Impacts of Experimentally Obtained Harmonic Spectrums of Residential Appliances on Distribution Feeder

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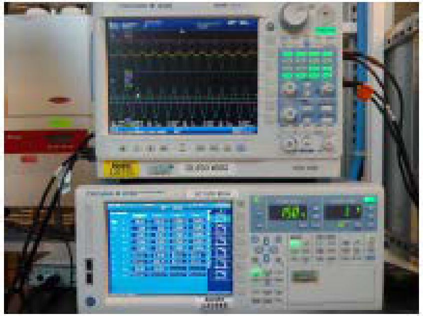
Contents

Load Monitoring

Power supply and measurement details

Equipment
Grid simulator, RS270 Ametek (Configurable power supply)
Oscilloscope, DL850 Yokogawa
Power analyzer, WT1800 Yokogawa
Voltage and current probes for measurement



Photos by NREL

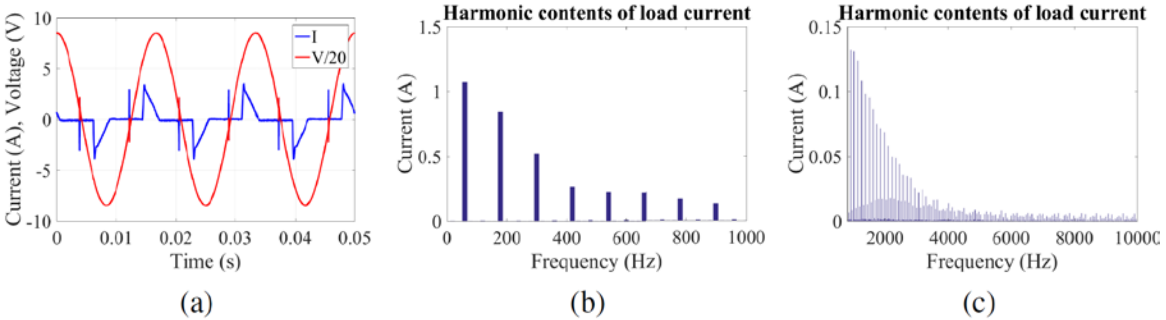
Laboratory setup for the experimental measurement

Appliances categorized as:

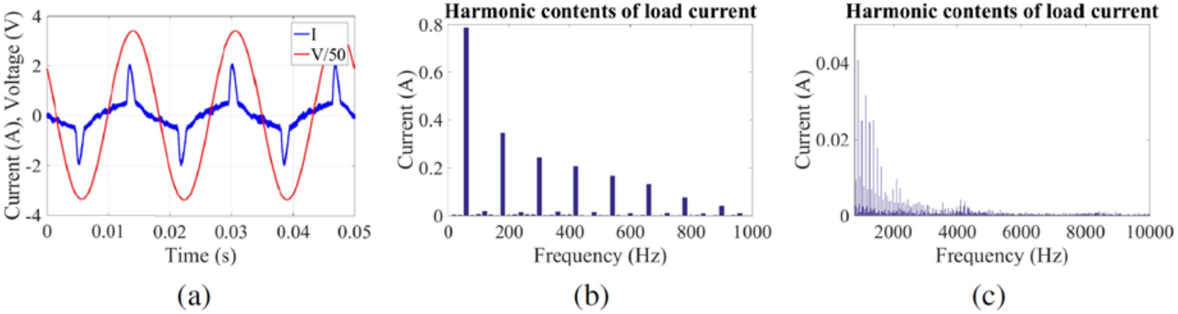
- Indoor lighting loads
- Power electronic loads
- Resistive loads
- Motor loads
- Aggregated loads.

Sample Spectra Generated

- Harmonic spectrum of several household appliances were generated.
- Spectrum for a lighting and power electronics load (PEL) are shown:
  - Fig. a: current and scaled voltage
  - Fig b: lower order harmonic components
  - Fig c: higher order harmonic components.
- How do we use these data?



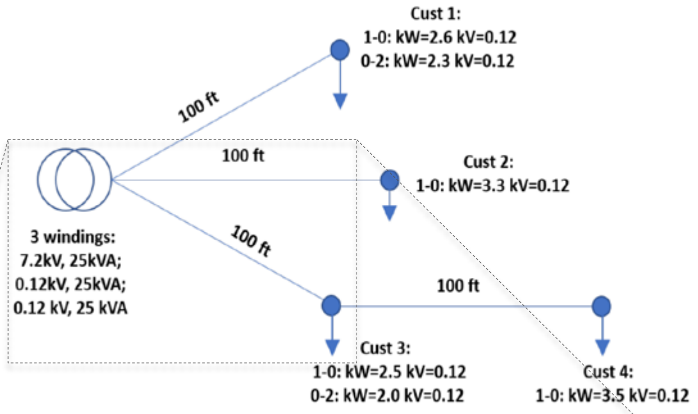
Experimental measurement of CFL lighting loads



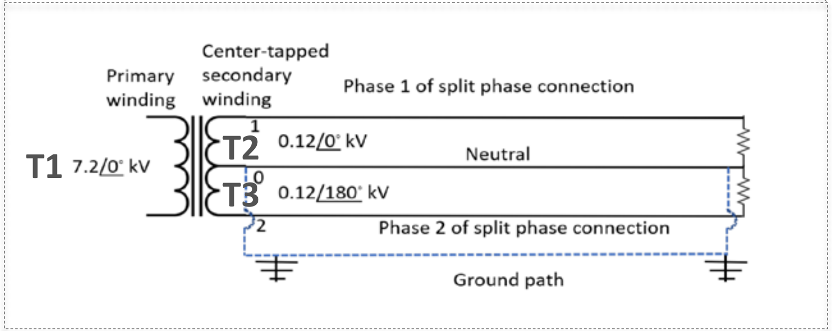
Experimental measurement of computer, a PEL

Distribution Secondary Model Used

- Impact of any load's harmonics is most clearly observable at the line directly connected to it.
- A detailed secondary model was used.
- Secondary was extracted from the 'J1' feeder.
- Accurate triplex conductor model was used.
- Effect of ground path was also included to accurately capture neutral current.



Detailed secondary model used

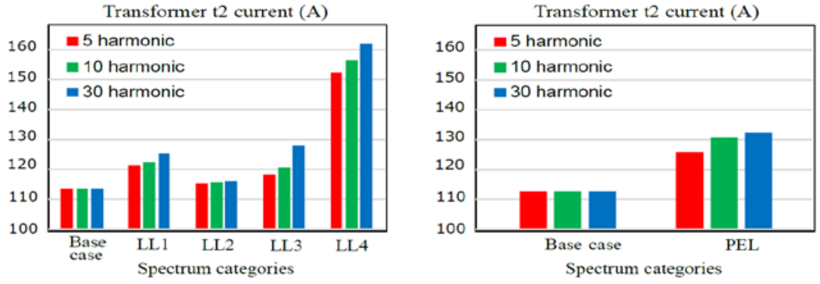


Triplex conductor for split-phase connection

Impact of Harmonic Spectra on Current

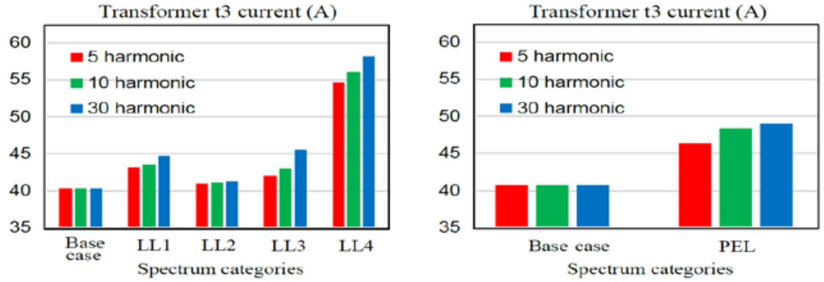
- All loads on the secondary were assumed to have the same spectrum.
- All loads had the same power factor of 0.9 inductive.
- This helped in assessing the impact from harmonics alone.
- For base case analysis, no spectrum was used.
- Sensitivity to 5, 10, and 30 harmonic spectra was done.

$$I_{rms} = \sqrt{\sum_{h=1}^{h_{max}} I_{h_{rms}}^2} = \sqrt{I_{1_{rms}}^2 + I_{2_{rms}}^2 + .. + I_{hmax_{rms}}^2}$$



(a) (b)

Transformer terminal, two current



(a) (b)

Transformer terminal, three current

5 halogens (LL2), 6 LEDs (LL3), 6 CFLs (LL4), and assorted lights (5 halogens, 12 LEDs, and 11 CFLs) (LL1)

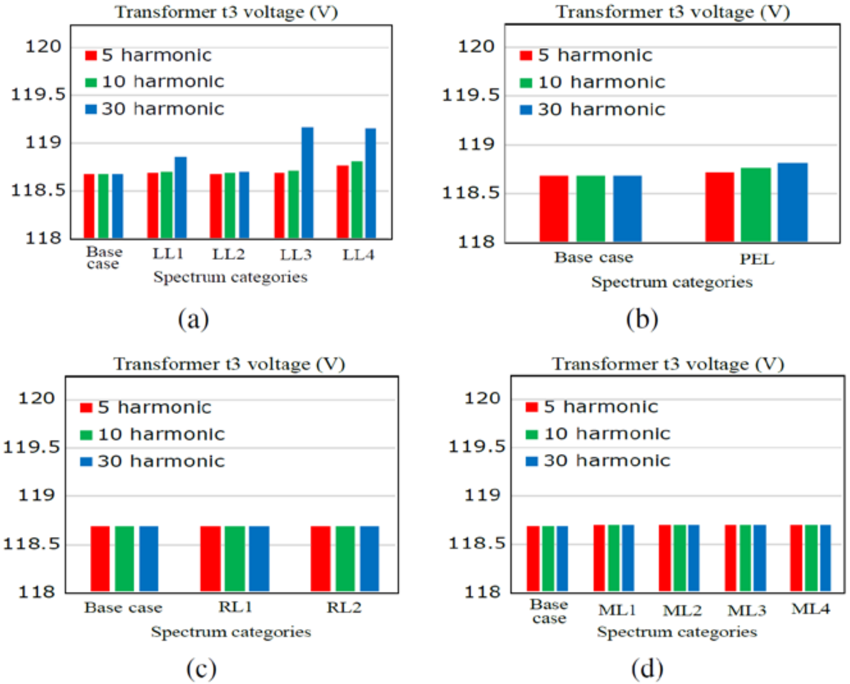
Impact of Harmonic Spectra on Voltages

- Voltage distortion is usually small in power systems compared with current distortion, as shown here.

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} V_{h_{rms}}^2} = \sqrt{V_{1_{rms}}^2 + V_{2_{rms}}^2 + .. + V_{hmax_{rms}}^2}$$

- Due to negligible harmonic spectra, (c) resistive and (d) motor loads do not distort system parameters.

- Impact of distorted voltage on device performance is shown in subsequent slides



Range (RL1),
Resistive water heater (RL2)

Refrigerator (ML1), window air conditioner (ML2), HVAC (ML3), and heat pump water heater (ML4).

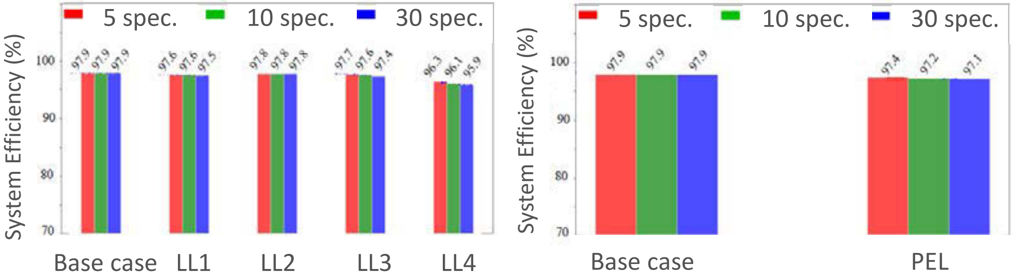
Transformer terminal, three voltage

Impact of Harmonic Spectra on System Efficiency

- System efficiency: input real power at 60 Hz - total system losses.

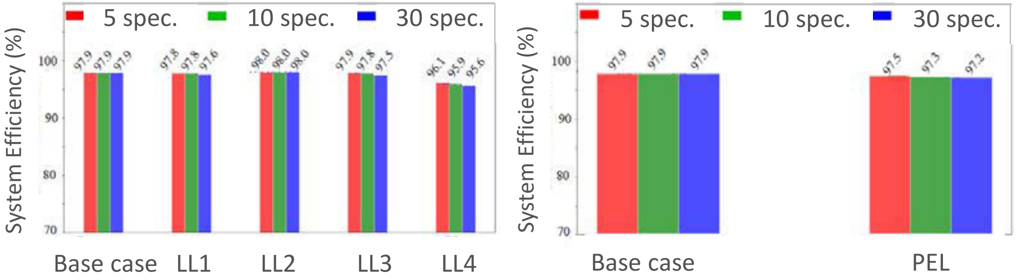
$$\eta_{sys} = \frac{P_{in_{h=1}} - \sum_{h=1}^{h_{max}} loss_h}{P_{in_{h=1}}}$$

- System losses were obtained by summing losses on all lines and transformer for all harmonics.
- Power factor (PF) of fundamental of each load type was also considered.
- For compact fluorescent lamps (CFLs), system efficiency could reduce from 97.9% to 95.6%.
- Losses could be underestimated by 110%.



(a) (b)

System efficiency with PF=0.9 inductive

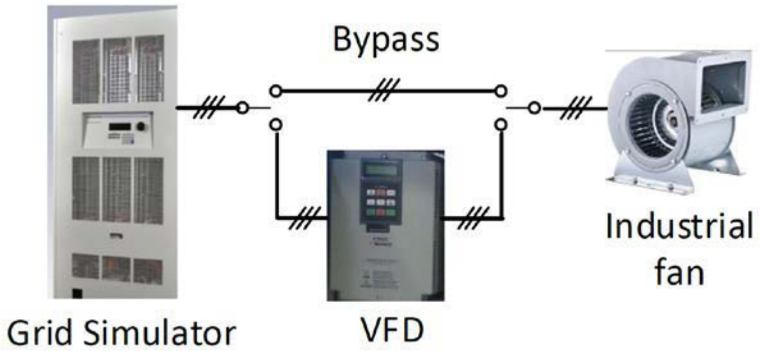


(a) (b)

System efficiency with actual fundamental power factor

Impact of Harmonics on Device Performance

- Impact of distorted source voltage on device performance was tested.
- A three-phase centrifugal fan with a variable-frequency drive (VFD) that can be bypassed and a rating of 10 kVA was selected.
- A grid simulator was used to control the input voltage.
- The input voltage was the transformer terminal voltage obtained from the harmonic load flow study.
- The voltage spectrum obtained for CFLs at 0.86 PF was used in this evaluation.

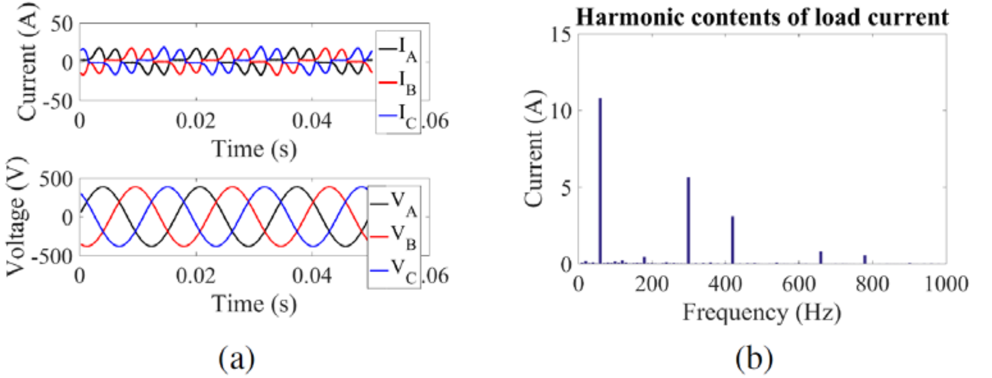


Impact of Harmonics on Device Performance

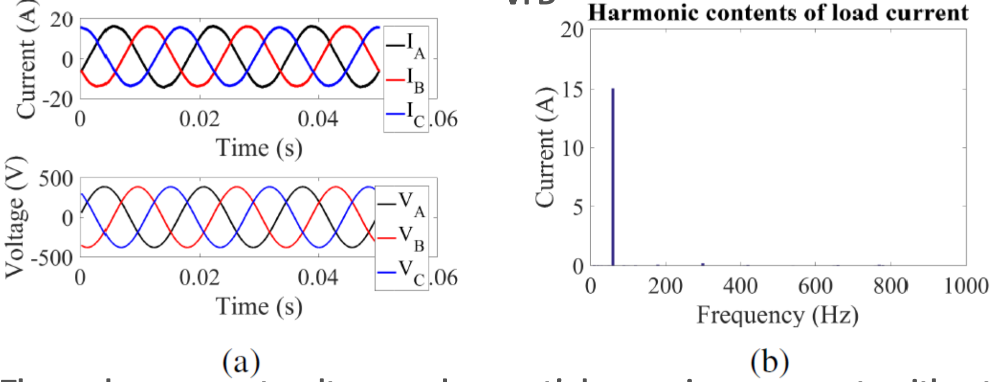
- Operating case with no harmonics on source voltage
- Without VFD, the power factor is worse than with VFD.
- The VFD case, however, has a much higher total harmonic distortion (THD).

TABLE II
IMPACT OF SOURCE VOLTAGE HARMONIC ON LOAD CURRENT

		No har	5 har	10 har	30 har
Case I: Fan with VFD	THD (%)	60.66	54.31	41.38	51.37
	IRMS (A)	8.97	9.36	9.34	9.53
	$\cos^{-1} pf(°)$	5.99	10.18	6.93	6.93
Case II: Fan without VFD	THD (%)	1.48	8.11	9.99	9.79
	IRMS (A)	10.67	11.3	10.358	11.2
	$\cos^{-1} pf(°)$	36.74	35.04	37.2	34.87



Three-phase current, voltage, and current's harmonic components with VFD



Three-phase current, voltage, and current's harmonic components without VFD

Impact of Harmonics on Device Performance

- Operating case with five harmonics on source voltage

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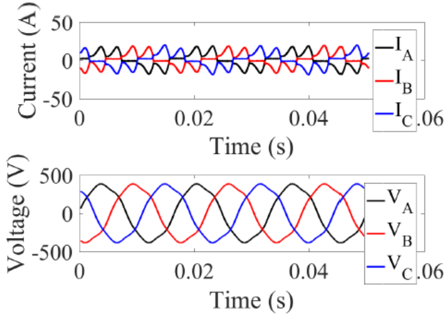
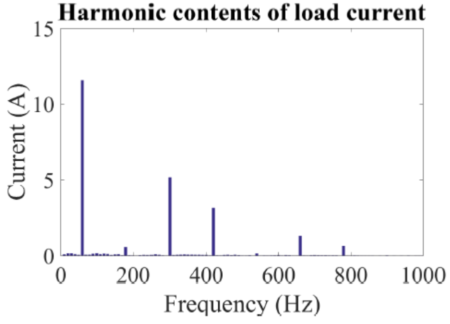
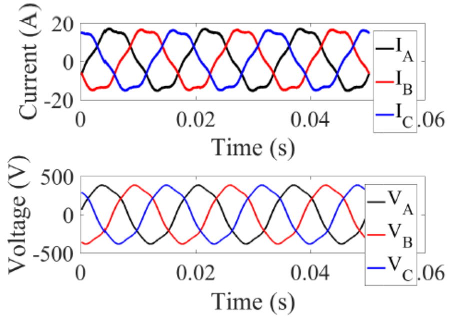


(c)

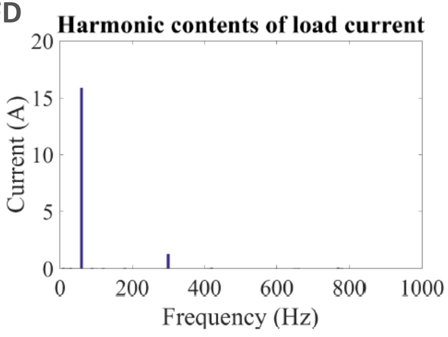


(d)

Three-phase current, voltage, and current's harmonic components with VFD



(c)



(d)

Three-phase current, voltage, and current's harmonic components without VFD

Impact of Harmonics on Device Performance

- Operating case with 10 harmonics on source voltage

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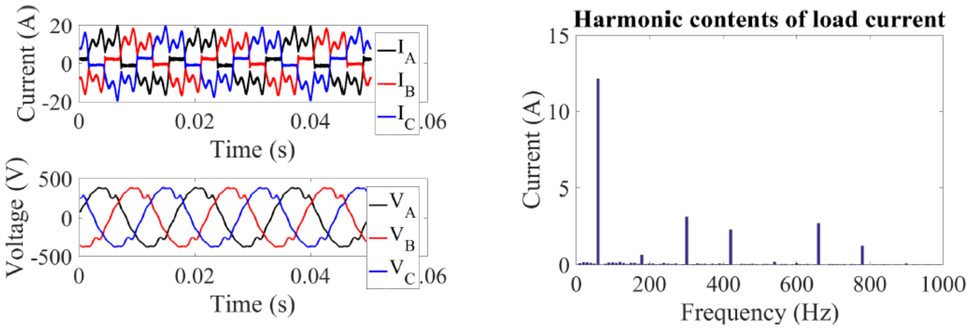
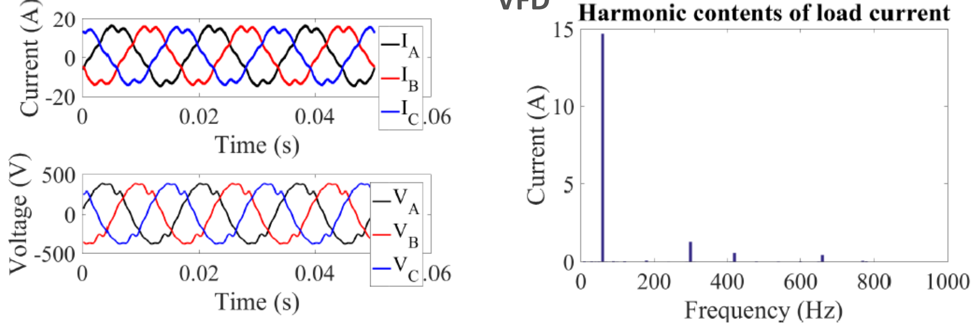


(e) (f)

Three-phase current, voltage, and current's harmonic components with VFD



(e) (f)

Three-phase current, voltage, and current's harmonic components without VFD

Impact of Harmonics on Device Performance

- The harmonics on the load current increase for Case II, whereas for Case I they decrease.
- This is attributed to the phase angle cancellation of the harmonic spectrums, which reduces THD.
- This result cannot be generalized and highly depends on the system impedance.
- I_{RMS} in general increases over base case, which suggests higher losses.

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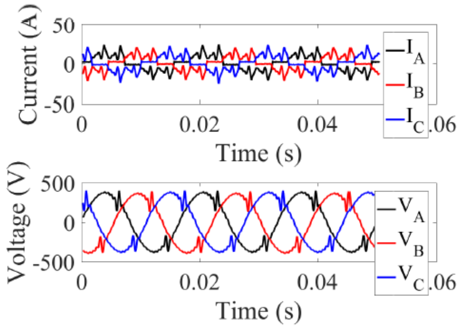
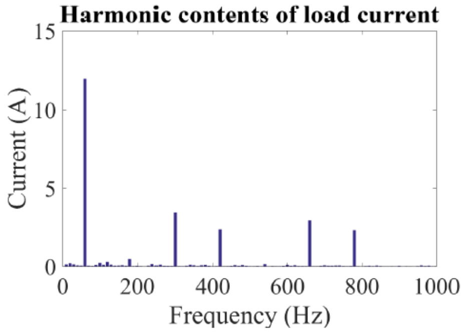
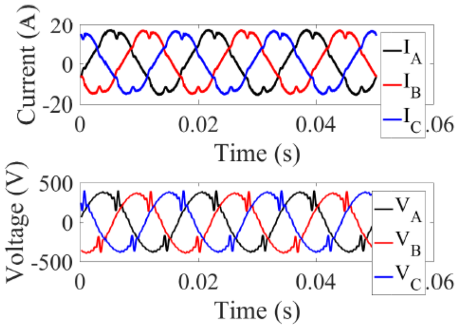


(g)



(h)

Three-phase current, voltage, and current's harmonic components with VFD



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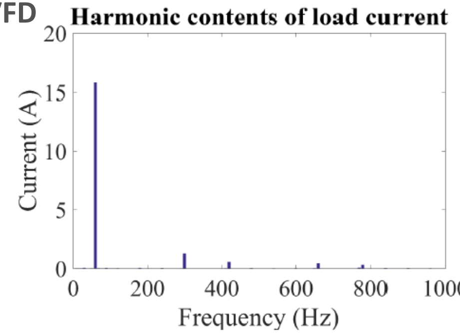

(h)

Three-phase current, voltage, and current's harmonic components without VFD

Conclusion and Future Work

Conclusions:

- This paper presented a complete cycle:
  - Harmonic spectra were determined through laboratory experiments.
  - These spectra were then used to conduct a detailed distribution system impact study using harmonic power flow.
  - The harmonic data of the transformer terminal voltage as obtained from the harmonic power flow study was used to generate the source voltage of the grid simulator to assess changes in operation of electrical devices.

Future work:

- Future studies will include equivalent modeling of the harmonic characteristics of different loads and incorporating these effects in the existing ZIP load models.

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Thank you

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