Estimating the Net Harmonic Currents Produced by Selected Distributed Single-Phase Loads: Computers, Televisions, and Incandescent Light Dimmers

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Abstract

Individually, single-phase power electronic-based loads pose no problem to power systems. In total, however, they have the potential to raise harmonic voltages and currents to unacceptably high levels. The purpose of this paper is to give guidelines for modeling the net harmonics currents produced by these loads, and to describe the following two key factors used to determine the guidelines:

1. harmonic current cancellation due to phase angle diversity, and
2. attenuation due to system impedance and the corresponding voltage distortion that tend to reduce the net harmonic currents produced by these loads.

1. Motivation and Previous Methods

Large single-point harmonics-producing loads have been traditionally treated as fixed harmonic current injectors. The same method has been used to predict the harmonic levels in distribution systems caused by large numbers of distributed single-phase loads, where the typical harmonic current spectrum of one load is scaled in proportion to total load power. These assumptions result in an overestimation of harmonic current injection because phase angle cancellation among the individual loads, and attenuation caused by system impedance and voltage distortion, are neglected.

The results shown in this paper, and the conclusions drawn regarding phase angle cancellation and attenuation, are based upon analytical models and Monte Carlo simulations. Actual measurements have been used when possible to confirm the simulation results.

2. Cancellation of Harmonic Currents Due to Phase Angle Diversity

When several nonlinear loads are served by a common transformer or bus, their net harmonic current is the phasor sum of the individual currents. As a result, some level of phase cancellation will occur because of phase angle diversity unless the loads have precisely the same harmonic spectra [1], [2].

For illustration purposes, consider the situation shown in Figure 1, where a television and an incandescent light dimmer (dimmer adjusted for approximately one-half power) are served by the same wall outlet. The corresponding current spectra are given in Table 1. Because of phase cancellation, the current flowing through the wall outlet has lower total harmonic distortion (THDI) than either the television or dimmer. In the example given, the combined RMS harmonic current is less than that of the television or light dimmer taken separately.

The current diversity factor DF_h for any harmonic h is defined as the phasor magnitude of the net current, divided by the sum of magnitudes of the individual currents. For example, in Table 1, the diversity factor for the 5th harmonic is

$$DF_5 = \frac{30.9 \bullet 1.88}{49.2 \bullet 1.20 + 42.3 \bullet 0.88} = 0.60 \ .$$

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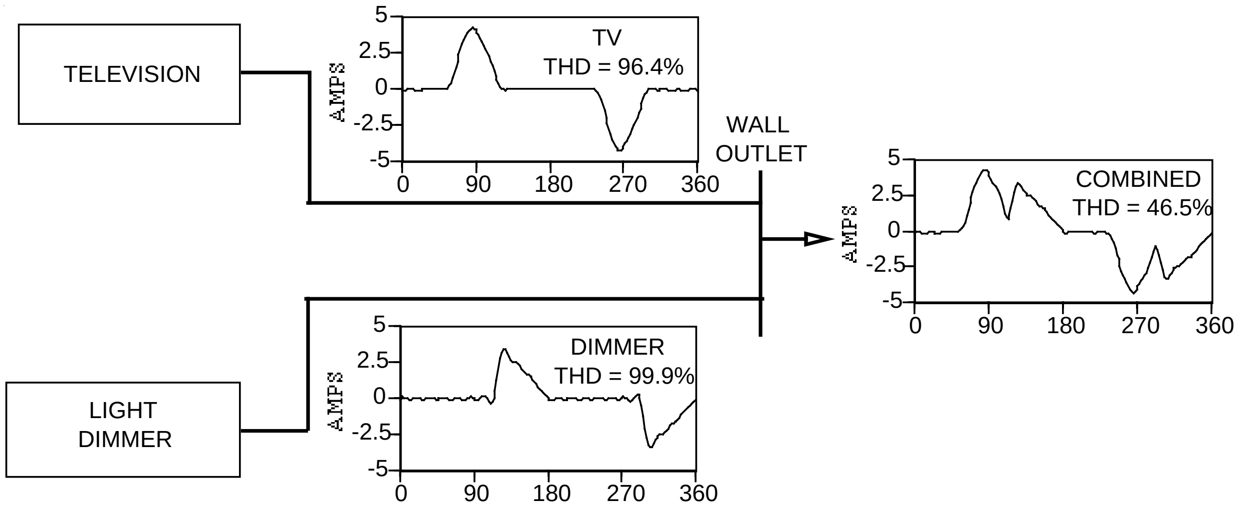

Figure 1. Example of Harmonic Current Phase Angle Cancellation for Television and Light Dimmer

Table 1. Harmonic Current Spectra (Sine Series) for Television and Light Dimmer Example

Harmonic	Television		Light Dimmer		Combined	
	Magnitude*	Phase Angle	Magnitude*	Phase Angle	Magnitude*	Phase Angle
1	100.0 (1.20A)	1	100.0 (0.88A)	-50	100.0 (1.88A)	-20.3
3	79.8	-173	76.6	31	23.3	148
5	49.2	12	42.3	122	30.9	49
7	20.5	-159	21.1	-111	21.0	-138
9	4.0	81	21.2	20	11.4	31.3
11	5.5	-13	17.7	128	6.0	106
13	3.1	175	12.2	-108	6.2	-121
15	0.8	-138	11.7	20	5.0	17

Variations in output power and circuit impedance significantly affect the current waveform of a capacitor-filtered diode-bridge rectifier load. For example, consider the full-power and half-power current waveforms of an unfiltered ASD heat pump, shown in Figure 2. This particular heat pump behaves electrically as a very large desktop computer or television. The two different waveforms have different harmonic current magnitudes and phase angles.

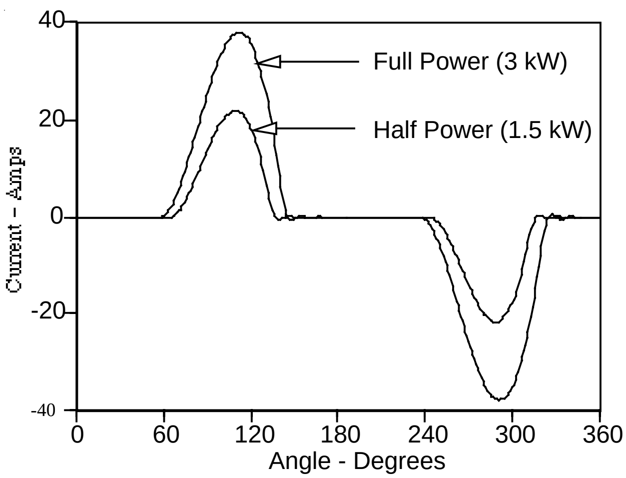

Figure 2. ASD Current Waveforms for 50% and 100% Power

The phase angles for current harmonics 3 - 15 are given in Figure 3 for 20% - 100% power levels. It is obvious that phase angle variation is much more pronounced for higher-order harmonics, so that one may expect more pronounced phase angle cancellation for higher-order harmonics.

3. Attenuation of Harmonic Currents Due to System Impedance and Voltage Distortion

Capacitor-filtered diode-bridge rectifier loads tend to distort their applied voltage waveforms in such as way as to reduce their current distortions from that otherwise produced by purely sinusoidal voltages [4]. This phenomenon is known as attenuation, and it can be as significant as 50% or greater. While not always true in power distribution systems having shunt capacitors and resonance, the assumption of attenuation will usually be valid within customer-owned facilities and should be taken into account when predicting net harmonic levels.

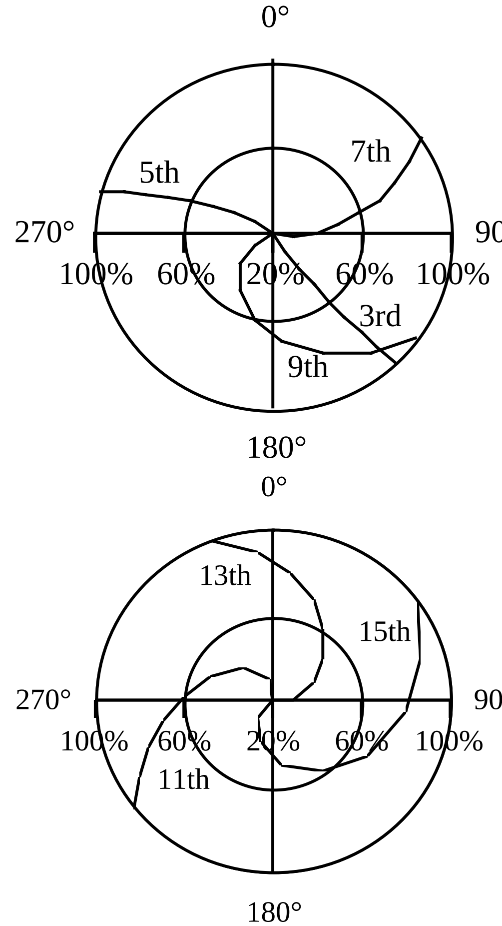

Figure 3. Harmonic Current Phase Angle Variation Versus Load Power for Heat Pump Example

In order to illustrate attenuation, consider N identical 100 W desktop computers served by the same 120 V branch circuit, as shown in Figure 4. The impedance of the branch circuit is a typical (0.4 + j0.25) Ω @ 60 Hz.

Figure 5 and Table 2 illustrate the harmonic current attenuation due to voltage distortion [3]. As N increases from one to five, the voltage distortion increases because the branch circuit is not a "stiff" bus. However, the current distortion decreases in response to the changing voltage waveform. There is no inconsistency here because the harmonic *amperes* increase with N, but not as rapidly as the fundamental amperes.

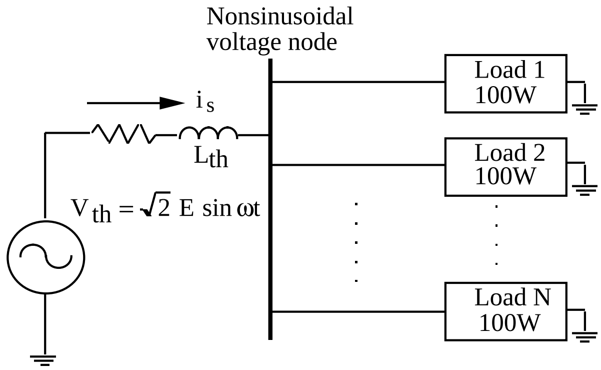

Figure 4. N Identical Computers Served by a 120 V Branch Circuit

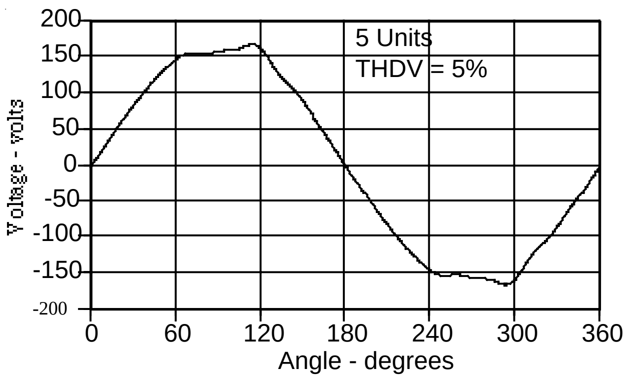

Figure 5: Distortion of Voltage Waveform with N Parallel 100 W Computer Loads

Table 2. Harmonic Amperes for N = 1 and N = 5, Along With the Corresponding Attenuation Factors

Harmonic h	Amps for N = 1	Total Amps for N = 5	AF_h for N = 5
3	0.79	3.89	0.98
5	0.70	2.98	0.85
7	0.57	1.93	0.68
9	0.43	0.98	0.46
11	0.29	0.29	0.20
13	0.17	0.14	0.16
15	0.08	0.22	0.55

The attenuation factor AF_h for the hth harmonic current is defined as the current to one load when only one load is connected, divided by the current to one load when N loads are connected. Hence, for the 7th harmonic,

$$AF_7 = \frac{1.93}{5 \bullet 0.57} = 0.68 \ .$$

4. Estimates of the Net Harmonic Currents Produced by Desktop Computers and Light Dimmers

Based upon analytical models and corresponding Monte Carlo simulations, it is now possible to estimate the net harmonic currents that can be expected from a large number of the following three types of single-phase power electronic-based loads, and for the following conditions (listed in Tables 3, 4, and 5):

Table 3. Net Harmonic Current Injection for Desktop Computers and Televisions Within a Building

Harmonic h	Percent of Operating Funda-mental Current	Current Diversity Factor DF_h	Amps per Operating kW (on 120 V base)
3	81	0.98	6.9
5	53	0.94	4.5
7	25	0.86	2.1
9	9	0.64	0.8
11	5	0.88	0.5
13	4	0.72	0.3
15	3	0.56	0.3

The results in Table 3 are taken from [4]. Assumptions are constant power devices, variations exist in branch circuit lengths and numbers of devices connected to each circuit, and harmonic damping due to other loads in the facility is insignificant.

Table 4. Net Harmonic Current Injection for Incandescent Light Dimmers Within a Building

Harmonic h	Current Diversity Factor DF_h	Amps in Per Unit of Rated Fundamental Current (on 120 V base) *
3	0.92	0.32
5	0.69	0.12
7	0.41	0.05
9	0.32	0.03
11	0.26	0.02
13	0.22	0.01
15	0.20	0.01

* For example, the rated fundamental current for 10 kW of incandescent lamps is 83.3 A. The column varies approximately as $3/h^2$.

The results in Table 4 are taken from [2]. The assumptions are that the lumen distribution is uniform over the 20% - 100% range, and that harmonic damping due to other loads in the facility is insignificant.

5. Conclusions and Key Findings

In conclusion, the key findings are

1. Harmonic current cancellation due to phase angle diversity, and attenuation due to system impedance and the corresponding voltage distortion, are two key factors that tend to reduce the net harmonic currents injected by large numbers distributed by single-phase loads.

2. Cancellation due to phase angle diversity is insignificant for the 3rd and 5th harmonics, but becomes increasingly significant for higher harmonics. Depending on load type, cancellation for harmonics above the 7th can easily exceed 50%. This observation is counter to the present-day strategy of harmonic guidelines that penalizes harmonics more-or-less in proportion to frequency.

3. The current harmonics produced by the most common high-distorting load, the capacitor-filtered diode-bridge rectifier, tend to distort the applied voltage in such as manner as to reduce the current distortion. In other words, these loads exhibit a partial self-compensating effect.

6. Acknowledgments

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7. References

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