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Dynamic capacitor bank

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED

Dynamic Capacitor Bank

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Thesis Advisor

Chairman of Department

DYNAMIC CAPACITOR BANK

By
J. Daniel Mendoza, Peter Roguski

SENIOR DESIGN PROJECT REPORT

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ABSTRACT

Low power factor systems run inefficiently and cause power companies to lose thousands of dollars with wasted power. Correction systems currently implement static capacitor solutions to offset this power factor; however, companies where the power factor varies significantly need a better solution. In this paper, we discuss a reactive power factor correction system that could greatly benefit companies with this problem. The system is in its prototype state, which comprises of a capacitor bank, sensing circuit, a switching circuit and a microprocessor; we named it the Dynamic Capacitor Bank. During our project, we were able to get a sensing circuit to sense load voltage and current, as well as design a switching circuit and an inductive load for testing of the system. Our system performed the necessary steps to correct a power factor; however, we were limited by the power levels allowed for a senior design project and could not show precise information. Overall, a Dynamic Capacitor Bank could greatly benefit systems with varying power factor.

ACKNOWLEDGMENTS

There are a few people who made this project possible and would like to give them the credit they deserve. First and foremost we would like to thank Dr. Khanbaghi, who acted as our advisor for the project, helping us with her expertise in control systems and pushing us in the right direction. Secondly we would like to thank the School of Engineering, not only for the funding to make the project possible, however also for the use of their lab space to create and test our prototype. Our finances and shipping logistics would not have been so easy if it was not for Lindsay Mulic helping make sure we got our components paid for and delivered on time. We would like to thank Yohannes Kahsai who runs the electrical engineering lab as he was able to provide us with all the test equipment and lab space we needed for the project. Lastly we would like to thank our families who made this experience at Santa Clara University a reality, as for without them, we would be nowhere.

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1 Introduction

This paper will describe and outline a power factor correction device, the Dynamic Capacitor Bank, and the applications that it can be used for. The introduction will cover the problem statement and the proposed solution, and then the paper will delve into the design documentation as well as the results observed. A section for a small scale model will be discussed as well as the scalability of the product when being used in a full sized system, and the benefits that can be had from both.

1.1 Problem Statement

Over the last few decades, engineers have worked to design environmentally friendly technologies to solve problems. These designs often involve solar and nuclear power as alternatives to oil. While this is a critical step in the right direction, the new type of generation will not change the fact that there is always a losses in other parts of the overall power system. A loss of power is a big problem in high power commercial and industrial electrical systems, due to the amount of power they draw, as well as the load they are providing energy to. Seen especially significant in large varying inductive loads, such as motors in mills. The mentioned systems currently use bulky and expensive static capacitor banks to improve power factor. There is a need for improved power factor in order for companies to meet legal regulations, minimize net energy required, and relieve stress on the transmission system put in place. Raising a need for more efficient and cost effective means to further improve the power factor of the systems, specifically focusing on significantly varying inductive loads. Hence it leads to the project objective, which is to design a dynamic capacitor bank system that improves the efficiency and reduces the cost of current implementations to improve power factor on both a small- and large-scale level.

1.2 Proposed Solution

For our senior design project, we designed and created a dynamic capacitor bank system. A dynamic capacitor bank system increases the power factor of an inductive load by sensing the amount of reactive power required by the inductors in the system and compensating for with capacitors. Current technologies use static capacitors that are calculated using predicted values of inductors. The problem with using static capacitors is that a system can have massive variations in inductance, which ultimately leads to an average of a low power factor. A dynamic capacitor bank averages a higher power factor due to its ability to react to the power factor in the system at real time. The dynamic capacitor bank has the potential to greatly benefit the system, as well as reduce stress on the utilities companies providing the power. The correct amount of reactive power in a system is very important as too little reactive power will cause voltage sags, and if left unchecked can lead to voltage collapses and thus power blackouts. Equally as detrimental to the system is too much reactive power in a system, which will cause surges of currents and can damage sensitive components. The Dynamic Capacitor Bank will prevent these conditions from happening, all while saving money and energy. With the only components that need to be added to the already existing system being a microcontroller, a few relays, as well as a voltage and current sensor, the cost increase of a dynamic system versus static system will remain minimal and help improve the return on investment of the system.

1.3 Purpose

This project promoted a humane and just world as it can be applied to any electricity-producing infrastructure, such as water mills in third world countries. Implementing the technology allows the countries to extract more usable energy from the systems that they already have in place. The little energy they have is vital as it enables farming appliances and other important machinery. Along with improving people's lives, it would help increase sustainability especially in first world countries. Our device helps make current power transmission systems more efficient, and therefore decreases the amount of lost energy that comes from burning fossil fuels. Large companies in the first world take a huge toll when they use current solutions to these problems. Currently, correction devices are expensive, and the cost exceeds the amount of money lost in an inefficient system. As a result, companies have little incentive to invest in this technology. Companies have the incentive that they lose less money when they allow power to be lost, so they choose to implement the inefficient systems. Santa Clara University's engineering school has a vision that its students will be "well-equipped to face the engineering and ethical challenges of the future." We took the role of this ideal student by using our low cost design, which would allow companies to make more ethical decisions. We hope to encourage companies to choose the most sustainable technology, by designing that technology to be the most economical.

1.4 Safety Considerations

A power-correcting device like a dynamic capacitor bank provides the most efficiency increase in high power transmission. As undergraduates we were not allowed to test with high voltages; therefore, our project was within a safe range of voltages. We designed a smaller scaled version with an intention to prove that the technology could be used in the high voltage systems. Loads that are generally inductive include AC units, generators such as windmills, and industrial motors. Due to the difficulty of scaling these down, we created a model of an induction motor.

2 Design Methodology

In this section the actual ideas and implementations behind this project will be discussed in detail. The product is broken down into sensing, switching, and the microprocessor, which all have their unique value to the project. First, however, is the load, which the system was tested with. It gives insight into what to expect from a common load that the correction could be used on.

2.1 Test Load

Our power corrective device is designed to correct loads that are inductive in nature. All loads have resistive, capacitive, and inductive components to them, but we are focusing on loads that can be characterized by their resistive and inductive effects. Examples of highly inductive loads include saws, mills, motors, transformers, ac units. An interesting property of these loads is that inductance values change under certain conditions. For example, for a company that generates power, depending on the demand, there may be a huge fluctuation. We designed an inductive load with the ability to manually change its value of inductance because our system dynamically responds to changes in inductance, which we must be able to predictably change. The test load circuit can be seen in the following figure. The sinusoidal wave seen in the picture relates to a 60-Hz sinewave with 5-volts peak to peak, and no DC offset.

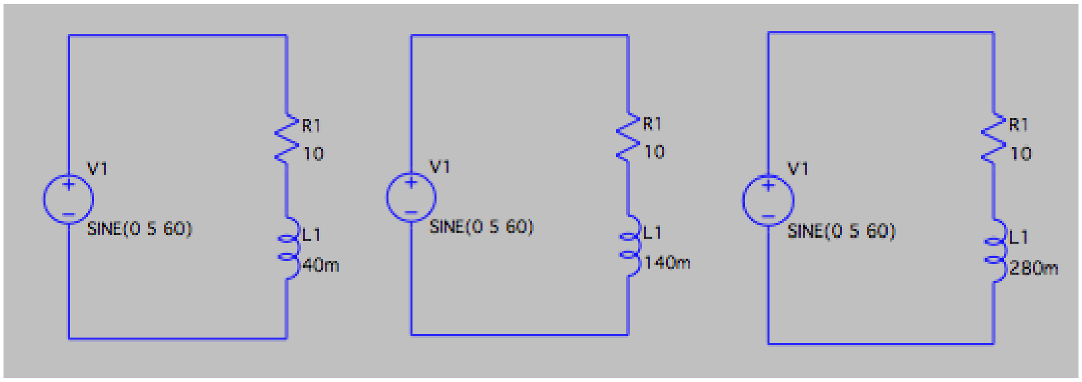

Figure 1: Three states of inductive motor model

State	Inductance	Power Factor	Capacitance Required
1	40 mH	0.66	100 uF
2	140 mH	0.24	50 uF
3	280 mH	0.125	25 uF

Table 1: Values of three states

The test load is composed of a resistor in series with three inductors, with two DPST switches separating the inductors. The test load was designed to be a simplified circuit that is electrically equivalent to a motor. A resistor was used to model the resistive effects in a motor, such as stator friction and mechanical power provided to load. To find values for components, we used MATLAB along with equations that relate inductance and resistance to power factor. We chose reasonable values for inductances of our test load, which were 40mH, 140mH, and 280mH, because along with our 10-ohm resistor, the system would perform at three distinct power factors. Using this model, we were able to have a test load with multiple cases for testing our system.

2.2 Sensing Circuit

The portion of our circuit that required the most engineering was the sensing circuit. Data from our inductive load must be sensed in the analog domain and manipulated in the digital domain in order to calculate power factor. This can be done by taking the cosine of the difference in angles between the voltage and current waveform. A more in-depth explanation of power factor can be seen in Appendix A. Once we had digital signals in the Arduino, which is a microcontroller that can compute equations and process data, we were able to calculate the points where the current and voltage signals cross the x-axis; we call these index values the zero index crossings. Once we had the zero index crossing we were able to find the phase angle between the current and voltage waveforms. Using the phase angle we were able to calculate the power factor and required capacitance for the system based off this reactive power.

2.2.1 Analog Signals

A signal conditioning circuit was used to start the sensing process. Once our signal was conditioned we were able to take the analog signals from our inductive load and translate them into the digital world that our Arduino can understand. Arduino boards have an A/D converter on board that we were able to use. The A/D converter was able to convert voltages in the range of 0 to 5 volts from the analog domain to digital. The signal coming from the motor model was between -2.5 to 2.5 volts, so our first objective was to design a circuit that conditioned our signal to fit within that range. We came up with a circuit that scaled down the voltage signal by 60% and biased it with a positive DC value of 2.5 volts. This circuit can be seen in the figure 2. Essentially, the circuit works by using a resistor divider to provide a desired biasing value. We had 5-volt supply directly from the Arduino, and we wanted a 2.5 v bias, so we chose a matched pair of large resistors to split the voltage in half; additionally, by using resistors that were large, we would have reduced power consumption due to less current pulled by the resistors. Another pair of resistors is used to scale down the signal amplitude by 60%. Again, we chose large resistors in order to reduce the pulled current and lessen the power consumption. An op-amp with its negative terminal shorted with its output give a buffer between the scaling and biasing resistor pairs. The capacitor C1 was used to filter any noise from the power supply and hold the steady bias of 2.5v. Having this op amp section was critical, as it allowed for more precise biasing.

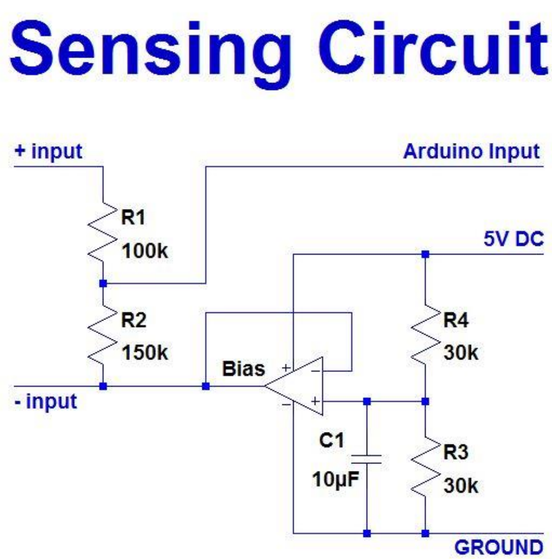

Figure 2: Voltage Sensing Circuit

Using this circuit, we successfully conditioned the signal to be in the range of the A/D converter. We designed a similar analog circuit for our current sensor, but its performance did not meet our requirements so we had to redesign our current sensor circuit. Specifically, the A/D was not precise enough. We bought a chip, the 1NA219 that had 12 bits of resolution rather than the 10 bits in our previous design. The extra two bits of resolution give us an increase of 3 times the resolution. The 1NA219 is a high side current sensor that is intended to be used at DC, but a quick inspection on its data sheet shows that there is no drop it performance for a signal at a 60Hz signal.

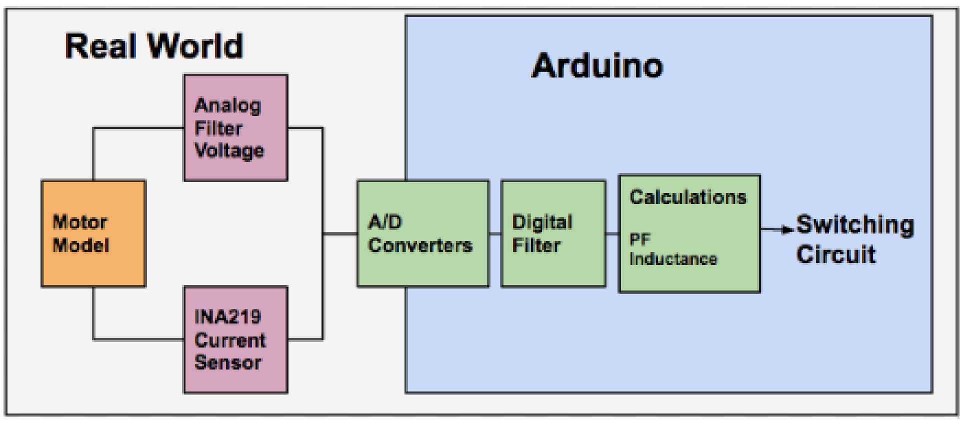

Figure 3: Block diagram for sensing

2.2.2 Digital Signals

Zero index crossings were required in order to calculate the phase angle of the signals. The algorithm depicted in the flow chart in Figure 4 describes the steps taken to find the zero index crossings.

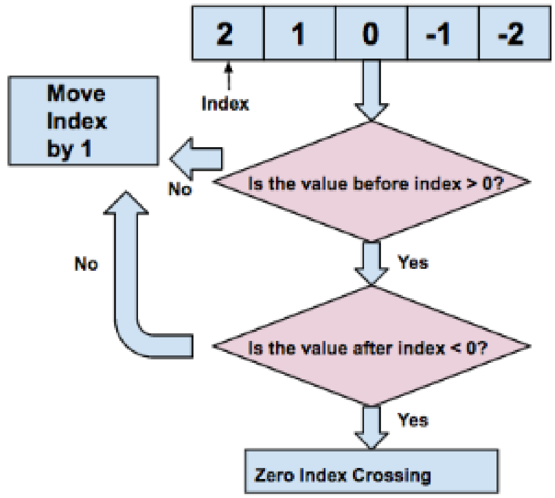

Figure 4: Zero-crossing flowchart

The algorithm starts with an array filled with values of current or voltage samples. The array is passed into the program, where it looks at the first value and sequentially checks if the previous index is positive and if the next value is negative. In a graph with an infinite number of points, this would always be a zero. If both of these statements were true, it returned the value for the zero crossing; if not, the program incremented the index and continued with the same procedure. We used our algorithm on the previous plot and we were able to find the zero crossings and calculate the current power factor. These values could be more precise; however, you can see on the plot in figure 5, the zero crossings are correctly found, but due to the amount of points per cycle, the zero crossings are not precise. In this image we can see that the values for Y are 0.25 for the voltage and 3.6 for the current. These numbers would ideally be right on the x-axis or significantly closer. In order to do find more precise values on the y-axis, we need to get more samples per cycle, this can be done a number of ways. For example, there are faster A/D converters on the market, which could give more points. Another way would be to up-sample and interpolate to give more resolution. We tested how beneficial up-sampling and interpolation would be. We found raw values from the A/D and the current sensor and plugged them into MATLAB. In Matlab, we inserted zeros between every value and ran a factor-of-two interpolator. We were able to get better values for the zero crossing in the voltage and slightly greater values for the current. If this were implemented in the microcontroller, it would be beneficial to up-sample and interpolate by slightly more.

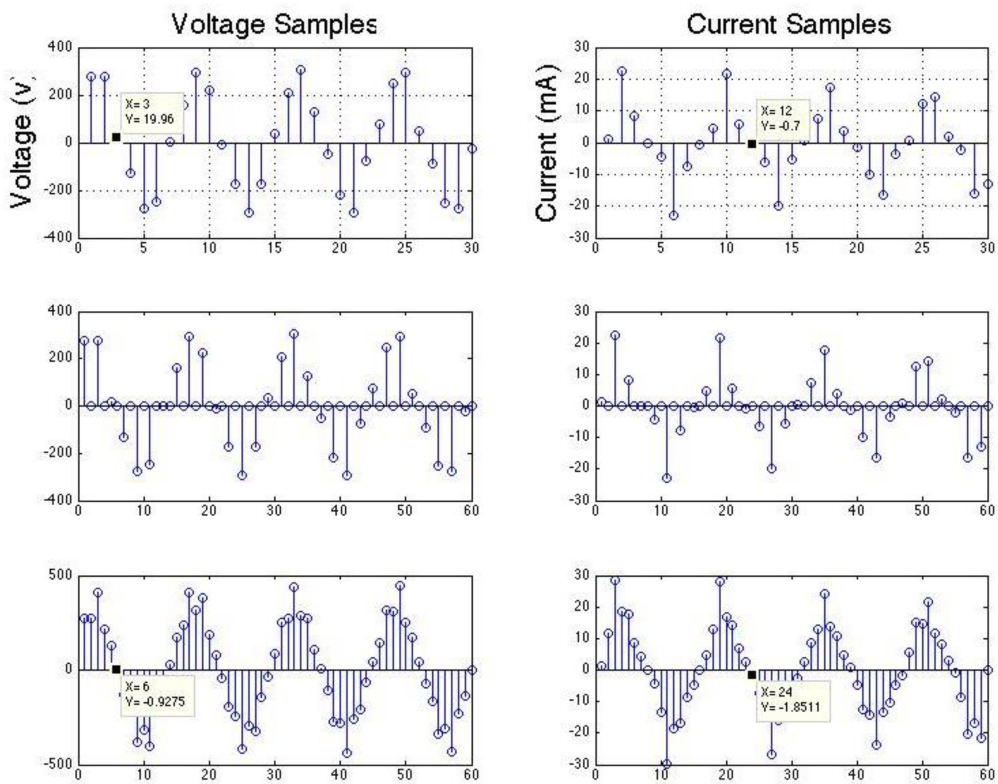

Figure 5: Zero Index Crossing Up sampled and Interpolated

2.3 Microcontroller

The brain of the project is an Arduino microcontroller. The microcontroller is critical to our project, as our circuits required, memory of past values, the ability to make speedy computations, and the flexibility to be reprogrammed for prototyping. We chose the

Arduino, because it has many resources, has an easy programming interface, and came equipped with useful components on the board such as an A/D converter.

2.3.1 Computations

The main advantage of having a microcontroller rather than using an analog circuit to do computation is that a microcontroller can provide calculations by using a single line of code and can be reprogrammed on the fly. In the appendices section A is the pseudo-code for the computations that were required by the Arduino. The Arduino was required to performed signal conversion, signal manipulation, and control of a bank. As was mentioned in the sensing portion above, the Arduino can convert 0-5 volt signals. It was mentioned that the Arduino has 10 bits of precision. This means that the signal in digital domain ranges from 0 to 1024; it then needed to be converted back into a voltage number when we analyzed it. These digital values were manipulated mathematically within the Arduino to convey the signal that was present in the test load. The Arduino must calculate an inductor value and finally a discrete number that relates to the amount of pins in the switching circuit that must be turned on.

2.3.2 Improvements

When a future group inherits this project for its senior design, it would benefit by using an FPGA (field programmable gate array), which is a highly customizable digital circuit. It has the ability to implement algorithms and is an ideal board for prototyping. If an FPGA were used, the test model could be implemented using digital switches, rather than mechanical ones. A specific section in a binary word could map to certain I/O pins that would either turn on or off multiple inductors and resistors. This would simplify the number of places where our circuit could fail, which is critical for prototyping. For our project we were limited by the speed that our A/D converters worked, because we toggled between two signals and thus divided the speed of sampling by two. In an FPGA not only would we be able to have full speed for each signal, we would not need to toggle between sampling, because we would be able to parallel process. Overall, a huge benefit would come from moving from an Arduino to an FPGA.

2.4 Switching Circuit

Connected to the load in parallel, the switching section of the circuit is what does the actual correction using the data from the microprocessor acquired by the sensing circuit. The only piece of data required is the amount of banks to activate. Through the use of pulse width modulation the gates of MOSFETs can be systematically triggered on and off as required by the system as it varies in real time. As each capacitor is switched on it helps to add reactive power to the overall system, thus allowing for the creation of the magnetic fields associated with common components in large industrial companies such as motors, transformers and relays. More precision can be added by having more banks of smaller values of capacitance. This is because it will allow for a larger range of capacitance with finer increments, meaning the desired reactive power can be correctly met. Shown below is a typical switching circuit for a 4-bank system, which was used for testing.

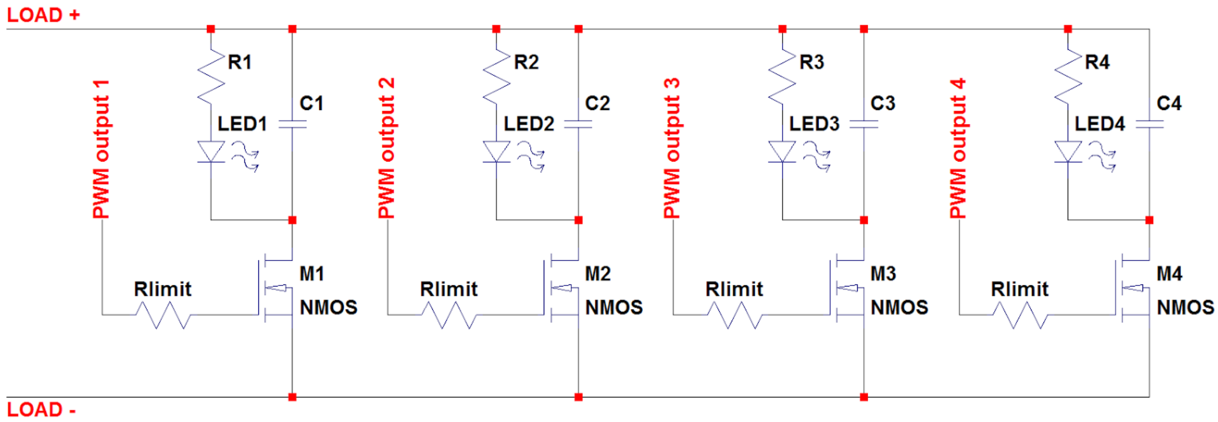

Figure 6: Switching Circuit for a 4 bank device

2.4.1 MOSFETs

The main parts of the switching circuit were the MOSFETs, which acted as voltage-triggered switches. To make it easy to control the gates, low side switching was implemented as the source can be tied to ground, meaning there is a fixed reference point. Knowing this fixed reference, as well as the voltage level outputted by the microcontroller, and the threshold voltage required to turn on the gate, the limiting resistor can be sized to allow for proper gate voltage to make sure the MOSFET is only conducting when it needs to be. MOSFETs also have the added bonus of allowing for isolation between the power electronics and sensitive microcontroller due to the gate capacitance. Since low side switching was put into place it was only natural to use N-Channel MOSFETs as they work well sourced to ground and would not have the body effect, which P-Channel MOSFETs would see. In small scale testing the PSMN1R1-30PL MOSFET from NXP was used. Some important specifications can be seen in the table below which were crucial in the decision to use such a component.

V_{DS} (Drain to source voltage)	Max 30 V
I_D (Drain current)	Max 120 A
R_{DSON} (Resistance drain to source)	Average 1.3 mΩ
V_{GS} (Threshold voltage gate to source)	Average 1.7 V
$Q_{G(tot)}$ (Total gate charge)	243 nC
t_{rr} (Reverse recovery time)	67 ns

Table 2: N-Channel specifications

Important in this table is first that the max stress the component can take is either 30 volts across it or 120 amperes through it. Due to power restrictions of the university these values will never be met, and the component will be able to handle any surges without heating up or breaking despite constant usage for however long it is plugged in. The drain to source resistance was important to minimize because more resistance means more power loss. When trying to save power with a device it would be a poor design flaw if all the power saved by adding capacitance to the system were lost due to a MOSFET with a large conduction loss. Similarly the gate charge and reverse recovery time will give critical insight into switching losses, which are minimal in this MOSFET. This was again due to the fact that more power should not be burned with the intent to actually save power and money in the end. Connected in the circuit the MOSFET is drained to the negative side of the capacitor, sourced to ground and the gate is attached to the limiting resistor which carries the pulse width modulation signal.

2.4.2 Capacitor Banks

While the switches are important the actual correction comes from the capacitor banks. The banks will vary in size depending on the system however will need certain characteristics depending on the size of the system. First and foremost they need to be able to handle the peak voltage across them plus more in case of a surge. If the capacitor is unable to handle the proper levels of voltage or current it will be detrimental to the overall system as it will heat up and possibly explode. Secondly one needs to have the correct value of capacitance to provide reactive power to the load. The equation below relates the amount of required capacitance depending on how much reactive power is in the system.

$$C = \frac{Q}{(2\pi f * V^2)} \qquad \text{(eq. 1)}$$

In the equation, reactive power (*Q*) can change and the maximum and minimum values need to be determine so that you can make the correct range and increments required. The frequency (*f*) is 60 hertz as the main application of the project is for alternating current systems in the United States, which has a strictly regulated 60-hertz signal. Lastly the voltage (*V*) is the peak-to-peak voltage of the system, which unlike the reactive power does not vary as it is a constant provided by the utilities. In the small scale model, the R60 series film capacitors from Kemet were used. This was mainly due to the fact that they were very precise with only a ±5% variation in capacitance which is very good for capacitors. As mentioned before the voltage rating is also very important, and these capacitors are rated for 40 volts of alternating current, which is plenty for testing purposes. Based on Equation 1 the capacitors were sized to be 22 micro farads; however, would need to be much larger for a real world application.

A very important part of the switching is not only the turning ***on***, but also the turning ***off***. When switched off a fully charged capacitor would be sitting on a floating node of the now open circuit MOSFET that can cause harmful results. To help keep the project safe, as well as help with debugging, an indicator LED and limiting resistor were added in parallel to each capacitor. First and foremost this LED acts as a fly-back diode. This allows for a safe means of discharge, as once the capacitor is disconnected from the load it can release all the built up energy burning it off in the resistor and LED. Besides a safe discharge the LED gives insight into what state each bank is in. Implementing a dual color LED, it allows for at higher voltages the LED to shine green. This green state means that the bank is fully charged and active. Lower voltage levels cause the diode to shine red, indicating that the bank is currently discharging or charging. Lastly at no voltage the LED does not emit light, meaning that the bank is fully off. While this charging and discharging is relatively quick and based off the time constant of the capacitor and resistor, it is noticeable to the eye and will help with debugging as it will alert you to a bank which may not be functioning as intended.

Once the banks are activated or deactivated as required, the system goes back to step one and starts to sense again, calculate, and switch the banks over and over correcting the load as long as it is connected to the system.

3 Results and Discussion

While a full-scale model would be impractical as well as unsafe to build, it was important to have some way to prove that results are possible in such a technology. In this section the small-scale model as well as the testing procedure are touched upon, giving insight into how the data were retrieved.

3.1 Small-Scale Model

For proof of concept as well as refining the idea, a small-scale model was needed. Rather than using a large system, we used a version which was scaled down by a factor of roughly 1000 for testing purposes. Below is the overall system block diagram with the actual device in the shades of blue.

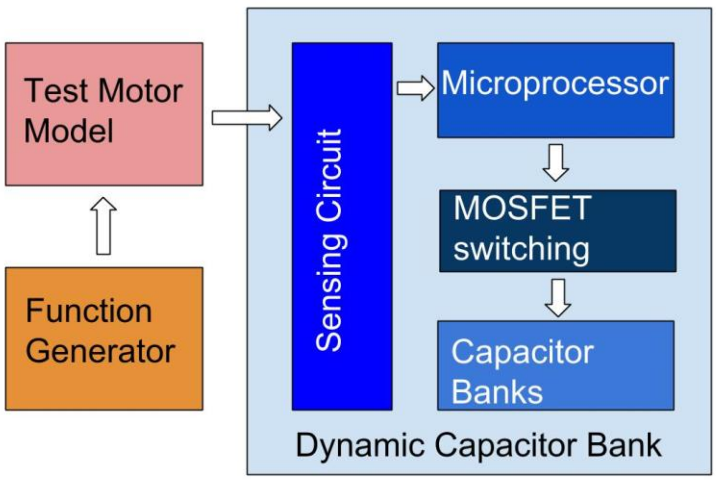

Figure 7: System block diagram

The model was just an accumulation of the previous sections, combining the switching circuit, sensing circuit and microprocessor. Once all the design changes were made to the sensing circuit, an analog waveform was sampled into the microprocessor and the wave could be recreated through the use of zero padding and interpolation. Once this new implementation was set, the zero crossing could be found more precisely. This zero crossing was important to finding the power factor because the delay between the voltage zero crossing and the current zero crossing can provide a phase difference when referenced to a 60-Hz signal. Once the phase margin has been determined, power factor is just the cosine of the angle created.

3.2 Test Procedure

Once we had our system built we had to test to verify that it was working as expected. Before we tested, we had to connect our circuits and the power supplies. The Arduino was powered by connecting it to a laptop via USB, but it has an on-board linear regulator that allowed an external battery input voltage of up 12 volts. The motor model was powered with a function generator that outputs a 5-volt peak to peak at 60 Hz signal. The MOSFETs in the switching circuit were turned on digital output pins on the Arduino. Once our circuit was powered, we had two different test methods depending on whether the signals of interest were analog or digital. If the signal of interest was analog we used an oscilloscope to probe the areas of interest that could be conveniently displayed on the oscilloscope screen. If we were looking at digital signals, we used the USB communication port on the Arduino to print values to the serial communication screen in the Arduino IDE. Once the values were printed, we could use MATLAB to analyze and plot the signals. If we were getting expected values, we would move on to test other sections of the circuit, if not we would make an adjustment and retest the circuit.

4 Scalability

The main problems of the project stemmed from the very strict power regulations that had to be met for the university. This prohibited and limited the project to simulations and small-scale models. Scaling the project up, however, is not only due to the fact that it would be easier to monitor power factor in a noninvasive way; however, it would need to be scaled up if it was ever to be put in a real system. Instead of using a test case of 5 volts peak to peak of alternating current signal, it would need to be scaled up at least one hundred fold to be even feasible to save money because only large industrial companies, those whose systems exceed 20 kilowatts, get charged fines and fees for peak reactive power as well as get charged for the total apparent power in the system rather than just the real power as seen in a residential energy bill. While the prototype needs more work before it is ready to be scaled, it is important to look into the financial feasibility of scaling.

4.1 Return on Investment

The main information a company wants to know is the return on investment, or ROI, of the system. This will let it know how long it will take for a product to pay for itself and how long its overall lifespan is so it can know how much profit to expect. Looking at two different test cases we will see how the effect of such a system could assist these companies. In these calculations we will be using a target power factor of 0.95 which is a very competitive result.

4.1.1 Case 1: 400 kW, 333 kVAR, Power Factor = 0.77

The first case would be a rather large industrial company whose system is 400 kW of peak real power and 333-kVAR of peak reactive power. These two levels will cause a power factor of 0.77, which is common; however, could be raised to something much better. First and foremost the initial cost of the system needs to be solved for. Obviously this varies depending on how large of a system is being correcting; however, based on research into different sized capacitors the price can be estimated at $35 per kVAR of correction. On top of this we also allotted $2000 for the microcontroller and switches, as well as the board, which will bring all the components together. This would make the following equation, which can be used for any system to find the rough cost expectation.

$$Cost = \$(2000 + (kVAR) * 35) \quad \text{(eq. 2)}$$

Using this equation as well as the value of peak reactive power the cost to install the system came out to be $13,655. Now the savings per year must be evaluated to know how many years it takes for the system to pay back. These large industrial companies are charged fees and fines for peak reactive power each month. The following equation takes the amount of kVAR saved and multiplies it with the fee per kVAR and months in a year to find yearly savings from reducing peak kVAR in the system.

$$Savings_{Fees} = \$(1.50 * (kVAR) * 12) \quad \text{(eq. 3)}$$

Applying Equation 3 to this test case leads to \$3600 saved each year. Besides just reduce fees the company will also use less power. By correcting the power factor there is a reduction of overall loses in the system. The amount of dollars saved from this reduction of energy can be seen in equation 4.

$$Savings_{Energy} = \$((kW)\left(1-\left(\frac{PF\ Old}{PF\ New}\right)^2\right)(0.05)(0.10)(8760)) \qquad \text{(eq. 4)}$$

The 0.05 comes from 5% losses assumed in the system, the 0.10 comes from the average of 10 cents per kWh charge, and 8760 comes from the amount of hours per year. When applying Equation 4 to this test case it is seen that \$6010 could be saved yearly. This savings can not only be looked at as a finical gain but also an environmental one as it means that 45 tons of CO_2 will be saved each year due to the reduction of kWh burned. This reduction of 45 tons of CO_2 would be the equivalent of planting 1000 trees and letting them grow for 10 years, which is rather substantial if this is just for one company over one year. Lastly to find return on investment, the cost of the system must be divided by the total yearly savings. In this case it would be 13,655 / (6,010+3,600) = 1.42 years to pay back the investment.

4.1.2 Case 2: 50 kW, 100 kVAR, Power Factor = 0.45

The second case is a smaller company that has an overall lower peak reactive power, but a much lower power factor. Using Equation 2 we can find the system to cost \$5,500. We are able to find the total savings per year to be \$3,230 from adding equation 3 to equation 4. Based off this initial cost and savings per year we can find the payback time to be 1.7 years.

4.2 Benefits of Larger Scale

The small scale models led to more problems as certain techniques to sense current and voltage could not be used. In larger systems non-intrusive methods such as the Hull effect could be used. The Hull effect is a ferrite ring which wraps around the power wire going into the system and based off the magnetic fields can determine the current without adjusting or impairing it. Instead of this method, the small scale model had to implement high side current sensing through the use of a precision resistor, which inherently adjusts the power factor. In a larger scale model we could also tap one of the inductors with another inductor, thus allowing to step down the high voltages to a manageable level. Once this lower level is obtained the microprocessor can actually read it, rather than using a resistive power divider which is inefficient and causes too much loss for the benefit it adds. With increased currents and voltage levels the system will be less susceptible to noise as the noise will be incredibly small compared to the signal. This is different from the small scale model where the original analog current filter we had produced noise roughly the same size as the current signals as they were all in the low milliampere range. As mentioned before in the bank section of the paper, an extended bank could allow for not only a larger range of capacitance but also more fine-tuned precision. This could cause some problems as it means there is a need to find smaller values of capacitors, however, that have large ratings for maximum voltages and currents. This will most likely limit how exact the correction can be; however, with already existing components the desired level of a 0.95 power factor should be feasible in most to all systems.

5 Ethical Analysis

The Markkula Center for Applied Ethics asks the question, “is more good done than harm?” which is an important first question to ask when pertaining to ethics. Based on what was stated in the introduction it would be a benefit for both the user who has a varying inductive load, as well as the utilities company who is providing the electricity. If the user is being charged for apparent power this solution will give him or her a direct cost reduction due to the fact he or she draws less current because they do not overdraw and wash back current in the form of reactive power. The fact he or she does not wash back this current is also a win for the utilities company who do not need to generate and transmit as much power overall, meaning its already near max capacity system can get a buffer of available system capacity. It has been seen in the past what happens when transmission systems have too much current and wires overheat and start to sag. A specific case was during 2003 when on a hot day many people all turned on their air conditioning (heavy inductive load) and the lines started to heat up, sagged, and hit a tree. This caused a massive power outage which effected upwards of 55 million people between Canada and the United States.

The Markkula Center for Applied Ethics also asks “Does the action promote the welfare of everyone?” which has a two part answer. First and foremost the project is intended to help keep the current power system working as intended. With the goal to optimize it, making sure electricity is still available to all who wish to take advantage of it. More important; however, is the people who directly come into contact with it. Part of the elegance of the design is that it is supposed to be a backend solution with minimal human interfacing; however, the setup and upkeep will require some interaction. Working with power, the main concern is to keep people safe. This is why safety measures will be taken seriously, so that setup is safe and easy for the person who has to install and maintain the system. One of the goals is for people to not know it is even working, but help keep life going as they know it, while keeping the people who know what is happening safe.

The last question posed is that of “Are the actions consistent with morals?” which is a harder question to address due to the varying definition of moral standards. It is usually said that being moral is to do good if you can. The project used our skills of control and power systems to create something which can improve and make a current system more efficient. While it is not directly saving lives or curing sickness, due to the lack of negatives or potential to be used for cynical purposes it is safe to say it is both an ethical and moral solution to a seen problem. All in all we hoped for a solution that is unobtrusive, safe, and elegant to help reduce the likelihood of voltage collapses and other detrimental side effects from having the incorrect amount of reactive power in a system. This is because prevention is much better than reaction due to the fact you do not have to wait for disaster to be motivated to find a solution. With safety a main concern, all parties involved can rest easy knowing they are not only benefiting from the system but knowing they will be safe while installing and maintaining it.

6 References

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7 Appendices

Appendix A: Power Factor Relationships

To understand our project in detail, a few key concepts are fundamental to the project. First concept is that there are 3 different types of power that all have their unique properties. First is "real power," represented by the letter P, which is the power that is actually being consumed by the load. Real power is also sometimes referred to as active power. Reactive power, represented with the letter Q, is the power required to create the magnetic fields associated with many different circuit components such as transformers, inductors and relays. The final part of the power triangle is apparent power, represented with an S. Apparent power is the total power that needs to be provided to the system, and it is a Pythagorean combination of both real and reactive power.

$$S^2 = Q^2 + P^2 \quad \text{(eq. 5)}$$

The angle that is created between the real and apparent power is called the phase angle, represented with the symbol theta, and it gives important insight into the difference between the voltage and current waveforms. This angle can then be used to find power factor, which is the ratio of real to apparent power in the system and helps quantify the performance of the system.

$$\theta = \tan(\frac{Q}{P}) \quad \text{(eq. 6)}$$

$$Pf = \cos(\theta) \quad \text{(eq. 7)}$$

Appendix B: Terminology and Abbreviations

PF: Power factor, the ratio of real to apparent power

Real Power (*P*): The actual power required to power the load

kW: Kilowatt, the measurement of real power

Apparent Power (*S*): The total power provided to the system

kVA: Kilovolt-ampere, the measurement of apparent power

Reactive Power (*Q*): The power required to create magnetic fields in certain components such as inductors, transformers, motors, and relays.

kVAR: Kilovolt-ampere reactive, the measure of reactive power

A to D: Analog to digital converter, sometimes referred to as an A/D or ADC

FPGA: Field programmable gate array, a highly customizable digital circuit

Arduino: Microprocessor that runs commands in a linear fashion

Appendix C: Arduino Code

```
#define samplesInCycle 30
#define pi 3.1415

#include <Wire.h>
#include <Adafruit_INA219.h>

int vSensePin = 0; //the pin

float averageV = 0;

Adafruit_INA219 ina219;

void setup() {

 uint32_t currentFrequency;

 Serial.begin(115200);
 pinMode(0, INPUT); //Voltage sensing input

 ina219.begin();

 delay(1000);

}

void loop(){
float iSamples[samplesInCycle];  //This is ment to hold a couple cycles of a 60Hz wave
from the sensor
float vSamples[samplesInCycle];  //To find this value we need to find the amount of
float filteredV[samplesInCycle]; //Stores the voltage signal after the bias is removed


int index = 0;
int printin = 0;
int i = 0;
int n = 0;
float sumV = 0;
int calcAverage = 0; //Will calculate an average when this is at zero. There average only
needs to be taken once
int zeroIndexVoltage = -1;
int zeroIndexCurrent = -1;
```

```
float phase = -1;
float pf = -1;
float current_mA = 0; //

delay(1000);
//Fills array with values, does ADC toggles between voltage and current
for(index = 0; index <samplesInCycle; index++){
  vSamples[index] = analogRead(vSensePin);
  iSamples[index] = ina219.getCurrent_mA();
}


//Find the sum of the samples
index = 0;

for(index = 0; index <=samplesInCycle; index ++){
 sumV = vSamples[index] + sumV;          //Running sum for voltage
}

  while(calcAverage == 0){
  averageV = average(sumV);
  calcAverage = 1;
  }

  for(i=0; i<samplesInCycle ; i++){ //Calculates the sum of all the values filtered from the
offset and in a voltage
  filteredV[i]= (vSamples[i] - averageV);
  }

   //Find zerocrossing for voltage
   n = 0;
  for(n=0; n < (samplesInCycle-2) ; n++){
    if( filteredV[n] > 0 && filteredV[n+2]<0) {
      zeroIndexVoltage = n+1;
      break;
    }
  }
  //Find zerocrossing for current
  n = 0;
  for(n=0;n < (samplesInCycle-2) ; n++){
    if( iSamples[n] > 0 && iSamples[n+2]<0) {
      zeroIndexCurrent = n+1;
      break;
```

```
    }
  }

   phase = findPhase(zeroIndexVoltage, zeroIndexCurrent);

   pf = findpf(phase);

 ////////////////////PRINTING SECTION////////////////////////////
  //Prints the Unfiltered output voltage
  printin = 0;
  for(printin = 0; printin <samplesInCycle; printin ++){
  Serial.print(filteredV[printin]);
  Serial.print(' ');
  }

  Serial.println(" "); //Space between voltage and current values

 //Prints the unfiltered output current
  printin = 0;
  for(printin = 0; printin <samplesInCycle; printin ++){
  Serial.print(iSamples[printin]);
  Serial.print(' ');
  }

delay(100);

/*
 //////////////////////////////PRINTING SECTION//////////////////////////////
  //Prints the filtered output voltage
  printin = 0;
  for(printin = 0; printin <samplesInCycle; printin ++){
  Serial.print(filteredV[printin]);
  Serial.print(' ');
  }

  Serial.println(" "); //Space between voltage and current values

 //Prints the unfiltered output current
  printin = 0;
  for(printin = 0; printin <samplesInCycle; printin ++){
  Serial.print(filteredI[printin]);
  Serial.print(' ');
  }
```

```
delay(100);

  Serial.println("Voltage Crossing Index \n");
  Serial.print(zeroIndexVoltage);
  Serial.println(" "); */

delay(100000);
index = 0;
}



//FUNCTIONS

float average(float sum){
  float average = sum/(samplesInCycle);
return average;
}


float findPhase(int zeroIndexVoltage, int zeroIndexCurrent){ //Using the zero index
crossings we can calculate the phase
  float samplingFreqI = 540;
  float samplingFreqV = 540;
  float sampleDelay = ((zeroIndexVoltage/samplingFreqV) -
(zeroIndexCurrent/samplingFreqI)); //What if current leads voltage
  float phase = 2*pi*60*sampleDelay;

  return phase;
}

float findpf(float phase){  //Calculates the power factor from the phase
   float pf = cos(phase);
   return pf;
}
```

Appendix D: Relevant Datasheet Sections

www.ti.com SBOS448F – AUGUST 2008 – REVISED SEPTEMBER 2011

Zerø-Drift, Bi-Directional CURRENT/POWER MONITOR with I²C™ Interface

Check for Samples: INA219

FEATURES

- SENSES BUS VOLTAGES FROM 0V TO +26V
- REPORTS CURRENT, VOLTAGE, AND POWER
- 16 PROGRAMMABLE ADDRESSES
- HIGH ACCURACY: 0.5% (Max) OVER TEMPERATURE (INA219B)
- FILTERING OPTIONS
- CALIBRATION REGISTERS
- SOT23-8 AND SO-8 PACKAGES

APPLICATIONS

- SERVERS
- TELECOM EQUIPMENT
- NOTEBOOK COMPUTERS
- POWER MANAGEMENT
- BATTERY CHARGERS
- WELDING EQUIPMENT
- POWER SUPPLIES
- TEST EQUIPMENT

DESCRIPTION

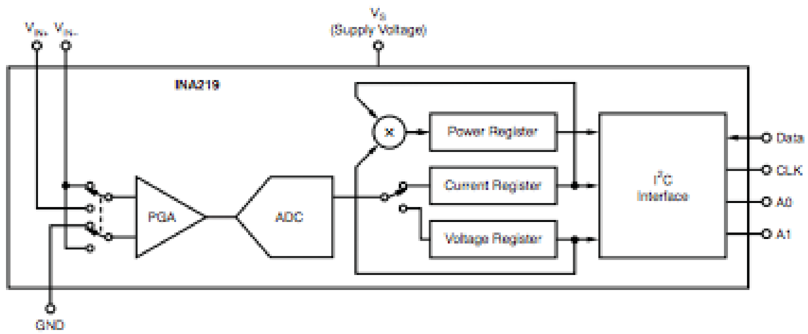
The INA219 is a high-side current shunt and power monitor with an I²C interface. The INA219 monitors both shunt drop and supply voltage, with programmable conversion times and filtering. A programmable calibration value, combined with an internal multiplier, enables direct readouts in amperes. An additional multiplying register calculates power in watts. The I²C interface features 16 programmable addresses.

The INA219 is available in two grades: A and B. The B grade version has higher accuracy and higher precision specifications.

The INA219 senses across shunts on buses that can vary from 0V to 26V. The device uses a single +3V to +5.5V supply, drawing a maximum of 1mA of supply current. The INA219 operates from –40°C to +125°C.

RELATED PRODUCTS

DESCRIPTION	DEVICE
Current/Power Monitor with Watchdog, Peak-Hold, and Fast Comparator Functions	INA209
Zerø-Drift, Low-Cost, Analog Current Shunt Monitor Series in Small Package	INA210, INA211, INA212, INA213, INA214



TYPICAL CHARACTERISTICS

At T_A = +25°C, V_{IN+} = 12V, V_{SENSE} = (V_{IN+} – V_{IN-}) = 32mV, PGA = ÷ 1, and BRNG = 1, unless otherwise noted.

FREQUENCY RESPONSE

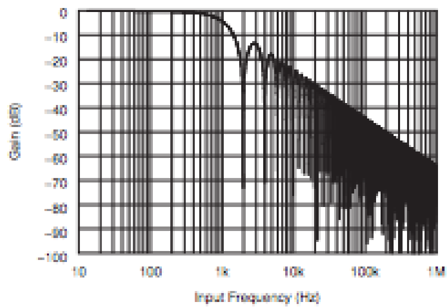


Figure 1.

ADC SHUNT OFFSET vs TEMPERATURE

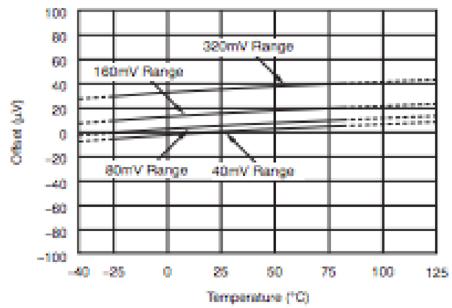


Figure 2.

ADC SHUNT GAIN ERROR vs TEMPERATURE

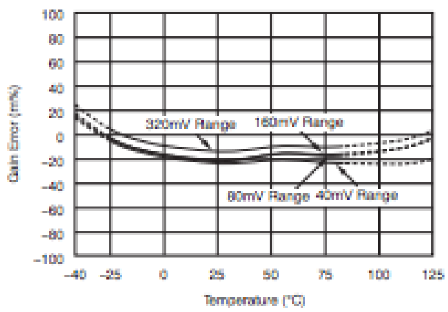


Figure 3.

ADC BUS VOLTAGE OFFSET vs TEMPERATURE

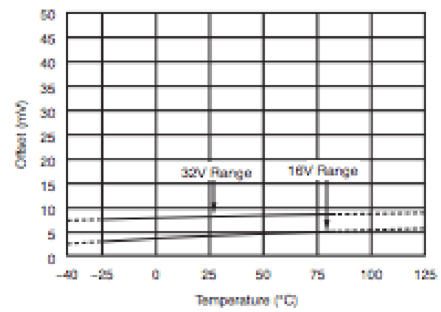


Figure 4.

ADC BUS GAIN ERROR vs TEMPERATURE

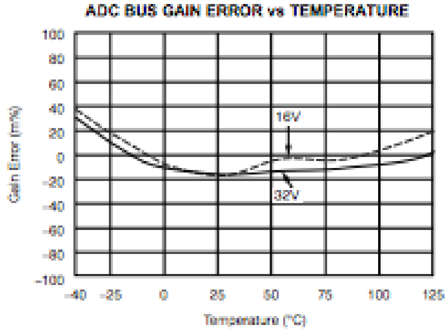


Figure 5.

INTEGRAL NONLINEARITY vs INPUT VOLTAGE

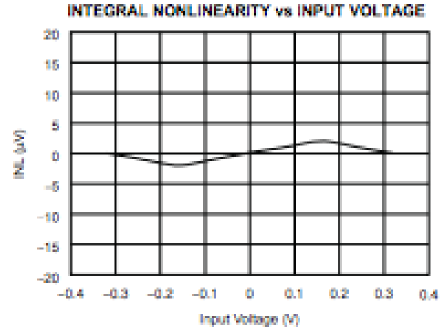
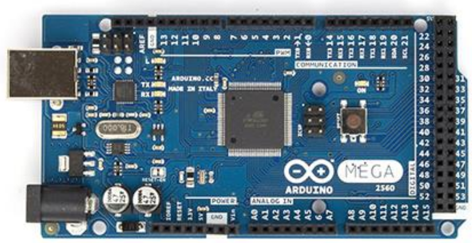
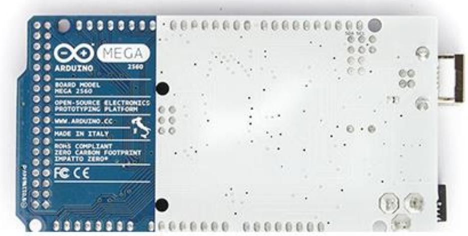


Figure 6.

Arduino Mega 2560



Arduino Mega 2560 R3 Front



Arduino Mega2560 R3 Back

Summary

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz