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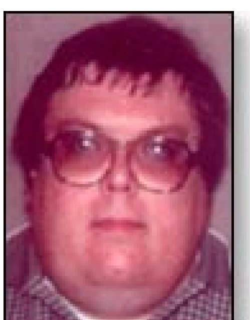

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Abstract

The detailed study of electrical power systems is a key element of many curricula in Industrial Technology. A novel laboratory set-up has been designed and implemented at the University of Northern Iowa as an instructional resource for teaching electrical power system and renewable energy concepts. The set-up consists of a photo-voltaic solar-cell array, a mast mounted wind generator, lead-acid storage batteries, an inverter unit to convert DC power to AC power, electrical lighting loads and electrical heating loads, several fuse and junction boxes and associated wiring, and test instruments for measuring voltages, currents, power factors, and harmonic contamination data throughout the system. This hybrid solar-wind power generating system is extensively used to illustrate electrical concepts in hands-on laboratories and demonstrations in the Industrial Technology curriculum.

Introduction

Electricity cannot be seen, felt, tasted, smelled, heard or (safely) touched. Providing Industrial Technology students with vivid, memorable, hands-on learning experiences in the area of electricity is a challenge for all educators in the Industrial Technology area. The traditional measuring instruments for electricity (oscilloscopes, voltmeters, ammeters, and power meters) and traditional signal sources (motors, transformers, resistors, inductors) are fine but have some drawbacks:

- They have a tendency to become repetitive and boring.
- They have an artificial, educational non-real-world feel.
- They may fail to convey the notion of the true complexity and interrelations of industrial electrical power systems.
- They may not capture the student's attention and motivate learning.
- They may not give an intuitive feeling for what electrical quantities *really* mean physically.

Iowa is a geographically large state with a low population density. Electrical power needs are supplied by a large number of local power companies. Due to the isolation of many dwellings, agricultural sites, and industrial sites, there is considerable interest in novel forms of electricity production. Two such forms of production are solar photo-voltaic (PV) cells based on DC-power generating arrays and wind-turbines based on propeller-driven DC-power generators. In fact, Iowa is now the home of the largest wind-turbine power installation in the world (Pecen, 1999). Electrical power generation and special sources of electric power, like wind-turbines, are frequently discussed in the public media and are very vividly in the minds of Industrial Technology students from daily-life experiences. The additional factor of the general concern and interest for environmental issues is a further enticement to attract the student's interest in these "green-technology" forms of electricity generation.

<u>Special Educational Issues of Wind-turbines and Photo-Voltaic Cells</u>

As the wind does not blow all the time nor does the sun shine all the time, solar and wind power alone are poor power sources. Hybridizing solar and wind power sources together with storage batteries to cover the periods of time without sun or wind provides a realistic form of power generation.

This variable feature of wind-turbine power generation is different from conventional fossil fuel, nuclear, or hydro-based power generation. Wind energy has become the least expensive renewable energy technology in existence and has peaked the interest of scientists and educators the world over. A simple relationship exists relating the power generated by a wind-turbine and the wind parameters:

$$P = 0.5\rho A\, C_p v^3 \eta_g \eta_b \qquad (1)$$

where,

ρ = air density (about 1.225 kg/m^3 at sea level, less at higher elevations).

A = rotor swept area, exposed to the wind (m^2).

Cp = Coefficient of performance (.59 to .35 depending on turbine).

v = wind speed in meters/sec

η_g = generator efficiency

η_b = gearbox/bearings efficiency

A mast-mounted anemometer (wind meter) allows the students to directly measure wind speed and to vividly relate this easily felt force-of-nature to electrical measurements.

Photo-Voltaic or PV cells, known commonly as solar cells, convert the energy from sunlight into DC electricity. PVs offer added advantages over other renewable energy sources in that they give off no noise and require practically no maintenance. PV cells are a familiar element of the scientific calculators owned by many students. Their operating principles and governing relationships are unfortunately not as pedagogically simple as that of wind-turbines. However, they operate using the same semiconductor principles that govern diodes and transistors and the explanation of their functioning is straightforward and helps to make more intuitive many of the principles covered in semiconductor electronic classes.

Most industrial uses of electricity require AC or alternating 60 Hz power. Wind-turbines and PV cells provide DC power. A semiconductor-based device known as a power inverter is used to convert the DC power to AC power. This device has a relatively simple operation that is a vivid illustration of many topics traditionally covered in power electronics classes.

The inverter also introduces the problem of power quality. Power quality is an extremely important issue in real-life industrial electric power systems. Power quality is the contamination of the voltage or frequency characteristics of electric power. The system exhibits many common problems of power quality such as voltage sag (sudden drops in voltage due to over demand of battery capacity and/or loss of wind or sun), harmonic contamination (errors in the 60 Hz frequency due to nonlinear loads such as computers, energy efficient light bulbs, laser printers, scanners), and voltage regulation problems (prolonged drops in voltage due to interactions of system elements). Power quality is an extremely important problem in industrial electricity applications and this setup offers unique opportunities for the students to study power quality problems in a real system.

Three major phases of the development and implementation of this facility have been completed. First, the set-up itself has been constructed and debugged. Second instruments for hands-on measurement of electrical quantities in the system have been acquired and deployed for hands-on lab use. And third, numerous simulations have been performed on PSCAD/EMTDC (1996), a well-known power system computer simulation package used by industry and universities. This software allows the students to make an intuitive link between the physical system present in the hands-on labs and the more abstract mathematical equations presented in their lecture notes and texts. Two such simulations are presented in this paper.

Literature Review

The literature in the subject areas of this paper is very extensive. An excellent textbook for instructional use is *Wind and Solar Power Systems* by Patel (1999) that covers the specific issues in this project in a style appropriate for Industrial Technology students. Sabin (1999) and coworkers have summarized the various standards and benchmarks used in large-scale power quality, and Koval (1999) and coworkers have presented similar finding for rural (small-scale) power quality problems. Many articles have appeared on the impact of new electronics technologies on power quality management, for example Poisson (1999) and coworkers have described the impact of DSP chips on the problem. Barbosa (1998) and coworkers have described the use of PWM (pulse-width-modulation) control schemes to power quality control.

Numerous studies have appeared describing the impact of power quality problems caused by PV systems from early work by McNeil (1983) and coworkers in to more recent work by Oliva (1988) and coworkers and most recently by Chowdhury (1999). The extensive literature on power quality aspects of wind generation includes work by Demoulias and Dokopoulos (1996) on transient power measurement and by Thiringer (1996) on harmonic contamination measurement issues. Taylor (1987) is responsible for some of the early practical work on power quality measurements in wind generation. Kariniotakis and Stavrakakis (1995) have written extensively on simulation problems in wind generator and power grid interactions.

Finally, many papers have been written on the electronics regulation/control aspects of the problem including a recent study by Neris and coworkers (1999) proposing an IGBT (Integrated-Base-Bipolar-Transistor) based regulator.

Methodology

In order to address the shortcomings of existing instructional techniques for electrical power systems, a hybrid wind-turbine and solar cell system has been implemented at the University of Northern Iowa. The system was designed and implemented with the following goals:

- To be completely different from traditional electricity labs and to be fresh and interesting.
- To be intimately related to real-world industrial power issues such as power quality.
- To show a complex, interrelated system that is closer to the "real world" than the usual simple systems covered in educational labs.
- To motivate learning by introducing such elements as environmental and economic concerns of practical interest to the students.

Establishment of a Wind/PV Hybrid Unit

The hybrid unit contains two complete generating plants, a PV solar-cell plant and a wind-turbine system. These sources are connected in parallel to a 12V DC line. The power is next connected to a DC to AC inverter and is then supplied from the inverter's output to a single-phase 60 HZ, 120 VAC load. The overall project structure is presented in Figure 1. The wind turbine is installed at the top of a steel tower that has a height of 18.3 meters and a diameter of 8.9 cm. The wind turbine depicted is a 0.7 kW unit and the solar panels depicted number four in all with a capacity of 50 Watts each. The instrumentation panel depicted monitors the outputs of the generator using digital panel meters.

A small wind turbine was chosen for its low maintenance and many safety features. One of the low maintenance features is the turbine's brushless alternator and an internal governor. The turbine generates 0.4 kW when turning at its rated speed of 47 km/hr and it is capable of generating up to 0.7 kW at its peak wind speed of 72 km/hr. The actual system's pictures are shown in Figure 2. The turbine's blades are made of a carbon fiber reinforced composite that will intentionally deform as the turbine reaches its rated output. This deformation effect changes the shape of the blade, causing it to go into a stall mode, thus limiting the rotation speed of the alternator and preventing damage in high winds. Another feature of the wind turbine is a sophisticated internal regulator that periodically checks the line voltage and corrects for low voltage conditions. The solar panels are 12 VDC units and were chosen for their ultra clear tempered glass that is manufactured for long term durability. Figure 3 shows the DC voltage measured across the 12 volt DC bus where the wind turbine and PV arrays outputs are connected. A slight ripple in power regulation can clearly be seen. This ripple is a function of the unpredictable nature of wind and sunshine along with the dynamic effects of the electrical load.

As mentioned earlier, one of the largest problems in systems containing power inverters is power quality. This problem becomes serious if the inverter used in the system does not have a good sinusoidal waveform output and causes problems such as harmonic contamination and poor voltage regulation. According to the IEEE (a professional society which codifies such issues) standards, a maximum of 3 to 4% total harmonic distortion (this is a quantitative measure of how bad the harmonic contamination is) may be allowed from inverter outputs. However, many inverter outputs have much more harmonic distortion than is allowed. The inverter used in this system has a power rating of a 1.5 KVA and was manufactured by Trace Technologies ®. The battery banks contain 4 deep-cycle lead-acid batteries connected in parallel. High power capacity heating resistors, energy efficient light bulbs, incandescent light

Figure 1. Established Wind/PV hybrid power generation unit.

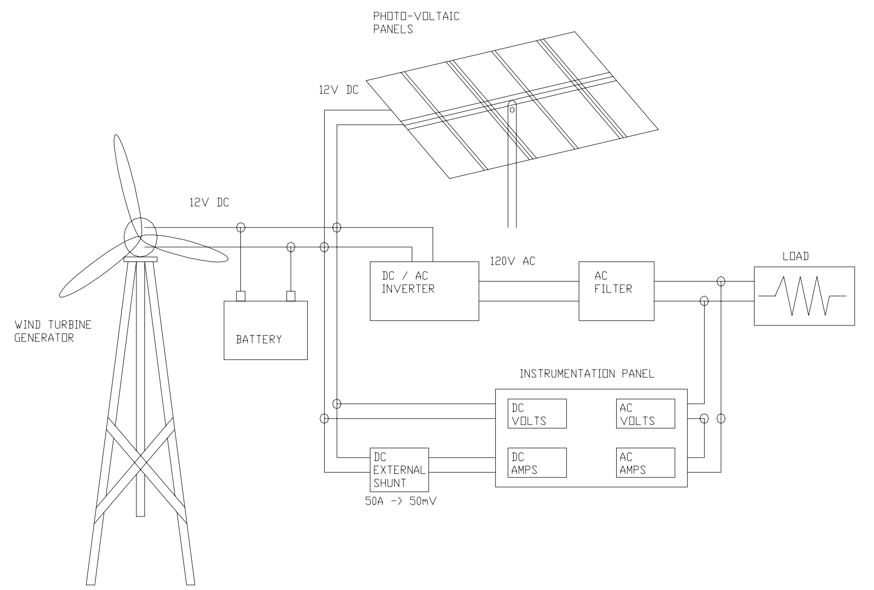
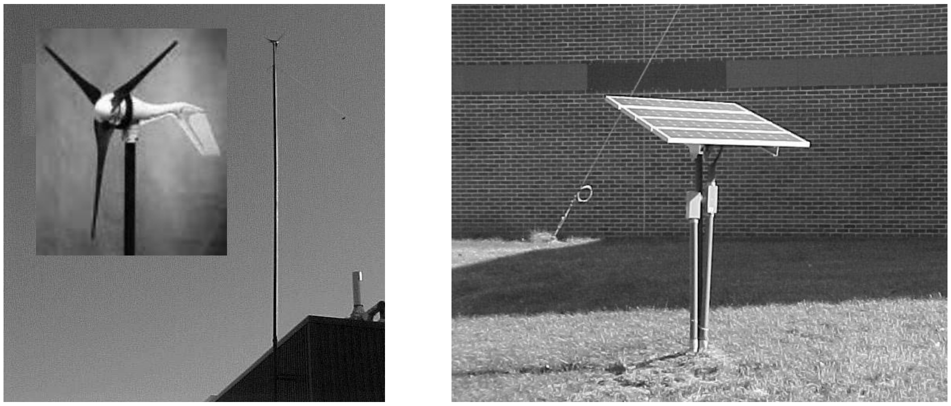


Figure 2. Actual pictures of wind/PV hybrid power station.



bulbs, and two small AC motors constitute electrical loads that can be applied to the system.

To monitor and store the voltage, current, power, and harmonic contamination data, two Fluke ® power quality analyzers (types 39 and 41) are used in the system. In addition, permanently mounted AC/DC digital panel meters form part of the system's instrumentation. A laptop computer is interfaced to the system via the Fluke power quality analyzers to store data in real-time. Figure 4 illustrates such data as voltage and current waveforms on the load side of the inverter in the case of small heat and lighting loads connected to the system. As shown in Figure 4, the current waveform is much more distorted than voltage waveform. Since current harmonic contamination has a more detrimental effects on industrial power quality problems than voltage harmonic contamination, the current harmonic spectrum of the inverter output is a vivid illustration of the pitfalls present in the measurement of real power quality problems in industrial simulations. Figure 5 illustrates the current harmonic spectrum in the case of nonlinear loads. A harmonic spectrum is a graphical plot of harmonic contamination on the y-axis and the frequency where this contamination occurs on the x-axis. This plot is commonly used in industry to study harmonic contamination and its possible remedies.

Voltage sags may cause a crucial damage to high precision measurement and protection devices, especially computer equipment present in many highly-automated industrial plants. A voltage sag example for the system is shown in Figure 6.

Simulation of the Hybrid System

Figure 7 presents the overall system including a passive RLC filter on the AC side of inverter. This filter is a circuit made up of a resistor (R), inductor (L), and a capacitor (C). Such filters are commonly installed in industrial situations to remedy power quality problems.

The inverter is of a twelve pulse type and the inverter and the control circuit models are both standard

Figure 3. DC voltage generated by hybrid wind/PV power system.

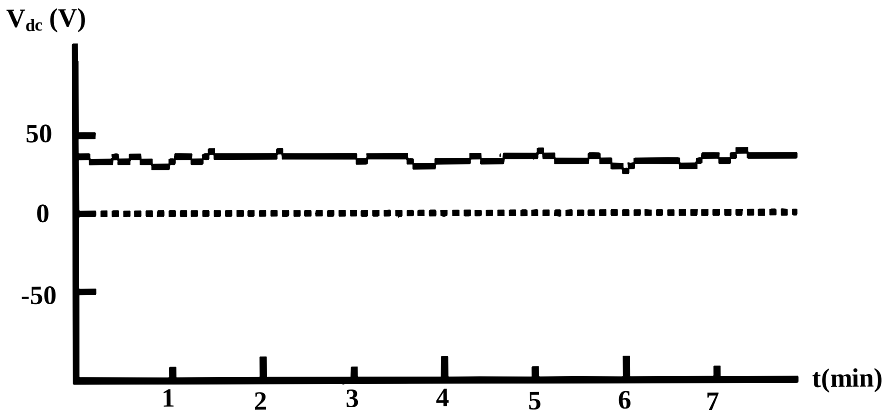


Figure 4. AC load voltage and current waveforms.

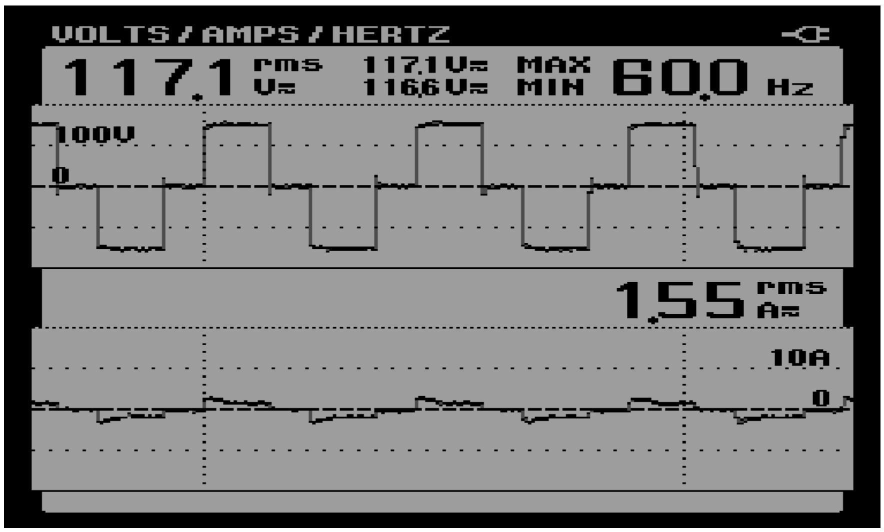
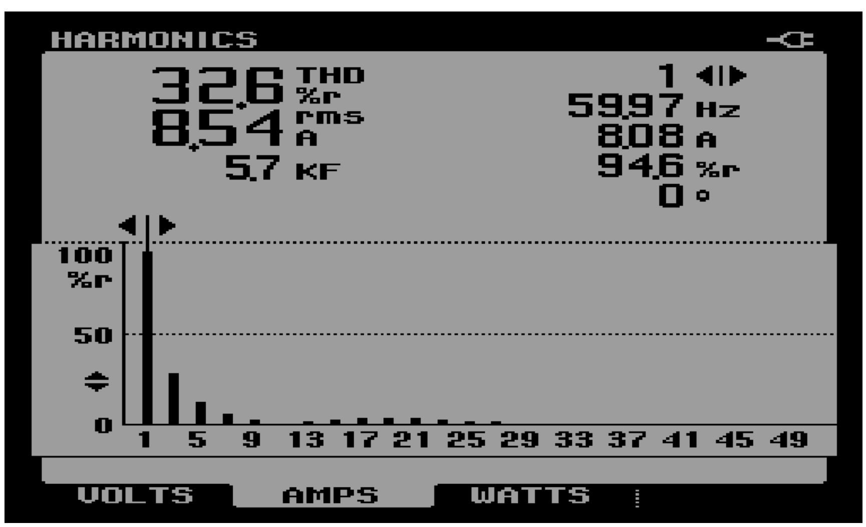


Figure 5. Current harmonic spectrum of the system when linear/nonli near loads are connected.



models in the PSCAD/EMTDC software package. Two simulation cases were run, with and without this RLC filter. Figures 8 presents raw and analyzed data for the system with and without the RLC filter. The students can vividly see from such simulations the practical remedies for power quality problems used in industry.

Findings

To date, the experience gained from using this setup in numerous hands-on labs and demonstrations has shown the following:

- The students find the system to be highly interesting and an enhancement to even simple tasks like learning how to use a voltmeter.
- The students gain a better intuitive knowledge of the generation and distribution of electric power than they can from textbooks and traditional lab experiments alone.
- The students' interest in electrical power systems is raised and they are able to gain a better physical understanding of the quantities and units involved.
- The system's use of a power inverters and of PV cells provides a vivid illustration of semiconductor issues and the students are better able to assimilate semiconductor concepts in their electronics classes.

Future Study

Figure 9 show the future direction of this project. A computer measurement and control bus will be added to the system. Computer controlled relays will be added to allow all the major elements of the system to be switched in and out of the system through computer programs. The measurement bus will be connected to all the major signals in the system and will allow for computerizes data acquisition simultaneously of all the major signals in the system. These improvements will allow for the study of more complex issues like power faults caused by sudden over voltages like lightning. These improvements will also allow the same benefits to instruction realized in electricity and electronics classes to be extended to control and instrumentation classes.

Conclusions and Recommendations

Obviously, a complete hybrid power system of this nature may be too expensive and too labor intensive for many Industrial Technology Departments. However, many of the same benefits could be gleaned from having some subset of the system, for example a PV panel, batteries, and an inverter, or even just a PV panel and a DC motor. The enhancements to instruction, especially in making electrical power measurements more physical, intuitive, and real-world are substantial and the costs and labor involved in some adaptation of the ideas in this paper to a smaller scale setup are reasonable.

The use of solar and wind hybrid power generation is an especially vivid and relevant choice for students of Industrial Technology in Iowa as these are power sources of technological, political, and economic importance in their state. In other places, other power sources could be used. For example hybrid combinations of wind power, solar power, geothermal power, hydroelectric power, tidal power, biomass generated power, power from incineration of solid wastes, and many other technologies could be considered depending on local interests and resources. The key elements of this test bed concept presented in this paper are two or more renewable power sources connected to a power grid with complex electrical interactions.

Figure 6. Voltage sags recorded in the wind/PV system.

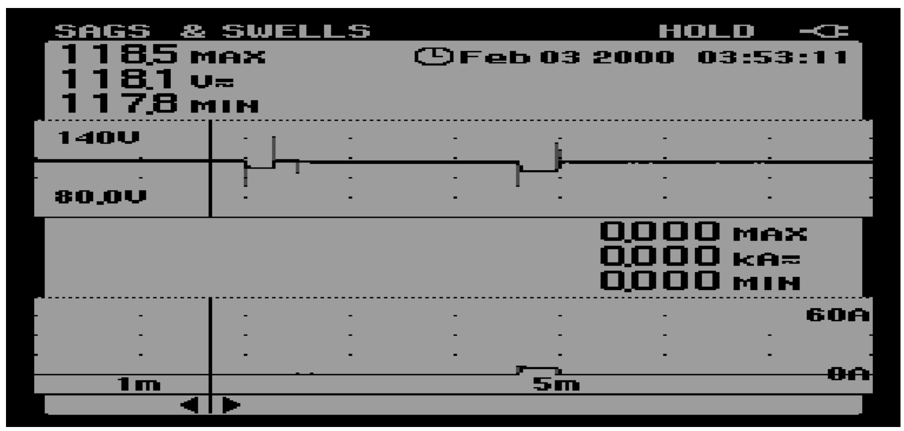


Figure 7. PSCAD/EMTDC Simulation of system with load and RLC filter.

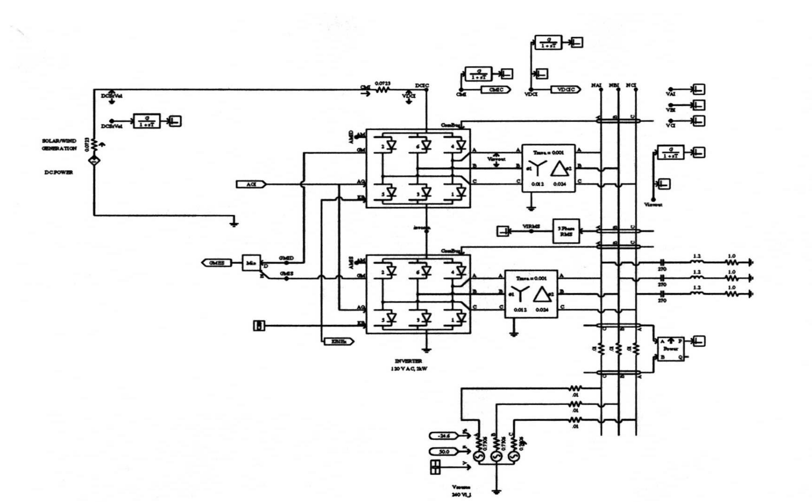


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Figure 8. Harmonic contamination (a) without RLC filter and (b) with RLC filter.

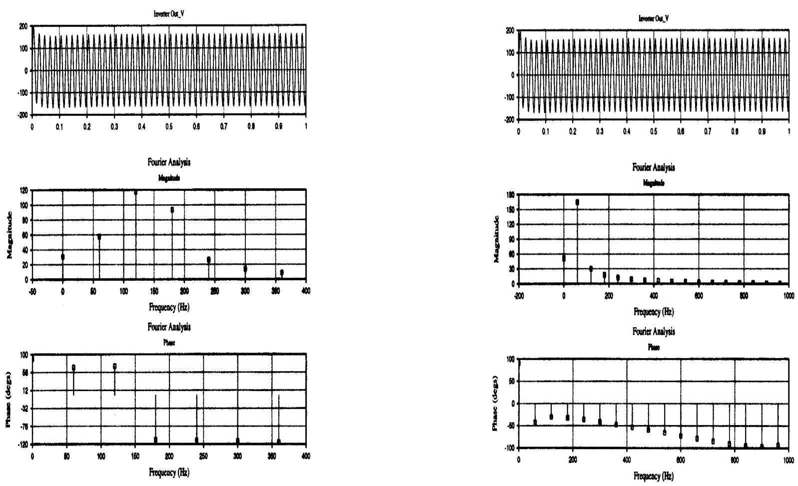

Figure 9. Block diagram of future research.