Modeling Dynamic Response of Inverter-Based Resources Using Waveform Measurements

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Dynamic Response of Inverter-Based Resources

Grid Disturbances

Sensor

Inverter-Based Resource (IBR)

Fault

Switch
Dynamic Response of Inverter-Based Resources

- Phasor-Level Dynamics

Dynamic Response of Inverter-Based Resources

Grid Disturbances

- Waveform-Level Dynamics

Dynamic Response of Inverter-Based Resources

Grid Disturbances

• Waveform-Level Dynamics

Dynamic Response of Inverter-Based Resources

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

![Graphs showing dynamic response](image)
Dynamic Response of Inverter-Based Resources

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

![Synchro-Waveforms](image)

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?

![Graphs showing IBR voltage and current responses](image_url)

- **Figure (a):** Voltage response over time.
- **Figure (b):** Current response over time.

**Diagram:**

- **Input:** $v(t)$
- **System:** IBR
- **Output:** $i(t)$

**Disturbance Response Diagram:**

- **Displacement:** $v(t)$
- **System:** IBR
- **Response:** $i(t)$
Modeling Dynamic Response of IBRs

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

\[
v(t) \rightarrow \text{IBR} \rightarrow i(t)
\]

Disturbance Response

“Normal” Disturbance

\[
\text{Voltage (V)}
\]

\[
\text{Current (A)}
\]

Time (ms)
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)

\[\text{(Half Cycle)}\]
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

\[ \Delta v(t) \xrightarrow{f(\cdot)} \Delta i(t) \]

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

\[
\begin{align*}
e_1(t) &= \Delta i_1(t) - f(\Delta v_1(t)) \\
e_1(t) &= \Delta i_1(t) - f(\Delta v_1(t)) \\
\vdots \\
e_{42}(t) &= \Delta i_{42}(t) - f(\Delta v_{42}(t))
\end{align*}
\]
Data-Driven Approach

- **Option 1**: Single Model

\[ \Delta v(t) \xrightarrow{f(\cdot)} \Delta i(t) \]

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

\[
e_1(t) = \Delta i_1(t) - f(\Delta v_1(t))
\]

\[
e_1(t) = \Delta i_1(t) - f(\Delta v_1(t)) \quad \text{(Same Model)}
\]

\[
\vdots
\]

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

**Poor Performance!**
Data-Driven Approach

- **Option 2**: Multiple Models

\[
\begin{align*}
\Delta v_1(t) & \rightarrow f_1(\cdot) \rightarrow \Delta i_1(t) \\
\Delta v_2(t) & \rightarrow f_2(\cdot) \rightarrow \Delta i_2(t) \\
\vdots \\
\Delta v_{42}(t) & \rightarrow f_{42}(\cdot) \rightarrow \Delta i_{42}(t)
\end{align*}
\]
Option 2: Multiple Models

\[
\Delta v_1(t) \xrightarrow{f_1(\cdot)} \Delta i_1(t) \\
\Delta v_2(t) \xrightarrow{f_2(\cdot)} \Delta i_2(t) \\
\vdots \\
\Delta v_{42}(t) \xrightarrow{f_{42}(\cdot)} \Delta i_{42}(t)
\]
Data-Driven Approach

- **Option 2**: Multiple Models

\[
\Delta v_1(t) \xrightarrow{f_1(\cdot)} \Delta i_1(t) \\
\Delta v_2(t) \xrightarrow{f_2(\cdot)} \Delta i_2(t) \\
\vdots \\
\Delta v_{42}(t) \xrightarrow{f_{42}(\cdot)} \Delta i_{42}(t)
\]

Test Data \rightarrow Model Selection

**Our Focus in This Presentation**
Data-Driven Approach

• Summary of Options²:

Data-Driven Approach

• Summary of Options\(^2\):

- Single Model
  - Time Domain
  - Frequency Domain
- Multiple Models / Model Selection
  - Time Domain
  - Frequency Domain

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:

  $$
  H_m = \frac{B_m \angle \psi_m}{A_m \angle \phi_m} = \frac{B_m}{A_m} \angle (\psi_m - \phi_m) \text{ at } \sigma_m + j\omega_m.
  $$
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:

$$H^k_m \text{ at } z^k_m = \sigma^k_m + j\omega^k_m, \quad k = 1, \ldots, K, \quad m = 1, \ldots, M.$$ 

- 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:

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

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

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

(Minimum Model Distance)
Step 3: Model Selection (Cont.)

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

\[ H_{m_k}^k \]

\[ H_{m_2}^{k_2} \]

\[ H_{m_M}^{k_M} \]

\[ z_1^{test}, z_2^{test}, \ldots, z_1^{test} \]

Model Library

Modal Distance (Previous Slide)
Step 4: Dynamic Response Estimation

- Given $H_{m_1^*}^{k_1^*}, H_{m_2^*}^{k_2^*}, \ldots, H_{m_M^*}^{k_M^*}$ 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

$$C_n = A_{n,\text{test}} |H_{m_n^*}^{k_n^*}|, \quad \varphi_n = \phi_{n,\text{test}} + \angle H_{m_n^*}^{k_n^*}.$$
Some Experimental Results

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

- **Baseline method**: Single Model Approach

- Additional modes improve performance (bigger library).

MSE = Mean Square Error
Some Experimental Results

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

\[ \Phi = \sqrt{\sum_{n=1}^{M} \left| \tilde{z}_{n,\text{test}} - \tilde{z}_{m_n^*} \right|^2} \]

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

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

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

\[
\Phi = \sqrt{\sum_{n=1}^{M} \left| z_{n,\text{test}} - z_{m_n}^* \right|^2}
\]

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

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


- **WMUs and Synchro-Waveforms:**


Thank You!

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