Nonintrusive Identification of Electrical Loads in a Three-Phase Environment Based on Harmonic Content

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Abstract

This paper describes a signature construction for identifying loads based upon harmonic content of the current measured at a metering socket. Data gathered from ten loads at a commercial site served to experimentally validate the signature construction. The repeatability of current harmonics was investigated during transients and steady-states of several single, split-phase, and three-phase loads monitored in isolation.

1. Introduction

Nonintrusive monitoring of a multi-load electrical circuit detects turn-on and turn-off times of all connected loads. When these turn-on and turn-off events are combined with load signatures, an energy audit can be computed to provide energy profiles, time-of-use, and energy costs. This energy audit can be used to identify energy hogs, reschedule loads, detect aging loads, and identify malfunctioning loads with the potential of lowering energy costs.

Previous work by Hart viewed the power consumption of loads as a normalized admittance power waveform [1]. He developed load signatures based on discrete changes in a power waveform that indicated the turn-ons and turn-offs of loads. Hart's work was extended by the authors of this paper to recognize loads that had spiking, ramping, and small oscillating behavior between discrete changes [2]. The load signature is defined by discrete changes in the normalized power level consumed by a load. However, these techniques cannot recognize loads that exhibit non-discrete changes in power and larger oscillations during steady-state as might be generated by fluorescent lighting, refrigeration equipment, AC variable speed drives, and other nonlinear loads.

Leeb investigated harmonics of the 60 Hz current waveform during turn-on durations by screening the output of Finite Impulse Response FIR filters that were matched to transient features of fluorescent lighting loads [3]. By correlating the output of these filters with a load signature, Leeb was able to extract the signatures of fluorescent lighting that is typically found in large buildings in the presence of other loads. While nonintrusive lighting detection may be useful, including Leeb's matched filters for every kind of load would be prohibitively expensive. Moreover, it has not been determined that Leeb's load transient identification could identify loads other than fluorescent lighting.

2. Harmonic content of loads in a three-phase environment

Electrical loads as observed from the power metering socket in a three-phase environment can be 3 phase Δ connected, 3 phase Y connected, split-phase Y connected, or single phase Δ or Y connected as shown in Fig. 1. At a commercial site, the voltage supply typically is a Y connected 3 phase 60 Hz supply.

Loads supplied by a phase-to-ground voltage may generate the fundamental and its harmonics of current on that phase. For example, assuming that non-multiples of the 60 Hz voltage fundamental are not considered, the loads on $V_{Ag}(t)$ generate a current with N-1 non-zero harmonics, $\sum_{n=1}^{N} I_n^A \cos(60 \cdot 2\pi \cdot nt + \theta_n)$. These current harmonics can be described by the nth *harmonic energy*, $|I^A_n|$, and the nth *harmonic energy ratio* $=|I^A_n/I^A_1|$.

Typical examples of current harmonic generating loads include: thyristor-controlled loads such as switching-mode power supplies typically used in computers, ballasts for gas-discharge lamps in fluorescent lighting, battery chargers, air conditioners, HVAC equipment, heat pumps, and color television sets [4],[5].

For this paper, it is assumed that the harmonic distortion of the current does not cause supplied voltage harmonics or voltage distortion through non-zero source impedance [4]. With distorted supply voltages, current harmonics generated by a load might not be distinguishable from harmonics in the supply voltage.

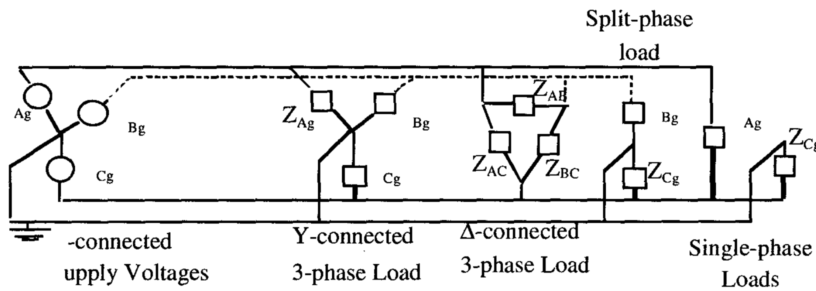

Fig. 1. Several electrical loads in a three-phase environment.

Also, loads having AC variable speed drives with cycloconvertors or loads like arc welders and arc furnaces which generate non-integer, or noncharacteristic, harmonics are not included in the experimental work reported in this paper.

3. Transients vs. steady-state harmonics

Typically, an electrical load forms a steady-state after turn-on or turn-off, such as seen in the power waveform of the fluorescent canopy lights in Fig. 2. Some loads are composed of multiple parts which may turn on and then turn off several times before the load completely stops consuming current. The behavior of these loads can be classified as a sequence of turn-on and turn-off events and steady-state. The waveform of the canopy lights shows first a turn-off that occurs as a sharp decrease in power at about 80 seconds. As the canopy lights do not consume any power from about 80 seconds to 130 seconds, a steady-state occurs. Next, a turn-on occurs as a small sharp increase in power at about 130 seconds. A steady-state follows until a small spike and increasing ramping at about 340 seconds signal another turn-on that settles to a steady-state at about 415 seconds.

As the 60 Hz current waveform is different during transients than during steady-state, it is reasonable to assume that the harmonic content of the current waveform differs during transients and steady-state. To develop a harmonic signature it is useful to know if the harmonic content is repeatable during transients and the steady-state. Here, repeatability of harmonic content is defined as a relatively low standard deviation of the current harmonic content.

Several experiments were done to test the repeatability of harmonic content during transients and steady-state for several single-phase, split-phase, and 3-phase loads. Data were gathered from a Circle-K convenience store in California with a BMI/Dranetz Power Platform 1 (PP1) unit. The monitored loads included: two 208 V 3 phase HVACs, two 208V 3 phase walk-in coolers, a 208V 3 phase walk-in freezer, a 208V 3 phase three-door freezer, a 208V single-phase Icee maker, a 208V 3 phase dairy merchandiser, and two 115V single-phase fluorescent canopy lights. To calculate the harmonic content of these loads, a 256 point Fast Fourier Transform (FFT) was taken on sections of the current data in each phase. The appropriate coefficients corresponding to the harmonic energy in each harmonic were extracted from the results.

The amplitude of the current fundamental energy varied widely during transients in contrast to the current fundamental energy during steady-state. For example, when the FFT was taken from samples during the spike at turn-on of a HVAC at about 0.5 seconds and just after the spike at about 0.7 seconds in Fig. 3, the harmonic energy was spread from the fundamental to the 15th harmonic; yet, it was confined to the fundamental and the 3rd, 5th, and 7th harmonics just after the spike, as shown in Table 1. Dashes and unlisted harmonics indicate no detected harmonic energy.

Therefore, the current harmonic energy ratio instead of harmonic energy was used to compare repeatability during transients and steady-state. Furthermore, the levels of the harmonic energy varied widely between measurements. To minimize the variation between measurements, the harmonic energy ratio during the transient was calculated immediately after the spike shown in Fig. 3. This period of the transient generally exhibited ramping or small oscillations that gave more repeatable harmonic content within transients than during the period of initial spike or sharp decrease.

The average standard deviations in current harmonic energy ratio were computed for odd harmonics of all ten loads monitored in isolation and for each phase during several measurements of transients and steady-state for all common frequencies. Common frequencies have non-zero values in at least one phase.

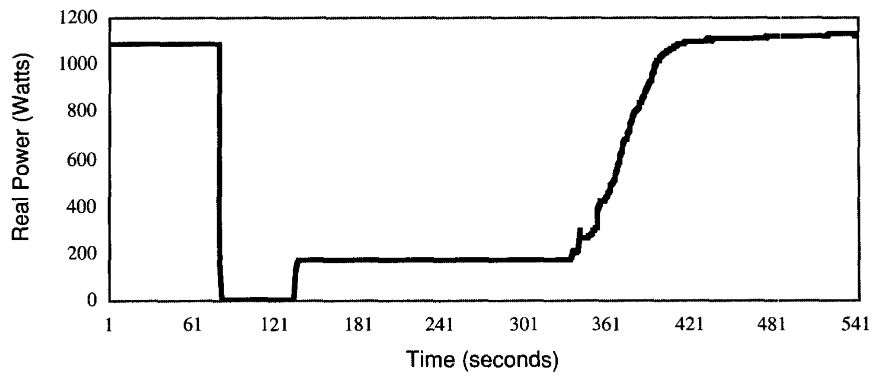

Fig. 2. Real power waveform of 115V, 1.1kW, single phase canopy lights at a Circle-K convenience store, recorded during turn-off then turn-on. Real Power is proportional to the root-mean-squared current when the supply voltage is constant.

Freq. (Hz)	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
60	48.2	51.0	39.2	22.4	23.4	16.8
120	4.7	9.6	5.7	-	-	-
180	1.8	3.5	3.3	0.4	0.4	0.4
240	0.2	0.6	1.0	-	-	-
300	0.4	1.0	0.4	0.6	0.8	0.6
360	0.4	0.4	0.4	-	-	-
420	-	-	-	0	0.2	0.2
480	0	0	0.4	-	-	-
540	0	0.2	0	-	-	-
660	0	0.2	0	-	-	-
900	0	0.2	0	-	-	-

Table 1. Harmonic energy during HVAC turn-on, on the left during spike and on the right just after the spike.

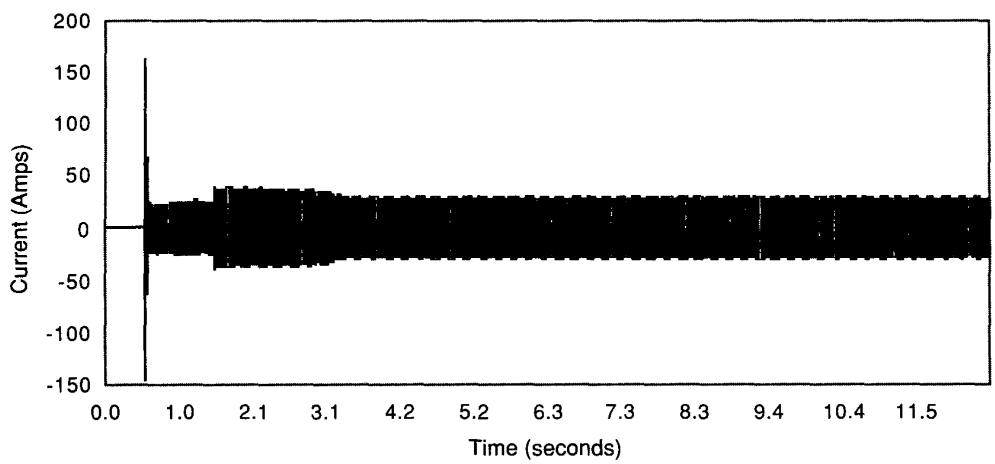

Fig. 3. Current on Phase A of 208V, 3 phase, 6.3kW HVAC turn-on.

For example, if one measurement taken of a load that has 2nd and 3rd harmonics present while another measurement has only the 3rd harmonic present, only the 3rd harmonic is considered the common frequency between the two measurements. The results are given in Table 2.

Steady-state	Transient	Freq. (Hz)	Harmonic
0.00479	0.03629	120	2nd
0.00456	0.00989	180	3rd
0.00259	0.00997	300	5th
0.00180	0.00137	420	7th

Table 2. Average standard deviations in harmonic energy ratio for common harmonics.

These results show that the steady-state had 2 to 10 times lower average standard deviations than during transients, excluding the 7th harmonic that had about the same average. The results would indicate that the harmonic content is more repeatable during steady-state than during transients.

To further assess repeatability, instances were counted when a non-zero harmonic energy ratio for one measurement was found to be zero for the same harmonic in other measurements. With an increase of such cases, the harmonic content is considered to be less repeatable. It was observed that non-repeatable measurements occurred for nine of the loads during transients, yet only occurred for one load during steady-state. This single occurrence during steady-state was due to a very low (0.5%) harmonic energy ratio for one harmonic and zero for the same harmonic in another measurement. From this, it is again concluded that the harmonic content is more repeatable during steady-state than during transients.

4. Developing signature of harmonic energy for a three-phase environment

The observations described in Section 3 indicate that a harmonic signature should be based upon the harmonic energy of a load that is most reflective of steady-state. Consider the envelope of a typical current waveform for two loads in parallel shown in Fig. 4. Notice that the steady-state and therefore the steady-state harmonic energy after an event is most stable just before the next event. This suggests that the harmonic energy of an event should be measured just before the next event occurs. However, as more than one load may generate harmonics at the same time, the harmonic energy due to a load should reflect the harmonic energy difference before and after an event of that load, e.g., m_2 - m_1 is the harmonic energy due to event e_2 of a load. In practice, events are recognized separately on each phase of multiphase loads for ease of detection.

The measured harmonic energy for the ten loads investigated is shown in Table 3. The 5th harmonic energy, for example, for the three-phase HVAC#1 was 1 for Phase A, 0.8 for Phase B and 0.6 for Phase C. Similarly, for the split-phase 3-door freezer, the fundamental energy was 17.3 for Phase A and 17.4 for Phase B. The single-phase Canopy Lights#1 had 3rd harmonic energy of 2.6 for Phase A. The even harmonic energies for the HVAC#1 and the Icee Maker are shown in bold to highlight that other loads have no detected even harmonic energy. A dash indicates zero harmonic energy.

The signature of each of the ten loads is defined as a measure of harmonic energy corresponding to that load in Table 3. It is a vector of length 27 corresponding to all 8 harmonics plus the fundamental on all 3 phases. No value on a phase of a harmonic indicates a zero value for that element in the vector. For example, Canopy Lights#1 is represented as the vector [13.2, 0, 0, 0, 0, 0, 2.6, 0, 0, 0, 0, 0, 0.8, 0, 0, 0, 0, 0,4, 0, 0, 0, 0, 0, 0, 0].

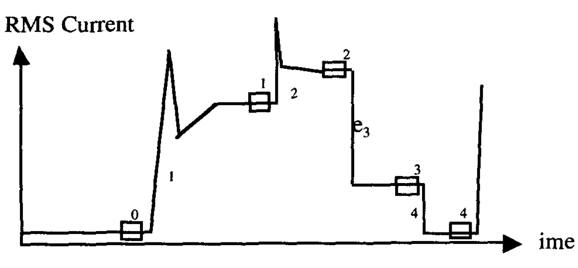

Fig. 4. m_n is the Nth measurement of harmonic energy and e_n is the nth event of turn-on or turn-off.

Loads	Fund.	2nd	3rd	4th	5th	7th	9th
HVC1	28.1/29.3/20.2	-	0.2/0.2/0.2	**0.2/0.2/0.2**	1/0.8/0.6	0.2/0.2/0.2	0/0.2/0.2
HVC2	25.4/26.4/18.6	-	0.4/0.2/0.6	-	0.8/0.8/0.6	0/0.2/0.2	-
DyMer	9.6/6.7/9	-	0.4/0.2/0.4	-	-	-	-
3dFrz	17.3/17.4	-	0.2/0.2	-	0.2/0.2	-	-
Icee	15.5/13.4	**1.2/1.2**	0.6/0.8	-	1/1	-	-
CL1	13.2	-	2.6	-	0.8	0.4	-
CL2	12.8	-	2.6	-	0.8	0.6	-
Cool1	10/11/13.3	-	0.2/0/0.2	-	0.4/0.4/0.4	-	-
Cool2	14/11.2/14.7	-	0.2/0/0	-	0.4/0.2/0.4	-	-
Freez	7.5/10.6/9.2	-	0.2/0.2/0	-	-	-	-

Table 3. Harmonic energy of ten loads from the Circle-K convenience store.

To quantitatively assess the distinctness of signatures, two measures were implemented. A normalized city-block distance (CBD) metric was chosen to account for differences in harmonic energy present in load signatures [6]. To take advantage of harmonic distribution within loads and on different phases, the Hamming distance (HD) metric was chosen as well [7]. The CBD for two load vectors $\underline{x} = [x_1 \ldots x_{27}]$ and $\underline{y} = [y_1 \ldots y_{27}]$ is $\sum_i |x_i - y_i|$ for all i where $x_i, y_i \neq 0$ [6]. Index i ranges across the harmonics present in both vectors $\underline{x}$ and $\underline{y}$. For the HD computation, an element of a load vector is quantized to 0 if the element value is zero and to 1 otherwise. The HD is then computed on these quantized vectors $\underline{x}$` and $\underline{y}$` as $\sum_i |x_i^` - y_i^`|$ where index i ranges across all the harmonics [7]. The CBDs between loads are shown in the lower triangle of Table 4. The upper triangle of the table has the computed HD metric. The diagonal of Table 4 is labeled with all zeros.

As either the presence or absence of harmonic content, measured by HD, or a difference in the harmonic content, measured by CBD, may be sufficient to distinguish two loads, both HD and CBD are equally considered with the same order of magnitude in range by defining LVD as the sum of CBD and HD. LVD for all of the loads is shown in the lower triangle of Table 5. A low LVD value for two loads indicates that they are harder to distinguish than two loads with a higher LVD value.

To determine whether the limited accuracy of the PP1 unit measurement and the variation in harmonic energy due to the measured condition would make a significant impact on the defined LVD metrics, a 5% variance on each of the elements of a harmonic vector was assumed with 1% due to PP1 measurement errors and 4% due to the variation in calculating the harmonics. The LVD was then recomputed when the harmonic energy of the loads may vary up to 5% such as to minimize the value of LVD with variance. This minimal LVD is shown in the upper triangle of Table 5. It is assumed that the harmonic energy variance may cause the HD of the quantized vectors $\underline{x}$' and $\underline{y}$' to decrease by 1 unless the HD is zero, or indicates the absence of harmonics, where HD is assumed to be still zero.

Two loads are considered distinct if despite up to a 5% variation in load harmonic energy, LVD is greater than zero. It is observed that all the examined loads can withstand this 5% variation and still be distinct. Therefore, the measured harmonic vectors of the ten loads can be considered to be the unique signatures that are distinguishable.

This suggested signatures that may serve to discriminate among loads during a monitoring period. Given our experience gained by studying nonintrusively monitored residence and commercial loads, the following algorithm for load identification is proposed: 1) power level change as described in [2] as well as its harmonic energy as described in this paper are recorded; 2) power level change is to be compared to the load library to select the load corresponding to that change; 3) if the change cannot be identified with any single load, it is assigned to several most possible loads from the library; 4) the harmonic energies of the most possible loads are compared to the harmonic energies reported at the change (before and after the change); 5) search for the lowest LVD among the most possible loads, the list of these loads narrows down to either a single load or to a few loads that can not be distinguished. End of Algorithm.

5. Conclusions

A method for measuring the harmonic content of electrical loads from a three-phase environment is described. By measuring the harmonic energy of the non-zero harmonics of the fundamental of current, a signature of a load can be developed. Additionally, experimentation with current data from ten nonlinear three-phase loads at a convenience store gave evidence that measuring the harmonic energy of a load during steady-state is a repeatable measure of harmonic content. City-block and the Hamming distances can be computed between measurements of the harmonic content for the loads to show the distinctness of the harmonic signatures of the loads. These two quantitative measures give evidence that different loads can be distinguished using the harmonic content signature proposed in this paper despite a 5% variation in their measured harmonic content.

References

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	HVC1	HVC2	DyMer	3dFrz	Icee	CL1	CL2	Cool1	Cool2	Freez
HVC1	0	6	11	11	13	13	13	9	10	12
HVC2	9.2	0	5	5	7	9	9	3	4	6
DyMer	56.7	47.9	0	4	6	6	6	2	1	1
3dFrz	46.7	38.7	28.4	0	2	4	4	4	3	3
Icee	54.7	46.7	26.8	10.8	0	6	6	6	5	5
CL1	70.5	62.4	23.3	25.3	22.5	0	0	6	5	5
CL2	71.0	63.0	23.1	25.9	23.1	0.6	0	6	5	5
Cool1	46.3	38.3	10.8	28.2	26.6	31.7	31.5	0	1	3
Cool2	41.1	33.1	16.4	25.0	23.8	30.5	31.1	6	0	2
Freez	54.5	46.5	6.8	26.2	25.4	29.3	29.1	8.6	13.8	0

Table 4. Lower triangle shows CBD while upper triangle shows HD.

	HVC1	HVC2	DyMer	3dFrz	Icee	CL1	CL2	Cool1	Cool2	Freez
HVC1	0	7	61.3	51.3	61.0	72.5	78.1	48.4	44.0	60.0
HVC2	9.2	0	46.9	37.2	47.3	65.9	66.5	34.8	30.3	46.4
DyMer	56.7	47.9	0	28.3	29.2	26.1	25.9	9.3	13.0	4.8
3dFrz	46.7	38.7	28.4	0	8.3	25.7	26.3	27.7	23.2	25.1
Icee	54.7	46.7	26.8	10.8	0	24.9	25.5	28.1	24.0	26.3
CL1	70.5	62.4	23.3	25.3	22.5	0	0.2	34.0	32.2	31.1
CL2	71.0	63.0	23.1	25.9	23.1	0.6	0	33.9	32.3	30.3
Cool1	46.3	38.3	10.8	28.2	26.6	31.7	31.5	0	3.2	8.1
Cool2	41.1	33.1	16.4	25.0	23.8	30.5	31.1	6	0	11.9
Freez	54.5	46.5	6.8	26.2	25.4	29.3	29.1	8.6	13.8	0

Table 5. Lower triangle shows LVD = CBD + HD from Table 4. Upper triangle shows the minimal LVD obtained when load harmonic energy from Table 3 may vary up to 5%.