Analysis of Harmonic Distortion Levels in Commercial Buildings

Keywords:
ASD/AC Drive
Customer PQ Concerns
Fluorescent Lighting
Harmonic
Nonlinear Loads (3rd Harmonic)
Office Buildings
PC
SMPS/Switch Mode Power Supply

Section 1: Introduction

This case study describes harmonic distortion concerns for commercial buildings and presents a method for evaluating these concerns based on typical load characteristics. Important characteristics of major nonlinear loads in these facilities are summarized in three major categories - electronic loads, lighting, and HVAC equipment. The characteristics developed are then used to analyze the range of harmonic distortion levels which can exist in commercial buildings. The potential for harmonic cancellation with these different types of harmonic producing loads is analyzed in particular. Conclusions are developed regarding the impacts of these loads on commercial building harmonic distortion levels and the impacts on the overall power system.

Evaluation of harmonic distortion in commercial buildings is becoming increasingly important for a number of reasons:

-An increasing percentage of building load is consisting of electronic equipment supplied by switched-mode power supplies. These power supplies can have input currents with very high harmonic content.

-New high efficiency fluorescent lighting uses electronic ballasts and can have significantly higher harmonic content than conventional fluorescent lighting using magnetic ballasts.

-Much of the HVAC load in buildings is being converted to adjustable speed motor drives in order to improve overall efficiency. These drives produce significant harmonic currents.

The harmonic currents from these different sources can result in concerns for neutral conductor overheating, transformer overheating, and interference with communication system. The cumulative effects of the different sources depends on the equipment characteristics and the overall system design.

The overall harmonic levels depend on how the individual harmonics from these different loads combine. The voltage distortion levels depend on the circuit impedances as well as the harmonic generation characteristics. These factors are evaluated in the following sections and important conclusions are developed.

Section 2: Harmonic Current Source Characteristics

In commercial buildings, sources of harmonic current generation are usually small in size and large in number. To facilitate a computational procedure for determining the impacts of harmonic currents from these loads on the electric power system, a number of assumptions are necessary. A primary assumption is that all nonlinear loads in a commercial facility fall into one of three categories:

Electronic Power Supplies:

Almost all productivity equipment used in the modern office environment falls into this category. Personal computers, workstations, and peripheral devices such as printers and copiers all contain circuitry for converting utility-supplied ac voltage to dc which is supplied to microelectronics components. These loads are normally single-phase (although power supplies for larger mainframe or minicomputer systems may be three-phase) and are supplied from receptacles at 120 V. Rated power for single-phase electronic power supplies can range from 200 W, typical of many personal computer systems, to several kW, as might be found in a sophisticated engineering workstation or file server. A line current measurement from a branch circuit serving exclusively computer load is shown in Figure 1.a with corresponding spectrum shown in Figure 1.b.

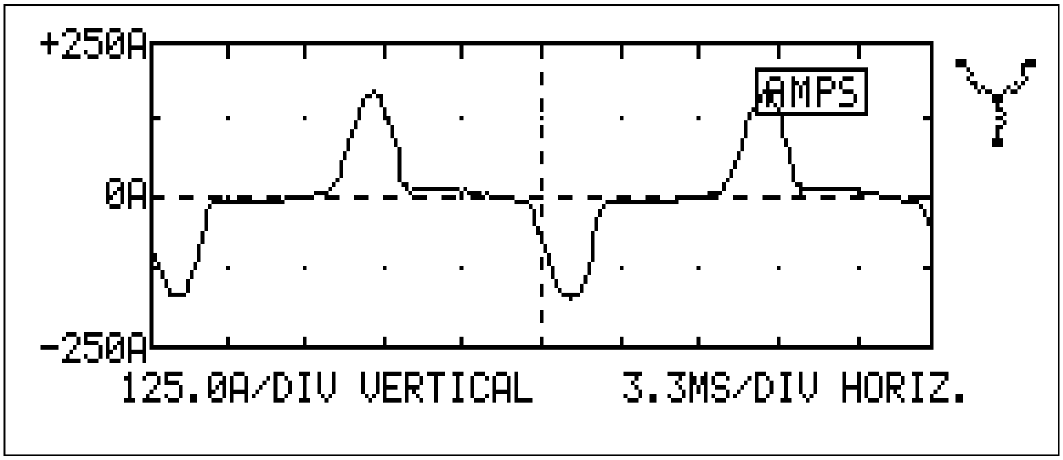
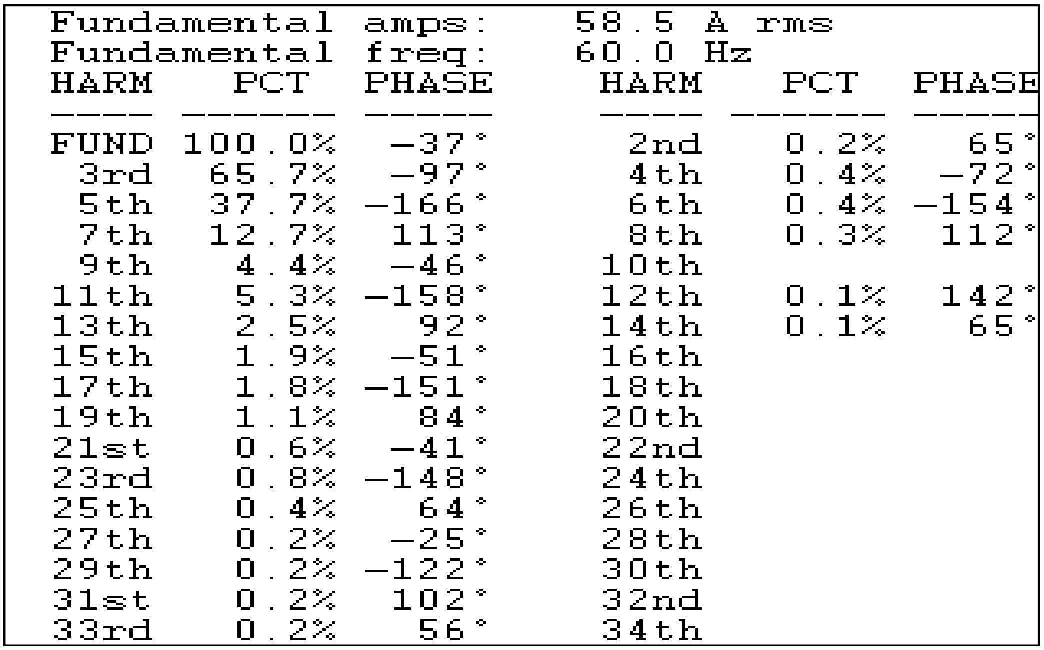


Figure 1a: Phase Current Waveform for Circuit Supplying Electronic Loads



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Fundamental amps:    58.5 A rms
Fundamental freq:    60.0 Hz
HARM    PCT   PHASE     HARM    PCT   PHASE
----  ------  -----     ----  ------  -----
FUND  100.0%   -37°      2nd    0.2%     65°
 3rd   65.7%   -97°      4th    0.4%    -72°
 5th   37.7%  -166°      6th    0.4%   -154°
 7th   12.7%   113°      8th    0.3%    112°
 9th    4.4%   -46°     10th
11th    5.3%  -158°     12th    0.1%    142°
13th    2.5%    92°     14th    0.1%     65°
15th    1.9%   -51°     16th
17th    1.8%  -151°     18th
19th    1.1%    84°     20th
21st    0.6%   -41°     22nd
23rd    0.8%  -148°     24th
25th    0.4%    64°     26th
27th    0.2%   -25°     28th
29th    0.2%  -122°     30th
31st    0.2%   102°     32nd
33rd    0.2%    56°     34th
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Figure 1b: Phase Current Spectrum for Circuit Supplying Electronic Loads

Fluorescent Lighting:
The relationship between voltage across and current through a fluorescent lamp is nonlinear due to the characteristics of the electrical arc which is responsible for illumination. However, harmonic current generation by fluorescent lighting systems is strongly influenced by the type of lamp ballasts used. Although fluorescent lamps with magnetic ballasts draw nonsinusoidal currents, there is currently more concern about electronic ballasts. The voltage current characteristics of electronic ballasts vary over a considerable range, with about 30% THD in the line current near the average. Harmonic current generation in electronic ballasts is due to the operation of a single-phase diode-bridge rectifier, just as is found in electronic power supplies. Passive power factor correction circuitry reduces THD to lower levels.

A line current from a lighting circuit serving one common type of electronic ballast is shown in Figure 2.a and corresponding spectrum is shown in Figure 2.b.

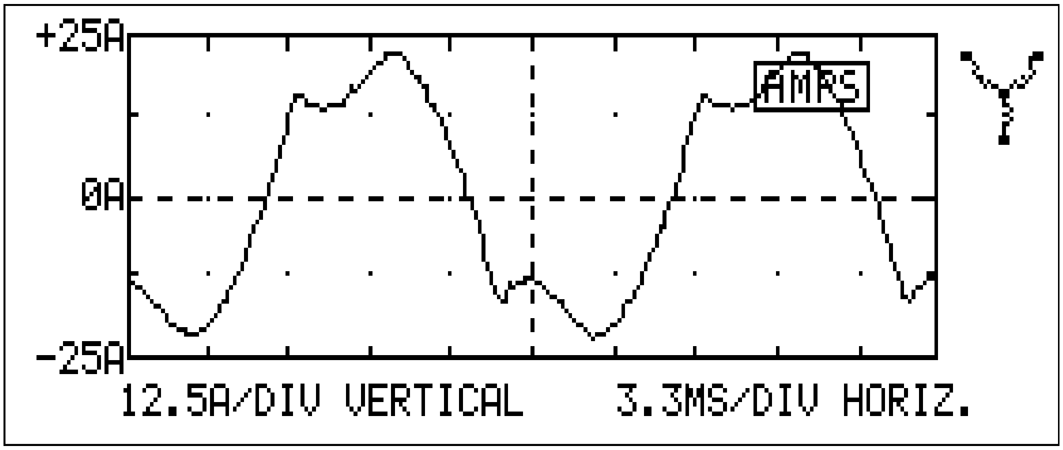
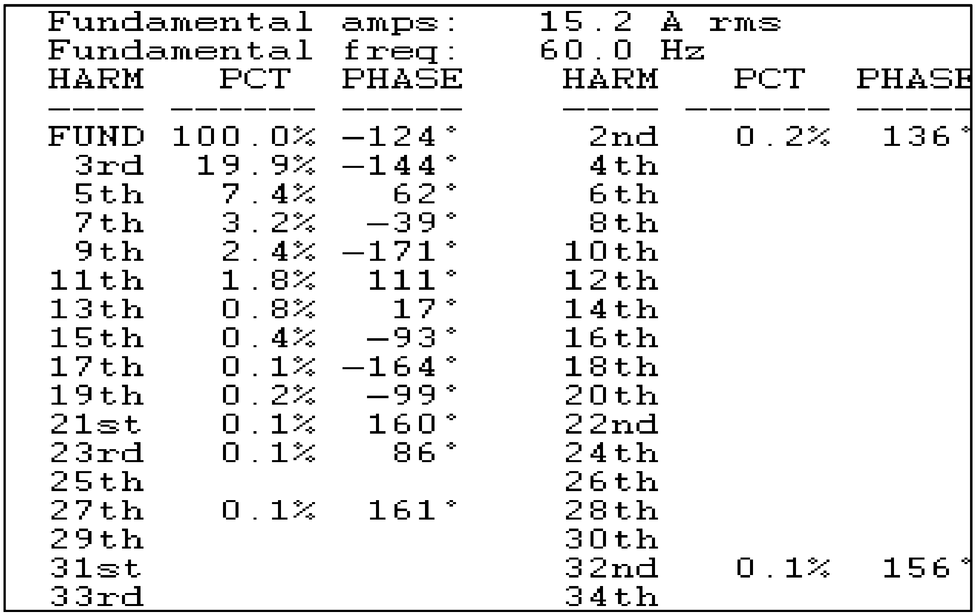


Figure 2a: Input Current for a Typical Fluorescent Light with Electronic Ballast



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Fundamental amps:    15.2 A rms
Fundamental freq:    60.0 Hz
HARM    PCT   PHASE    HARM    PCT   PHASE
----  ------  -----    ----  ------  -----
FUND  100.0%  -124°     2nd    0.2%   136°
 3rd   19.9%  -144°     4th
 5th    7.4%    62°     6th
 7th    3.2%   -39°     8th
 9th    2.4%  -171°    10th
11th    1.8%   111°    12th
13th    0.8%    17°    14th
15th    0.4%   -93°    16th
17th    0.1%  -164°    18th
19th    0.2%   -99°    20th
21st    0.1%   160°    22nd
23rd    0.1%    86°    24th
25th                   26th
27th    0.1%   161°    28th
29th                   30th
31st                   32nd    0.1%   156°
33rd                   34th
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Figure 2b: Input Harmonic Spectrum for a Typical Fluorescent Light with Electronic Ballast

Adjustable-Speed Drives (ASDs) for HVAC:
Induction motors are being replaced by ASDs in fan and compressor applications for increased energy efficiency. A typical ASD for HVAC systems connects to the ac power system through a three-phase diode bridge rectifier circuit. An input current waveform to a small ASD in an HVAC application is shown in Figure 3.a and corresponding spectrum is shown in Figure 3.b.

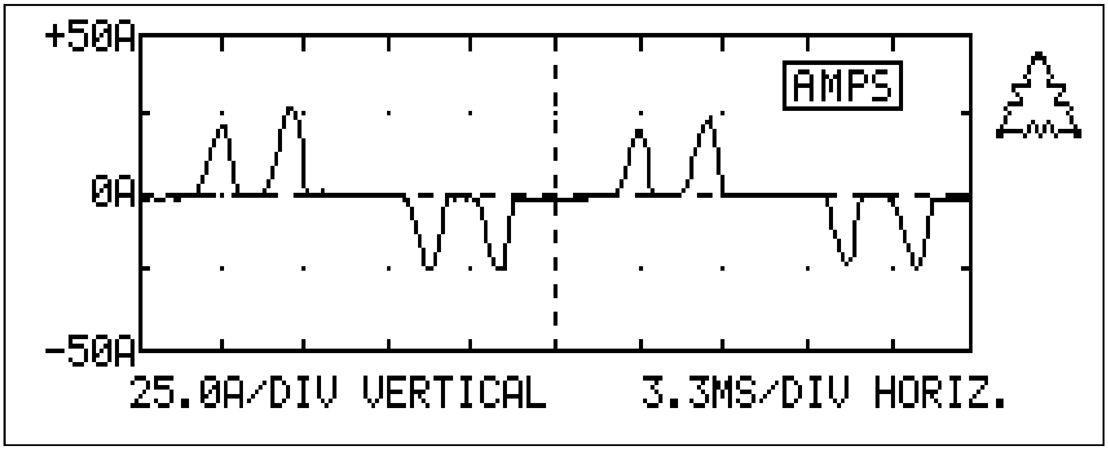
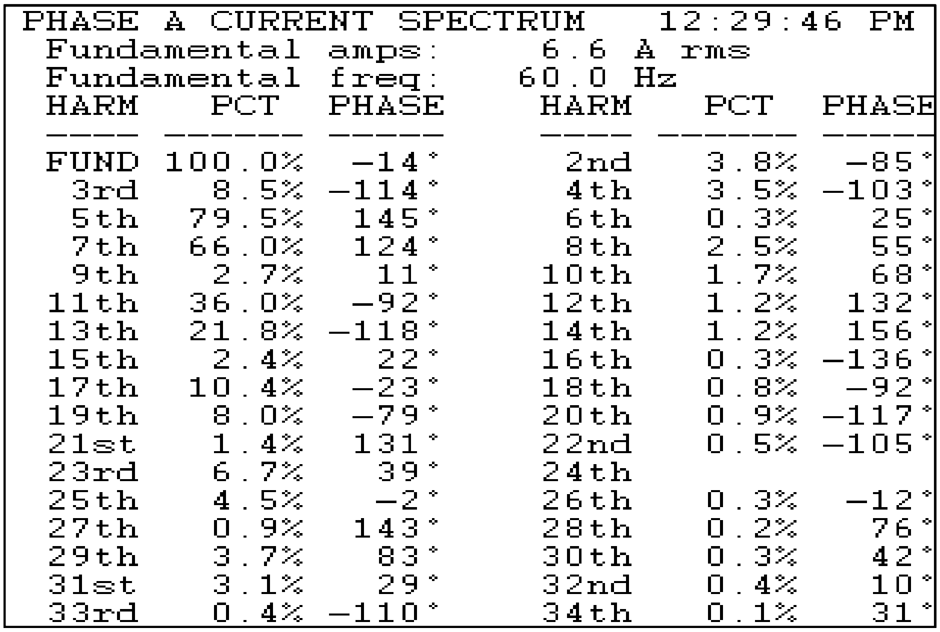


Figure 3a: Typical ASD Input Current Spectrum for HVAC Applications



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PHASE A CURRENT SPECTRUM    12:29:46 PM
 Fundamental amps:    6.6 A rms
 Fundamental freq:   60.0 Hz
 HARM   PCT  PHASE    HARM   PCT  PHASE
 ---- ------ -----    ----  ------ -----
 FUND 100.0%  -14°     2nd   3.8%  -85°
  3rd   8.5% -114°     4th   3.5% -103°
  5th  79.5%  145°     6th   0.3%   25°
  7th  66.0%  124°     8th   2.5%   55°
  9th   2.7%   11°    10th   1.7%   68°
 11th  36.0%  -92°    12th   1.2%  132°
 13th  21.8% -118°    14th   1.2%  156°
 15th   2.4%   22°    16th   0.3% -136°
 17th  10.4%  -23°    18th   0.8%  -92°
 19th   8.0%  -79°    20th   0.9% -117°
 21st   1.4%  131°    22nd   0.5% -105°
 23rd   6.7%   39°    24th
 25th   4.5%   -2°    26th   0.3%  -12°
 27th   0.9%  143°    28th   0.2%   76°
 29th   3.7%   83°    30th   0.3%   42°
 31st   3.1%   29°    32nd   0.4%   10°
 33rd   0.4% -110°    34th   0.1%   31°
```

Figure 3b: Typical ASD Input Harmonic Spectrum for HVAC Applications

A common element associated with the dominant sources of harmonic current generation in commercial facilities is the diode bridge rectifier. The "pulsed" nature of the ac input current is due to filter capacitance on the dc-side of the rectifier circuit. Another important feature of these loads is their power factor. Since the individual diodes in the rectifier circuit cannot be controlled, and turn on and off in response to the voltages on the ac and dc sides of the bridge, the phase displacement between the fundamental frequency ac voltage and fundamental frequency ac current will remain nearly constant, at a value very close to zero. The corresponding fundamental frequency power factor, or displacement power factor, is then very near unity.

True power factor is a measure of the ratio between the actual power delivered and the product of rms voltage and rms current and can be quite poor for these nonlinear loads.

This is mostly due to the high harmonic content in the current. Traditional utility schemes for metering reactive power respond to fundamental frequency phase displacement and will, for these loads, indicate a power factor very close to unity. The actual power factor will be much lower, and will have effects on the power system similar to poor displacement power factor. In the case of an aggregate load consisting almost entirely of computers, for example, the displacement power factor may be above 0.95, with a true power factor as low as 0.6 to 0.7.

Because the displacement power factor for diode bridge rectifier load is constant, the input current waveshape to an aggregate load of one of the three types described can look very much like the input current to an individual load. Figure 1.a is an example of this phenomena where the measured current is for a whole circuit full of electronic loads but looks similar to the current for an individual load.

This makes the task of computing the "equivalent" harmonic current sources within the facility much easier. By assuming a single, representative harmonic current spectrum for each of the described classes of nonlinear loads, an aggregate source as seen from the main can be approximated from the connected kVA or kW demand for each type of load.

Section 3: Effects of Harmonics

Harmonic currents and voltages in the power system deliver almost no useful work, and adversely affect system capacity. High levels of harmonic voltage distortion can cause misoperation of sensitive control equipment, and create additional losses and heating in shunt-connected equipment such as motors. Harmonic current distortion can cause interference with communications circuits and may result in the need for derating of transformers. Harmonic currents from single phase loads in three phase circuits can result in high neutral currents which can result in the need for increased neutral conductor ratings.

Section 4: Simplified Circuit for Harmonic Analysis of Commercial Buildings

For purposes of analysis, the simplified representation shown in Figure 4 for the loads in a commercial buildings is assumed. Electronic loads are supplied through step down transformers with a delta-wye connection. Fluorescent lighting loads are supplied directly from the 480 V level but are connected line-to-neutral (277 V). HVAC loads are three phase loads supplied at the 480 V level. This simplified representation can be used to illustrate the impact of harmonic producing loads at various points in a commercial building.

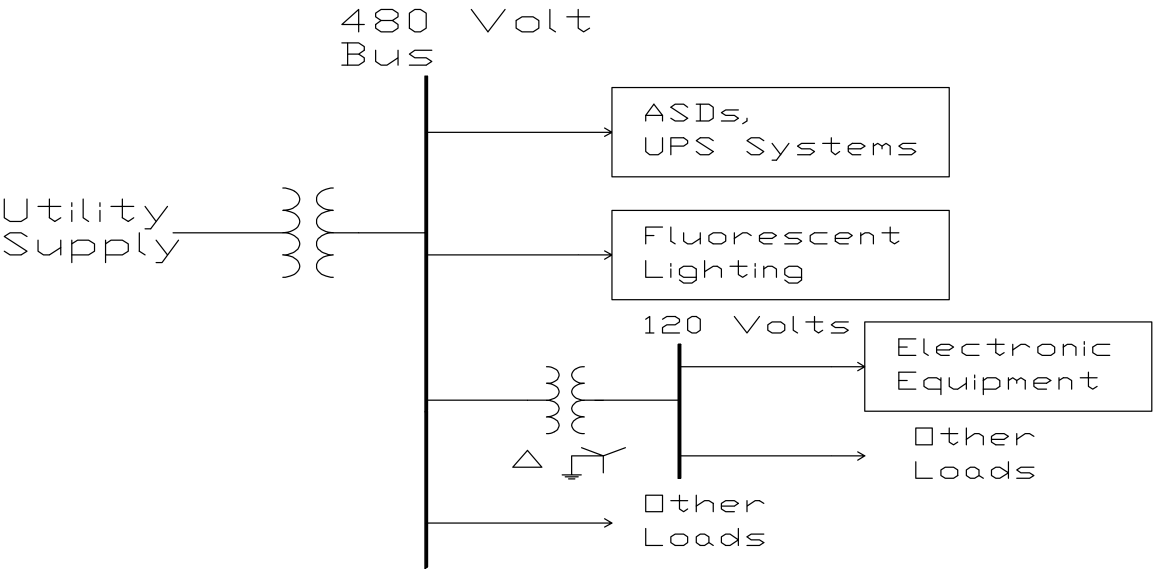

Figure 4: Simplified Representation for Commercial Building Loads

Section 5: Concerns for Neutral Current Magnitudes

When single phase electronic loads are supplied with a 3-phase, 4-wire circuit, there is a concern for the current magnitudes in the neutral conductor. Neutral current loading in 3-phase circuits with linear loads is simply a function of the load balance among the three phases. With relatively balanced circuits, the neutral current magnitude is quite small. This has resulted in a practice of undersizing the neutral conductor in relation to the phase conductors.

With electronic loads supplied by switch-mode power supplies, the harmonic components in the load currents can result in much higher neutral current magnitudes. This is because the odd triplen harmonics (3, 9, 15, etc.) produced by these loads show up as zero sequence components for balanced circuits. Instead of canceling in the neutral (as is the case with positive and negative sequence components), zero sequence components add directly in the neutral. The third harmonic is usually the largest single harmonic component in single phase power supplies or electronic ballasts.

The impact on the required rating for the neutral conductor can be estimated using the typical waveform given in Figure 1.a. For this waveform, the third harmonic is approximately 70% of the fundamental. If we assume that the loads on the three phases are balanced and all have this same characteristic, then the rms phase current and rms neutral current can be approximated by the equations shown in Figure Eq.1.

$$I_{phase} = \sqrt{\left(I_1^2 + I_3^2\right)} = \sqrt{\left(1.0^2 + 0.7^2\right)} = 1.22$$

$$I_{neutral} = \left(I_3 + I_3 + I_3\right) = \left(0.7 + 0.7 + 0.7\right) = 2.1$$

$$I_{neutral} / I_{phase} = 2.1 / 1.22 = 1.72$$

Figure Eq.1: Phase and Neutral Current Calculations

The neutral current in this case will be 172% of the rms phase current magnitude. It is worth noting that this doesn't have anything to do with the square root of three and it is not a theoretical maximum for the neutral current magnitude (the theoretical maximum is 300% of the rms phase current). The conclusion from this calculation is that neutral conductors in circuits supplying electronic loads should not be undersized. In fact, they should have almost twice the ampacity of the phase conductors. An alternative method to wire these circuits is to provide a neutral conductor with each phase conductor. Figure 5 illustrates how the neutral current is dominated by the third harmonic component in this type of circuit.

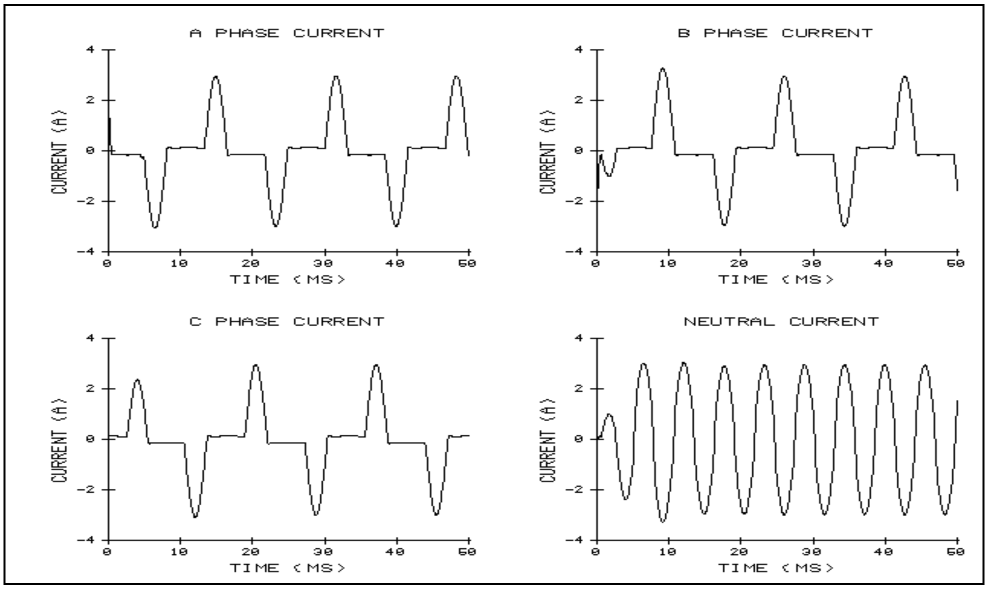

Figure 5: Phase Currents and Neutral Current for a Circuit Supplying Electronic Loads

It is worth noting here that the neutral current concern is not as significant on the 480 V system. The zero sequence components from the power supply loads are trapped in the delta winding of the step down transformers to the 120 V circuits. Therefore, the only circuits with any neutral current concern are those supplying fluorescent lighting loads connected line-to-neutral (277 V). In this case, the third harmonic components are much lower. A typical electronic ballast should not have a third harmonic component exceeding 30% of the fundamental (the waveform in Figure 2.a only has 20% third harmonic). For this worst case analysis, the neutral current can be calculated as shown by the equations in Figure Eq.2.

$$I_{phase} = \sqrt{\left(I_1^2 + I_3^2\right)} = \sqrt{\left(1.0^2 + 0.3^2\right)} = 1.04$$

$$I_{neutral} = \left(I_3 + I_3 + I_3\right) = \left(0.3 + 0.3 + 0.3\right) = 0.9$$

$$I_{neutral} \,/\, I_{phase} = 0.9 \,/\, 1.04 = 0.87$$

Figure Eq.2: Phase and Neutral Current Calculations

This means that the neutral current magnitude should always be less than the phase current magnitude in circuits supplying fluorescent lighting load. In these circuits, it is sufficient to make the neutral conductors the same size as the phase conductors.

Section 6: Requirements for Transformer Derating

One of the important impacts of harmonic currents from nonlinear loads is additional heating in transformers. Transformers which are not specifically designed to supply nonlinear loads must be derated to account for the additional winding eddy current losses caused by harmonic currents. A procedure for establishing transformer capability for supplying nonsinusoidal load currents is defined in ANSI/IEEE Std C57.110.

As an example of applying the procedure outlined in the standard, Figure 6 illustrates the required transformer derating as a function of the percentage of the load made up of electronic power supplies. The figure illustrates that transformers supplying virtually all electronic loads may have a capability less than 50% of the nameplate rating. Requirements for derating the main service transformer are much less severe as a result of harmonic cancellation within the commercial building, as discussed in the following sections.

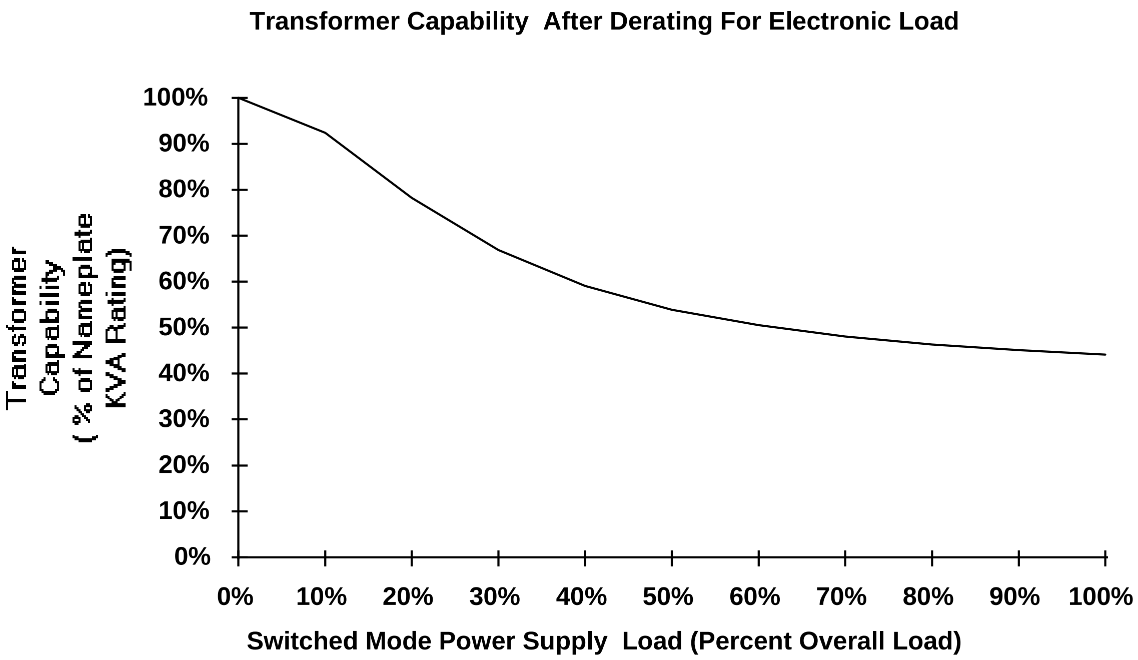

Figure 6: Transformer Capability for Supplying Electronic Loads

Section 7: Harmonic Levels at the Service Entrance

Harmonic voltage and current levels at the service entrance are a function of the combined harmonic producing characteristics of all the loads and the system response characteristics. The three different types of harmonic producing loads do not all produce harmonic components which add at the service entrance. In fact, cancellation between the different harmonic producing loads can be quite significant.

The first factor that helps reduce harmonic levels at the service entrance is the delta-wye connection of transformers supplying electronic power supply loads. Figure 7 illustrates the current waveform at the transformer primary and secondary for a transformer supplying virtually 100% electronic loads. The waveform on the primary side of the transformer does not include the balanced triplen harmonics (trapped in the delta winding) and the fifth and seventh harmonic components are phase shifted so that they may cancel with fifth and seventh harmonic components from fluorescent lighting loads.

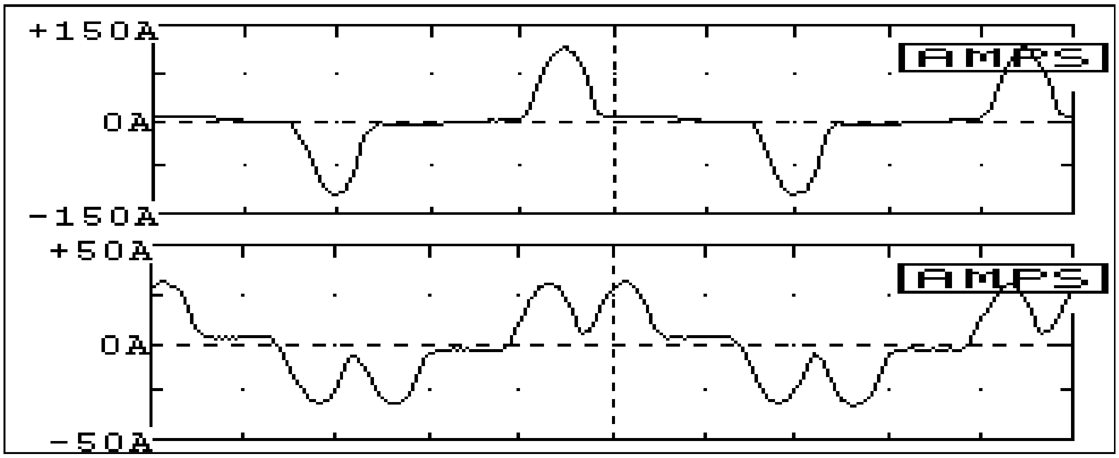

Figure 7: Current Waveforms From Secondary (Top) and Primary (Bottom) of Delta/Wye Step-Down Transformer

Figure 8 illustrates the harmonic cancellation that can occur for a typical commercial building supply. The figure shows the current waveforms at various locations in the facility and gives the harmonic distortion of each waveform. The harmonic current distortion for the 120 V circuit supplying electronic loads is 104%. This results in a high neutral current magnitude for this circuit, as discussed previously. The current distortion at the 480 V primary of the step down transformer is reduced to 30%. The remainder of the load from the 480 V bus is dominated by fluorescent lighting with a current distortion of 15%. When the fluorescent lighting load and the electronic circuit load currents are combined at the 480 V level, the current distortion is reduced to 9%. The current distortion for the total current at the service entrance is only 7%.

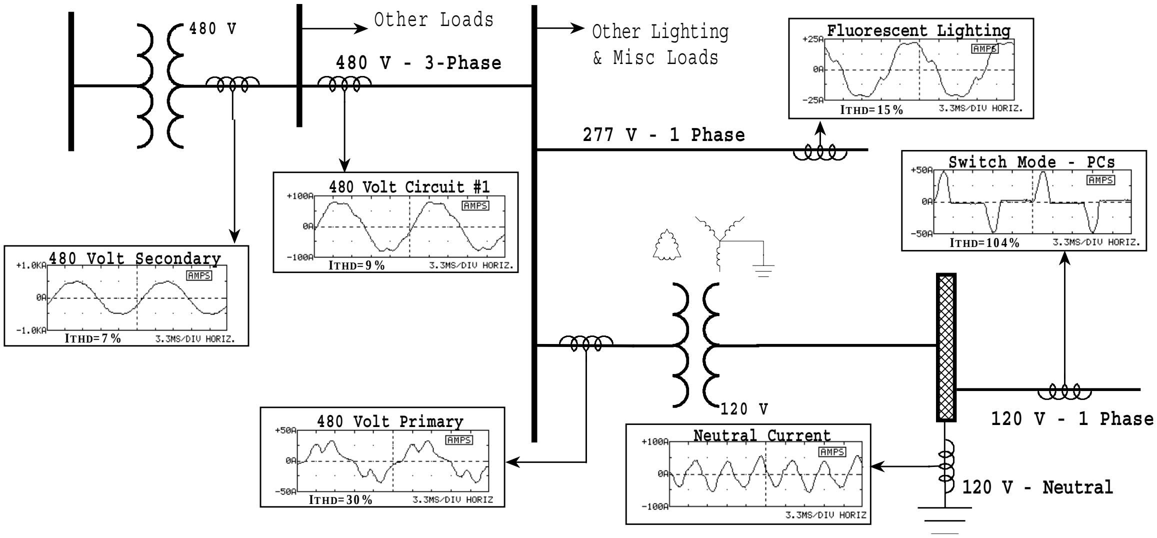

Figure 8: Example of Harmonic Cancellation for Commercial Building Loads

The example described above and illustrated in Figure 8 is not an unusual one. It illustrates that the current distortion at the service entrance can be significantly lower than the current distortion associated with individual circuits within the building. In order to evaluate the impact of harmonic cancellation for more general load characteristics, four different scenarios were analyzed using the simplified commercial building representation described previously. These scenarios are based on a survey of actual building load characteristics and are an attempt to represent the range of load characteristics that can be encountered.

The loading scenarios and the resulting harmonic distortion levels at the service entrance are summarized in Table 1. The harmonic voltage distortion levels are calculated based on the assumption that the main transformer has an impedance of 6% and is loaded to 75% of its nameplate rating. The results support the conclusion that the most significant harmonic problems in commercial buildings are associated with 120 V Circuits. The cancellation associated with typical loads should prevent major harmonic problems at the service entrance for most buildings. This cancellation also significantly reduces the harmonic currents being injected onto the utility system by these customers.

Case	Description	% Electronic Loads	% Lighting Loads	% ASD Loads	% Voltage THD	% Current THD
1	Base Case	20	30	5	3.5	14.5
2	High Lighting Load	20	60	5	3.9	17.1
3	High Electronic Load	40	30	5	5.7	21.8
4	High ASD Load	20	30	10	5.1	20.3

Table 1: 480 Volt Service Entrance Harmonics Resulting from Commercial Building Nonlinear Loads

Section 8: Summary and Conclusions

Harmonic current generation from nonlinear loads in commercial buildings as offices become more automated and energy efficient equipment with nonlinear characteristics replaces older, less efficient linear loads. The harmonic impacts can be estimated from generalized harmonic source characteristics of three basic types of nonlinear loads:

- electronic loads with switch-mode power supplies

- fluorescent lighting

- adjustable speed drives used for HVAC applications

The most significant harmonic problems occur at the low voltage buses and circuits supplying electronic loads. At these locations, high neutral current magnitudes and transformer heating can be very important and must be considered in the system design.

At the main service entrance, the harmonic current distortion and the resulting voltage distortion can be reduced by cancellation between the different types of nonlinear loads. The simplified circuit with the different types of nonlinear loads represented provides a convenient means of estimating harmonic distortion levels and identifying potential problems.