Harmonic Enhanced Load Modeling and Data Generation

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Acknowledgment

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  ▪ Title: Continual Harmonic-Enhanced Load Modeling (HELM) project
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• PNNL Team
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What We Cover Today

• Harmonic Load Models
  - Harmonics in loads
  - Impact of harmonics
  - Gaps in existing models
• The HELM approach
• Current results and plan
Harmonics: Concept

- Power system is designed to operate at frequency of 60Hz (fundamental).
- Harmonics are the integer multiples of the fundamental (*typically, only odd*)

\[
s(t) = \sum_{k=-\infty}^{+\infty} S[k] \cdot (\cos(k \omega t) + j \sin(k \omega t))
\]

*Fourier series establishes the equivalence between time-domain and frequency domain, for periodic waveforms*
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Example: current waveform of a desktop computer
Harmonics: Sources

• Major source of harmonics are different nonlinear loads and devices

• Power-electronic loads:

  - Adjustable Speed Drives (ASDs) THD 28%
  - Line Commutated Converter THD 30%
  - Voltage Source Converters (high power) THD 33%

• Other nonlinear loads:

  - Transformer THD 76%
  - Fluorescent lamp THD 18%
  - Induction motor loads THD 10%
    (air-conditioner) THD 6%
    (refrigerator)

Grady, "Understanding Power System Harmonics", UT Austin, 2012
Effects of Harmonics in Grid

• Overheated transformers (current harmonics)

• Harmonics lead to inaccuracies in ZIP models

• Blowing of capacitor fuses (voltage harmonics)

• Distributed generation (DG) increases harmonics

17% loss in transformer kVA rating due to eddy current loss factor of 0.1

63% error in ZIP model at 5% THD in voltage [McLorn et al, 2017]

40% increase in capacitor RMS current due to 10% THD in voltage

Tian et al, 2017, demonstrated the impact of growing penetration of power-electronic distributed generation on the THD of the network voltages

Grady, "Understanding Power System Harmonics", UT Austin, 2012
Tian, et al, "Harmonic reduction via optimal power flow and the frequency coupling matrix", 2017
Gaps in Existing Load Models

• **Conventional ZIP**: constant impedance (Z), current (I), and power (P), evaluated only at the fundamental frequency

\[ S \approx S_1 \]
\[ = V_1 \cdot I_1 \]
\[ = a V_1^2 + b V_1 + c \]
Gaps in Existing Load Models

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- **Adjusted ZIP**: small multiplying factor to account for current harmonics
  - No consideration of voltage harmonics
  - Only cumulative, not individual harmonics
  \[ S \approx V_1 \cdot (I_1 + I_H) \]
  \[ = S_1 (1 + \alpha) \]

RMS of only the fundamental components

allow a small correction factor, accounting for harmonics in current
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- **Norton Model**: linear relationship between corresponding harmonic components of the load current and voltage
  - No cross-coupling between current and voltage harmonic components
  \[ S \approx \sum_{k=1}^{k_m} V_k I_k \]
  \[ = \sum_{k=1}^{k_m} y_{kk} V_k^2 \]
  \[ I_k = y_{kk} V_k \]
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• Harmonic Load Models
• The HELM approach
• Current results and plan

- Overall framework
- HELM modeling algorithms
- Setup for data generation
Proposed HELM Framework

Electromagnetic modeling of PE and other resources, and synthetic data generation

Use time-series (point-on-wave) measurements to develop the harmonic-enhanced models, using optimization and machine learning (ML) methods

$S = f (V_1, V_3, V_5, \ldots)$

Harmonics-Enhanced Load Model (HELM)

Demonstrate the impact of model enhanced model on operations. Example: transformer overheating, optimal dispatch

Use-Case Demonstration (economic dispatch)

Continually enhanced load models

Sensor measurements (current, voltage, power)

Data Generation and Validation
Harmonic-Enhanced Modeling: Frequency Coupling Matrix & Linear Regression

• Frequency Coupling Matrix (FCM)
  - Allows cross-coupling between load current and voltage, via a linear relationship
  - Also generalized Norton model, cross admittance matrix, harmonic admittance matrix
  - Linear regression (least squares) algorithm to identify the FCM from data

\[
S \approx \sum_{k=1}^{k_m} V_k I_k \\
= \sum_{k=1}^{k_m} \sum_{l=1}^{k_m} y_{kl} V_k V_l
\]

\[
\begin{bmatrix}
I_1 \\
I_3 \\
\vdots \\
I_{km}
\end{bmatrix}
= 
\begin{bmatrix}
y_{11} & y_{13} & \cdots & y_{1,k_m} \\
y_{31} & y_{33} & \cdots & y_{3,k_m} \\
\vdots & \vdots & \ddots & \vdots \\
y_{km,1} & y_{km,3} & \cdots & y_{km,k_m}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_3 \\
\vdots \\
V_{km}
\end{bmatrix}
\]

Drawback: assumes linearity in relationship between harmonics
Harmonic-Enhanced Modeling: Nonlinear Regression via Neural Network

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  ▪ Allows cross-coupling between load current and voltage, via a linear relationship
  ▪ Also generalized Norton model, cross admittance matrix, harmonic admittance matrix
  ▪ Linear regression (least squares) algorithm to identify the FCM from data

• Nonlinear Coupling Model
  ▪ Allows cross-coupling between load current and voltage, via a nonlinear relationship
  ▪ Feedforward neural networks to perform nonlinear regression analysis

\[
\begin{bmatrix}
I_1 \\
I_3 \\
\vdots \\
I_{k_m}
\end{bmatrix} =
\begin{bmatrix}
f_1(V_1, V_3, \ldots, V_{k_m}) \\
f_3(V_1, V_3, \ldots, V_{k_m}) \\
\vdots \\
f_{k_m}(V_1, V_3, \ldots, V_{k_m})
\end{bmatrix}
\]

More generalized model, but possibly higher data requirement
**Synthetic Data Generation**

- PSCAD-based simulation models for feeder-wide interaction between multiple houses with PE and nonlinear loads: laptop, desktop, HVAC, PV inverter
- Generate synthetic harmonics data by varying the terminal voltage THD

- Address dearth of feeder-wide data in harmonic studies
- Capture the impact and interactions of emerging PE load
Synthetic Data Generation

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Switches used to create various load compositions and harmonic patterns in each house
Synthetic Data Generation

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What We Cover Today

• Harmonic Load Models
• The HELM approach
• Current results and plan
  - Validation results
  - Ongoing work
Results: Accuracy of FCM (linear regression)

- **Accuracy** of the identified harmonic load models
- **Low reconstruction loss** (largely <1%) across all cases
- Reconstructed current signal closely matches observation

- Contribution of non-fundamental harmonic components to power
- Parasitic power observed to be 2-3% of the ZIP load estimate (i.e., the fundamental power)

Parasite power is the cumulative contributions to power from all non-fundamental harmonics

**Accurate estimate of harmonic load model. Improvement over ZIP.**
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**Accurate estimate of harmonic load model. Improvement over ZIP.**
Results: Real data and neural network model

- Real data from MIT REDD 2011 study used for validating neural net models
  - Single house measurement over 1 month used for validation
  - Different load compositions (clusters) identified based on harmonic patterns
  - Comparing least squares (LS) and machine learning (ML) methods for accuracy

Nonlinear model outperforms linear FCM under high data environment

- ML-based nonlinear regression model requires high data
- ML (nonlinear) outperforms LS (linear) in load composition 1 with most data-points
- LS outperforms ML in load composition 5 with the fewest data-points
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Nonlinear model outperforms linear FCM under high data environment
Continuing directions and outreach

• **Continual update** of load models
  - Methods such as recursive least squares and transfer learning for online updates

• **Studying the feeder-level impact** of harmonics
  - Eddy (harmonic) current losses causing **overheated transformers**
  - Inaccurate load models leading to **sub-optimal dispatch** of DERs
  - Extension to T+D studies with aggregated harmonic models

• **Real-world experimental data** collections and validation
  - Ongoing discussions to collect house-level harmonic measurements at varying voltage

• **Publication** (ISGT 2022):
Thank you

Questions?

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