Practical Classroom Demonstrations of Power Quality Issues

Herbert L. Hess
Department of Electrical Engineering
University of Idaho, Moscow, Idaho

Abstract

Several simple classroom demonstrations safely and conveniently illustrate common power quality issues: voltage distortion, voltage flicker, and current harmonics. A voltage distortion demonstration shows the everyday effects of having many personal computers or switch mode power converters in a small area. A flicker demonstration uses a light bulb to illustrate dramatically line voltage variations caused by the fusing system of ordinary laser printers. A current harmonic demonstration conveniently shows the effect of a capacitive filter on the harmonic content of the ac line current. All demonstrations use only laboratory equipment and instrumentation that is readily available in an academic setting.

Introduction

In the past few years, the quality of power has become an important issue for the electric utility companies. Customers have come to notice deviations from the expected single frequency, constant amplitude, sinusoidal voltage that is the nominal product of their local utility. Sensitive power electronic loads have become an indicator of less than perfect voltage quality. Often, the effects of imperfect voltage quality may seem insignificant to utility engineers. Unfortunately, these effects may range from mere irritation of a blinking digital clock to lost or spoiled products. In many cases, ironically, these same power electronic loads cause the "dirty power" as well.

Certain industries, for example, the semiconductor process industry and certain food processing industries, are especially sensitive to power quality issues. They often write power quality specifications with economic premiums and penalties into their contracts with the electric utilities. In fact, several of these customers with sensitive loads have begun to request the teaching of power quality as part of the undergraduate power engineering programs.

Power quality problems occur on the utility distribution grid at voltage levels that are too high for safe investigation by most third-year and fourth-year students. Power quality problems often are intermittent in nature. However, this paper presents demonstrations that show power quality phenomena in a fashion that is both practical and safe. Three demonstrations to illustrate the following issues are given: voltage distortion on the residential and commercial power distribution grid, flicker and sags, and current harmonic distortion. Required equipment is ordinarily within the capability of any undergraduate program electrical engineering program: an oscilloscope, a low frequency spectrum analyzer, a simple function generator, a laser printer, and an ordinary three-wire extension cords.

Elementary Demonstration of Voltage and Current Distortion

There is noticeable voltage distortion of the utility voltage in most distribution locations. This is particularly true in buildings with the combination of older wiring and a large number of switch mode power supplies. Nearly all personal computers have switch mode power supplies. Many academic buildings contain several computers and such buildings are more than a few years old. This makes a typical academic building an excellent place to show the aggregate effects on the utility system of large numbers of switch mode power supplies.

This demonstration can be set up in seconds in a typical academic setting: an undergraduate electronics or power laboratory or in a classroom. Equipment for this demonstration is fairly simple and common in an academic environment: a transformer that steps 120V single phase down to a safer level, such as 12 Volts, and an oscilloscope with standard voltage probes and clamp-on current probes.

A special cable helps in capturing the current waveform. The cable is a short, three-wire, 16 gauge or larger, extension cord, approximately 20 cm in length with the outer jacket stripped off a portion of its length, but with the individual insulation intact on the three insulated inner wires of the cord. Enough of the outer jacket should be removed to permit the clamp-on current probe to fit around each insulated inner wire individually.

Setup is per Figure 1. The special cable is placed in series with the oscilloscope's power cord or in series with the power cord of any other convenient equipment containing a switch mode power supply. Placing the special cable in series with the oscilloscope's power cord uses the oscilloscope as both experimental apparatus and measurement apparatus, requiring one fewer piece of equipment.

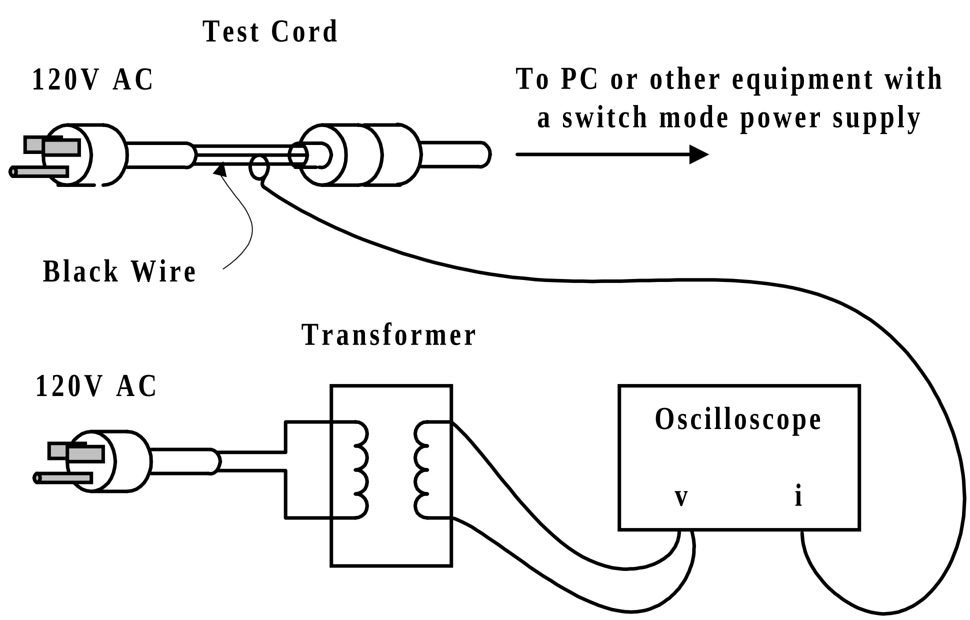

Figure 1
Experimental Configuration for Measuring Voltage and Current Distortion

However, students find the demonstration more pertinent if the special cable is in series with the power cord of a personal computer. The point being made by this variation on the demonstration is the aggregate effect of large numbers of switch mode power supplies. Most students use personal computers often and they commonly see great numbers of personal computers placed quite close to each other.

The two plugs shown in Figure 1 are plugged into a common 120 Volt receptacle, preferably the two sides of the same receptacle. The voltage, stepped down to a safe level, appears at the output of the transformer. The current probe is clamped around one of the insulated wires of the special cable, either the black (hot) wire or the white (neutral) wire.

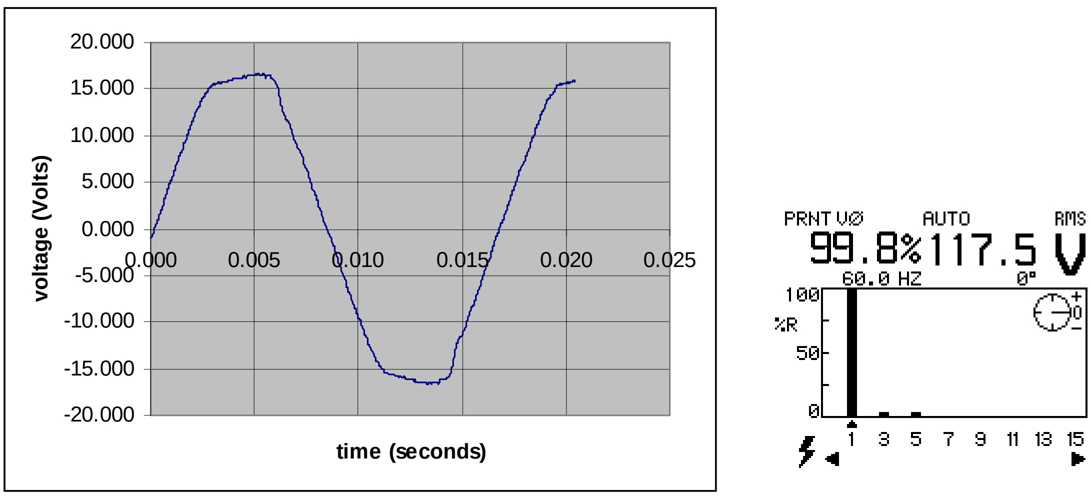

Figure 2
Typical Distorted Voltage Waveform and Its Frequency Spectrum
Demonstration of Voltage and Current Distortion on Utility Distribution System

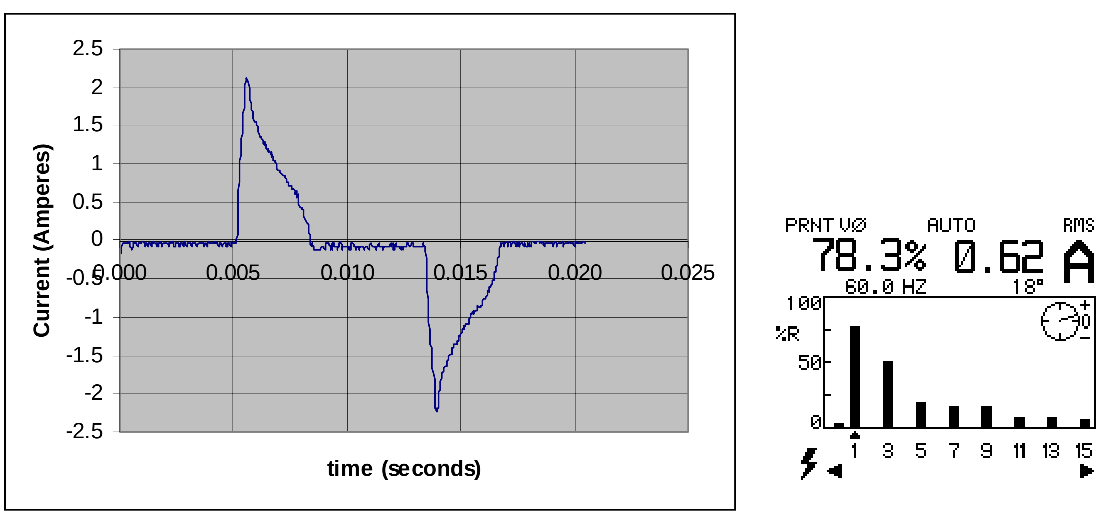

Figure 3
Typical Current Waveform and Its Harmonic Spectrum
Demonstration of Voltage and Current Distortion on Utility Distribution System

Typical waveforms for voltage and current are shown in Figures 2 and 3, respectively. The frequency spectrum is included for reference, measured by a Fluke 41 Power Harmonics Analyzer. Though a display of the spectrum adds to the information presented, the spectrum is not necessary to make the point about harmonic voltage and current distortion.

The voltage waveform shows a slight, but obvious distortion. The distortion appears most noticeable near the voltage peak, which is the same interval in time that the current is flowing. This flattening occurs because the current causes a series voltage drop on the system impedance during that time interval, distorting the voltage sine wave. Details of this behavior are explained in references [1] or [2].

Demonstration of Voltage Flicker

IEC 1000-3-3 defines flicker as the noticeable variation in intensity of a light source.[3] Flicker may occur at any repetition rate, rapid or slow. On the utility distribution system, flicker occurs in response to variations in distribution voltage amplitude, hence the common designation "voltage flicker”.[3] Voltage flicker is defined as a percentage of the rms fundamental voltage amplitude. The threshold of perception varies greatly with the frequency of the flicker. Psychological studies show flicker to be most noticeable in the range of six to eight Hertz.[3]

Loads that exhibit rapid variations in current magnitude are the most common cause of flicker. The variation in current magnitude appears as a voltage drop on the system impedance, which causes a corresponding variation in distribution voltage to the user. Though large loads such as arc furnaces are well known to cause flicker, the most common cause of flicker in the office and residential environment is the fusing system of photocopiers and laser printers. Further discussion of flicker, particularly flicker caused by fusing systems and appropriate mitigation strategies for it, is found in reference.[4]

A simple demonstration of flicker may be built using the most common source of flicker, a fusing system (in this case, a laser printer), a 100-foot-long, 16-gauge, three-wire extension cord having at least two female receptacles, and a portable incandescent light, such as a drop light. The connection diagram is shown if Figure 4.

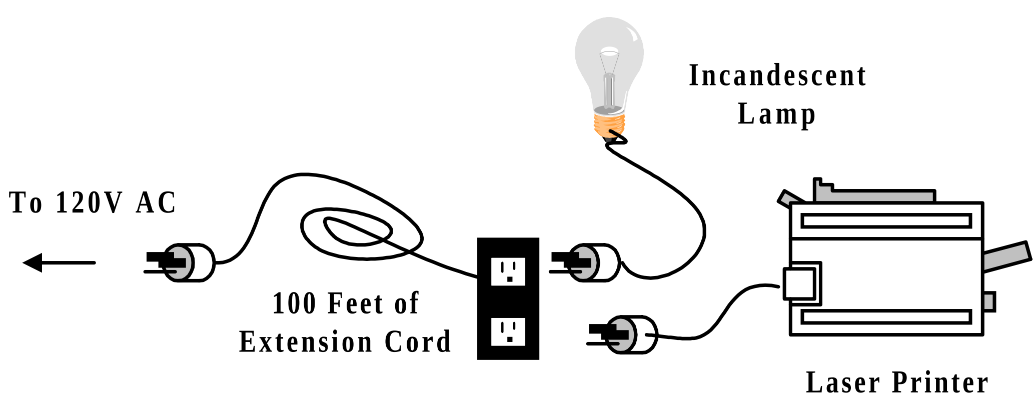

Figure 4
Connection Diagram for Flicker Demonstration

The hundred-foot extension cord is sufficient to create a noticeable voltage drop in series with the utility distribution system. The laser printer draws current pulses of approximately 30 Ampere and the impedance of a 16-gauge extension cord of this length is ordinarily about half an ohm. The resulting voltage drop of about 15 Volt is sufficient to be quite noticeable without dropping the voltage so low as to cause the undervoltage protection of the laser printer to disconnect the laser printer from the distribution network. The flicker behavior of the light is quite pronounced in this experiment, to the point of appearing nearly to flash between dim and bright intensity. The lamp will flicker at the same rate at which the laser printer's current varies, typically anywhere from 0.2 Hertz to 10 Hertz, depending on the laser printer model.

Demonstration of Current Harmonics

Diode bridge rectifiers are a very common means of converting line frequency alternating current to pulsating direct current. Their advantage is that, for the cost of four cheap diodes and a filter capacitor, the task of rectifying is quickly, easily, and reliably done. Most small power supplies have a diode bridge facing the line.

Unfortunately, these circuits are notorious for the large current harmonic distortion that they draw. Total Harmonic Distortion (THD) in the current exceeding 100% is not uncommon. This distortion occurs in sharp current pulses, synchronous with the line voltage and always having a fundamental frequency component that lags the line voltage by just a few degrees at most. A discussion of how these pulses are generated, with examples, is given in each of the following three references.[1,2,5]

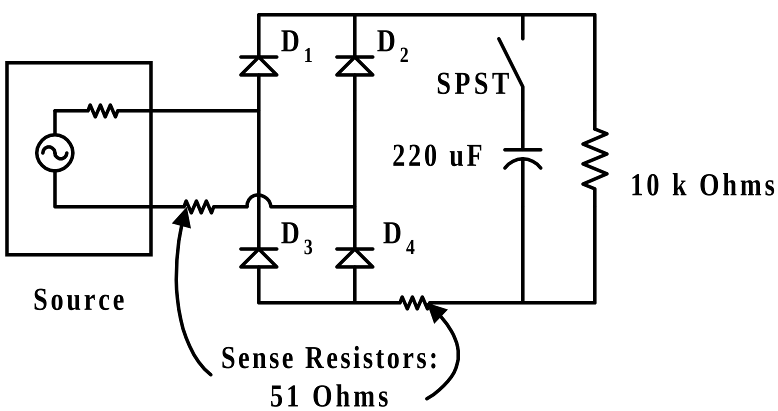

Figure 5
Rectifier Circuit
Demonstration of Current Harmonics

A simple rectifier circuit can be used to demonstrate these current harmonics. A diagram of that circuit is shown in Figure 5. The source in that circuit may be one of two types. The safer type is a simple function generator with an approximate 3000 Ohm impedance, such as the HP2912. With a function generator, a higher frequency of operation and a smaller capacitor are options.

Instead of the function generator, it is also reasonable to use a small step-down transformer (120Volt / 12 Volt, for example) connected directly to the power line. Care must be taken to physically shield exposed connections if this method is chosen. The transformer provides the necessary isolation for an oscilloscope reading of the current on the dc side, measured across its sense resistor.

The diodes are common rectifier diodes, such as the 1N4002. A 220 uF, 35 Volt or larger, filter capacitor and 10 kOhm, 1/4 Watt, load resistor form the output. In series with the filter capacitor is a single pole, single throw switch. Sense resistors (51 Ohms, 1/4 Watt) allow the user to avoid using a current probe. The ac side sense resistor is placed appropriately so that an oscilloscope need not be isolated to read the voltage across it, even if a grounded function generator is chosen for the voltage source. (In the case of a grounded function generator as a source, the oscilloscope must be isolated before measuring any voltages on the dc side.)

With a sinusoidal input voltage and the switch open, the waveforms of both voltage and current are identical: single frequency sinusoids on the ac side and full wave rectified sinusoids on the dc side. Examples are shown in Figure 6 and Figure 7, respectively. The currents are those appearing in the sense resistors. Due to the resistive load, the source voltage and the load voltage have identical waveforms as their respective currents. With the switch closed, the waveforms become those shown in Figure 8 and Figure 9.

The output voltage is dc with negligible ripple. The input voltage is the same single frequency ac, but with a barely noticeable distortion. A better demonstration of the input voltage distortion is explained in the first demonstration of this paper.

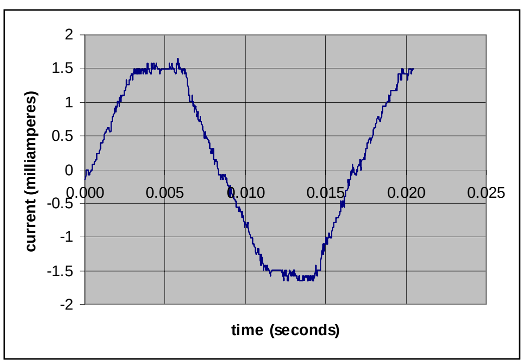

Figure 6
Input Current without Capacitor Filtering
Demonstration of Current Harmonics

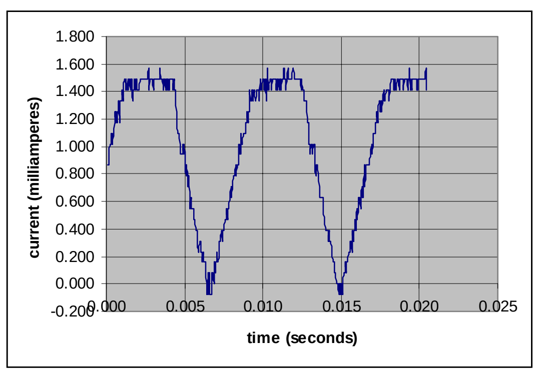

Figure 7
Output Current without Capacitor Filtering
Demonstration of Current Harmonics

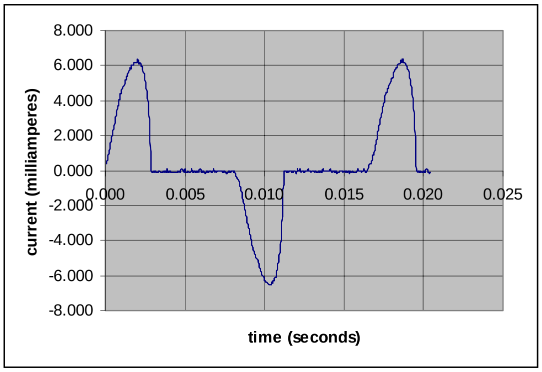

Figure 8
Input Current with Capacitor Filtering
Demonstration of Current Harmonics

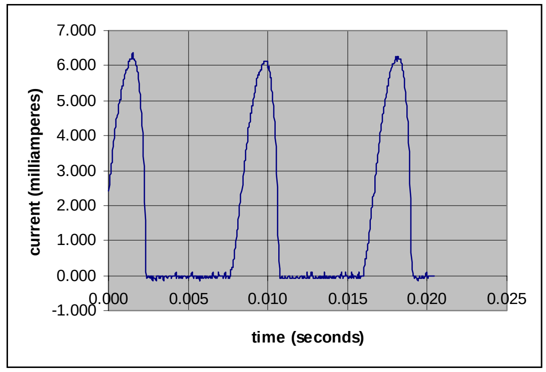

Figure 9
Output Current with Capacitor Filtering
Demonstration of Current Harmonics

With this circuit, the presence of current harmonics becomes dramatically visible. It is easy to turn the switch on and off, inserting and removing the capacitor for rapid comparison of the current waveforms. This makes the harmonics much easier to identify and reveals their potential for trouble. A spectrum analyzer can also help explain the harmonic distortion.

Conclusions

This paper presents three demonstrations for safely illustrating power quality issues. First, a method is explained to show line voltage distortion that is common to facilities with large numbers of switch mode power supplies, such as found in most personal computers. Second, a topology to safely and dramatically show voltage flicker on a ordinary light bulb is proposed. Third, a circuit that shows the current distortion common to diode rectifier circuit with large capacitor-based filters is given. Instrumentation is of the type common to most educational facilities for electrical engineering and electrical engineering technology: oscilloscopes, function generators, small transformers. Each of the demonstrations proposed in this paper can be quickly assembled in an ordinary undergraduate laboratory and in most classrooms as well. Though the demonstrations use ordinary utility power, appropriate safety considerations have been built in, making them safe for use among inexperienced students.

References

[1]N. Mohan, *Power Electronics: Converters, Applications, and Design* (New York: Wiley, 1995), pp. 95-100.
[2]R. Dugan, M. McGranaghan, and W. Beaty, *Electric Power Systems Quality* (New York: McGraw-Hill, 1996, pp. 127-128, 136-138.
[3]International Electrotechnical Commission, *IEC Standard 1000-3-3*, 1997.
[4]M. Hirst and H. Hess, "Low Flicker Universal Power Converter for Filament-Based Heating Processes," *Conference Record of the 1997 Applied Power Electronics Conference*, Atlanta, Georgia, 27 February 1997, pp. 1062-1068. To be published in the IEEE Transactions on Industry Applications in 1998.
[5]P. Krein, *Elements of Power Electronics* (New York: Oxford, 1998), pp. 166-174.

HERB HESS received the BS degree in 1977 from the US Military Academy, the SM degree in 1982 from the Massachusetts Institute of Technology, and the PhD degree in 1993 from the University of Wisconsin-Madison. He is Assistant Professor of Electrical Engineering at the University of Idaho. His interests are in power electronic converters and electric machine drives.