A Low Cost Power Quality and Energy Savings Laboratory for Undergraduate Education and Research

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Abstract

This paper describes the design and implementation of a power quality and energy savings laboratory at Merrimack College. Merrimack College is a liberal arts institution north of Boston, MA, which has a small ABET accredited ECE department with 6 faculty and about 90 students. There is strong student interest in learning about power, and local utilities seek graduates with expertise in power. A new course in Power Quality (PQ) has proven popular. A laboratory experience, which includes elements of power quality and energy savings, has been designed and implemented. In addition, the ECE department now requires a sophomore level class in embedded controllers. An extension to the PQ laboratory experience that incorporates embedded controllers has also been designed.

The lab set up is based on maximizing student understanding in conjunction with minimizing costs. The students learn causes, impacts, and solutions of PQ problems. They learn how to design a power factor correction capacitor bank and an LC filter to mitigate harmonics. They also conduct simulations of the power system network, and analyze system data. The students are taught methods of calculating energy savings due to the addition of PQ components to the network. One implemented design resulted in savings of over 5 kWh, which based on local rates conservatively gives a yearly savings of $2,600 for the science building alone. The PQ components consist mainly of reactors, capacitors and the monitoring system.

A further, complementary laboratory experience incorporating low cost embedded microprocessor designs used to control the PQ system via a remotely accessible, secure TCP/IP Ethernet link has been designed. This additional circuitry allows real time monitoring of the network and modification of the PQ elements based on dynamic loading 24 hours a day. Implementing such a system can yield yet additional energy savings. The embedded processor students, both from ECE and Computer Science, are planned to have remote access to the lab and will be encouraged to help with the development via laboratory assignments.

An Introduction to Power Quality and the Power Quality Problems in the Mendel Science Building

It is the objective of the electric utility to supply its customers with a sinusoidal voltage of relatively constant magnitude. The generators that produce the electric power generate a very close approximation to a sinusoidal signal. However, there are loads and devices on the system that have linear and nonlinear characteristics and result in voltage sag, voltage spikes, voltage
transient, voltage surge, low power factor, voltage unbalance, current unbalance, and harmonics distortion of both the voltage and current signals. As more nonlinear loads are introduced within a facility, these waveforms get more distorted. Figure 1 shows both a sinusoidal and non-sinusoidal current waveform.[1]

![Waveform with Distortion](image.png)

**Figure 1 – Sinusoidal and non-sinusoidal current waveform**

The advancement and wide application of adjustable speed drivers, electronic devices, microprocessors, etc. in many areas have significantly contributed to the voltage and current distortion in distribution systems. This has created the need for better understanding of the impact of harmonic distortion on control and instrumentation in power systems, industrial equipment and even household appliances.

Harmonics and Harmonic Filters

A harmonic is an integer multiple of the fundamental frequency. For example, the third harmonic in a 60 Hz system is 180 Hz; the fifth harmonic is 300 Hz, and so on. The nonlinear devices needed in a power system, including power converters, arc-furnaces, adjustable-speed motor drives, electronic power supplies, dc motor drives, battery charges, electronic ballasts, gas discharge lighting devices, transformers, personal computers, and monitors cause current and voltage harmonic distortion. A nonlinear load may be defined as a load that, having a sinusoidal voltage applied to it passes a non-sinusoidal current. A nonlinear device is one in which the current is not proportional to the applied voltage. In other words, while the applied voltage is sinusoidal, the resulting current is distorted “garbage”. The increasing use of these nonlinear devices causes the problem of harmonic distortion to grow. Ultimately the harmonic currents will travel to the power source through the power system's wires. The wire’s impedance will cause a voltage distorted waveform from the voltage drop caused by the distorted current. Figure 2 is a good example of current harmonic distortion seen in the Mendel Science Building due to the nonlinear loads.
One way to correct problems like those seen in the Mendel Building is through the use of filtering. Filtering is a common harmonic mitigation technique used in industrial and utility power systems. There are two basic types of filters, shunt and the series filters.

The shunt filter provides a low impedance path to harmonic currents at its tuned frequency. The shunt filter consists of inductance, capacitance, and resistance elements that are connected in series.

The series filter presents a high impedance at its tuned frequency to block harmonic currents at that frequency. The advantage of using shunt filters over the series one is that the shunt filters carry only a fraction of the load current while the series filters carry full load current.

Power factor and power factor correction

Power factor (PF) is the ratio of real (active) power used in the circuit to the total power (apparent power) supplied by a utility, also is defined as the cosine of the power factor angle (θ). The basic formula for power factor is the mathematical ratio of the real power (P) to the apparent or total power (S). The equation \[ PF = \frac{P}{S} = \cos \theta \]

In the sinusoidal waveform with only the fundamental frequency is present; the power factor is commonly referred as the displacement power factor (DPF) using the above equation. In the non-sinusoidal waveform that is caused by harmonics, the power factor angle is different than what would be for the fundamental waves alone. The presence of harmonics introduces additional phase shift between the voltage and the current that leads to a new definition of the power factor referred as the true power factor (TPF). This is also calculated using the above equation, including both fundamental and harmonic frequencies.

The unity power factor is when the load is totally resistive at the time the angle θ between the voltage and the current is zero degrees and the magnitude of the real power equals apparent

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Figure 2 – Actual Measurement from the Mendel Science Building

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power. Most industrial loads are resistive and inductive and have lagging power factor that means the current lags behind the voltage. In theory the power factor can reach to unity, but in practice it cannot without some form of power factor correction devices. Figure 3 shows the power triangle that represents the relationship between real, reactive, and apparent power.

![Power Triangle](image)

**Figure 3 - Power Triangle**

Reduction of reactive power (kVAR) in the power system will improve the power factor. One method to improve the power factor and minimize the apparent power is to add capacitor banks (power factor correction) in parallel to the load. However, a potential side effect of adding these capacitors is to create a resonance with the inductance of the power system. This is mainly due to the transformer inductance which produces a voltage rise in the power system especially during the light load periods. Converting some of the capacitor banks into harmonic filters will avoid such problems. Switching capacitor banks in and out as needed will regulate the voltage rise.

Mendel's distribution system at Merrimack College focus was on correcting the power factor and harmonic mitigation. Initial measurements indicated that the power factor was 0.73 with a dominate 5th harmonic. There was a desire to achieve at least 0.95. The initial design analysis included a calculated value of 77 kVAR of capacitor banks to improve the power factor to the desirable value. However this initial value was found to cause a resonance with the 11th harmonic which is seen in Figure 2. Eventually a 3-phase 50 kVAR 5th harmonic filter to avoid the resonance at the 11th harmonic was installed and the desired results were achieved. The final component values are:

- The equivalent signal-phase capacitance of the capacitor bank at frequency 60Hz = 576 µf
- The inductance of the reactor at the fundamental frequency = 553.3 µH with a resistance of approximately 0.5 ohms.

**Real Time Monitoring, Analysis, and Filtering of the Mendel Science and Engineering Building**

In an effort to help automate and allow remote access and control to the PQ laboratory, a complementary digital laboratory experience incorporating low cost embedded microprocessor
designs is being used via a remotely accessible, secure TCP/IP Ethernet link. The block diagram for the system is shown in Figure 4.

![Figure 4 - Power Quality System Network](image)

This additional circuitry allows real time monitoring of the power network and modification of the individual PQ elements based on dynamic loading 24 hours a day. This system may eventually yield yet additional energy savings over and beyond any static system used today. The embedded processor students, both from Electrical Computer Engineering and Computer Science, have access to the lab and are encouraged to help with the development via laboratory assignments and by directed study.

**PQ Related Courses and Student Involvement:**

The Power Quality Lab has a direct connection to the following four courses:

1. **Embedded Controller Design (EE-227)** - Today’s computers fall into two categories. The first uses high performance microprocessors such as the Pentium Class of Processors. The second category focuses on issues of space, cost, low power consumption, and fast development in products such as wireless phones, automobiles, security systems, and washing machines. This course focuses on the second category and the Hardware and Software design of these controllers.

   This course was initially taught in the Spring Semester of 2003 with 8 students. At the time of the writing of this paper there are 19 students and each will have at least one specific laboratory assignment using and potentially enhancing the PQ Laboratory. Since the course also requires a final project, a few of the students are focusing on parts of the PQ laboratory. The results of this effort will be presented in June.

2. **Power Engineering and Power Quality (EE-455)** - The Power Engineering Course teaches students the fundamentals of power system and power quality problems, causes, impact, and solutions. This course was last taught in the summer of 2003 with 15 students.
In this course, three major areas were covered. The first area was about general power quality causes such as harmonics and transients. The second area involved harmonics: the causes, impacts, and solutions. The third area was about low power factor and how to improve it.

3. EE-490 – Direct Study / Research for Electrical Engineering

Three students were approved and completed EE-490A during the Fall Semester of 2003. Their focus was on the measurement, analysis, design, and testing of the Power System in the Mendel Science and Engineering Building.

The first student focused on learning about low power factor and the existence of harmonics in power systems, along with causes and solutions. After reading a number of references, he obtained a good background in this area. He then began implementing the mathematical formulas related to filter design and power factor correction using the arbitrary example of the 5th harmonic. His next step was to implement the calculations using Microsoft Excel. Using the 5th harmonic example as a benchmark, he obtained excellent agreement between hand calculation and computation. In his final step he used data collected by another student (see below) that was recorded from the power system of Mendel, and inserted the data into his spreadsheet. At this point he designed a harmonic filter used for the 3rd through the 7th harmonics. He used the specifications of an actual filter implemented in Mendel Hall, and found the comparison between computation and experimental result to be credible and realistic.

The second student's project was to take measurements of Mendel’s power system. He investigated the power quality of the power system and then simulated the system using commercial software, Simulink. This allowed the simulation and analysis of the impacts on the power system by adding the harmonic filter designed by the first student. The data was collected and was used by the first student.

The third student investigated the use of Fuzzy Clip software. He explored the functionality of the software and how to use it for PQ analysis.

The professor and the three students held bi-weekly meetings to discuss the three projects and participated in the measurement taking and the testing of the harmonic filter. Observing an instantaneous drop in demand exceeding 5 kWh helped engage the students in the learning experience of power quality and energy savings. Involving undergraduate students in these projects proved enjoyable and valuable for both students and professor.

4. CS-490 - Direct Study / Research for Computer Science

A Computer Science Student is currently taking CS-490A with a focus on embedded applications. His focus is on enhancing the PQ Laboratory through the use of embedded microcomputers (also used in EE227A) and developing an Ethernet based data control system and interface. Some of the major areas that have already been completed include:

- Microprocessor / Power interface design, assembly, and final testing,
- Secure login,
• Manual remote activation and deactivation of the power filtering control circuitry (which engages and disengages the filters),
• Remote monitoring and control of the Embedded Microprocessor via TCP / IP,
• Remote (Features / Options) Menu implementation and execution,
• “Fail Safe” software routines including too many login attempts and timeouts, and
• Implementing all of the above (minus the Filters and Ethernet card) with a total hardware cost so far of less than $25.

Conclusion and Plans for the Future

At the time of this writing (March, 2004), the lab is still evolving but much has already been accomplished. In summary,

• The Mendel power system has been evaluated,
• The 5th harmonic initial design has been installed,
• Initial power measurements have been completed and the potential savings looks to be approximately $2,600 a year,
• The first Power Engineering and Power Quality (EE-455) course has been completed with 15 students and two of them followed up with a directed study in the following semester,
• The first Embedded Class (EE-227) has also been completed with 8 students,
• The second Embedded Class is now underway with 19 students (237 % enrollment increase over the previous year), one of them another EE Professor interested in the PQ Lab, and
• The first Computer Science Student Directed Study is now underway focused on the PQ Lab with significant headway already described above.

Plans for the next few months include:

• Around the clock power data collection (Voltage, Current, Harmonics, all 3 phases and Neutral),
• Manual temperature measurement of Key Power Components, Power Closet, and Cabinet, and outside air,
• Manual remote security monitoring (doors closed / open, lights on, etc),
• Encrypted login (at no additional cost),
• Local (Campus only) web access of power data.

Long Term Plans include:

• Automated Temperature Measurement,
• Automated Security Monitoring with alarms,
• Remote (WWW) web access of power data,
• Remote Secure Control of all systems via the WWW, and
• Making this type of system affordable by the average homeowner (Very Long Term) and create energySTAR® homes.
Many devices today, such as computer monitors, have the energySTAR® label because they conserve energy. Why not create energySTAR® buildings that conserves all of the power used from within?\[6\]

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