Power Electronics for Energy Efficiency - Integrating Commercial Drive Development Platforms and Pumps for Real World Learning

Athula Kulatunga, Ph.D., CEM, Associate Professor
Mike Bastick, Undergraduate Research Assistant
IR- Power Electronics Development and Application Lab
ECET Department, Purdue University, W. Lafayette, IN, USA

Introduction

Power electronics is the "enabling technology" behind many applications that have come to everyday use in the commercial and industrial setting. Power electronics allows electrical power conversion and management to be very efficient and fast. Today's cell phones, computer networks, and plasma TVs are results of power management advancements. Power electronics made it possible to take advantage of the "affinity laws." Examples such as variable motor drives coupled to pumps and fans, brushless dc (BLDC) applications in washing machines, and electric vehicles demonstrate the rising trend of power electronics integration into products and processes. Other applications include energy efficient lighting, class-D audio, and electric tools. There is no doubt that electrical/electronics engineering technologists must have some background in power electronics. The challenge is to get learners excited about the technology and learn how to apply it. Since the applications, most of the time, consist of a mechanical system, some understanding of the mechanical system is needed.

Educators[1] have found that teaching power electronics in an integrated setting-- studying the characteristics of the final element of an application first and then exploring how to control them using power electronic topologies-- attracts more learners. For example, the electrical engineering department at the University of Minnesota used to teach power electronics and electrical machines as two separate elective courses, and the enrollment had reached to a level so that the cancellation of the courses was imminent. Since the courses have been redesigned as integrated courses, the power electronics course has more than 70 students every semester, and the drive course has more than one hundred. Ironically, students from many other engineering disciplines are enrolled in the drive course. Textbooks [2] have been written to prepare engineering students for research and design. The related workshops conducted by UM have been sponsored by the National Science Foundation (NSF), the Office of Naval Research (ONR) of the US Navy, and American Electric Power (AEP). The material developed by UM can be adopted for engineering technology learners by adding more hands-on activities and circuit development practices.

International Rectifier Corporation, one of the world leaders in power management technologies and power semiconductor manufacturing, sponsors a lab at Purdue University's ECET Department. The lab is known as International Rectifier Power Electronics Development and Application Lab (IR-PEDAL) and is designed to promote energy efficient power electronics applications in industrial and consumer applications. IR_PEDAL currently focuses on power conversion, electric drives, and class-D audio amplifiers. This paper will discuss how commercially available reference design can be adopted into power electronics learning. The topics include descriptions related to equipment, data collection, needed technical knowledge, useful data, and safety issues.

Making it Exciting

Researchers have shown that learning becomes very effective if the learner can relate the subject matter to his or her internal frame of reference. Many students choose engineering technology because they like the hands-on approach. Incorporating the learning into a real world application and retrieving the necessary knowledge as the understanding of the application develops keeps learners as active participants in the learning process.

The success of power electronics-based motor drives is due to a phenomenon known as the "affinity laws." The laws say:
1. Flow produced by the device is proportional to the motor speed.
2. Pressure produced by the device is proportional to the motor speed squared.
3. Horsepower required by the device is proportional to the motor speed cubed.

For example, a variable torque load at 50 percent speed needs to deliver only 12.5 percent of the horsepower required to run it at 100 percent speed. The reduction of horsepower means that it costs less to run that motor. The left circle of Figure 1 depicts the graphical representation of the law.

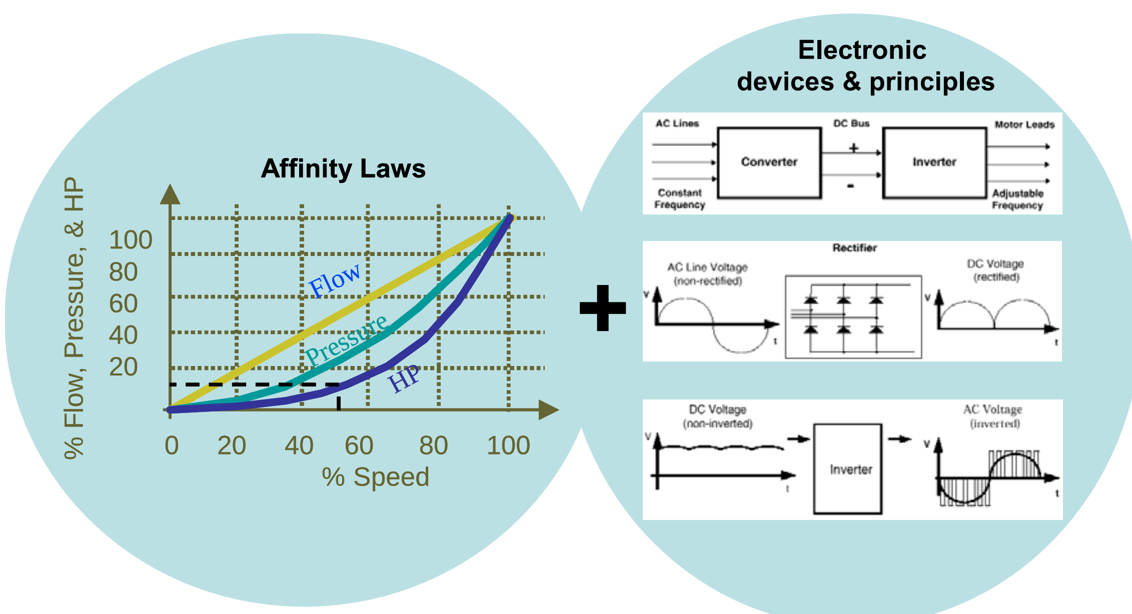


Figure1 An integrated approach to learning power electronics

Having been introduced to the affinity laws and explored the inefficiencies associated with traditional methods of speed control such as gear boxes and pulley systems, and the traditional methods of flow control such as inlet vanes and outlet dampers, the learners will be excited to see how power electronics help to save energy.

The right circle of Figure 1 depicts the major concepts required to understand the operation of a motor drive. All variable speed drives do two things: 1) convert or rectify ac supply voltage to dc bus voltage, and 2) convert or invert the dc bus voltage to pulse width modulated (PWM) waveform by switching a bank of Insulated Gate Bipolar Transistors (IGBT) to produce a simulated 3-phase ac voltage. There are may other techniques used in producing a simulated ac output. This paper limits the discussion to PWM only.

Figure 2 outlines the required knowledge for a sample learning activity suitable for the commercial drive development platform. The middle part of the figure illustrates the major components of the system. The surrounding boxes indicate a topic that can be explored in detail to teach the system operation. Starting from the left, ac supply is fed into the controller from a wall outlet. In side the controller, the ac supply is converted into fixed dc voltage known as dc bus voltage. Then, by using a set of IGBTs, the dc voltage is converted into a pulse with modulated (PWM) 3-phase voltage, which then goes to the motor. A program in a microcontroller switches the gates of IGBTs to create this 3-pahse waveform.

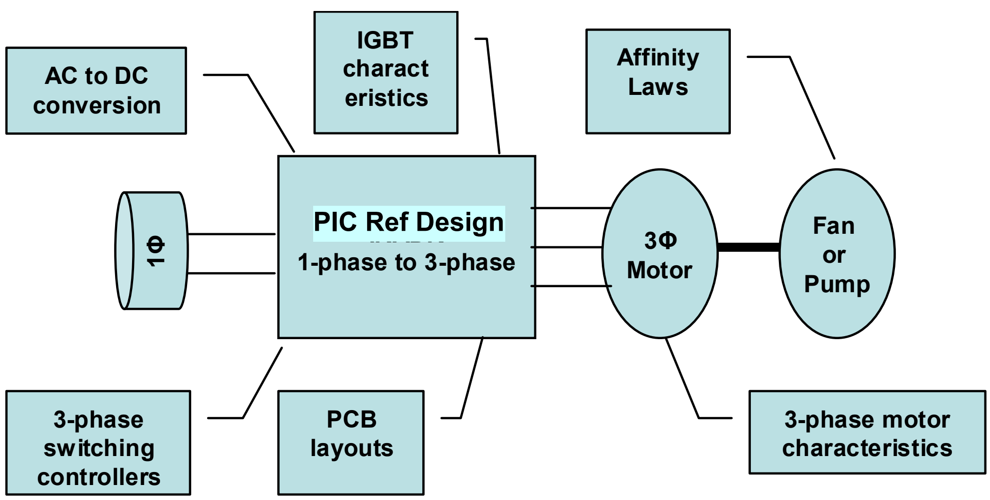


Figure 2 Various subject matter that can be integrated into the learning activity

The depth of each area can be varied to accommodate the skill level required by the educational objectives. For some areas, computer simulation may enhance a learner's internal reference.

Experiment Development

Safety First

This experiment requires students to work with electrical power supplied by the utility source. If the power is obtained from 110V, which has about a 170V peak, the bus voltage will reach to about 300V. Extreme precautions must be taken when working in this environment. The first thing is the safety glasses. Even though the development board comes with a plastic shield mounted on it, many things can go wrong when a rotating motor and high voltage are present.

Learners must be reminded that the common terminals of all oscilloscopes are connected to the earth ground. The negative terminal of the dc bus of the motor controller is not at the same ground potential. An apparently innocent connection between two commons can cause expensive damage to circuitry and may expose the learners to electrical shock hazards. To prevent the above, 1) use an isolation transformer to power the development board, and 2) use differential probes to measure voltages with respect to unknown ground potentials.

Finally, wire the lab power supply through a simple start/stop contactor circuit with accessible emergency stop buttons. Make sure that students don't work alone. Go over the safety procedures thoroughly and let students know what to do when something goes wrong.

Why PICDEM™

There are many manufacturers that market motor drive development platforms which offer the same features discussed here. Microchip's PIC microcontroller is used in many universities and colleges. It has been around for a while and was chosen because the PCB layout helps the learner locate different blocks of the circuit and it contains test points that are easily accessible to the user. The microcontroller, PIC18FXX31, can be programmed, while the same board can be used to implement brushless dc (BLDC) motor drives as well. It is very handy to use 110V single-phase as the input and still produce a 3-phase output because some electronics labs may not have 3-phase power readily available.

PICDEM Description

Figure 3 identifies the location of major components of the development board. The user manual provides a detailed description of each block.

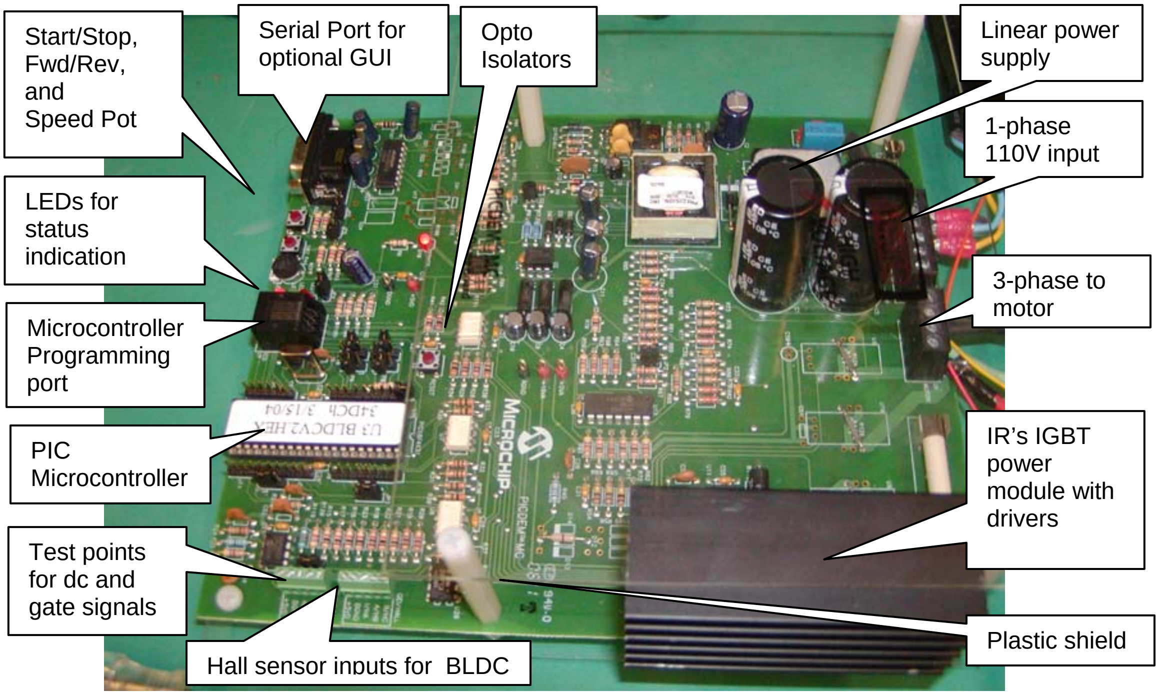


Figure 3 Major components of the development board

Many circuitries such as serial communication, micro controller programming ports are available to make circuit development easier. However, as a stand alone driver, only the following may be necessary: rectifiers, line filters, boost regulator, microcontroller, start/stop/reverse bush buttons, speed potentiometer, IGBT power module, +5V and +15V power sources. Figure 4 is the block diagram of the above circuit.

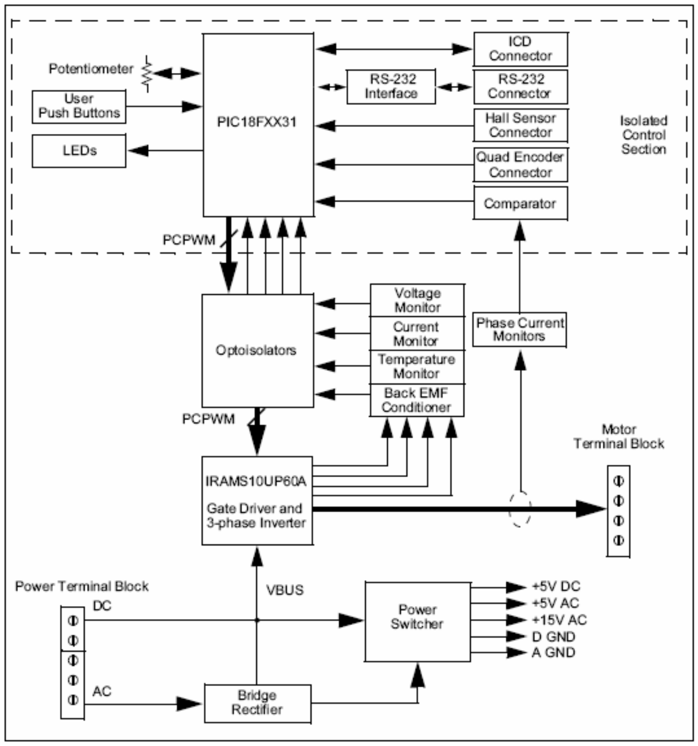


Figure 4 Block diagram of the Microchip Development Board [3]

There are a total of three User Push Buttons connected to PIC18FXX31 in Figure4: the Reset, SW1, and SW2. The Reset is directly connected to the MCLR pin of the microcontroller, and pushing this button will cause a hard reset of the controller. Pushing SW1 will turn the motor on or off, and SW2 changes the direction of the motor. Four LEDs are used to indicate 1) normal running condition, 2) forward and reverse rotation, 3) over voltage, 4) over current, and 5) over temperature conditions.

In order to control the speed, the potentiometer is used; the value is read by the microcontroller's analog to digital controller (ADC) and interpreted into the desired speed. The microcontroller is a PIC18F4431, a 40-pin DIP package. This is responsible for all the communication through the RS-232 port as well as all on-board functions. This can be replaced by a 28-pin DIP package which fits in a socket that is hidden underneath the 40-pin microcontroller. Some of the functions that the PIC18F4431 are responsible for are sending a PWM to the IGBTs and monitoring the voltage, current, and temperature to assure the motor is running properly and will not be damaged. It also must monitor the hall-effect sensors if a Brushless DC motor is being used so that it can determine its position.

The IGBTs or 3-phase Inverter Power Module receives a pulse width modulation from the PIC18F4431 and translates this into the correct power levels for the motor. The package made by International Rectifier, IRAMS10UP60A, contains both the drivers and inverters needed to perform this task and also monitors its own temperature. The inverter module requires 15V power.

The power supply module takes either 120V AC or DC voltage input. If the source is AC the power is sent through a diode bridge rectifier to convert it to a range of DC voltages. These include a digital 5V, analog 5V, and analog 15V.

The development board also contains a range of sensors used to monitor different aspects of the board and the motor it is controlling. These contain sensors that monitor voltages, currents, phases, and temperatures. They also consist of hall-effect sensors and a Back EMF conditioner; these are all crucial to the operation of the motor and the board. For example, the voltages, currents, and temperature must all be monitored to make sure they do not get too high, or damage may result. The usual course of action is that if these levels become too great the motor and development board will be shut down in order to protect them. The need for the hall-effect sensors and back EMF detector is to detect the position of the motor. The hall-effect sensors are to be used with the Brushless DC motor, and they help the development board determine the position of the motor to a great degree, much better than the back EMF method for AC Induction motors. This method measures the amount of distortion in the power going to the motor and attempts to determine the position of the motor. This is not very accurate, and there are better methods that can be used, such as a closed-loop feedback.

Useful Measurements

Inductions motors (IM) are designed and operated at a specific voltage and frequency. Thus the ratio between volts and hertz (V/Hz) must be maintained to preserve the motor's characteristics. The speed of an IM depends on the frequency and the number of poles. Since the poles are fixed for a given motor, the speed can be varied by varying the frequency as long as the V/Hz ratio is maintained. By using many different switching topologies, power electronics based variable speed drives attempt to maintain the V/Hz ratio. If the ratio is maintained, the full torque can be generated, theoretically, even at zero speed. However, PWM based drives may go down to 50 rpm before stalling the rotor. A simple PWM controller does not use speed feedback and assumes that the motor is not overloaded and the rotor turns at an approximate speed according to the frequency. This is not a limitation in pumping and fan type applications. If precise flow control is needed, a closed loop control could be possible, which is beyond the goal of this paper.

Table 1 summarizes typical electrical and mechanical measurements used to verify motor characteristics. The same measurements can be used to verify the performance of the power electronics motor driver under varying torque conditions. Using these data, graphs can be developed to trace the relationships among speed, torque, line voltages, and line currents. Table 2 summarizes useful measurements for troubleshooting any three-phase switched mode motor speed controller. Notice the recommended instrument for each category.

Table 1 Motor related measurement

Measurement	To verify	Instrument
3-phase Line to Line voltage	V/Hz ratio Line imbalances Rated voltage Voltage harmonics	Fluke 434 power analyzer or similar
3-phase line current	Current ratings Symmetry	Fluke 434 power analyzer
V & I Motor harmonics	Motor overheating Power factor	Fluke 434 power analyzer
Speed	V/Hz ratio Torque Vs. Speed characteristics	Non-contact tachometer
Torque	Torque Vs. Speed characteristics	Torque gauges with a brake or dynamometer setup

Table 2 Induction motor controller related measurements

Measurement	To verify	Instrument
Dc bus voltage	Rectification Status of bus capacitor Regeneration IGBT operation	Oscilloscope with differential probes or DMM
+5V dc supply	Microcontroller supply	DMM
+15V dc supply	Intelligent power (IGBT) module operation	DMM
Microcontroller output to power module	V/Hz ratio Torque Vs. Speed characteristics	Oscilloscope with differential probes – 3 channel simultaneously
Power module output to the motor	IGBT switching Phase angle between phases Output voltage	Oscilloscope with differential probes – 3 channel simultaneously Or Fluke 434 power analyzer

Equipment

Since the three-phase output is generated by chopping a dc bus voltage according to a PWM signal, it is very important to have the ability to monitor all three phases simultaneously. This allows the developer to detect any abnormalities of microcontroller outputs and the inverter. The new Fluke 434 power analyzer allows the user to take all three line to line voltages and line currents simultaneously at the motor terminals. Learners find that the automatic display of voltage-current (V-I) vector diagram is very appealing and helpful in troubleshooting. Current and voltage harmonics are easily obtainable with their total harmonic distortion (THD) levels.

When it comes to board level measurements, as mentioned before, differential probes become very handy and provide safety. The switching frequency applied to an inverter of a PWM based driver may vary from 5kHz to 20kHz. A standard lab Oscilloscope is adequate unless switching characteristics and power dissipation of IGBTs or MOSFET switches during the transients are under consideration. For higher end analyses, a LeCroy™ Waverunner type oscilloscope, as shown in Figure 4, with a differential amplifier would be an ideal companion.

Figure 5 depicts the equipment set up. The torque gauge appears at the left, and the Fluke 434 meter is located at the bottom right. The 110V power to the controller located on the table comes though a 1-to-1 isolation transformer. The induction motor is a 1/3 HP, 8-pole, inverter duty 3-phase induction motor. The microcontroller is programmed for open-loop induction motor operation.

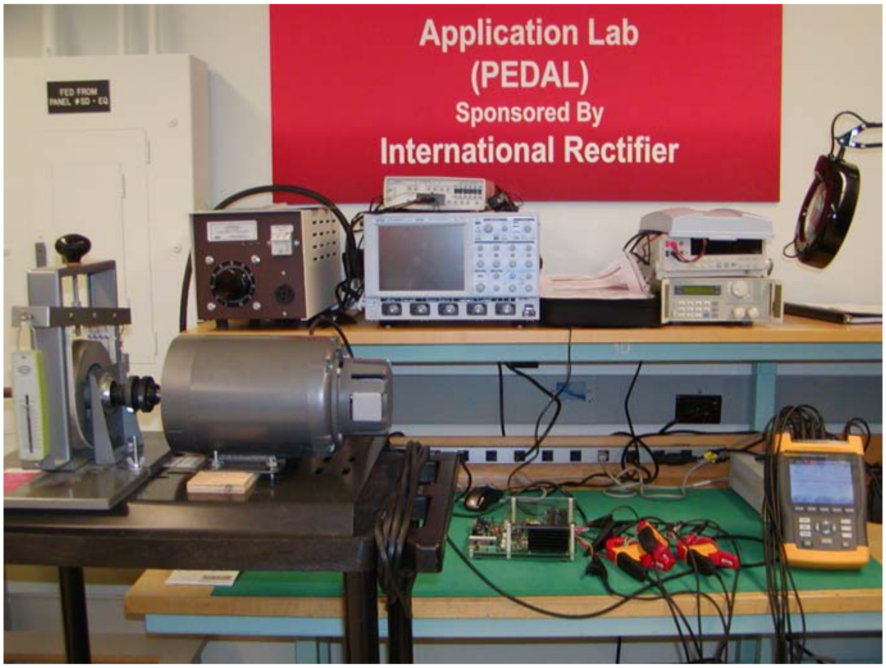


Figure 5 Equipment set up for the experiment

Data

The objectives of data collection include 1) to examine how line voltage, line current, and speed varies as the applied torque goes up, 2) to verify the driver's ability to maintain V/Hz characteristics, and 3) to examine the effects of harmonics in motor operation.

Two sets of data were collected even though more would be necessary for statistically justified conclusions, one at the maximum potentiometer, speed adjustment, setting and the other at the mid position of the potentiometer.

Maximum Speed

Table 3 Motor voltage, current, and rpm responses for increasing torque at max speed (I_P = peak current, V_{L-L} = line to line voltage of 3-phase voltage)

Table 3 Motor test data

Torque (inch-oz)	Speed (RPM)	Actual I_p (mA)	$V_{L-L\ rms}$ (Volt)
0	883	567	211
12	880	600	209
24	870	633	207
36	855	733	204
48	840	833	202
60	824	933	200
72	800	1100	196

The rated voltage of the motor is 208V, 3-phase. The driver maintained the line to line voltage within ±10% range. As shown in Figure 6, as the torque increased, motor speed and line to line voltages dropped somewhat and the motor current went up. Best fit curves for each are generated to compare with the same three graphs obtained in Figure 10.

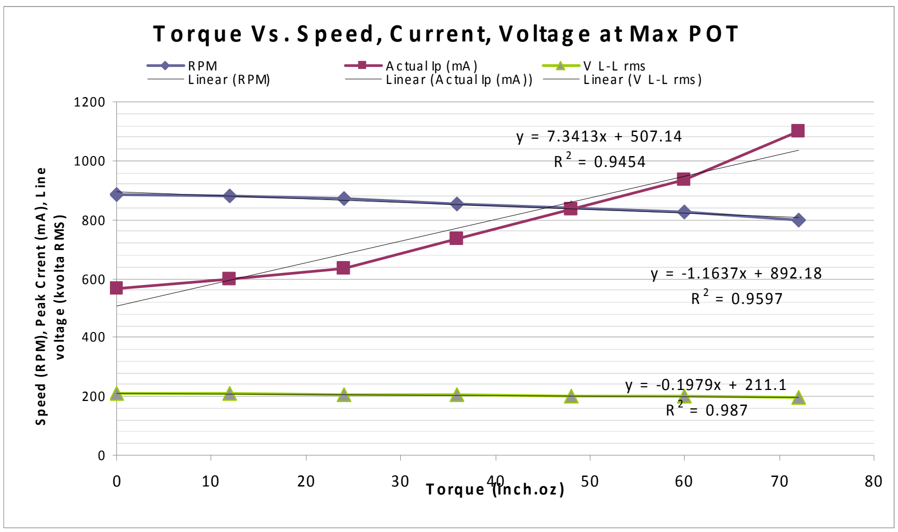
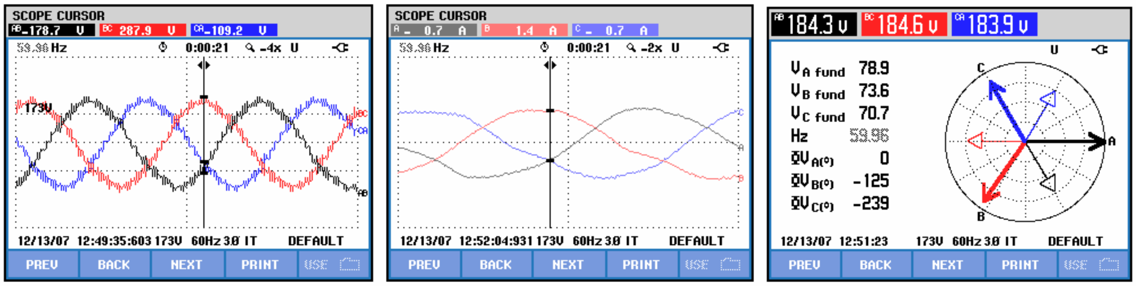


Figure 6 Variation of motor speed, current, and voltage as torque is increased

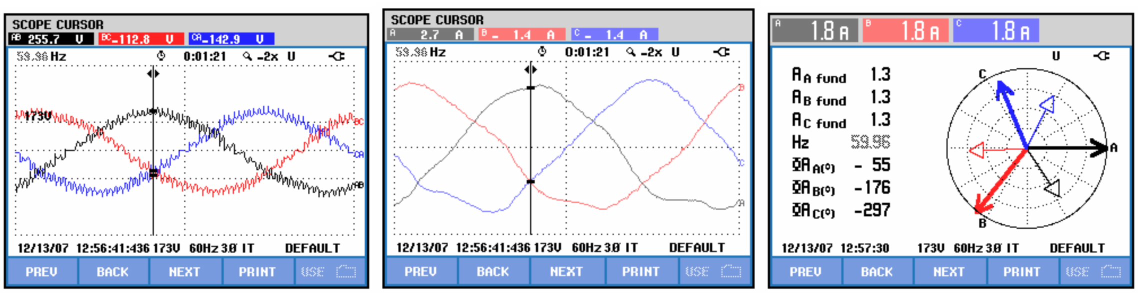
Figure 7 below shows the simulated three phase output measured by the Fluke 434 meter with no load. The voltages are 120 degrees out of phase. However, the voltage fluctuations are obvious due to switching effects. Line currents are hardly sinusoidal, indicating the presence of harmonics. Phase angle of the fundamental frequency seems equal for all three phases.



(a) (b) (c)

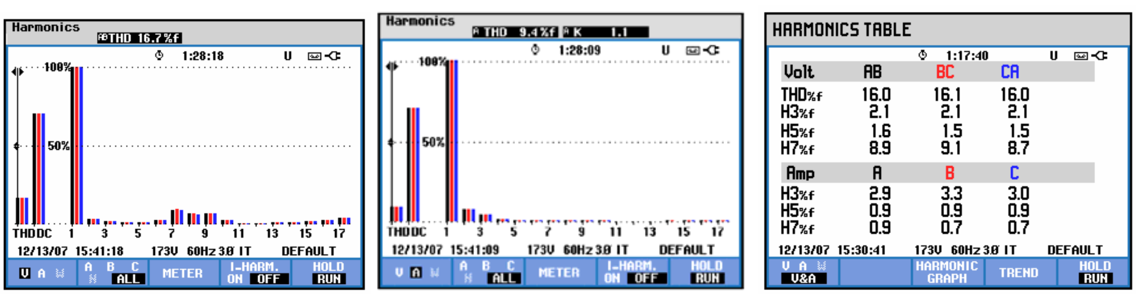
Figure 7 (a)Voltage, (b) current, and (c) phasor diagram at full speed with no load

Figure 8 depicts voltage, current, and phasor information with a 72 inch-oz load on the motor shaft. There are no major variations compared to the unloaded condition other than the increased current. According to Figure 9, the voltage and current THD levels fall below 17% and 10% respectively. This high voltage THD does not reflect on the supply side. However, it causes extra heat in motor winding, especially at the beginning and the end of each winding.



(a) (b) (c)

Figure 8 (a) Voltage, (b) current, and (c) phasor diagram at full speed with 72 inch-oz load



(a) (b) (c)

Figure 9 (a) Voltage, (b) current harmonics, and (c) THD values at full speed and 72 inch-oz torque

<u>Medium speed</u>

The same data taken for the maximum speed are recorded by setting the speed potentiometer at its mid position. The motor speed went down to about half of the maximum. The output voltage is reduced to about half the value of the earlier case to maintain the V/Hz ratio.

Figure 10 is the result of the data in Table 4, which has some unique similarities to Figure 6. The current curves have a positive slope around 7.0. The speed curves have negative slope around -1.1. The voltage curves vary around -1.15. This data indicates that the drive maintained a fairly solid V/Hz ratio under loaded conditions and in two different speed settings.

Table 4 Motor voltage, current, and rpm responses for increasing torque at mid speed

Torque (inch-oz)	Speed (RPM)	Actual I_p (mA)	$V_{L\text{-}L\ rms}$ (Volt)
0	450	500	117
12	447	533	115
24	440	567	112
36	437	633	112
48	396	833	109
60	377	900	108
72	387	967	106

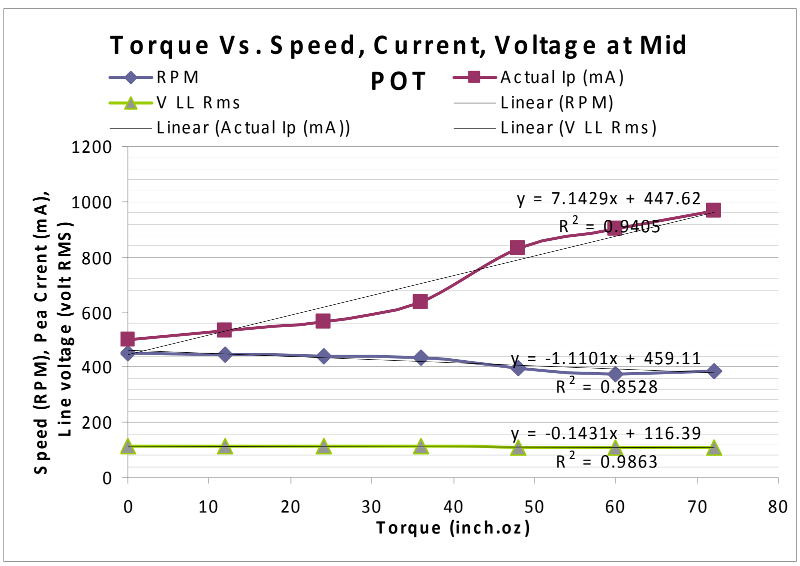
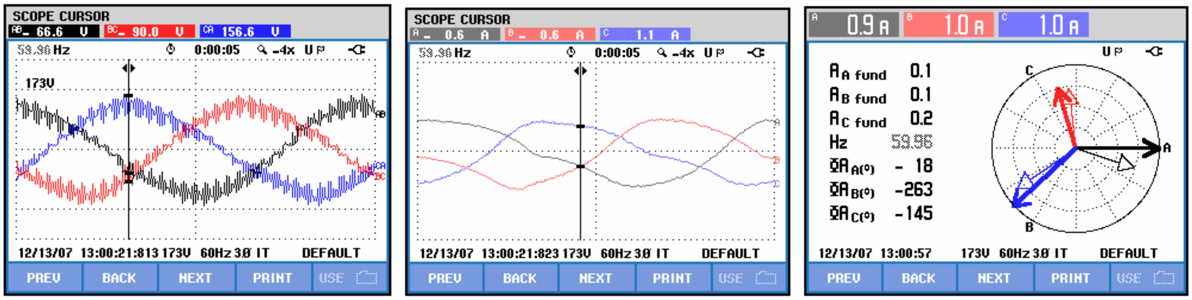


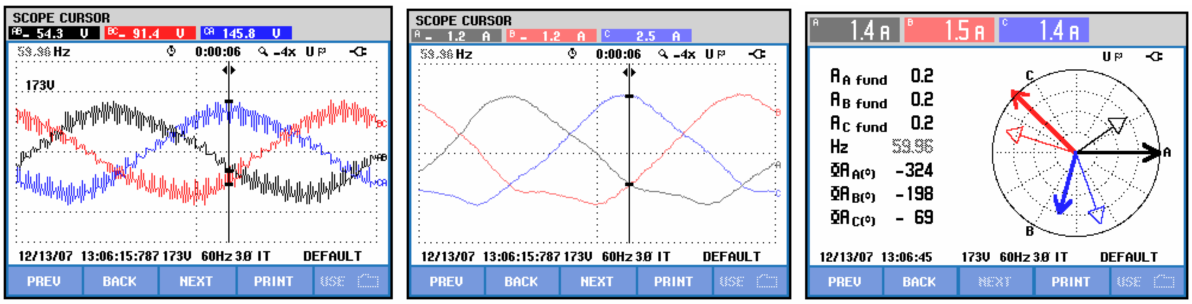
Figure 10 Variation of motor speed, current, and voltage as torque is increased

Compared to the maximum speed data, the phase angle of the fundamental, Figure 11, became smaller at the medium speed. However, the phase angle increases, see Figure 12, as the load is added to the motor shaft. The THD levels for voltage and current have risen to 16% and 19% respectively. See Figure 13.



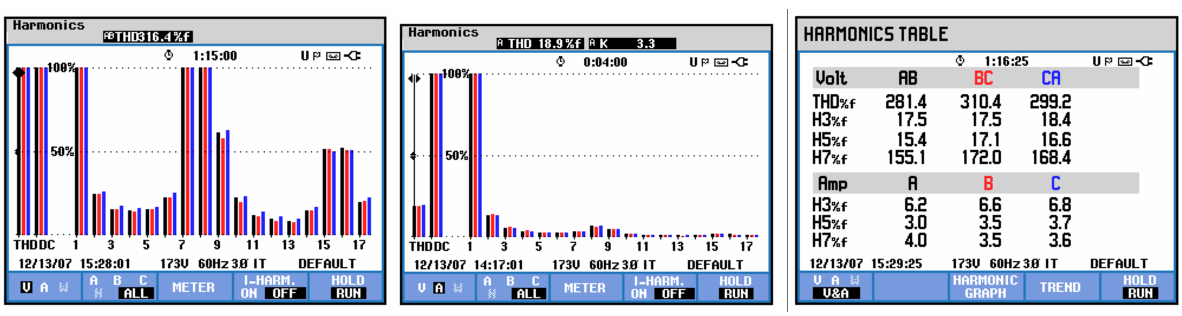
(a) (b) (c)

Figure 11 (a)Voltage, (b)current, and (c)phasor diagram at medium speed with no load



(a) (b) (c)

Figure 12 (a)Voltage, (b)current, and (c) phasor diagram at mid speed with 72 inch-oz load



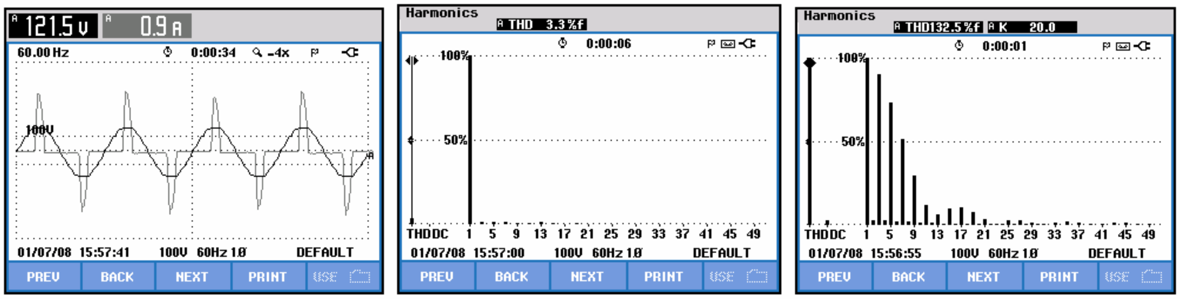
(a) (b) (c)

Figure 13 Voltage and current harmonics at full speed with 72 inch-oz torque

The above data reveals that the motor is under great stress when it is subjected to switched mode speed regulation. Naturally, inverter duty motors are more expensive than a standard induction motor. By maintaining the V/Hz ratio, the switched mode driver preserves the operating characteristics of the induction motor. If the motor can withstand the effects of switching, significant energy can be saved at lower speed in pumps and fan applications, according to the Affinity laws.

<u>Harmonics in Power Line</u>

According to Figure 12 above, voltage and current harmonics are way over the utility mandated levels. To investigate the harmonics in the power line, the single phase line that fed the motor driver must be examined. As shown in Figure 14, the voltage THD falls less than 5% (14.a) but the current THD is above the 20% level (14.b). This discovery may be used to investigate another topic in power electronics: harmonics filtering.



(a) (b) (c)

Figure 14 (a)Voltage and current wave forms, (b) harmonics content of voltage, and (c) harmonic content of current at the 110V input power

Applying to Real World

A low cost pumping application test-stand is shown in Figure15. The pumping test-stand consists of a centrifugal pump, clear pipes to observe the flow, a flow meter with 4-20 mA output, a pressure gauge, and a set of valves that can be used to alter the flow path. This set-up allows the controller to be operated in a closed loop fashion as well. A motor can be coupled to the pump. Different motors such as BLDC and reluctance motors can also be coupled to test their behavior under load.

For learning energy efficiency, students may adjust the speed of the motor via the variable speed drive discussed above. The objective of the activity could be to develop graphs of the affinity laws. Connect the 3-phase power analyzer to measure the power of the motor. If a Fluke 434 is not available, a less expensive but commonly used Fluke 43B can be used. Increase the motor speed and record the flow, pressure and power. Then use Excel to plot the speed versus flow, pressure, and power, which would yield a graph similar to the one in Figure 1. Guide learners to calculate the energy saving due to reduced speed as compared to traditional inlet vanes or output damper flow control methods as shown in Figure 16.

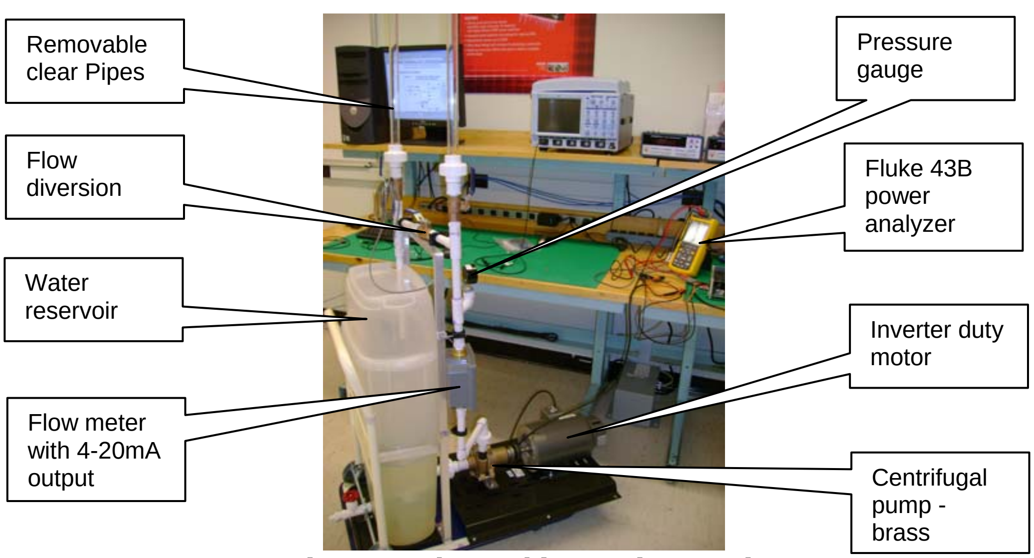
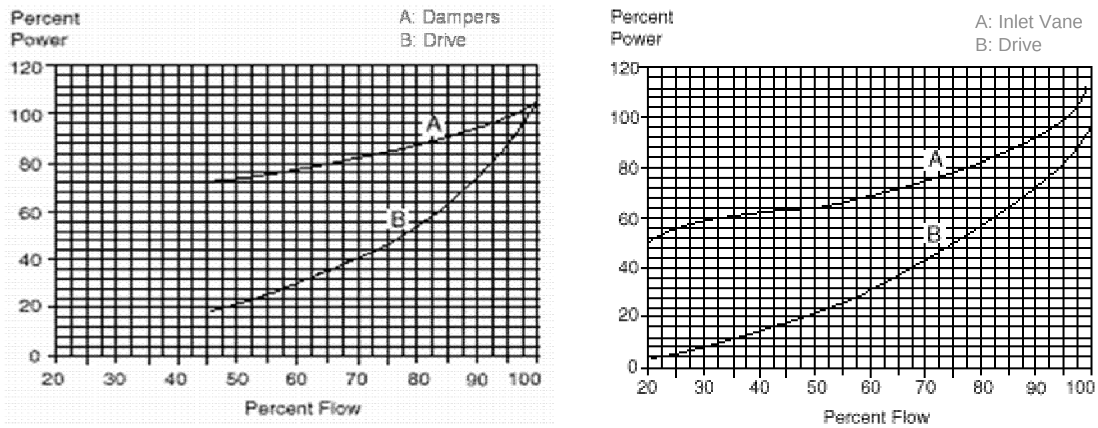


Figure 15 A pump test-stand to go with variable speed motor drive to experiment with the Affinity Laws



(a) (b)

Figure 16 Energy saving potential comparison between a) a variable speed drive and outlet damper control and b) a variable speed drive and an inlet vane control

Conclusions

Energy efficiency of products and systems must be considered in all aspects of product development. Power electronics allows energy efficiency improvements in a cost effective manner. Engineers and engineering technologists with understanding in power electronics are high in demand. As a first step, the learners must understand how power electronics help save energy. To understand this, the characteristics of both electrical and mechanical components must be explored.

This paper provides information and useful data that can be used to develop lab activities for one or more sessions. By teaching necessary theoretical knowledge for each block in Figure 2, this hands-on activity lays the foundation for very exciting learning in power electronics. The activity is designed to integrate previous knowledge of analog electronics, digital electronics, and motors while exploring how they are applied in real world applications to serve a great cause – energy efficiency. Each sub topic can be expanded to include other motors such as BLDC [4] and switched reluctance motors [5].

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