# HARMONIC IMPACT ON POWER SYSTEM DESIGN

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## Abstract

Traditional power system analysis assumes linear loads from resistance and electromagnetic devices. Many loads are nonlinear because of electronic switching power supplies used in computers, variable frequency ac drives, and uninterruptible power devices. The power system design and analysis for these systems is considerably more complex. Traditional definitions and terms must be redefined for the nonlinear systems. The meters and sensors require a different design. The addition of harmonic currents demands that the wiring and electromagnetic devices must be de-rated. The mathematics for analysis has more terms and is more tedious. The paper provides tools for resolving these problems.

## 1. Introduction

The advent of switching power supplies has changed the design of many power units. Solid-state phase-converters, variable speed AC drives, soft-start controllers and uninterruptible power supplies have been widely applied. Nevertheless, as with any engineering problem there are trade-offs. These solid-state controlled power devices have created harmonic problems on the AC power lines.

The solid-state power units are very cost effective. Much of the iron that existed in classical power supplies has been replaced to achieve this economy. As a result, little filtering is available on the unit. The consequence is harmonic currents imposed on the feeder line.

The harmonics have created higher currents and resulting heat losses in devices placed on the same line with the solid-state power unit. The equipment on both sides of the solid-state unit is affected.

The costs associated with these problems are just now becoming apparent as more of the solid-state devices are being used by industry and as the units represent a major part of the load on a circuit.

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Motors placed on the same line that feeds the solid-state power units are exposed to excessive heating and shortened life. The detrimental effect of the nonsinusoidal current on the motor load can also be observed. This is most noted in excessive torsional vibration on the machine.

Correction of this problem has usually consisted of estimates on safety factors and resizing necessary for the equipment placed on the same line. This resize includes conductors, transformers and motors. Some effort has been made to use conventional filters to correct the problem. These efforts have often resulted in large cost because of the size of the equipment.

Another problem is the measurement and monitoring of these currents. Many instruments and monitoring circuits use techniques that are not RMS but are simply prorated to achieve RMS values under linear loads.

The University of Tulsa's Power Applications Research Center, has been conducting research into power system problems including harmonics. The IEEE has awarded The Myron Zucker Grant to Drs. Durham and Strattan to investigate methods of analyzing and correcting industrial harmonics [1]. This paper describes some of that research.

There are no easy fixes to the difficulties caused by harmonics. Nevertheless, it is important to understand the problem. Attempted solutions to harmonics problems often incorporate filters. However, these create another set of problems because of resonance and the resulting excessively large current magnitudes. An effective design has not become apparent.

## 2. Linear vs Nonlinear

A linear, sinusoidal load has the current proportional to the instantaneous voltage. A delay in the time between the voltage and the corresponding current is generally used for power factor descriptions.

A nonlinear load caused by switching power supplies results from the current being switched off during part of the cycle. The nonsinusoidal current yields a waveform rich in harmonics. Figure 1 is a typical plot of a sinusoidal voltage and nonsinusoidal current resulting from a switching power system.

Fig. 1. Sinusoidal volts, nonsinusoidal amps

The basic nonlinear circuit used in most switching power systems can be represented by a full wave rectifier. The typical diodes may be thyristors (silicon controlled rectifiers) or similar solid-state devices. These nonlinear elements do not conduct current during part of the cycle, but conduct during another part. Figure 2 is a typical single-phase circuit.

Fig. 2. Switch mode power supply

Switching converters create primarily odd-harmonics. Three-phase rectifiers basically consist of three single-phase circuits. Because of the wiring configuration, three-phase converters do not produce third harmonic currents. The remaining harmonics are less intense. The neutral conductor serving single-phase switched power supplies from a grounded wye, three-phase system will have a very high level of third harmonic content.

Characteristic harmonics depends on the number of pulses (#) used in the converter. The value k is any integer.

n = k * # pulses +- 1

Noncharacteristic harmonics include the even harmonics resulting from beat frequencies and unbalance on the AC power system.

## 3. Fourier: Frequency vs Time

A nonsinusoidal current waveform is rich in harmonics. This is most apparent from noting the Fourier series. Any alternating waveform can be represented by the summation of a fundamental frequency and its harmonics.

i = I0 + I1sin(1wt + è) + 12sin(2wt + è)

+..+ Insin(nwt + è)

The term i is the instantaneous value at any time. The I terms are the maximum amplitude for each of the harmonic frequencies. The angular frequency w is 2ãf. The phase shift angle represents the time delay between the reference voltage waveform and the current. The n subscript and coefficient of frequency indicates the harmonic number.

The time domain wave is a plot of the current amplitude versus time for the curve. The frequency spectrum is a plot of harmonic amplitude versus harmonic frequency number.

## 4. Harmonic Definition

The harmonic factor (HF) is used to describe the total harmonic distortion (THD) on the waveform [2]. Harmonic factor is the ratio of the RMS value of all the harmonics to the RMS value of the fundamental. A similar description can be given for voltage. The first equation is for odd harmonics, while the second is a generalized form with n as the harmonic number.

HF = ÿû{I32 + I52 + I72 +...}/I1

HF = û{äIn2}/I1

An angular representation is not appropriate for describing the power factor on a distorted waveform. The total power factor is defined by the ratio of average power to the product of the RMS voltage and current.

pf = avg power/ Vrms*Irms

This value will equal the angular displacement power factor only for the linear, sinusoidal case.

## 5. Measurement and Sensing

Voltage and current measurement definitions must be based on the waveform characteristics.

Effective. The effective value of a waveform is the equivalent DC heating value of a resistance on the wave. Thermal meters apply the input to a resistance and measure the heat generated. Although this is accurate, it is very slow and therefore not practical for modern instruments.

Root Mean Square. The effective value is defined by the root-mean-square (RMS) value of the signal.

I = û{1/T + [i2 dt]}

Each instantaneous amplitude sample is squared then multiplied by the time interval between the samples. All the values are integrated (summed). The total is divided by the elapsed time over the period. Then the square root is extracted. The RMS value of a sinusoid is 1/û2 or 0.707 times the maximum amplitude. Electrodynamometer, iron vane and true RMS digital meters measure this value.

Peak Or Crest. The crest value is the peak or highest amplitude the wave achieves during the cycle. The crest factor is the ratio of the peak value to the RMS.

CF = Peak / RMS

The crest factor for a sinusoid is û2 or 1.414.

Half-Period Average. The half-period average is the mean value for half the cycle. Again this compensates for the negative half-cycle performance. The mean for a sine wave is 2/ã. Most analog and digital meters measure this value and indicate the RMS assuming a sinusoidal waveform.

Form Factor. Form factor is the ratio of the RMS to the mean.

FF = RMS / Mean

For a sine wave the form factor is ã/2û2 or 1.111.

Approximation. An approximation that has been used depends on the pulse being very narrow compared to the period of the wave. The approximation is for a narrow rectangular pulse. Nevertheless, it provides some indication of sinusoidal shaped pulse.

RMS = Peak * û[T0/T]

Since RMS calculations are complex, many monitors measure either peak or average values. These values are scaled by the appropriate factor to yield an RMS equivalence. Although this may be acceptable for pure sinusoids, the electronic monitors will be inaccurate for nonlinear systems.

Most meters and sensors are intended only for the power line frequency. The coupling transformers are designed for that particular frequency. However, the harmonics tend to be far outside the range of the coupling resulting in a distorted waveform throughout the monitor. Wide band transformers should be used on all instruments monitoring harmonics.

## 6. Distributed Elements

For most circuit analysis, the inductors, resistors, and capacitors can be considered as lumped parameters. However, all the elements can be defined as being distributed in a cylinder of length l, radius r, and cross sectional area A. The distributed definitions are given. These will be modified for harmonic circuits.

R = p l/A

$$L = u\ l/A$$

$$1/C = 1/e\ l/A$$

## 6.1 Skin Effect

The resistance is often considered independent of frequency. At a fixed frequency the circuit resistance is constant. However, the skin effect phenomenon indicates that resistance is impacted as the frequency increases. Because of the skin effect the effective cross-sectional area is reduced, resulting in higher resistance.

The electromagnetic relationship for resistance indicates its dependance on frequency [3]. The skin effect ratio is identified.

$$mr = r\ \text{û}\{\text{ã}fu/p\}$$

Therefore the resistance effect changes as a function of the square root of the frequency change. This function is shown in figure 3 as proposed by Stevenson [4].

Fig. 3. Ratio of AC to DC resistance

It should be noted that skin effect relationships are appropriate only for conductors that are large enough to have a radius greater than the skin effect depth. At 60 Hz, this would be wires sized in MCM.

Since skin effect is primarily a resistance value, its heating is primarily dependent on current.

## 6.2 Core Loss

The core loss in a magnetic device is described by the hysteresis and eddy current. Core losses are primarily dependent on voltage rather than current. These losses depend heavily on frequency. The core losses can be correlated to a fundamental frequency.

$$P(core) = a f + b f2$$

$$P(hys) = a f$$

$$P(eddy) = b f2$$

Hence the core losses can also be compared to the frequency change.

$$P(hys)n = P(hys)1 * n$$

$$P(core)n = P(core)1 * n2$$

## 7. Rerating

Quantity of harmonic distortion varies depending on the device, load, and type of switching power supply.

Personal computers and similar single-phase equipment typically have a total harmonic distortion near 100%. There is as much energy in the harmonics as in the fundamental. This is because of the large third harmonic component.

Three-phase power systems, where the third harmonic has been removed, typically have a harmonic distortion of approximately 15%, However, the distortion can be significantly larger.

The power losses increase dramatically with frequency. This is due to wire resistance times the current squared as well as hysteresis and eddy current changes. Hence, all equipment that has only a power frequency rating must be reevaluated for harmonic induced problems [5].

### 7.1 Resistance Losses and Wire Size

The current magnitude of each of the harmonics typically decreases with increasing frequency. For a square wave this is inversely proportional to the harmonic number. However, the square root of the summation of the squares (RMS) of these currents results in a much larger total current supplied by the line.

$$I(line) = \hat{u}\{I12 +...+ In2\}$$

The current relationship can be defined in terms of the harmonic distortion.

$$I(line) = I1 \hat{u}\{1 + HF2\}$$

Furthermore, with the resistance and losses increasing with frequency, the summation of all resistance losses creates a large heating load on the power system.

$$P(cu) = I12 R1 +...+ In2 Rn$$

This heating will impact the size of all wires, whether in system wiring or in magnetic devices. If a relationship can be established for the change in resistance due to frequency and the current can be related to frequency, then the equation can be combined into a function of current and of resistance.

P(cu) = I(line)2 * R0 * res freq corr

The phase wiring must be large enough to supply the fundamental and all the harmonics that exist in the line. If there is twice as much current required, the ampacity of the wiring must be doubled. The wire diameter will be twice as large. For a single conductor, the area will be four times as large.

The National Electrical Code permits paralleling conductors only when the size is AWG 1/0 or larger [6]. For most circuits, this indicates that larger wire size will be required.

## 7.2 Neutral

The neutral wiring in a system carries the unbalanced current. This unbalance increases as the harmonics increase, since the phase balance is cancelled. As a result the neutral conductor must be rated substantially higher than for normal balanced systems.

The harmonic component (HC) of the RMS line current can be determined [7].

Ih(line) = I1 * HF / û{1 + HF2}

HC = HF / û{1 + HF2}

The neutral must carry this unbalance from each of the lines. For a three-phase system the neutral current can be defined in terms of harmonics.

I(neut) = 3 I1 * HF / û{1 + HF2}

The increase in neutral wire size must take into consideration all the harmonic components.

HC(neut) = 3 HF / û{1 + HF2}

In the limiting case, the increase in the harmonic component causes a three times increase in current. For a harmonic factor of 100%, the increase is 2.12. Hence, a common rule of thumb is to increase the neutral by a factor of two.

One major assumption has been made: that the resistance does not change appreciably. The current and resulting harmonic component factor must be squared and multiplied by the resistance change to obtain a factor for the increase in heating.

Where the three-phase system primarily supplies single-phase receptacles, a separate neutral should be run for each receptacle circuit. Because of the large neutral currents that can result from the combination of the currents from each phase, common neutrals should be avoided.

## 7.3 Magnetic Device Losses

Ratings of magnetic devices such as reactors, transformers and rotating machines are based on the heating created by a 50/60 Hz sine wave. The increase in other frequencies typically will cause these devices to overheat and perhaps be destroyed.

Core losses are more a function of voltage than current since they are primarily a shunt effect. As a result, the heating due to increase in frequency depends on the voltage frequency rather than the current frequency.

If the voltage waveform from the device is primarily a sinusoid, the hysteresis and eddy current is not appreciably changed by current harmonics caused by the switching supply. Nevertheless, the wiring losses can still dramatically impact the heating.

For three-phase systems, the third harmonic will be present in the windings of the magnetic devices as circulating currents. This can be true even if the line currents do not contain third harmonics.

Unfortunately, there are no standards for derating magnetic devices. Industry experience has shown that overheating of transformers can occur even when underloaded.

Some guidance can be obtained by the ratio of the apparent power rating to the harmonic factor for voltage and for current. Although this may not be appropriate in all environments, it is a reasonable basis for beginning the evaluation of derating [8].

Several key assumptions and simplifications are made. Correction for the change in resistance with the current frequencies should be considered. Second, a similar correction for disturbance of the sinusoidal voltage should be evaluated.

## Switching Power Supply Measurements

Measurements of the line current for two typical office and lab electronic units were performed. The measurements confirm that most of the harmonics are in the current waveforms for switching power supply equipped units. These measurements show that THD levels for typical switching power supplies are about 100 per cent.

The electronic load units were a Telex 1260 AT type personal computer and the Hewlett Packard 1362A Dynamic Signal Analyzer. The analyzer is used to measure its own input power.

The current waveforms were analyzed for spectral content using the HP 3562A signal analyzer. This instrument provides the RMS magnitude of each frequency component. It also calculates the THD.

The true RMS values of the voltage and current were measured with a Fluke 8060A true RMS digital multi-meter. A Fluke Y8100 DC/AC current probe was used with the multi-meter for current measurements.

The power to each device was measured using a Weston 432 electrodynamometer type wattmeter.

The current waveforms were acquired using Pearson model 110 wide-band current transformers. The transformers have a band pass of 1 Hz to 20 MHz and a sensitivity factor of 0.1 volt/amp. The Fluke Y8100 AC/DC Current Probes also provide a good wide-band current waveform signal.

The measured line current waveform to the Telex PC is shown in figure 4(a). The line current to the HP 3562A signal analyzer is shown in figure 4(b).

Fig. 4a PC line current, time domain

Fig. 4b Analyzer line current, time domain

The frequency spectra of these waveforms are shown in figures 5a and 5b. These data were acquired and displayed using the HP 3562A signal analyzer.

The voltage RMS value was 124.7 V. The voltage waveform was not significantly distorted with a THD = 1.7%. The peaks of the current waveforms were closely aligned in time with the voltage peak.

Fig. 5a  PC current, frequency domain

Fig. 5b  Analyzer current, frequency domain

A summary of the measurement data are shown in table 1.

The distortion levels are similar between the two loads. The distortion level, at over 100%, illustrates the severity of the harmonic distortion problem on distribution wiring systems.

Table 1
Measured Current Data

| Waveform | Telex 1260 | HP 3562A |
|---|---|---|
| (Units) | P Computer | Sig Anal |
| RMS (A) | 1.50 | 2.71 |
| Peak (A) | 3.82 | 7.41 |
| C F | 2.55 | 2.73 |
| THD (%) | 114 | 113 |
| Power (W) | 112 | 210 |
| PF-total | .599 | .621 |

| Harmonic component<br>No. | Hz | A RMS | A RMS |
|---|---|---|---|
| 1 | 60 | .985 | 1.740 |
| 3 | 180 | .842 | 1.464 |
| 5 | 300 | .616 | 1.029 |
| 7 | 420 | .355 | .612 |
| 9 | 540 | .123 | .277 |
| 11 | 660 | .033 | .103 |
| 13 | 780 | .102 | .134 |
| 15 | 900 | .097 | .116 |

## 8. Passive Filters

Normally the first attempt to solve harmonic problems is by using filters. Passive filters consist of networks of inductors and capacitors added to the circuit input. When the elements are properly selected, the network can be tuned to certain frequencies. A capacitor connected to ground will shunt the frequency, while an inductor connected in series with the circuit will choke or block the frequency. In addition, the element will cause a change in the power factor.

Two major problems arise when adding elements to the network. First, the element may form a resonant frequency with the circuit. This can create very large currents.

The second problem is particularly peculiar to power frequencies in the 50 to 60 Hertz region. A filter to remove the third harmonic will be designed for 180 Hertz. However, the bandwidth between the first and third harmonics is only 120 Hertz. Even with a sharp cut-off filter design, the roll-off of the filter will cause some attenuation (loss) at the fundamental power frequency.

From system modelling, it has been observed that practical filters will have excessive losses or inadequate harmonic attenuation for most utilization loads. For large power systems, the impedance is somewhat different, and some of these problems are not as severe [9].

## 9. Active Filters

For small loads, an alternative is active filters consisting of electronic feedback networks. These are often called active power factor correction devices. If the harmonics are reduced, then the power factor will be improved. There are several alternate methods of implementing active filtering.

These techniques use pulse-width modulation control on the switched current using a flyback inductor. All the inductor energy stored during the on-time of the power switch is delivered to the load during the off-time.

The preferred technique uses average current and voltage feed forward. With this method, a design to achieve less than three percent harmonic distortion and power factor better than .995 may be possible. A block diagram is shown in figure 6. The preregulator is an average current mode boost converter with an input from the controller.

Fig. 6 Active filter block diagram

## 10. Active Filter Design

A low power unit power factor preregulator was constructed for a nominal 50 watt load. The design can be scaled for larger loads. The design specifications are as follows.

Voltage input, RMS: 80-135 V

Voltage output, DC: >135*1.414 = 190 V

Power output, watts: 50

Switching frequency: 100 kHz

The test results are shown in table 2. The second through the thirteenth harmonics are recorded as a percentage of the fundamental. The values are shown with the feedback regulator (fr) and operating as a normal switch mode power supply without the regulator (w/o).

The test results illustrate the large improvement in power factor and reduction in harmonic distortion on the input current. This method is best suited for integration within a device. However, it can be incorporated as an interface to a switched mode power supply.

Table 2
Test Results of Harmonic Correction

TEST: Rload = 1600 Ohms

| Power | Vout | Vin | Iin | VA | W | PF |
|---|---|---|---|---|---|---|
| fr | 213 | 124.6 | 0.268 | 33.3 | 32.9 | 0.988 |
| w/o | 169 | 124.5 | 0.285 | 35.5 | 18.1 | 0.509 |

| Harmonic | 2 | 3 | 5 | 7 | 9 | 11 | 13 | |
|---|---|---|---|---|---|---|---|---|
| %I fr | 0.12 | 5 | 2.2 | 2.3 | 1.1 | 0.7 | 1.1 | |
| %I w/o | | 93.3 | 84.4 | 73.0 | 58.7 | 45.0 | 30.7 | |
| %V all | | 0.34 | 0.1 | 0.5 | 0.7 | 0.4 | 0.11 | 0.2 |

## 11. Conclusion

A discussion of harmonics created by electronic switching power supplies has been presented. The harmonic frequency and amplitude depends on the pulse type supply used. Filters may be used for certain harmonics. However, the filters may induce other problems such as resonance. Furthermore, for many loads, the filters do not have a narrow enough bandwidth and add attenuation to the basic load.

Measurement of harmonic-rich voltage and current can only be done effectively with true RMS sensor circuitry. Many meters do not properly record signals with harmonics.

Wiring and magnetic devices must be derated to compensate for the additional losses caused by the harmonics. A method of determining the harmonic component and derating is presented.

Active filters can be used to reduce harmonic levels and to improve the power factor of the load. These are particularly adaptable for small loads.

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## Vitae

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Dr. Durham has developed a broad spectrum of electrical and facilities projects for both U.S. and international companies. Based on his extensive background, he has become a recognized author who has published numerous papers, articles, and manuals and has conducted training in such diverse topics as electrical power design, management, and microcomputer applications.

Robert Strattan received a BS degree from Wichita State University, Wichita, Kansas in 1958 and the M.S. and Ph.D. degrees in 1959 and 1962 respectively, all in electrical engineering, from Carnegie Mellon University, Pittsburgh, Pennsylvania.

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