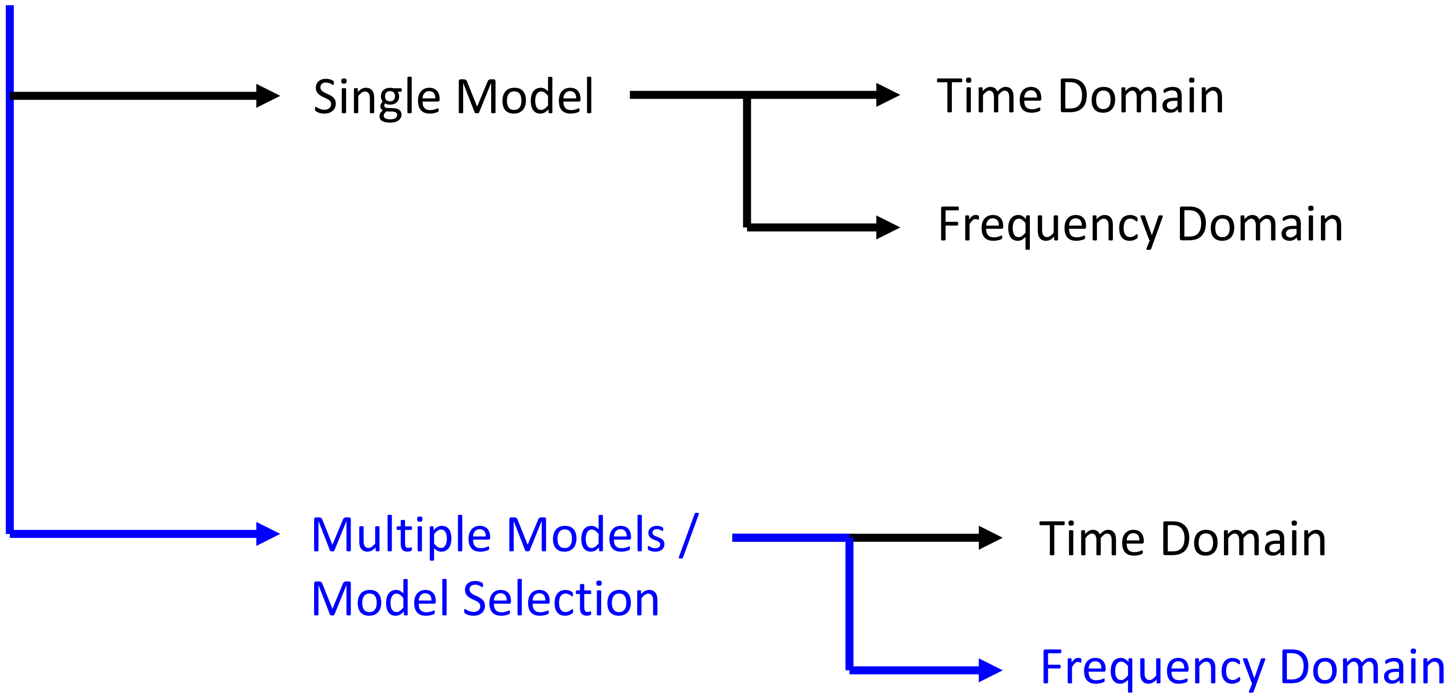

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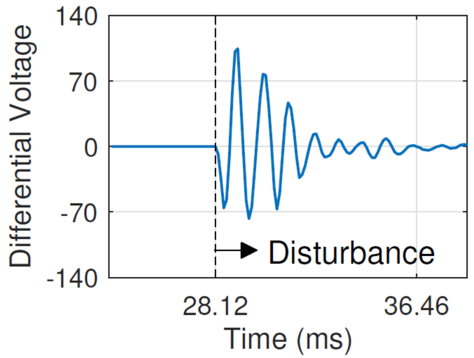
Step 1: Modal Analysis

- Consider one pair of training data: $\Delta v(t)$ and $\Delta i(t)$.

- Apply modal analysis (e.g., Prony Method) with M modes to obtain:

$$\Delta v(t) = \sum_{m=1}^{M} A_m e^{\sigma_m t} \cos(\omega_m t + \phi_m),$$

$$\Delta i(t) = \sum_{m=1}^{M} B_m e^{\sigma_m t} \cos(\omega_m t + \psi_m),$$



- At dynamic each mode m, we can define the equivalent admittance of the IBR at that particular mode $z_m = \sigma_m + j\omega_m$ as the following complex number:

$$\mathbf{H}_m = \frac{B_m \angle \psi_m}{A_m \angle \phi_m} = \frac{B_m}{A_m} \angle \left(\psi_m - \phi_m \right) \quad \text{at} \quad \sigma_m + j\omega_m.$$

Step 2: Library Construction

- Now consider all the $K = 42$ pairs of training data.

- We can construct a *library* of $K \times M$ dynamic models:

$$\mathbf{H}_m^k \quad \text{at} \quad z_m^k = \sigma_m^k + j\omega_m^k, \qquad \begin{array}{l} k = 1, \ldots, K, \\ m = 1, \ldots, M. \end{array}$$

- Each model corresponds to ***one*** dynamic mode that is derived from ***one*** disturbance; thus adding up to $K \times M$ models using modal analysis.

Step 3: Model Selection

- Let $\Delta v_{\text{test}}(t)$ and $\Delta i_{\text{test}}(t)$ denote the differential voltage and the differential current waveform for a given test disturbance.

- Apply modal analysis to the input test signal:

$$\Delta v_{\text{test}}(t) \longrightarrow \text{Dynamic Modes: } z_{n,\text{test}} = \sigma_{n,\text{test}} + j\omega_{n,\text{test}}$$

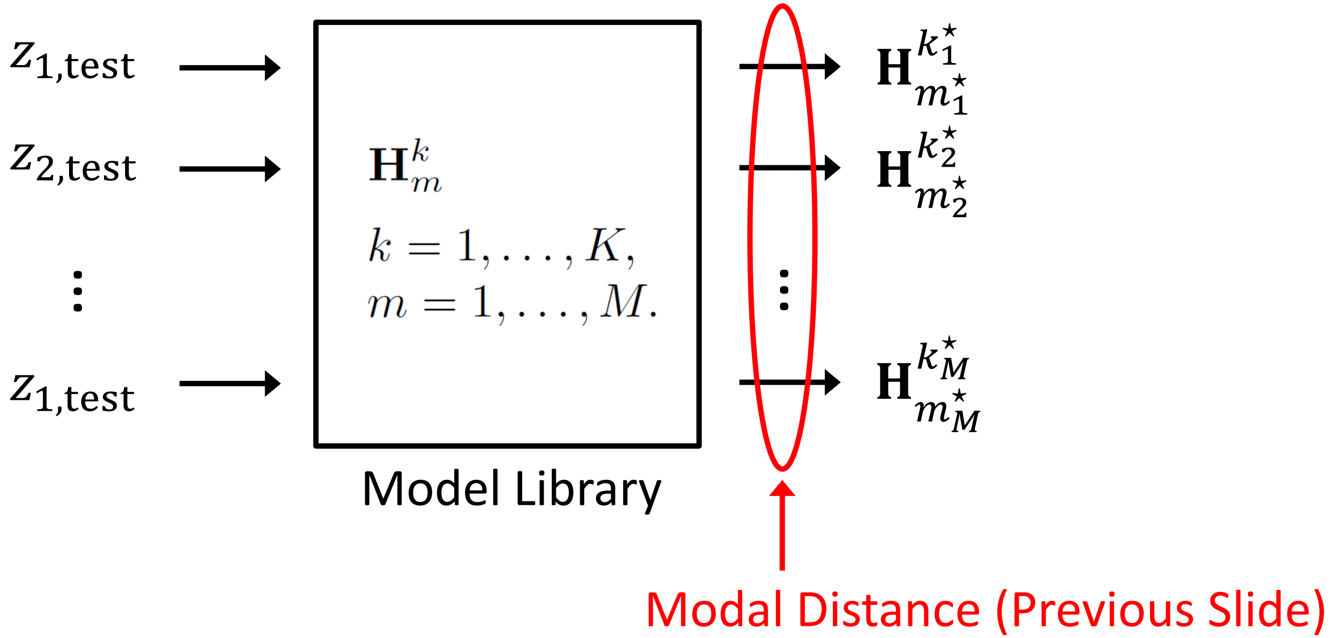
- For any such dynamic mode n, we obtain (based on input-voltage):

$$[\, k_n^\star, m_n^\star \,] = \underset{k,m}{\arg\min} \; \left| z_{n,\text{test}} - z_m^k \right|^2 .$$

(Minimum *Model* Distance)

Step 3: Model Selection (Cont.)

- Accordingly, we obtain n models corresponding to the n modes:



Step 4: Dynamic Response Estimation

- Given $\mathbf{H}_{m_1^\star}^{k_1^\star}, \mathbf{H}_{m_2^\star}^{k_2^\star}, \cdots, \mathbf{H}_{m_M^\star}^{k_M^\star}$ for each test input voltage signal $\Delta v_{\text{test}}(t)$.

- We estimate the output signal $\Delta i_{\text{test}}(t)$ as follows:

$$\hat{\Delta i}_{\text{test}}(t) = \sum_{n=1}^{M} C_n e^{\sigma_{n,\text{test}} t} \cos(\omega_{n,\text{test}} t + \varphi_n),$$

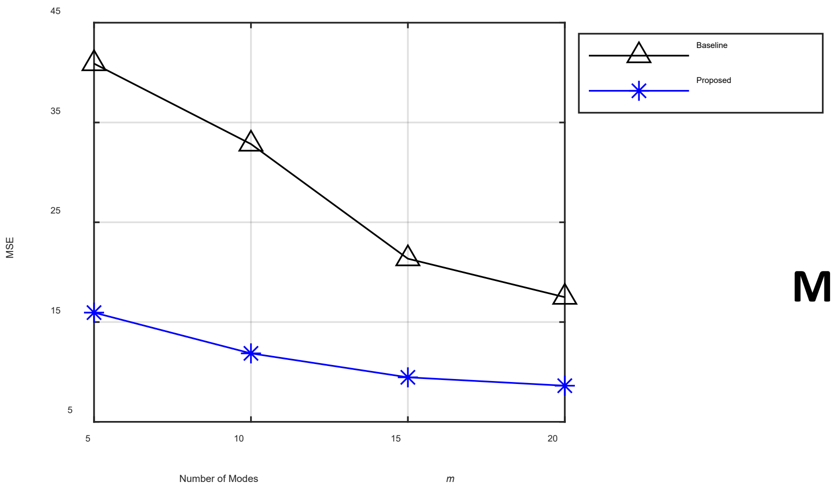
where

$$C_n = A_{n,\text{test}} \left| \mathbf{H}_{m_n^\star}^{k_n^\star} \right|, \quad \varphi_n = \phi_{n,\text{test}} + \angle \mathbf{H}_{m_n^\star}^{k_n^\star}.$$

Some Experimental Results

- Results best on 21 Test Disturbances (**Out-of-Sample Tests**)

- **Baseline method**: Single Model Approach

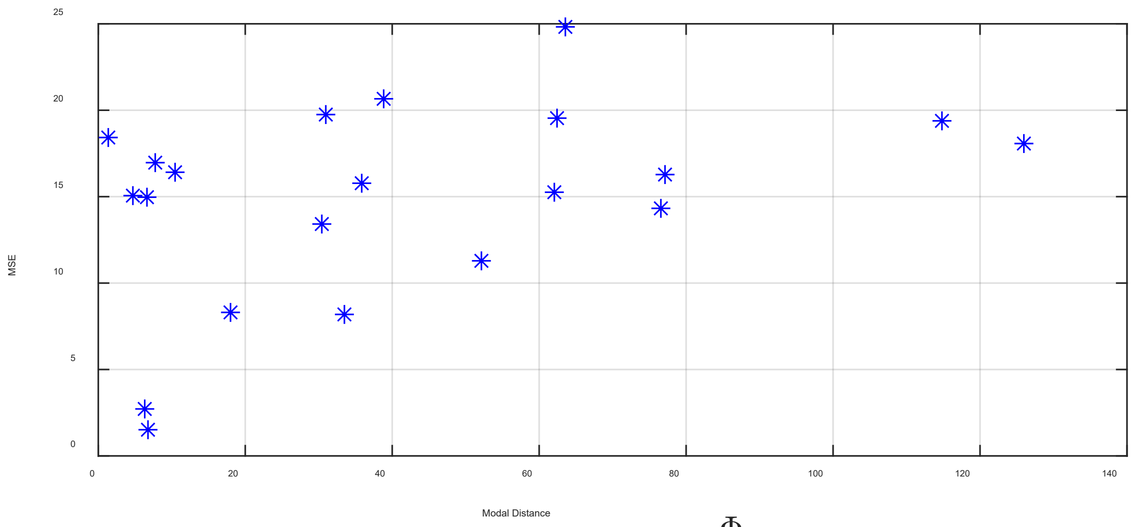


MSE = Mean Square Error

- Additional modes improve performance (bigger library).

Some Experimental Results

- Impact of **Modal Distance** (of Individual Test Samples):



$$\Phi = \sqrt{\sum_{n=1}^{M} \left| z_{n,\text{test}} - z_{m_n^\star}^{k_n^\star} \right|^2}$$

Φ

- Shorter modal distance (from library) leads to better output estimation.

Some Experimental Results

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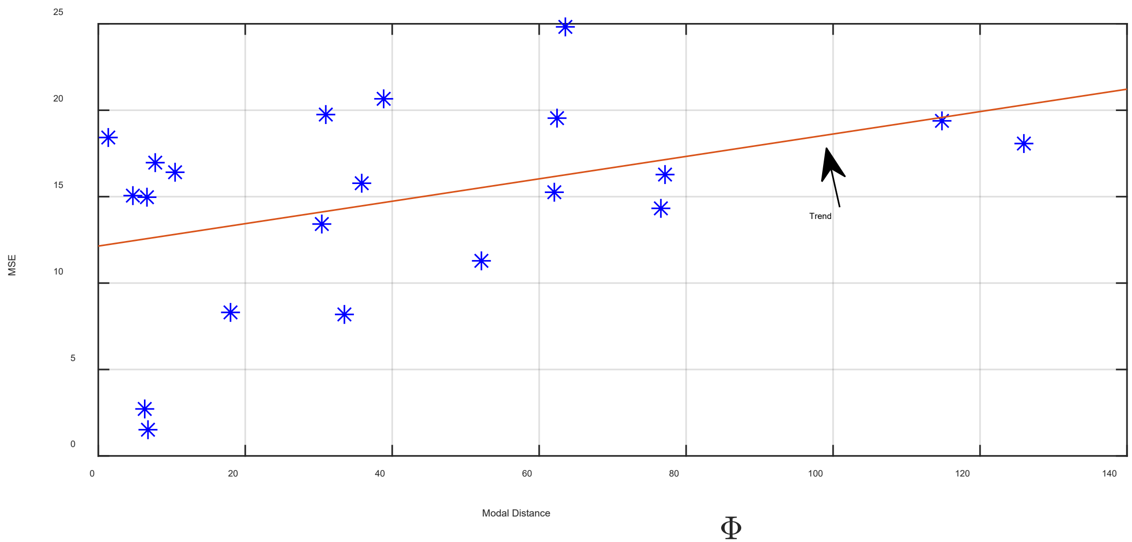

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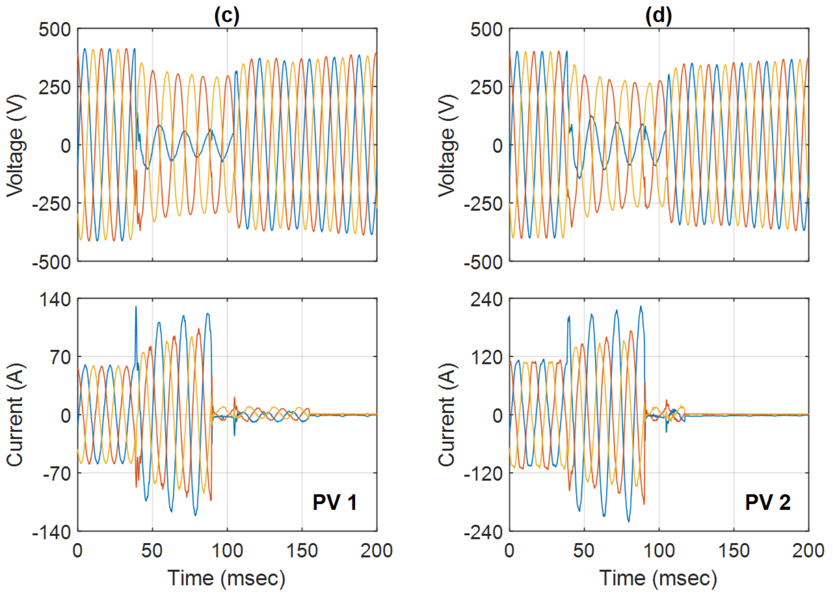
Some Potential Use Cases

- **1)** Dynamic Analysis of Individual IBRs (Diagnosis, Trip Prediction, etc.)
- **2)** Comparing Dynamic Response of IBRs (Synchro-Waveforms)
- **3)** Aggregate Dynamic Response
- **4)** Potential Ripple Effects
- **5)** Other (To be Explored)



IBR 1 / WMU 1

IBR 2 / WMU 2

Further Reading

- WMU-Based Dynamic Load Modeling (Will be Published Soon):

  F. Ahmadi and H. Mohsenian-Rad, “Data-Driven Models for Sub-Cycle Dynamic Response of Inverter-Based Resources Using WMU Measurements,” *Submitted to an IEEE Journal* (Under Review), January 2023.

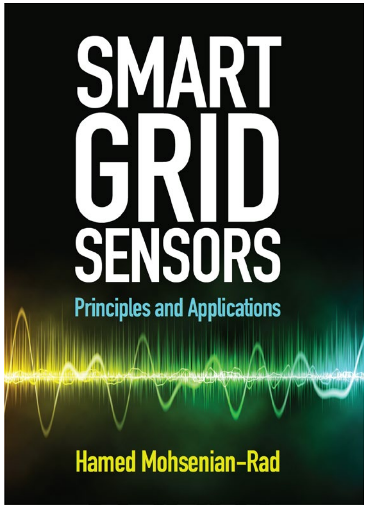
- WMUs and Synchro-Waveforms:

  [1] M. Izadi and H. Mohsenian-Rad, “Characterizing synchronized Lissajous curves to scrutinize power distribution synchro-waveform measurements,” in ***IEEE Trans. on Power Systems***, vol. 36, no. 5, p. 4880, Sept 2021.

  [2] M. Izadi and H. Mohsenian-Rad, “Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks,” in ***IEEE Trans. on Smart Grid***, vol. 13, May 2022.

  [3] M. Izadi and H. Mohsenian-Rad, “synchronous waveform measurements to locate transient events and incipient faults in power distribution networks,” in ***IEEE Trans. on Smart Grid***, vol. 12, no. 5, pp. 4295, Sept 2021.

Chapter 4



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Thank You!

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