Development of a Laboratory Experiment to Demonstrate Power Quality Issues

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ABSTRACT

Less than 15 years ago, harmonics were not even mentioned in an article[1] listing all of the problems with electrical power that could cause malfunctions or damage to electronic equipment. However, the widespread application of electronic devices in business and industry is causing new problems for power systems. Nonlinear loads, such as the power supplies for electronic devices, introduce harmonic currents into the power system, which can cause failures in power system equipment as well as in other loads. Evidence of harmonic problems include circuit breakers tripping when they shouldn't or failing to trip when they should, overheated neutral conductors or transformers, erratic operation or tripping of adjustable speed drives, blown power factor correction capacitors, and communication interference. The problems are different, but their causes are related.

Since every user of the power system contributes to the problem, I believe all electrical engineers and technicians need to have a basic understanding of power quality issues. All undergraduates in the EET curriculum at Purdue are being provided with such a background in the form of lecture material and hands-on laboratory experience. Because of budget constraints, emphasis was placed on developing an experiment that could be performed with inexpensive loads and use equipment that is available in most electronics and power laboratories (e.g., oscilloscope, true-RMS voltmeter). During the development of the experiment, our department was fortunate enough to receive a gift from the Fluke Corporation of Power Harmonic Analysis Meters, which greatly enhanced the students' laboratory experience.

This paper discusses some of the basic theory of harmonics and their effects on the power system, followed by a description of the laboratory experiment.

INTRODUCTION

What are harmonics?

The voltage waveform received from the power company normally consists of a single frequency sinusoid. For linear loads on the power system (resistors, inductors, and capacitors) the current will also be a single frequency sinusoid. However, some loads are nonlinear loads and cause a nonsinusoidal current when a sinusoidal voltage is applied. Nonlinear loads often contain some type of switching device that causes noncontinuous operation. Examples include the power supplies for electronic devices including computers, programmable controllers, and office equipment; variable frequency motor drives; and electronic ballasts for fluorescent lights. Although the current is not sinusoidal for a nonlinear load, it is periodic, assuming the load is in a steady-state operating condition.

The mathematician Fourier showed that any periodic waveform could be represented by a series of sinusoids whose frequencies are integral multiples of the frequency of the original waveform.[2] Thus nonsinusoidal currents due to nonlinear loads will contain harmonic components whose frequency is an integral multiple of the power system frequency (60 Hz in North America). Figure 1 shows a 60 Hz sine wave, having an amplitude of 100. Also shown are third (180 Hz) and fifth (300 Hz) harmonics with different amplitudes. The actual amplitude of the harmonics and their phase relationships would of course depend on the shape of the original nonsinusoidal waveform. Harmonic currents can cause a variety of problems in the power system.

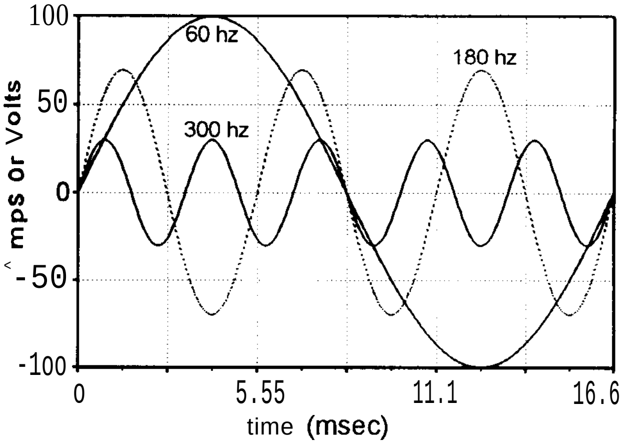


Figure 1: Example of first, third, and fifth harmonics

Effects of harmonics

Harmonic currents can affect many devices in the power system including transformers, conductors, motors, and circuit breakers.[3] Overheating and erratic operation are possible when harmonics are present. Since these effects have been previously described, they will not all be explained in detail here. However, two key areas which formed the basis of the power quality experiment will be described after a discussion of why they were chosen. These are the effects of harmonics on certain types of metering equipment and the effects of harmonics on neutral conductors in a three-phase system.

THEORY OF A POWER QUALITY EXPERIMENT

Before developing objectives and procedures for an experiment to illustrate harmonic phenomena, several factors had to be considered. The first consideration was the existing equipment in the laboratory and what could be done with it. In our lab, each station has a two-channel oscilloscope and a true-RMS digital multi meter (DMM). While we had a variety of motors, transformers, and R-L-C loads, we did not have a nonlinear load that the students could measure conveniently. Thus it was clear that additional devices would have to be acquired. This, of course, brought up the issue of cost, since finds are very limited.

While deciding what type of equipment to obtain, it was necessary to consider what phenomena could be reasonably observed. For example, attempting to measure the additional heating of conductors due to harmonics would require fairly elaborate equipment and might not contribute much to the students' learning. On the other hand, using the oscilloscope and true-RMS meter, the students could measure the peak value of a waveform and its RMS value. Those measurements would allow them to calculate the crest factor of the waveform. They also could measure the waveform with an average responding meter, which would allow them to compare the response of different types of meters when harmonics are present. Since many students have a tendency to believe whatever a piece of test equipment tells them, I felt this would be a valuable lesson for them.

Another area that could be easily investigated was the problem of high neutral currents in a three-phase system that is feeding single-phase nonlinear loads. Again, this could be easily done with the existing test equipment, although new loads would be required. Because this is a real problem in industrial and commercial facilities, I felt this would also provide a good learning experience for the students.

Following the selection of these two phenomena for the laboratory exercise, we were fortunate to obtain a donation of FlukeF41 Harmonic Analysis Meters for each station in the lab. They were incorporated into the experimental procedures, so the description that follows includes them. These meters provide a wide variety of information to the students, including the harmonic content of a waveform, total harmonic distortion (THD), and crest factor. However, the majority of the lab could be accomplished with the oscilloscope and true-RMS DMM. Before discussing the equipment setup, I will briefly discuss the theory behind these two phenomena.

Meter response to harmonics

As previously mentioned, most students believe you just hookup a meter and whatever it says must be correct. Unfortunately that may be a bad assumption if more than one frequency is present in the waveform. Since voltages and currents in the power system traditionally were solely 60 hertz, many meters were designed to take advantage of that fact, resulting in a cheaper meter. Most AC meters actually rectify the AC waveform in order to determine an RMS value.

Figure 2 shows two rectified waveforms; one a single-frequency sinusoid and the other composed of several harmonics. Consider first the rectified sine wave. The waveform has a peak value of 100, and as is well known, the RMS of the waveform is 70.7 (the peak divided by the square-root of two). Analog meters and less expensive digital meters, however, do not actually calculate the RMS. Instead they respond to the average value of the rectified waveform. It can be easily shown that the average of a rectified sine wave is 2/π times the peak value—63.7 in this case. Since the meter should show the RMS value of 70.7, the average value is "multiplied" by 1.111 to obtain the proper reading. Note that in the case of an analog meter, the multiplication is done simply by redefining the numbers on the scale. Since the meter responds to the average, but reads out the RMS, it is called an *average responding, RMS calibrated* meter. This works fine, as long as the waveform is a single-frequency sinusoid.

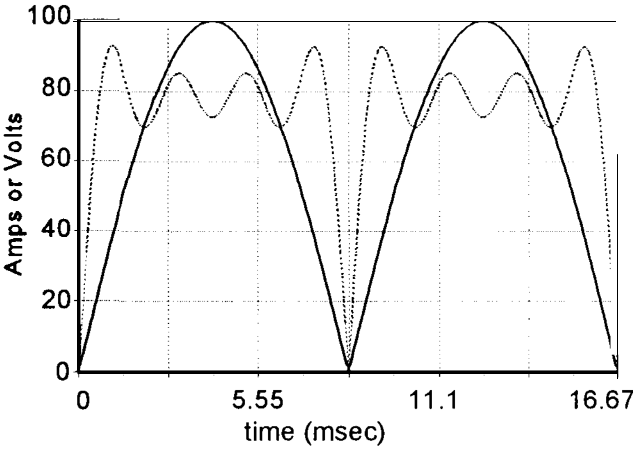


Figure 2: Rectified sine wave and harmonic containing wave

The second waveform in figure 2 is the rectified sum of several harmonics:

$$f(t)=100\left(\sin 377t+\frac{\sin 1131t}{3}+\frac{\sin 1885t}{5}+\frac{\sin 2639t}{7}\right)$$

These terms are, of course, the first four terms of the Fourier series for a square wave, and the waveform in Figure 2 is in fact beginning to approximate a rectified square wave. An average responding meter would rectify the waveform, as shown in figure 2, and would respond to the average, which can be shown to be 74.6. The meter would then multiply by 1.111 to yield a meter reading of 82.9. In fact the RMS of the waveform can be readily calculated as 76.5, so in this case, the meter would be reading too high. In other cases, the average responding meter may read too low.

Three-phase neutral currents

Figure 3 shows a system consisting of a balanced three-phase, 60 Hz source feeding three identical single-phase loads, connected in a wye (star) configuration. A balanced source means that all three phases have the same voltage magnitude and the phases are 120^{O} apart in time. The current on the neutral connection, I_n, will be the sum of the currents in the three phases. Consider first what happens if the loads are linear loads.

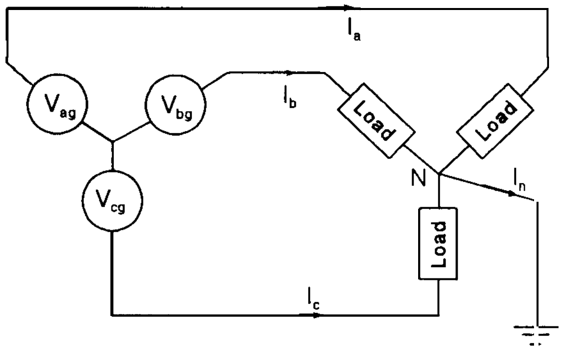


Figure 3: Three-phase, wye-connected power circuit

three-phase set of 60 Hz currents. Figure 4 shows three 60 Hz sinusoids (the curves with the solid lines) that represent a balanced, three-phase set of currents. Note that at any point in time, the sum of the three currents is zero; thus, the neutral current will be zero in a balanced three-phase system. Unfortunately, students and practicing engineers always expect this to be the case, and it may not be. Suppose the loads in figure 3 are nonlinear and cause harmonic currents.

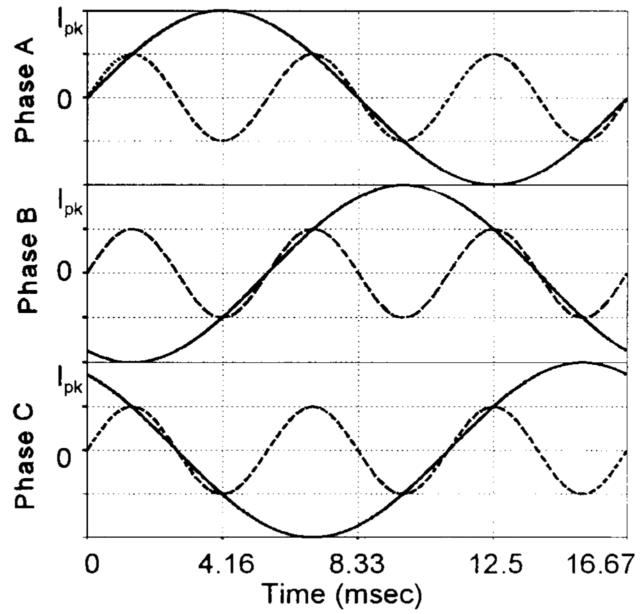


Figure 4: Three-phase fundamental and third harmonic

Figure 4 also shows third harmonics (180 Hz), chosen arbitrarily to have a peak value that is one-half of the fundamental peak. Triplen harmonics (the third and any harmonic whose frequency is a multiple of the third) are a problem for the three-phase system. The reason is that they are identical on all three phases. Thus when the load currents add together at the neutral point, the third harmonics don't cancel; instead they add algebraically. This may result in a higher RMS current on the neutral conductor than on the phase conductors. Since only the phase conductors are protected by fuses or circuit breakers, the neutral could actually carry more than rated current, resulting in overheating and damage. If the loads of figure 3 caused the current components shown in figure 4, the neutral current would be 1.5 times the current in any one of the phases.

THE EXPERIMENT SETUP AND RESULTS

Meter readings in the presence of harmonics

To illustrate the performance of average responding meters when harmonics are present, requires a load with variable harmonic content. To keep the cost low, I chose a commercial incandescent lamp dimmer switch with a light bulb as its load. A dimmer mounted in a plastic receptacle box costs less than $5.00. The dimmer switch operates like a triac; adjusting the dimmer "chops" out part of the sine wave, changing the RMS voltage to the load. Figure 5 (obtained with the Harmonic Analysis Meter) shows an example of the dimmer switch output voltage.

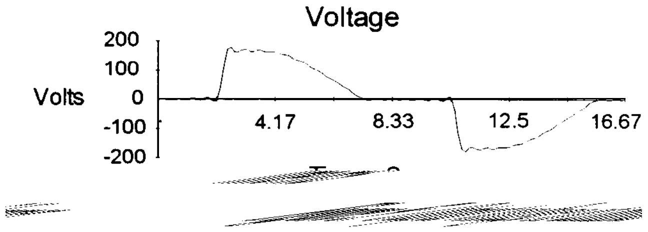
Students were instructed to measure the output voltage of the dimmer using both average-responding and true-RMS voltmeters. By varying the voltage, they could observe how the accuracy of the average-responding meter was affected by the harmonics. The percent error was calculated from the measured voltages as a percent of the average-responding meter reading. Crest factor is obtainable from an oscilloscope and true-RMS meter; however, the Harmonic Analysis Meters provided that information directly.

The crest factor for a sine wave is the square-root of two (1.4 14). Observation of Figure 5 indicates that reducing the voltage will lead to a higher crest factor as the delay angle is increased toward 90°. Using the Fluke F41 meter, it was found that as the voltage was decreased both the crest factor and the THD increased. To provide the students with a visual indication of the effect of harmonics on the average-responding meter, I had them plot the error as a function of the crest factor, as shown in Figure 6. Clearly as the crest factor (or the THD) increases, the meter becomes much less accurate. This proved to be quite a revelation for some students.

The effect of harmonics on neutral current

The second portion of the experiment required single-phase nonlinear loads. For our lab's eight benches, we needed 24 nonlinear loads. Again it was necessary to find something inexpensive. Since the students were used to working with lights as a load, I decided to use compact fluorescent lamps as the nonlinear loads. Compact fluorescent lamps have an internal electronic ballast. Early models had extremely high THD levels, but with the heightened awareness of power quality issues, manufacturers have changed their designs to provide lower THD. This turned out to be a good choice because our local utility was providing compact fluorescent lamps to customers as part of a demand-side reduction program. They donated some that had been returned in working condition. They could have been purchased for about $50.00 per lab station.

Students connect three bulbs as a three-phase wye load and observe the phase and neutral currents, shown in Figure 7. Due to the pulse-like shape of the phase currents, there is virtually no cancellation when the phase currents add together at the neutral point. These currents could be observed on an oscilloscope, but these were captured to the



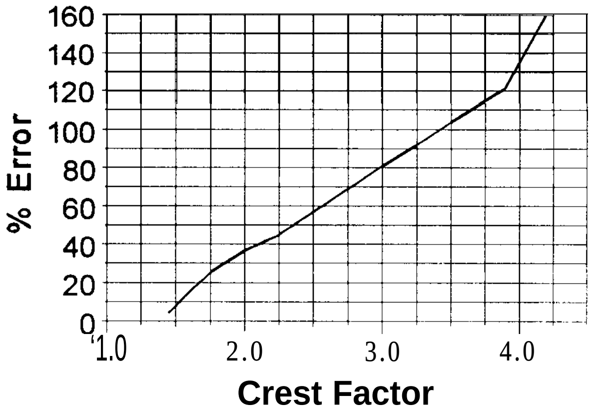


Figure 6: Effect of crest factor on the accuracy of an average-responding meter

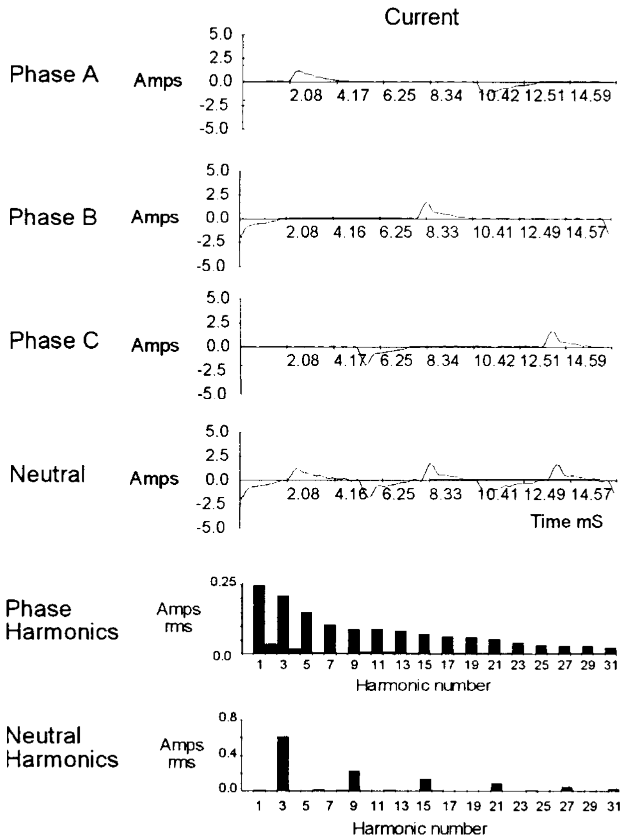


Figure 7: Phase and neutral currents and harmonic content for three single-phase nonlinear loads

PC with the Harmonic Analysis Meter. The phase current shows a wide spectrum of harmonic content; essentially all of the odd harmonics are present. The neutral current, however, shows only harmonics whose frequency is a multiple of three times the power system frequency. This demonstrates very vividly to the student that all harmonics except the third and its multiples cancel for balanced three-phase loads.

CONCLUSION

A power quality experiment was designed and implemented at relatively low cost. While it was originally designed to use the existing laboratory equipment (oscilloscope and true-RMS meter), it was found that the use of a Harmonic Analysis Meter provided more information and simplified the running of the experiment. This allowed the students to concentrate more on the phenomena they were observing rather than the mechanics of taking the data. At the time this paper was written, two classes (100 students) had accomplished the laboratory. They indicated that the experiment emphasized the importance of using a “true-RMS” meter and also made the concept of high neutral current more real to them.

ACKNOWLEDGMENTS

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BIOGRAPHY

TIM SKVARENINA is an Associate Professor of EET at Purdue University, where he teaches undergraduate electrical machines and power systems. He has a BSEE and MSEE from Illinois Institute of Technology and a Ph.D. in EE from Purdue. He joined Purdue in 1991, after serving 21 years in the U.S. Air Force. He is a Senior Member of IEEE and a Member of ASEE, Tau Beta Pi, and Eta Kappa Nu.