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

Preprint

Jinia Roy, Akshay K. Jain, and Barry Mather

National Renewable Energy Laboratory

Presented at the 2020 IEEE Texas Power and Energy Conference
College Station, Texas
February 5–7, 2020

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-75751
February 2020

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

Preprint

Jinia Roy, Akshay K. Jain, and Barry Mather

National Renewable Energy Laboratory

Suggested Citation
Roy, Jinia, Akshay K. Jain, and Barry Mather. 2020. *Impacts of Experimentally Obtained Harmonic Spectrums of Residential Appliances on Distribution Feeder: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-75751. https://www.nrel.gov/docs/fy20osti/75751.pdf.

© 2020 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-75751
February 2020

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Electricity. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

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

Jinia Roy, Akshay K Jain, and Barry Mather
Power Systems Engineering Center, National Renewable Energy Laboratory
Golden, CO 80401, USA
E-mail: jinia.roy@nrel.gov; akshay.jain@nrel.gov; barry.mather@nrel.gov

***Abstract*—Owing to the increased use of power electronic-based appliances and energy-efficient home equipments such as modern lighting loads, the percentage of nonlinear loads has increased in the distribution system, which can impact system performance, loss, and stability. Thus a comprehensive knowledge of their power quality and harmonic analysis is essential to improve the load models, voltage stability assessment, determination of possible interactions at harmonic frequencies, protection planning, and the effect of system impedance. This paper focuses on harmonic load flow analysis for multiple residential load types to determine the expected impacts on an modeled distribution secondary. For this study, the household appliances include lighting, power electronic, resistive, and motor loads with a nominal supply voltage of 120 V single-phase or 240 V split-phase at a nominal frequency of 60 Hz. The harmonic spectrums, as obtained from the experimental evaluation of real loads, are used to inform the harmonic load flow for a detailed secondary network, including the distribution service transformer extracted from a real distribution feeder's model. Additionally, the impact of voltage harmonics on a three-phase test load is presented with experimental results. The harmonic data of the transformer terminal voltage, as obtained from the former load flow study, are scaled to generate the source voltage for the three-phase configuration of the grid simulator to make the test setup very similar to a typical secondary design in the U.S.**

***Index Terms*—Equivalent power loss, load modeling, harmonic power flow, OpenDSS, residential loads, total harmonic distortion.**

I. Introduction

Owing to the ever-changing load landscape and the introduction of power electronics-based equipment for increased energy efficiency in both residential and commercial applications, there is a growing concern of the increased harmonic content on the distribution network [1], [2]. Residential nonlinear loads include modern lighting technologies such as compact fluorescent lamps (CFLs); light-emitting diodes (LEDs); electric vehicle chargers; adjustable-speed-drive-based home appliances; modern entertainment systems; and heating, ventilation, and air conditioner (HVAC) units. These nonlinear loads can decrease system efficiency, distort supply voltage, and consequently impact the performance of other loads connected to the same local utility supply [3]. Numerous studies are reported on the harmonic analyses of residential loads. However, most of them do not consider data from the experimental tests and are primarily focussed on CFL lighting [4], [5].

This paper presents the harmonic load flow study for a set of residential loads and the impacts of their harmonic contents on the distribution feeder. Residential appliances can be grouped into five different categories: lighting, power electronics, resistive, motor, and aggregated loads. Of these loads, it is not straightforward to obtain the harmonic characteristics for aggregated-type equipment, loads consisting of combinations of other types of loads (e.g. dishwashers), as these characteristics are dependent on the stage of operating cycle as well as their mode of operation [6]. So, the present load flow studies are executed for the rest of the four categories. The load flow is presented for different resolutions of harmonic spectrums (e.g., 5, 10, and 30 spectrums), and are compared to study the value of high-resolution harmonic load flow studies.

This paper also presents the impact of the voltage harmonic on a three-phase test load through experimental results. The harmonic data of the service transformer terminal voltage, as obtained from an initial load flow study, are used along with a grid simulator as the source for a centrifugal fan with and without a variable frequency drive (VFD). The effect of harmonics of the source voltage on the system operation is different for the fan operating with and without VFD, and thus both the scenarios were tested to obtain a comparable result.

The rest of the paper is organized as follows. Section II presents details of the experimental setup for recording the harmonic spectrum of the residential loads and a description of the test feeder selected for the harmonic load flow study. In Section III, results from OpenDSS harmonic load flow are presented for different test scenarios of the harmonic categories. Section IV details the impact of harmonic components of the system voltage on the equipment through experimental results. Section V concludes the paper and discusses future work.

II. System description and experimental setup

A. Experimental setup

Fig. 1 shows the experimental setup to obtain the harmonic characteristics of the household appliances (Figs. 1a and 1b) and measurement setup (Fig. 1c). Details of the measurement equipment are given in Table I. A grid simulator, an Ametek

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

(a) (b) (c)

Fig. 1. Laboratory setup for the experimental measurement of the residential appliances. (a) Range, washer, tumble dryer, computer, window air conditioner, lighting; (b) heat pump water heater, range; (c) scope and power analyzer used for measurement.

RS270 rated at 270 kVA, is used for emulating the grid supply. It remotely controls voltage magnitude, phase, and frequency for the output AC power. An oscilloscope and a power analyzer are used to capture the voltage and current waveforms. MATLAB was used to post-process these collected waveforms. The output of this post-processing stage were CSV files, which contained the spectrums, both current magnitude and angles, for different appliances. These spectrum files were used to simulate the grid impacts of different load types by conducting harmonic load flow analysis on a detailed secondary grid model. The harmonic power flows were conducted in OpenDSS, an open-source electrical power systems simulation platform [7].

B. System description for load flow study

Impact of any given load on a feeder's voltages and currents can be best captured by monitoring the line and transformer directly connected to it, which is usually the secondary. Thus, the grid impact study presented in this paper is conducted on a detailed secondary model extracted from a real distribution feeder's model. By focusing the study on a secondary model, voltage, current distortions, and system losses can be more accurately assessed. Python code was created to extract the secondary downstream of each distribution transformer of the publicly available J1 feeder [8]. A single-phase secondary network being supplied through a center-tapped distribution transformer was chosen. This network originally distributed power to three residential loads in a star configuration, as shown in Fig. 2. A fourth load was added after load 3 to generate a more realistic secondary network.

The secondary networks in North America consist of a 120/240-V split-phase system for service drops [9]. These service drop lines are made up of two 120 V phase cables and a neutral conductor. These lines are usually insulated and twisted together to create a triplex cable. Detailed triplex cable models are used in the OpenDSS test circuit model with actual impedance measurements. This triplex line can provide supply either at 120 V by connecting loads between either phase cable and the neutral line, or at 240 V by connecting loads between the two phase cables of opposite phases. The loads connected at 240 V are usually high-demand loads such as water heaters and HVACs. These high-demand devices will typically present load equally to both phases of the split-phase connection; however, smaller loads connected to just one phase of the split-phase connection will create load imbalances. This imbalance is also modeled in the developed test circuit, shown in Fig. 2. While residential customers 2 and 4 do not have loads connected at 240 V, customers 1 and 3 have loads connected to both the phases of the split-phase connection. The load connected between the first-phase conductor and neutral (1-0) is different from the load connected between the second-phase conductor and neutral (0-2) to realize some load imbalance. The neutral cable used in North American secondary networks is grounded both at the distribution transformer and at the residential customer's service panel. Thus, two current return paths exist, i.e., the neutral conductor and the ground path. The ground impedance in reality is nonzero, and thus the current is split between the two paths. It was essential to model this behavior so that the system's losses could be more accurately determined by accounting for the actual current flowing through the neutral. The ground impedance model used in this model can be found in [10]. Fig. 3 shows a detailed model of the triplex cable and ground path used for connecting each of the four loads to the distribution transformer.

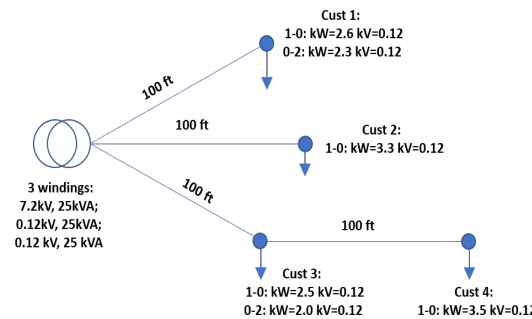


Fig. 2. Secondary network used to test grid impacts

III. Results and Discussions

Harmonic power flows were performed on the test circuit described in Section II. In the harmonic power flow mode, OpenDSS performs power flow studies after converting the load model to its Norton equivalent. Power flow is performed for each individual harmonic frequency specified in the harmonic spectrums. The current magnitudes and angles for each frequency correspond with the values specified in the spectrums, as obtained from experimental data. In this case study, the same spectrum was applied uniformly to each residential load to allow simple comparison between cases. OpenDSS

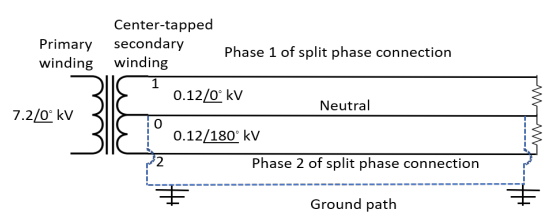


Fig. 3. Detailed line model used in the test circuit

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

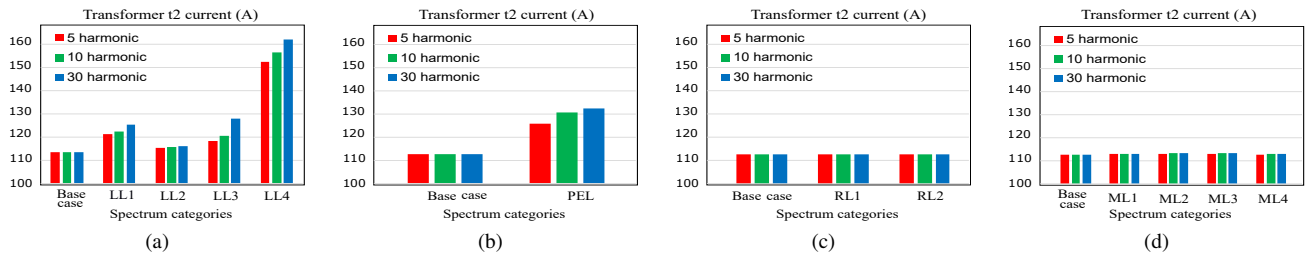


Fig. 4. Transformer terminal 2 current with the fundamental power factor (pf) being 0.9 inductive for all the loads: (a) Lighting loads, (b) power electronic loads, (c) resistive loads, and (d) motor loads

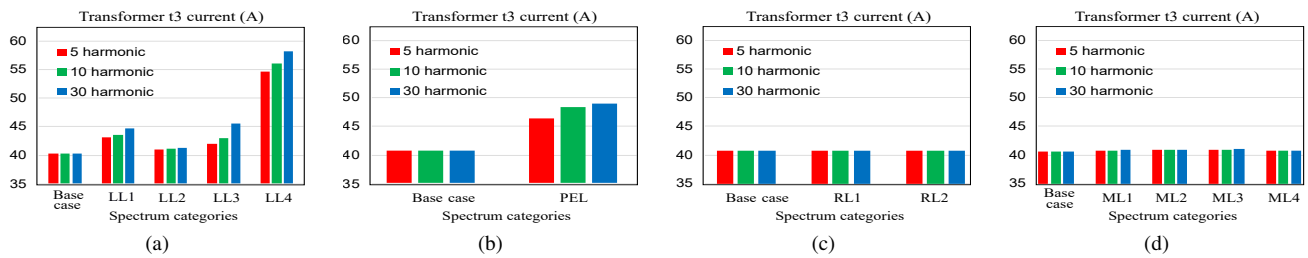


Fig. 5. Transformer terminal 3 current with the fundamental pf being 0.9 inductive for all the loads: (a) Lighting loads, (b) power electronic loads, (c) resistive loads, and (d) motor loads

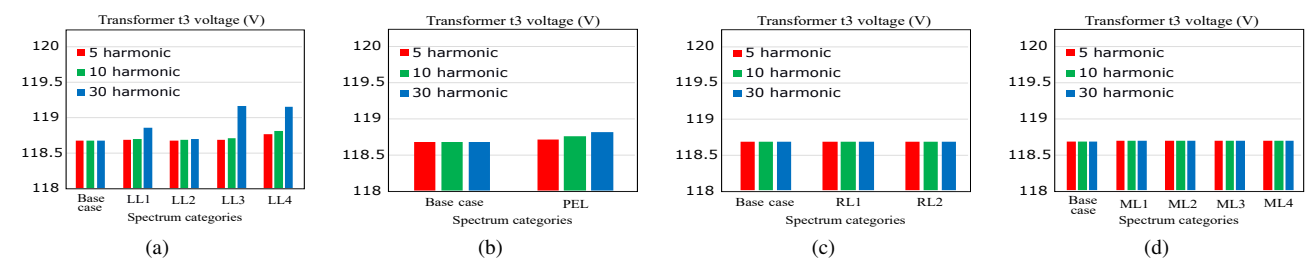


Fig. 6. Transformer terminal 3 voltage with the fundamental pf being 0.9 inductive for all the loads: (a) Lighting loads, (b) power electronic loads, (c) resistive loads, and (d) motor loads

TABLE I
POWER SUPPLY AND MEASUREMENT DETAILS

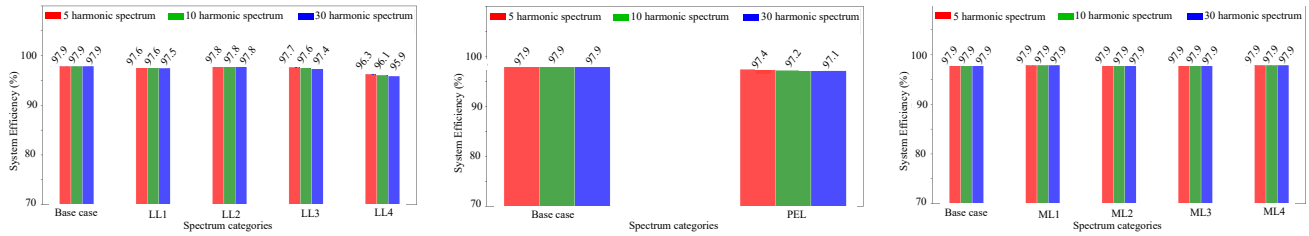
Equipment
Grid simulator, RS270 Ametek (Configurable power supply)
Oscilloscope, DL850 Yokogawa
Power analyzer, WT1800 Yokogawa
Voltage and current probes for measurement

is used to determine the actual current injection, based on the load kW and percentage current value specified at each spectrum frequency. This was done so that the impact of each load type on grid parameters could be studied independently. This may not be realistic, as each residential load's harmonic spectrum would be a mix of different load types. However, the results presented here provide an upper bound on the grid impacts each load type would have.

The results obtained with different load spectrums are compared against a base case. In the base case no harmonic spectrum is applied to the loads, and all loads are assumed to have a power factor (pf) of 0.9 inductive, a commonly used value for residential loads in distribution systems analysis. Furthermore, different sets of harmonic spectrums, specifically for 5, 10, and 30 multiples of the fundamental, are used to compare the trade off between harmonic load flow complexity and harmonic impact results. Two scenarios were analyzed: Scenario 1, where all loads have a pf of 0.9 inductive for all the spectrums; and Scenario 2, where load pf corresponds to a fundamental pf of the corresponding load, (e.g., from test data, the fundamental pf of CFLs is 0.86, while that of a resistive water heater is close to 1). Scenario 1 helps in highlighting the impact from harmonics alone, as the pf is same for all load types, while Scenario 2 presents the more realistic grid impacts of specific loads.

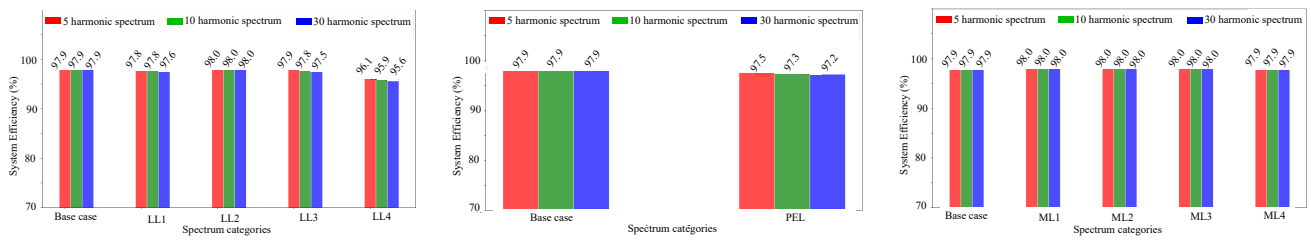
Figs. 4 and 5 present the root mean square (RMS) current for terminals 2 and 3 of the distribution transformer, respectively, while Fig. 6 shows the RMS of transformer terminal 3 voltage [refer to Fig. 2] for Scenario 1 only. Terminal 2 of the transformer represents the secondary winding connected between phase conductor 1 and neutral, while terminal 3 is the secondary winding connected between phase conductor 2

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.



(a) (b) (c)

Fig. 7. System efficiency plots with different residential appliances with the fundamental pf being 0.9 inductive for all the loads: (a) Lighting loads, (b) power electronic loads, and (c) motor loads. Plot for resistive loads is not presented, as they do not have significant harmonic spectrums.



(a) (b) (c)

Fig. 8. System efficiency plots with different residential appliances with the fundamental pf being equal to the corresponding load displacement pf: (a) Lighting loads, (b) power electronic loads, and (c) motor loads. Plot for resistive loads is not presented, as they do not have significant harmonic spectrums.

and the neutral, as shown in Fig. 3. As mentioned in Section II, the loads connected to terminals 2 and 3 of the distribution transformer are unbalanced; hence, the RMS currents for both terminal 2 and 3 are presented. However, the voltage is very similar across both terminals, and only results for terminal 3 are presented. The RMS voltages and currents plotted in these figures are obtained using (1) and (2) [11].

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

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

where h_{max} is 5, 10, or 30, based on the scenario being simulated.

The secondary network efficiency is shown in Figs. 7 and 8 for all loads and two different fundamental pf scenarios. Fig. 7 corresponds to Scenario 1 (i.e., the fundamental pf of 0.9 inductive load), while Fig. 8 corresponds to Scenario 2 with a different fundamental pf for each load. For a given load type, the system efficiency is the difference between the input real power at the fundamental frequency on the primary winding of the transformer, and total system losses obtained by summing real losses on all lines and transformers for all multiples in the spectrums, as shown in (3).

$$\eta_{sys} = \frac{P_{in_{h=1}} - \sum_{h=1}^{h_{max}} loss_h}{P_{in_{h=1}}} \tag{3}$$

where h_{max} is 5, 10, or 30, based on the scenario being simulated.

Figs. 4–8 are presented by combining different loads in the same load category in a single plot. In Figs. Xa (where X is 4–8), the lighting loads include 5 halogens (LL2), 6 LEDs (LL3), 6 CFLs (LL4), and assorted lights (LL1), which are a combination of 5 halogens, 12 LEDs, and 11 CFLs. Most power electronics appliances, like TVs, phone charging stations, CD players, radios, printers, or computers, have similar load characteristics, as they all are implemented by similar AC-DC interfaces (switched mode power supply) to power the internal circuit. Thus, the results are shown for a typical computer in Figs. Xb, which is representative of similar power electronics loads. Both the lighting and power electronics loads are single-phase loads. Figs. Xc show the results for resistive loads, a range (RL1) and a resistive water heater (RL2), both of which are two-phase loads. Results for motor loads are presented in Figs. Xd, which include a refrigerator (ML1), window air conditioner (ML2), HVAC (ML3), and heat pump water heater (ML4). The former two are single-phase, while the latter two are split-phase loads.

Results show that for resistive and motor loads, the load flow is not sensitive to the number of spectrums considered in analysis. However, this is more pronounced for the lighting and power electronics loads. Fig. 6 shows that harmonics do not have a significant impact on system voltages; however, Figs. 4 and 5 show that system currents can be significantly different due to harmonics. Lighting and power electronic loads can significantly increase the current flowing in the secondary network compared with the base case. The impact of this increased current flow can be seen in Fig. 7, which shows that

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

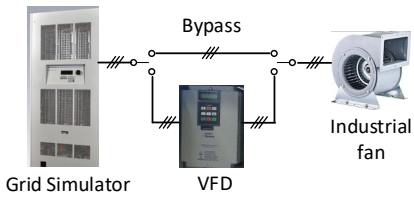


Fig. 9. Laboratory setup for the experimental measurement of the three-phase industrial fan with and without a variable frequency drive (VFD)

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

with lighting and power electronic loads, as higher harmonics are considered, system losses can even double, compared with the base case. System efficiency results in Fig. 8 for Scenario 2, where actual fundamental pfs are considered, show that for LL4 type loads with the load's actual fundamental pf, the system efficiency drops from 97.9% in the base case to 95.6% when 30 harmonics are considered. This implies a loss increase of 110% over the base case.

IV. IMPACT OF HARMONIC ON DEVICE PERFORMANCE

To study the impact of harmonic spectrums injected into the system by nonlinear loads, a three-phase centrifugal fan with a bypassable VFD and a rating of 10 kVA was selected. The effect of the source voltage harmonic content would be different for the fan operating with and without VFD, and thus both the scenarios are tested here to allow comparison. The laboratory test setup is given in Fig. 9, where a grid simulator is used to control the input voltage to the equipment under test (EUT). The details of the measurement setup are similar to Table I, as used for the residential load testing. The harmonic data of the transformer terminal voltage [refer to Fig. 2], as obtained from the load flow study, are used to generate the source voltage of the grid simulator for the experiment to make the test setup as close as possible to a real scenario. The voltage spectrum obtained for CFLs at 0.86 pf was used in this evaluation.

The test results are shown in Figs. 10 and 11 for the fan operating with VFD (Case I) and without VFD (Case II). Four different operating cases are considered for different harmonic profiles of the source voltage, which include:

i. Source voltage with no harmonic (Figs. 10a and 10b for Case I and Figs. 11a and 11b for Case II)
ii. Source voltage with up to the first 5 harmonic components (Figs. 10c and 10d for Case I and Figs. 11c and 11d for Case II)
iii. Source voltage with up to the first 10 harmonic components (Figs. 10e and 10f for Case I and Figs. 11e and 11f for Case II)
iv. Source voltage with up to the first 30 harmonic components (Figs. 10g and 10h for Case I and Figs. 11g and 11h for Case II).

For each of these four different scenarios, the steady-state three-phase voltage and current waveforms are presented, along with the lower order harmonic components for phase A current. The harmonic components for other two phases are similar to phase A. Table II gives the load current RMS and its corresponding total harmonic distortion (THD) and fundamental pf angle for both the cases. For the base case with no harmonic in the source voltage, the pf for the direct connect operation (Case II) is much worse than that with VFD (Case I); however, VFD has a very high THD. It can

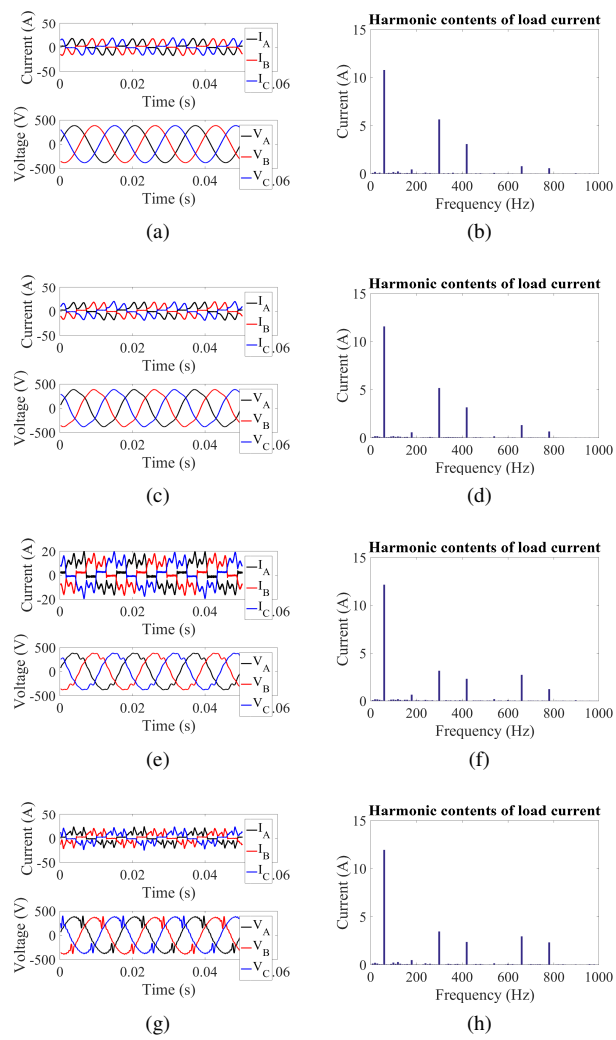


Fig. 10. Experimental measurement of 10-kVA industrial fan with a VFD showing, respectively, three-phase current, voltage, and lower-order harmonic components of phase A current with supply voltage having (a, b) no harmonic; (c, d) 5 harmonic components; (e, f) 10 harmonic components; and (g, h) 30 harmonic components.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

be observed that as more harmonic spectrums are included in the source voltage from zero to 5, 10, and 30, the harmonics on the load current increase for Case II, while for Case I it has decreased from the base scenario. This is attributed to the phase angle cancellation of the harmonic spectrums, thus reducing the THD, although this cannot be generalized and highly depends on the system impedance. However, in general, the load current RMS has increased for each of the cases with harmonic in source voltage, which implies the system losses will be higher than the base scenario.

V. Conclusion

This paper presented the impacts of the harmonic contents of a set of residential loads on a distribution secondary through a harmonic power flow study. Of the different load categories, the impact on feeder parameters was more significant for lighting and power electronics loads for the 5, 10, and 30 spectra considered. Also, the impact of the voltage harmonic on a three-phase 10-kVA fan has been presented through experimental results, which showed that the harmonic component of the load current can be increased by the harmonics present on the source voltage. Thus, this paper presented a complete cycle where harmonic spectra were determined through laboratory experiments, these spectra were then used to conduct a detailed distribution system impact study and then 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 studies will include equivalent modeling of the harmonic characteristics of different loads and incorporating these effects in the existing ZIP load models.

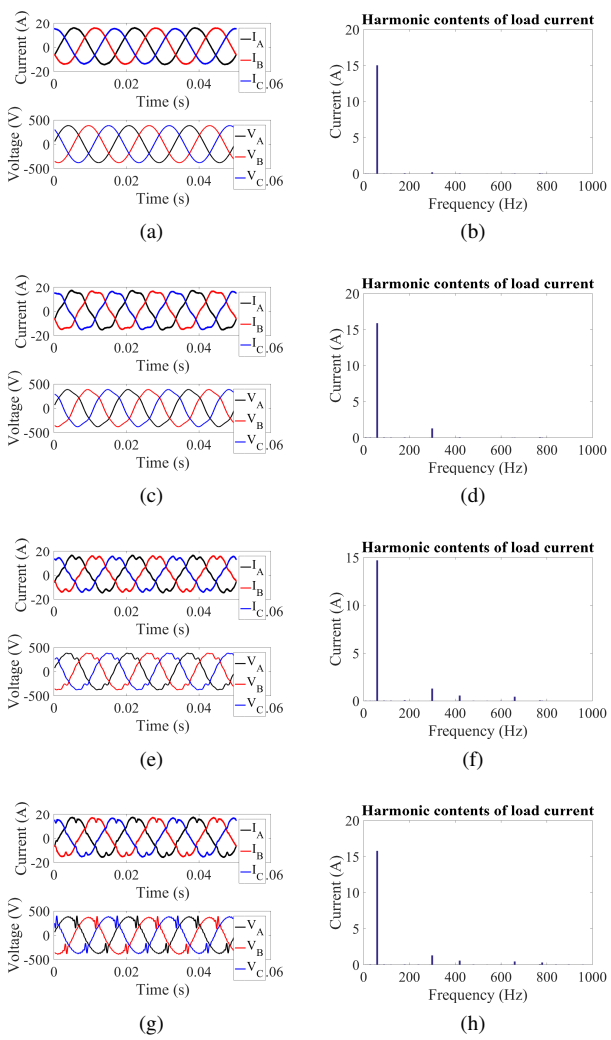


Fig. 11. Experimental measurement of 10-kVA industrial fan with direct connect showing, respectively, three-phase current, voltage, and lower-order harmonic components of phase A current with supply voltage having (a, b) no harmonic; (c, d) 5 harmonic components; (e, f) 10 harmonic components; and (g, h) 30 harmonic components.

Acknowledgments and Disclaimer

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Electricity. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

[1] D. Salles, C. Jiang, W. Xu, W. Freitas, and H. E. Mazin, "Assessing the collective harmonic impact of modern residential loadspart i: Methodology," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1937–1946, Oct 2012.

[2] C. Jiang, D. Salles, W. Xu, and W. Freitas, "Assessing the collective harmonic impact of modern residential loadspart ii: Applications," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1947–1955, Oct 2012.

[3] D. Kumar and F. Zare, "Harmonic analysis of grid connected power electronic systems in low voltage distribution networks," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 1, pp. 70–79, March 2016.

[4] N. R. Watson, T. L. Scott, and S. J. J. Hirsch, "Implications for distribution networks of high penetration of compact fluorescent lamps," *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1521–1528, July 2009.

[5] H. Sharma, W. G. Sunderman, and A. Gaikwad, "Harmonic impacts of widespread use of cfl lamps on distribution systems," in *2011 IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–5.

[6] J. Roy and B. Mather, "Study of voltage-dependent harmonic characteristics of residential appliances," in *2019 IEEE Texas Power and Energy Conference (TPEC)*, Feb 2019, pp. 1–6.

[7] "OpenDSS, a comprehensive electrical power system simulation tool," https://smartgrid.epri.com/SimulationTool.aspx, Sept. 2019, [Online].

[8] "Distributed PV Monitoring and Feeder Analysis," https://dpv.epri.com/feeder_j.html, Sept. 2019, [Online].

[9] "Service drop used in North America," https://en.wikipedia.org/wiki/Service_drop, Sept. 2019, [Online].

[10] W. Kersting, "Distribution systems modelling and analysis," 2012.

[11] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd, Ed. McGraw-Hill, 2012.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.