Harmonic Enhanced Load Modeling and Data Generation

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Acknowledgment

- **Sponsor**:
  - *Sensor Technologies and Data Analytics Program* (US DOE OE)
  - **Title**: Continual Harmonic-Enhanced Load Modeling (HELM) project
  - **Project Period**: FY21-FY22 (ongoing)

- **PNNL Team**
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What We Cover Today

- **Harmonic Load Models**
- The HELM approach
- Current results and plan

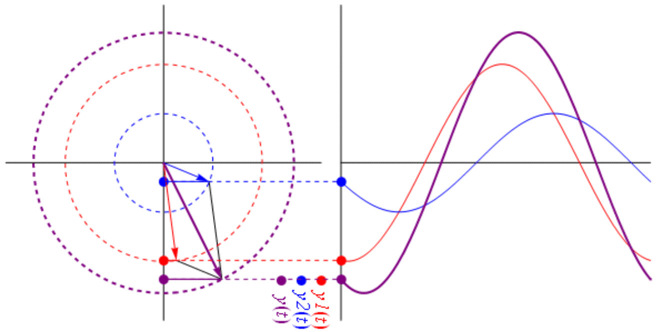
- Harmonics in loads
- Impact of harmonics
- Gaps in existing models

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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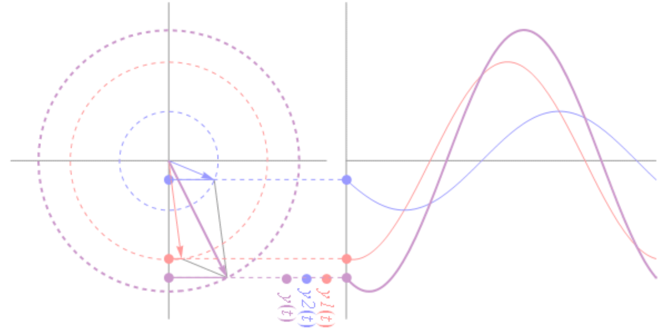

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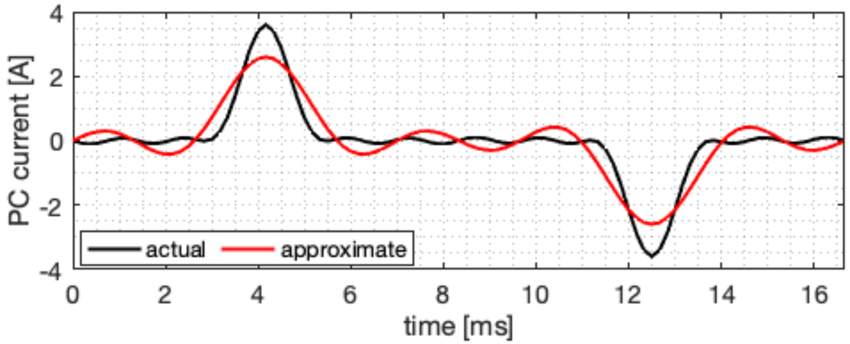
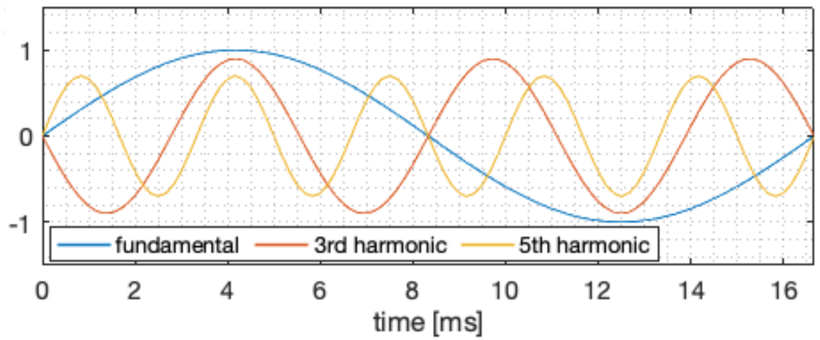
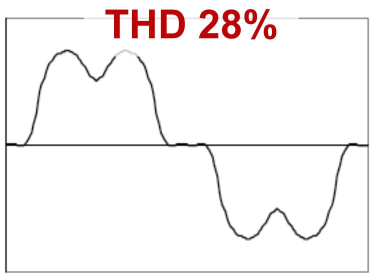
Example: current waveform of a desktop computer



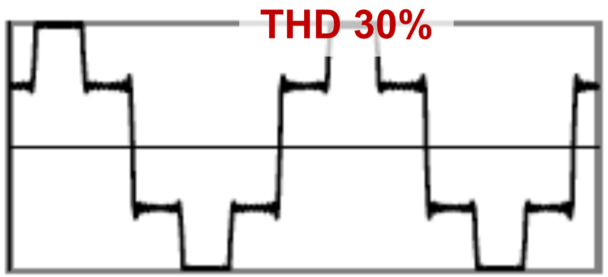


Harmonics: Sources

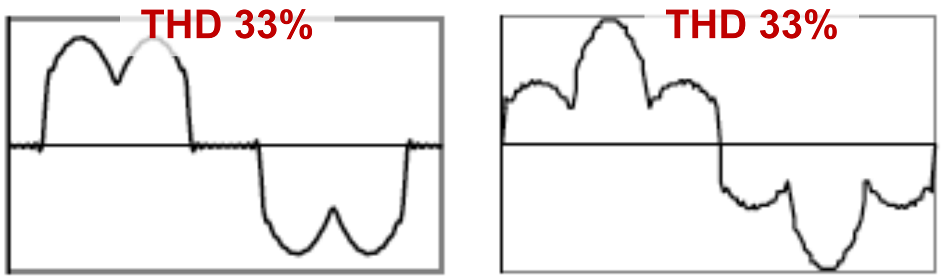
- Major source of harmonics are different nonlinear loads and devices
- Power-electronic loads:



Adjustable Speed Drives (ASDs)

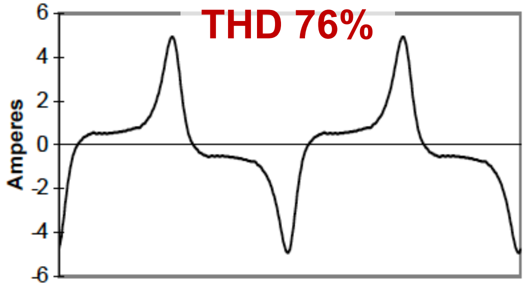


Line Commutated Converter

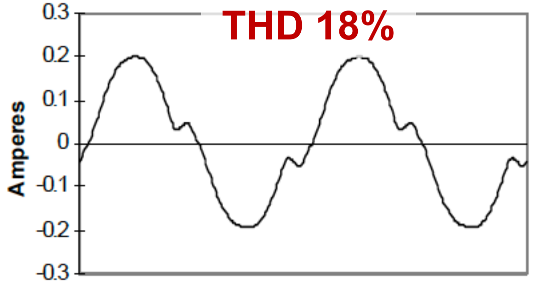


Voltage Source Converters (high power)

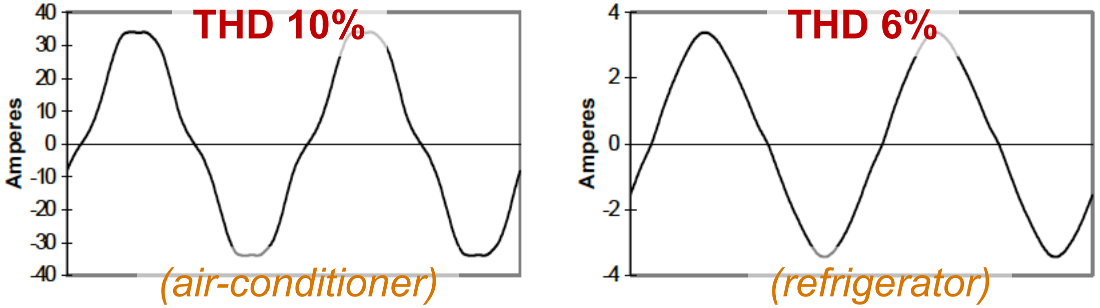
- Other nonlinear loads:



Transformer



Fluorescent lamp



Induction motor loads

Grady, "Understanding Power System Harmonics", UT Austin, 2012

Effects of Harmonics in Grid

- Overheated transformers (*current harmonics*)

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

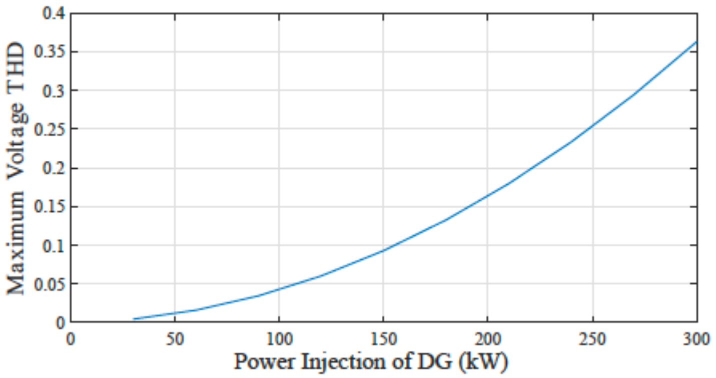
- Harmonics lead to inaccuracies in ZIP models

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

- Blowing of capacitor fuses (voltage harmonics)

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

- Distributed generation (DG) increases harmonics



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
McLorn, et al, "Enhanced ZIP load modelling for the analysis of harmonic distortion under Conservation Voltage Reduction", 2017

Gaps in Existing Load Models

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

$$
\begin{aligned}
S &\approx S_1 \\
&\boxed{= V_1 \cdot I_1} \\
&= a\,V_1^2 + b\,V_1 + c
\end{aligned}
$$

RMS of only the fundamental components

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RMS of only the fundamental components

- Adjusted ZIP: small multiplying factor to account for current harmonics
  - No consideration of voltage harmonics
  - Only cumulative, not individual harmonics

$$S \approx V_1 \cdot (I_1 + I_H) = \boxed{S_1(1+\alpha)}$$

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

$$S \approx \sum_{k=1}^{k_m} V_k\, I_k = \sum_{k=1}^{k_m} y_{kk}\, V_k^2\,, \quad \boxed{I_k = y_{kk} V_k}$$

linear relationship between current and voltage harmonics

What We Cover Today

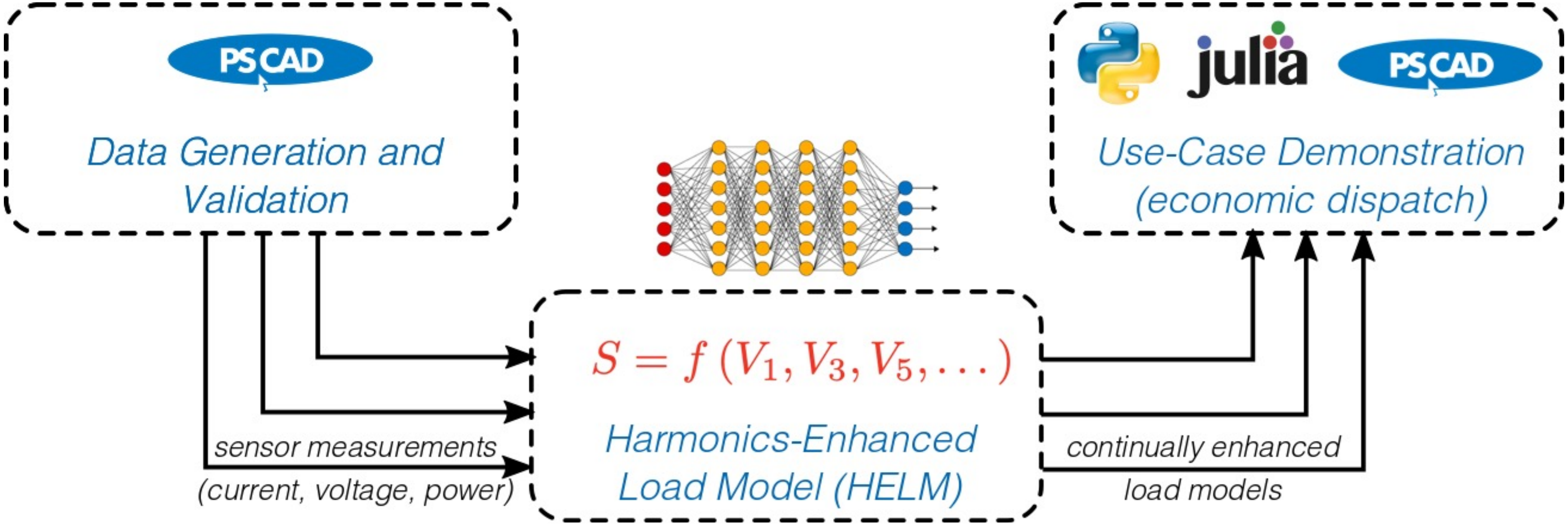
- Harmonic Load Models
- **The HELM approach**
- Current results and plan

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

Proposed HELM Framework

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

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



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

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

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

$$\begin{bmatrix} I_1 \\ I_3 \\ \vdots \\ I_{k_m} \end{bmatrix} = \underbrace{\boxed{\begin{bmatrix} y_{11} & y_{13} & \cdots & y_{1,k_m} \\ y_{31} & y_{33} & \cdots & y_{3,k_m} \\ \vdots & \vdots & \ddots & \vdots \\ y_{k_m,1} & y_{k_m,3} & \cdots & y_{k_m,k_m} \end{bmatrix}}}_{\text{FCM}} \begin{bmatrix} V_1 \\ V_3 \\ \vdots \\ V_{k_m} \end{bmatrix}$$

Drawback: assumes linearity in relationship between harmonics

Harmonic-Enhanced Modeling: Nonlinear Regression via Neural Network

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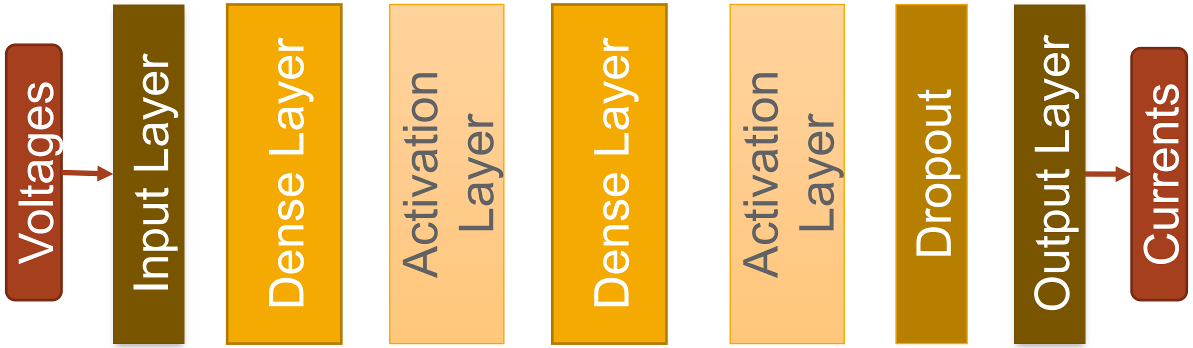
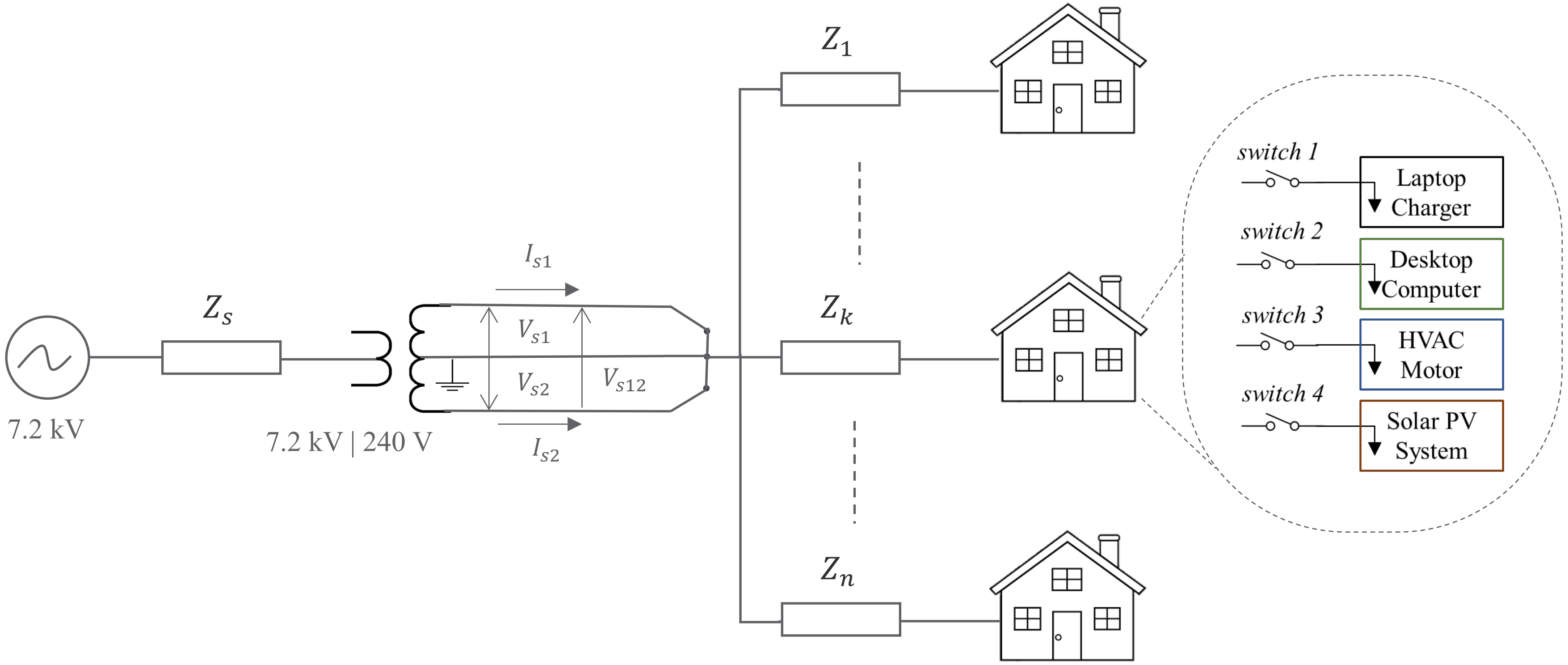
  - Allows **cross-coupling between load current and voltage**, via a linear relationship
  - Also generalized Norton model, cross admittance matrix, harmonic admittance matrix
  - Linear regression (least squares) algorithm to identify the FCM from data
- **Nonlinear Coupling Model**
  - Allows **cross-coupling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

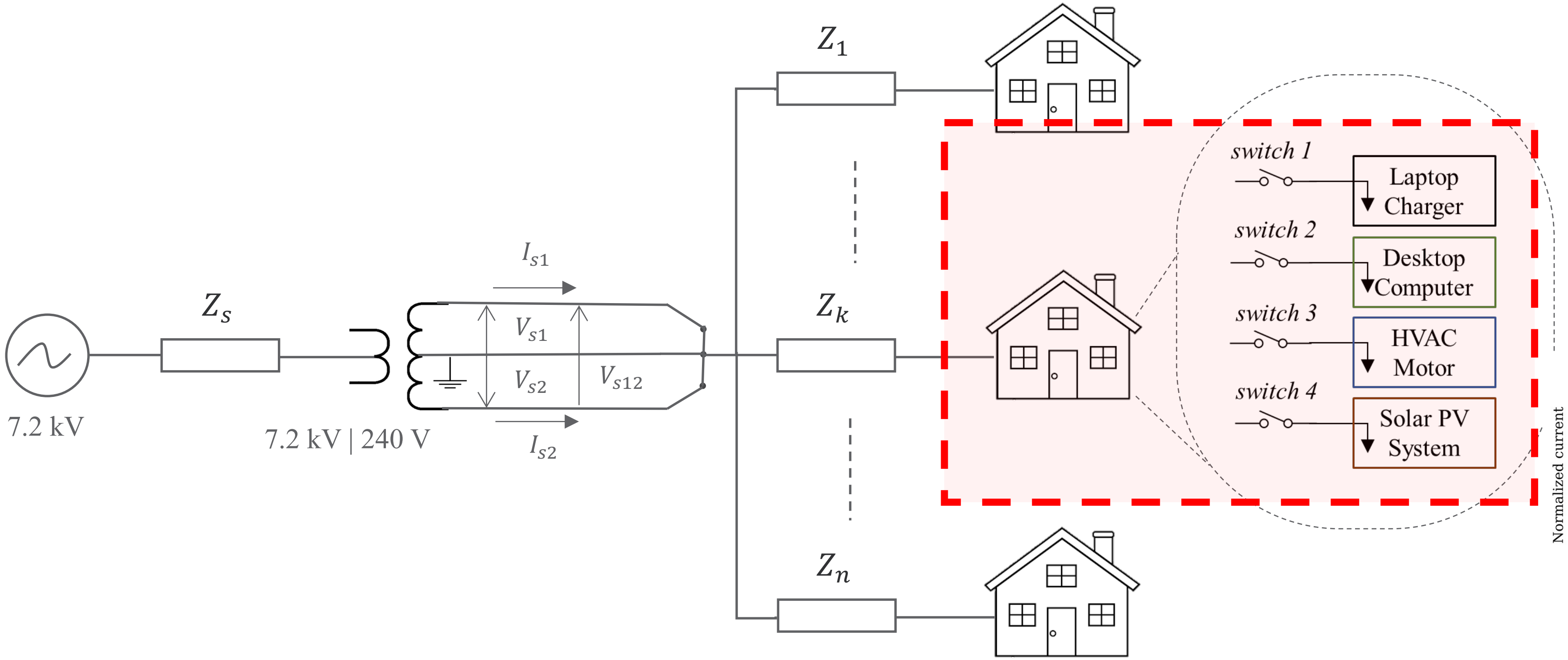
Synthetic Data Generation



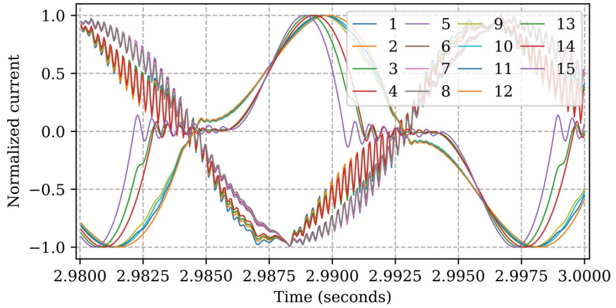
- Address dearth of feeder-wide data in harmonic studies
- Capture the impact and interactions of emerging PE load

- 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

Synthetic Data Generation



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



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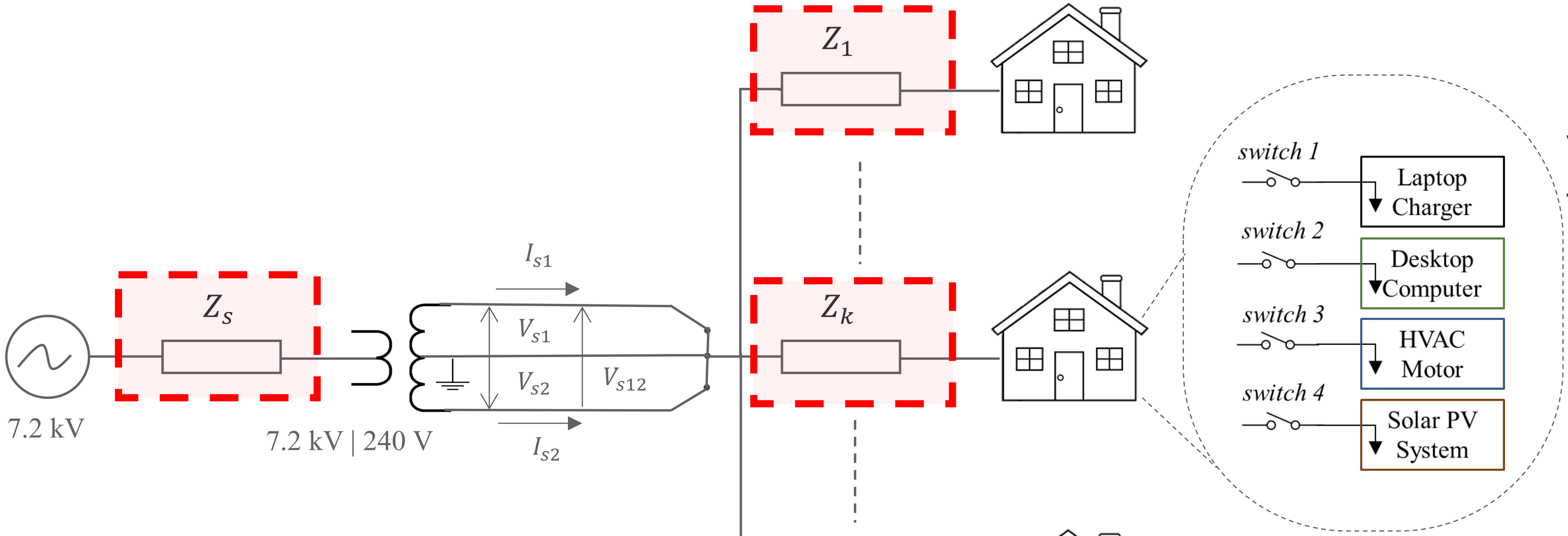
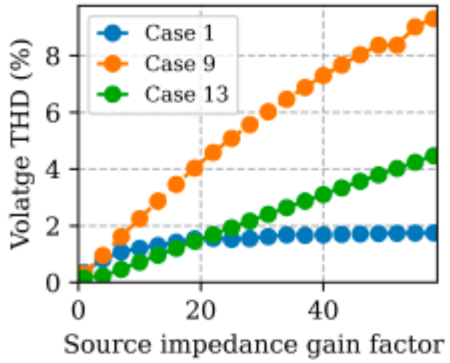


Vary the source impedance for different voltage THD at house terminals (mimic feeder-wide impact)



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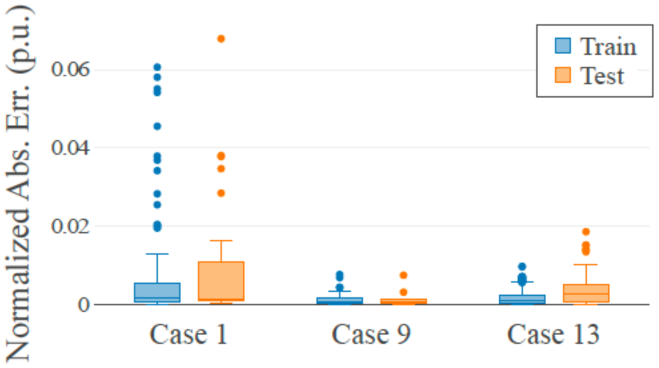
What We Cover Today

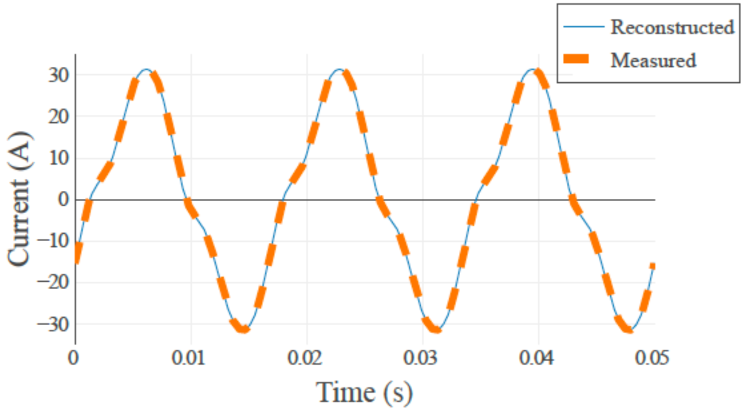
- Harmonic Load Models
- The HELM approach
- **Current results and plan**

- Validation results
- Ongoing work

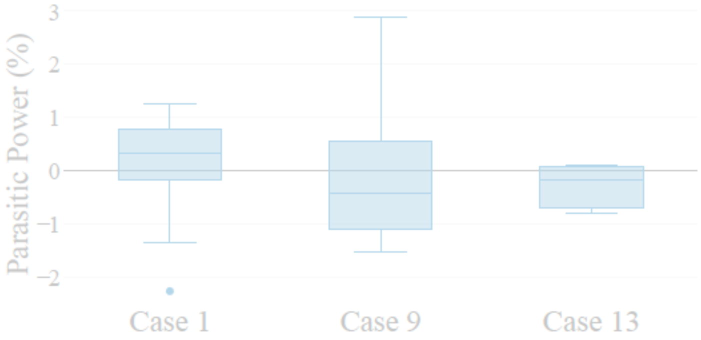
Results: Accuracy of FCM (linear regression)

- 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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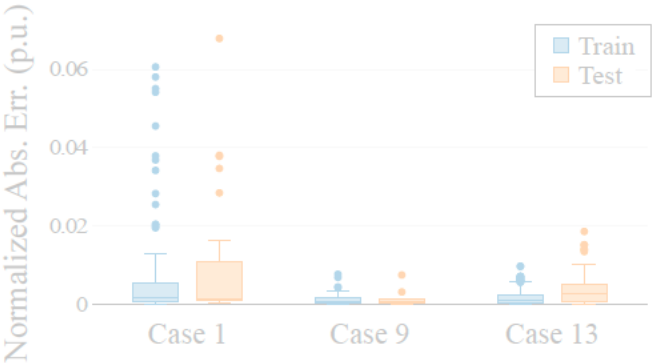

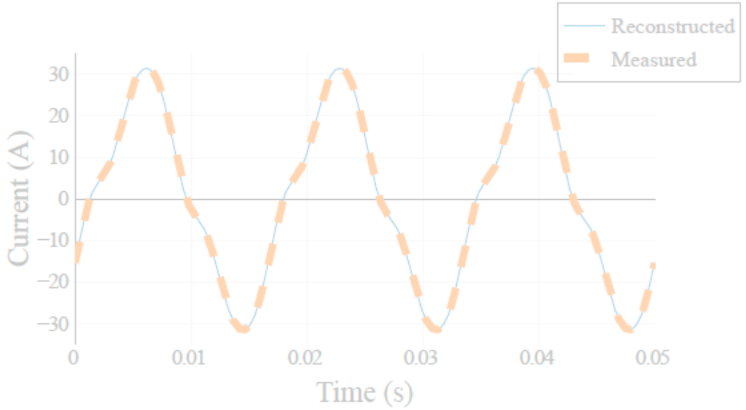

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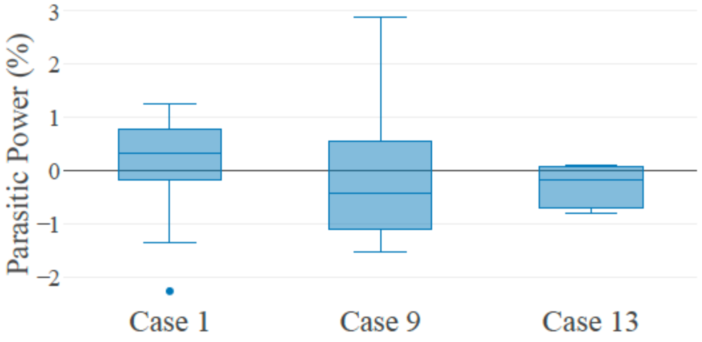

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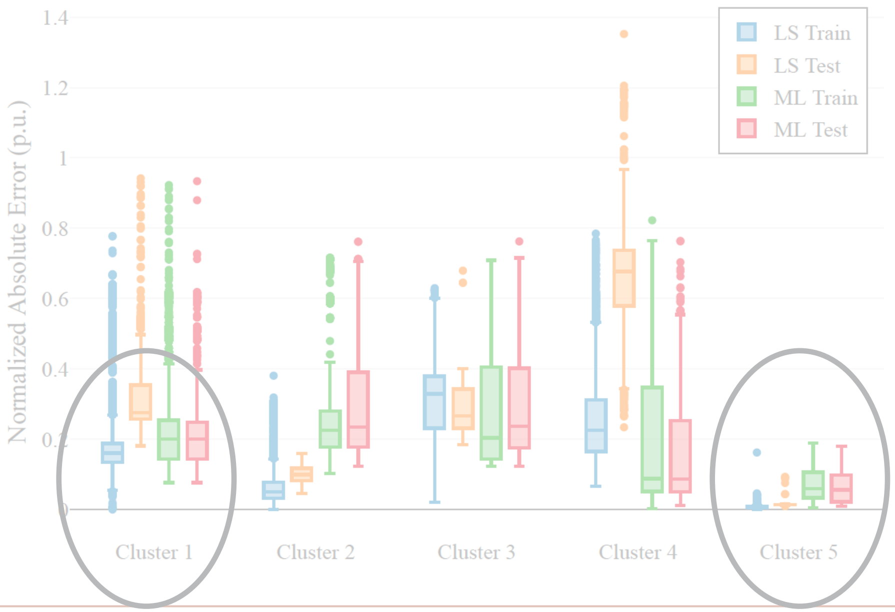
Accurate estimate of harmonic load model. Improvement over ZIP.

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



- *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*

Nonlinear model outperforms linear FCM under high data environment

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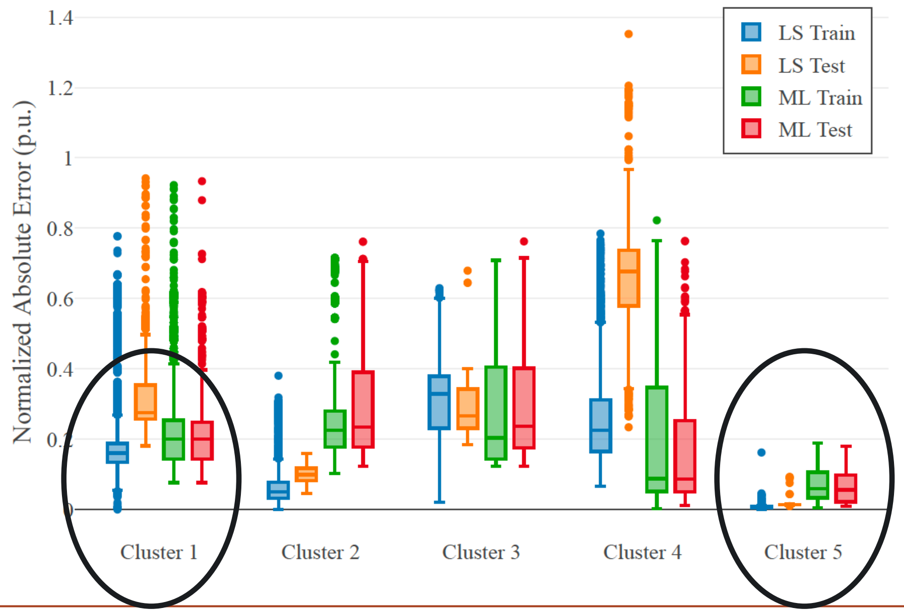

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Continuing directions and outreach

- 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):
  - Singhal, Wang, Reiman, Liu, Hammerstrom, and Kundu. "Harmonic Modeling, Data Generation, and Analysis of Power Electronics-Interfaced Residential Loads".

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Thank you

Questions?

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