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GRADO INGENIERIA ELECTROMECANICA

Smart Power Factor Corrector

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Resumen

El mercado está siempre en continuo desarrollo. Según la tecnología ha ido avanzando, hay un mercado muy importante que ha surgido como consecuencia, el mercado de la eficiencia. El consumidor está siempre deseando obtener más de su inversión, maximizar la eficiencia de su dinero. Así que partiendo de esta idea, de esta oportunidad de mercado, surgió la idea de trabajar en este concepto en relación con el mercado eléctrico.

Se decidió que la mejor manera de mejorar el consume de energía eléctrica era compensando la energía reactiva. Este concepto no es nuevo, puesto que la idea es usada de manera habitual en la industria o grandes consumes, pero los pequeños consumidores no se benefician de ella.

El Corrector Inteligente del Factor de Potencia ayuda a ahorrar energía compensando la energía reactiva no necesitada por los aparatos de utilización domestica . Según la sociedad ha ido avanzando, los ahorros y la eficiencia han llegado a ser considerados como parte del mercado de la investigación dentro del sector tecnológico, por lo que aparatos que optimizan la transferencia y el consume de energía están adquiriendo gran importancia.

El Corrector Inteligente del Factor de Potencia corrige de manera constante el factor de potencia de los consumos domésticos, por lo que el consume de corriente esta optimizado en todo momento. El aparato esta preparado para trabajar con un amplio abanico de consumos, siempre buscando optimizar su eficiencia

El Corrector Inteligente del Factor de Potencia consiste en sensores que recolectan información desde la línea del consume para así determinar el factor de potencia y el pico de potencia que es consumido en cada momento. La información es procesada por el micro controlador que calcula el factor de potencia y la cantidad de energía reactiva que es consumida. Usando estos valores calculados, el micro controlador controla los interruptores conectados al banco de condensadores que conecta tantos capacitor como sean necesarios para corregir el factor de potencia.

El Corrector Inteligente del Factor de Potencia se actualiza cada segundo para garantizar la máxima eficiencia. El dispositivo será capaz de enviar la información vía wireless a una dirección IP y así permitir al usuario monitorizar el trabajo del dispositivo. El progreso del dispositivo consiste en corregir el factor de potencia, escribir el código, hacer que cada subsistema funcione y combinar los distintos subsistema.

Abstract

The market is in continuous development. As the technology advances, there is a huge market gap that has been created, the market of the efficiency. The costumer is always willing to maximize the efficiency that they have with their money. So taking advantage of this idea, it came out the idea of working on this concept in relation with the electrical market.

It was decided that the better way to improve the consumption of electrical energy was by compensating reactive energy. This is not a new idea, but it is an idea that it is currently used in any industry and that the small consumers are not taking advantage of.

The Smart Power Factor Corrector device helps saving energy by eliminating reactive power in household appliances. As society advances, the savings and the efficiency are being considered as part of the market research of the technology sector, so devices that optimize energy transfer are becoming more relevant.

The device constantly corrects the power factor of household loads so that the current drawn by the system is optimized at every moment. This device is ready to work on a wide range of appliances, always attempting to improve its efficiency.

The device consists on sensors that collect data from the main power line to determine the power factor and the peak power being consumed at each moment. This information is processed by the microcontroller that calculates the power factor and the amount of reactive power being consumed. Using these calculated values, the microcontroller controls switches connected to a bank of capacitors to connect as many capacitors as needed to correct the power factor.

The device will update every second to ensure maximum power efficiency. The device will be able to send data wirelessly to an IP address and allow the user to monitor the device's work. The progress so far consists on: power factor correction testing, software coding, getting every subsystem to work, and we are currently combining all subsystems together.

Documento I: Memoria

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1. Introduction

1.1. Background

Currently there is a large amount of effort being put towards research relating to sustainable energy. Companies are constantly adapting themselves to the always changing market force and its tendency. Through the aid of science, we develop different ways to produce energy and use different sources of consumptions, like solar panels or electric cars. So the current market is improving the way of producing energy, but what can be improved in the consumption of the energy?

The first publications on economic efficiency of reactive power compensation appeared in the third decade of the 20th century. Reactive power compensation is mainly used in power distribution networks, for reducing energy losses, improving voltage profile in medium and low voltage networks, and improving reactive power balance in 110 kV distribution network. It is very commonly used in the industrial areas, places where they have high consumptions of energy, and as result they are charged for this reactive energy.

However, can you imagine bringing some of those advantages to the low voltage network? The fact of using AC electric energy implies that to different kind of energies are consumed by the devices, active and reactive energy. The active energy is the part of the energy that is related with the transformation of the electrical energy in heat, mechanical energy… but the reactive energy is related with the electromagnetic fields, and is the base of the way electrical engines work. But we produce more reactive energy than it is necessary.

The reactive power is not the main power used by these devices. Some technologies have been developed in order to solve this problem, as for example, static VAR compensators employing thyristor switched capacitors and thyristor controlled reactors to provide or absorb the required reactive power.

Correcting this reactive power is done easily by connecting capacitors in parallel with the load. Capacitors are most frequently installed in:

1. High voltage/medium voltage (HV/MV) stations, being the main Feeding Point (MFP) of the medium voltage network, as can be seen in (Figure 1).

2. Network switchboards (NS).

3. Medium voltage/low voltage (MV/LV) stations on the low voltage terminals of transformer.

4. Industries with high consumptions in order to decrease the reactive energy consumed and not being penalized by the electrical companies.

Figure 1- Capacitors being used to correct the power factor in industries

The power factor is an electric load parameter that is used for defining explicit ratio between active and reactive power. Power factor in Low Voltage (LV) networks range from 0.6 during the summer nights (load minimum) to 0.9-0.95 during the winter evenings, when the load is at a maximum. During wintertime, there is an increase of reactive power loads due to the high usage of heating devices. Power line losses directly depend on load as a function of time (daytime and season). [1] We have talked about how power factor works and how we are wasting energy when the power factor is not being corrected. Every household generates reactive power, and most of the time, they are producing more reactive power than needed. Our device is designed to compensate the amount of reactive power generated in household appliances. The aim is to focus on fixing the power factor from appliances that generates the most reactive power in the house, like refrigerators or air conditioners.

Figure 2 shows how 65.5% of the energy being used is from controlling the temperature of the house. 17.7% of energy consumption is from heating water and another 6.2% is for cooling areas in the house from the air conditioner. This shows the importance of improving the efficiency of all the devices whose aim is to produce heat in our houses. That data represents that we can work with the half electrical consumption of the house using the Smart power factor corrector in certain devices, because heating and cooling are responsible for most of the energy consumptions in homes.

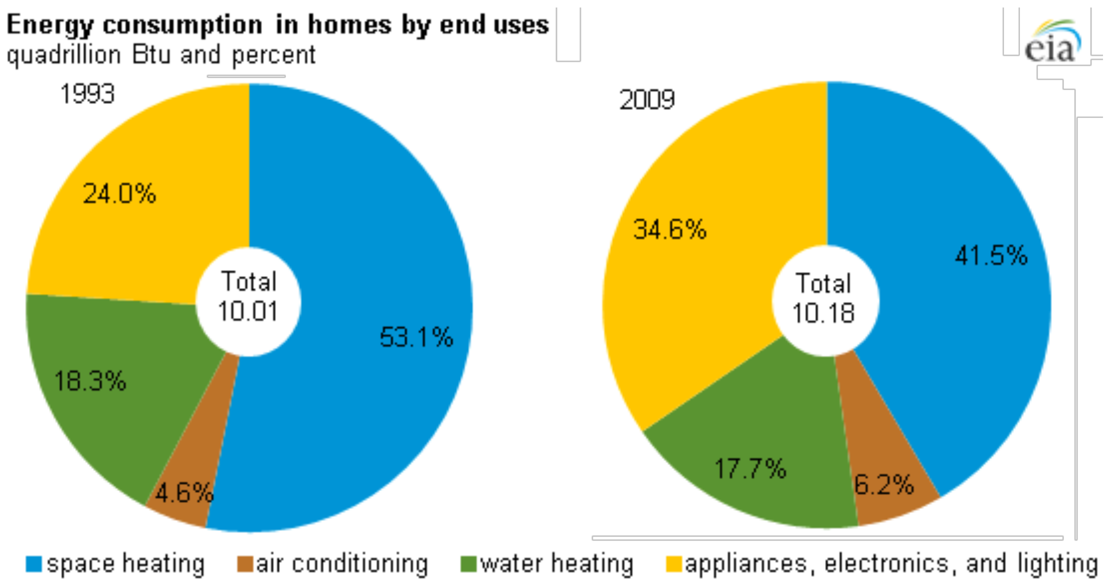

Figure 2-Utility Bill Cost Breakdown

There are also some other devices in which the improvement of the power factor can imply an improvement in the efficiency decreasing the losses. These devices are those who work thanks to electrical motors, such as the refrigerator, whose way of working is based on the pressure of an specific fluid controlled by an electrical motor.

Measured and quantified evaluations performed in power network and using the described reactive power compensating method in the depth of LV feeder indicate that losses caused by the reactive power are around 8 % of all technical losses in middle and low voltage network. The same losses in low voltage networks are even around 18 %. [1]

By correcting the power factor, we can obtain some relevant improvements in our electric circuit, for example:

- The closer the power factor is towards the unity power factor then current decreases.
- Drawing less current will lead to fewer losses due to thermal heating in transmission lines.
- This will lead to less stress on the materials and less power used.

After all, the aim of this project is very clear, fewer losses mean more efficiency and less current means less cost on materials. The result is increased savings that translates into less expenditure.

1.2. Purpose

The consumption of energy is part of the day by day house economy. Lots of ideas have emerged with the aim of saving money in utilities' bills. The smart power factor corrector can help the consumer by saving them money in household energy costs. It is also applicable to bigger consumptions, such as factories and commercial establishments.

The Smart Power Factor corrector will be focused on the common devices of our houses that consume reactive power such as air conditioners and refrigerators, reducing this reactive power and decreasing the losses, which implies savings for consumer.

1.3. Literature Review

i. Prior Work

The reactive energy is a really common subject when we talk about electricity. It is a problem that, since the use of electrical motors, engineers have tried to solve. In order to save money (saving energy) and to avoid overloads in the processing and generating lines, different ways of compensating the reactive power has been created. Most of these ways are based around using capacitors.

The reactive power is compensated in all factories, making these factories more efficient. The problem of the reactive power appears with one-phase systems and with three- phase systems. The market contains plenty of devices to correct the reactive power for one- phase or three phase systems. Most of the products on the market focus the correction in putting in parallel capacitors big enough to compensate an averaged amount of reactive power. The construction of the device changes between one-phase and three-phase systems, but the concept is the same. So these products are separated in two types, products designed for variable correction and products designed for fixed correction. The product has to be able to manage a specific voltage and current, and deal with overvoltages and overcurrents.

The different products for correcting reactive energy can be used for global compensation, partial compensation and individual compensation. One example of the products of the market for low voltage networks are the capacitors VarPlusCan (Figure 3) (fixed compensation) and VarPlusBox (Figure 4) (variable compensation), built by Schneider Electric. Both of them are built for three-phase systems. Schneider Electric Company recommends using fixed correction in those installations in which the reactive power does not exceed the 15% of the nominal power of the transformer, and variable correction if this reactive power overcomes the 15% of the nominal power of the transformer [2]. But these considerations would affect if our device were built for industries or high consumptions such as hotels.

Also, Eaton Powering Business Worldwide currently produces a product that corrects power factor using shunting capacitors. Unlike our project, Eaton provides power factor correction for industrial purposes that draw a high amount of power. They also do not provide a constantly updating system so the power factor can fluctuate with time. Our system will be similar to the one Eaton manufacturer's [3] but it would be on a smaller scale and be able to keep the power factor more constant. This solution of using corrective capacitors seems to be the most used and practical way to correct power factor.

Figure 3-Varplus Can Capacitors (Schneider Electrics)

Figure 4-Varplus Box Capacitors (Schneider Electrics)

ii. Patents

Three different patents have been identified related with reactive power and the power factor correction

1. Patent of ENDESA ENERGÍA, S.A.U., company from Spain that works in the electrical market. Inventor: AGRELO REGUEIRA, Juan Luis

This patent describes a device destined for low consumptions, consumptions below 15 kW. The device is designed for a global compensation of the reactive power. It would measure the power factor in the circuit breaker box, and a signal would be sent to a device connected to an electric outlet via PLC (power line communications) or RF radiofrequency. [4]

2. Reactive power compensation control system, United States Patent 3754184. Inventor: STONE, David W

This patent is designed for three-phase systems. It is designed for dynamic loads. A bank of capacitors is connected in parallel with the load, and a control circuit controls the connections. [5]

3. Reactive power compensation to minimize step voltage changes and transients, United States Patent 06900619. Inventors: Arnold P Kehrli, John A Diaz De Leon II, Douglas C Folts

This patent consists on a device that corrects a quantity of reactive power, measuring it each second, and using a controller switch to correct the reactive power [6]

iii. Relevant Codes and Standards

Relevant codes and standards should be accomplished in order to develop our project. Some of the most important are: IEEE Standard C37.26 and IEEE Standards 1459-2000. The first one consists of describing three methods to measure the power factor of inductive low-voltages, the methods could be used at any frequency and basically they are Ratio Method, DC decrement method and Phase relationship method (this is the one that is going to be used). The second standard breaks the power measurements into components that can characterize three things: the useful real power delivered to the load, the reactive power that can be compensated with conventional power factor correction, and the power components that require other methods of compensation (such as active filters).

· IEEE Standard 802.11, 2007-Wireless [7]

o Standard for Information Technology which states that our devices must operate in a 2.4 GHz ISM band and have a maximum data transfer rate of 600 Mbits/s.

· IEEE Standards 1-2000 [8]

o -General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation

· IEEE Standards 18-2012 [9]

· Power capacitors rated 216 V or higher, 2.5 kVAR or more, and designed for shunt connection to alternating-current transmission and distribution systems operating at a nominal frequency of 50 Hz or 60 Hz, are considered.

· IEEE Standards 1459-2000 [10]

o Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions

· IEEE Standard C37.26 [11]

o IEEE Guide for Methods of Power Factor Measurement for Low-Voltage Inductive Test Circuits [2]

· IEEE Standard C37.99 [12]

o IEEE Guide for the Protection of Shunt Capacitor Banks

2. Problem Definition

2.1. Problem Statement

Reactive power is only necessary in small amounts for household appliances. Lower power factors can dramatically increase the required current being consumed by an appliance to work correctly. As an example, correcting from a .6 power factor to a power factor of .85, will save up to 28% in current drawn.

From equations related with electrical energy, it is known that the apparent energy, measure in volt-amps (VA), is:

$$S = V \cdot I^{*}$$

Having AC current implies that the current and the voltage have their own phases. The reactive power is created when the current and the voltage are not in phase. So by correcting the power factor what we are really doing is reducing the diphase between the two waves.

The following equation can be used to calculate the amount of reactive power that is wanted to be produced by the bank of capacitors connected in parallel to the load:

$$\mathrm{P} \cdot \left(\tan\left((\varphi_{v} - \varphi_{i})\right) - \tan\left((\varphi_{v} - \varphi_{i})'\right)\right) = \mathrm{Qc}$$

$^{\varphi}$v is the angle of the voltage signal. $^{\varphi}$i is the angle of the current signal.

Where Qc is the reactive power the capacitor must provide; and $(\varphi_v - \varphi_i)'$ is the angle we want for the power factor once it is corrected. P is the power being delivered to the load.

This can lead to an estimated 15% cost reduction for wiring materials in a typical construction of a house. This can lead to savings of over $1000 for the materials costs in the wiring of a house. Depending on the voltage of the output, the power factor will be worst, as the voltage is greater. In our case, we are working with US networks that work with 120 V and 60 Hz of frequency.

Knowing that the resistance of a capacitance is dependable on the frequency, it is known that the capacitance needed to correct a certain amount of reactive power is:

$$C = \frac{Qc}{V^2 \cdot 2\pi \cdot f}$$

C is defined as the capacitance, V is defined as the voltage, and f is defined as the frequency. Qc is the reactive power the capacitor provides.

2.2. Project Requirements

The Smart Power Factor Corrector is a device whose main objective is to compensate reactive energy. In order to accomplish this objective, the requirements to accomplish are the next followings:

· The Smart Power Factor Corrector is a single-phase device. It is designed for low voltage networks, such as houses (120 V, 60 Hz). This is the reason that our device should be able to operate with single-phase voltage, in the case of USA 120 V.

· The Power factor corrector should be able to work at least with 10A. This is the amount of Amps usually required to work with low voltage motor.

· Since the voltage is 120V and the amps are 10A, the maximum amount of complex power which the device will have to work with is 1200VA.

· The device should be able to work providing an individual compensation to the load to which it is connected, such as refrigerators or other common consumptions.

· The Smart Power Factor Corrector has been designed for the use on household devices, mainly focusing on devices that have low power factors (0.6-0.8) and electrical motors, such as the refrigerator or the air conditioner. Then the device will have to be able to correct the power factor from 0.6 to 0.92.

· In order to make easy the transportation and to make possible put it in small places the maximum size of the metal box should be 1.5' x 1.0' x 0.5'.

· Since the idea is to always keep the amount of reactive power the more efficient as possible the corrections to the power factor, with updates as often as every 1 second.

2.3. Constraints

The constraints are boundaries on your design and design process, basically it is something that limits or restricts something, or your freedom to do something. There is a list of constraints that could be found in our project: Time, Safety, Budget and Codes.

1- Time/Schedule. Possibly one of the most overlooked constraints in any design project is time. Particularly, for this project many factors created time constraints. All the research must be finished within 3 months and we should include the prototype in this period. Moreover, we should have done our working demo by May as deadline.

2- Safety. Our research and the data that we can work with are very limited in order to follow safety procedures. At the beginning the Smart Power Team is going to deal with low sources of voltage, around 10 V, in order to check if the program and connections are working correctly.

The Smart Power Factor Corrector will be built in a metal box. This box has to be big enough to include the essential equipment and the security devices required. Also this box has to be isolated and connected to ground to avoid any kind of risk in case of touching it. To protect the device, the box will include a thermal-magnetic circuit breaker that will flip in case of a short circuit or overvoltage.

A main constraint we have is making the physical dimensions of the final project as small as possible so that it can be implemented inside homes and not be extremely noticeable. However putting the components too close together could cause the high voltages to transfer to the low voltage components and break those components. When designing our device, we will need to only include essential equipment and make the box big enough to hold all the components with enough room but small enough to be aesthetically pleasing.

3- Budget. The project is constrained by funding limits and has been designed to stay below a $500 limit. There are three devices which basically define our project's budget; they are the Arduino Shield ($90), the current sensor ($10), and the motor run capacitor ($60). For the switches, we have chosen a SainSmart 16 channel relay. The price is $40 and this component allows us to connect up to 16 individual capacitors for our capacitor bank.

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. 4- Legal. Many codes and standards are applied to the problem and are administered by IEEE or OSHA, for more information look at the I.C.ii section of this proposal. National Electrical Codes 2008 edition standards 460.6 through 460.12 will be used as reference for the charging, discharging, and grounding of capacitors [12].

. 5- Reliability. The device is based on a reliable technology. The capacitors can be broken due to overvoltages or overcurrents. But the capacitors chosen are supposed to be able to deal with common overvoltages of the network. But if a capacitors breaks due to one of these reasons, there is not any risk. This is because the capacitors are connected in parallel, and this kind of capacitors when they suffer overvoltages, they explode internally but with any risk. It is a really small explosion, and once the capacitor stops working, it becomes isolated thanks to the parallel connection. The device can be disconnected in any time, so the replacement of the broken capacitor should not suppose a problem.

3. Design Specifications

3.1. Design Overview and Deliverables

The Smart Power Factor device will be able to constantly correct and monitor the power factor of high power usage appliances in households. This device will be able to be easily tailored to specific household appliances and be able to correct the power factor up to the maximum allowed limit specified by the appliance's manufacturer. The Smart Power Factor device will be able to update and correct the power factor every second. Along with correcting power, it will be able to send data wirelessly and allow users to monitor their device from anywhere.

Figure 5 shows the voltage (red), current (green), and power signal (dark blue) leaving the wall entering an appliance. Before the power factor correcting device, the voltage and current has a phase shift. After the power factor correcting device, the current and voltage have zero phase shift. In a real world situations, the phase shift cannot be zero, but as you can see from the concept diagram, the power signal increases from the before correction to the after signal.

Figure 6 is a block diagram of what the device will be consisting of. First, we will retrieve a signal from the main input into sensors consisting of a diode, current sensor and voltage transformer. The voltages and currents need to be lowered to an amount that can be read by the microcontroller. The transformer will output into the input of the diode giving off only the positive values of the signal. The microcontroller will take the output of the diode and will process the signal through an algorithm. This signal will determine the amount of lag and we can convert that data into the amount of capacitance required to correct the power factor. The microcontroller will send outputs to switches that will turn switches on or off depending on how much capacitance is required for that moment of time. Along with sending data into the switches to change the capacitance, the microcontroller will be sending data to a wireless system. This wireless system is an attachment to the microcontroller, which will send a wireless signal to some monitoring display and display the power factor and any other useful information.

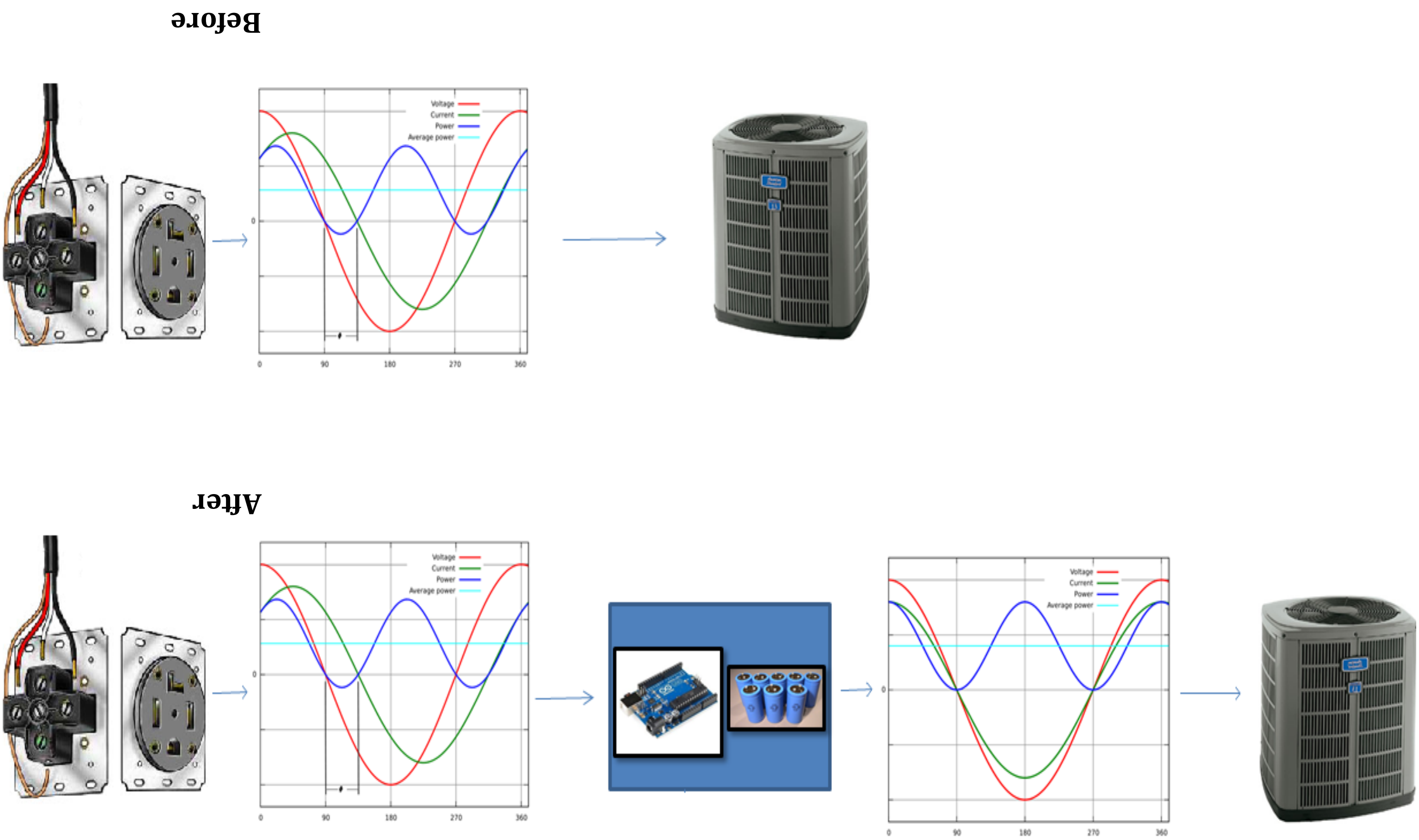


Figure 5-Concept Diagram

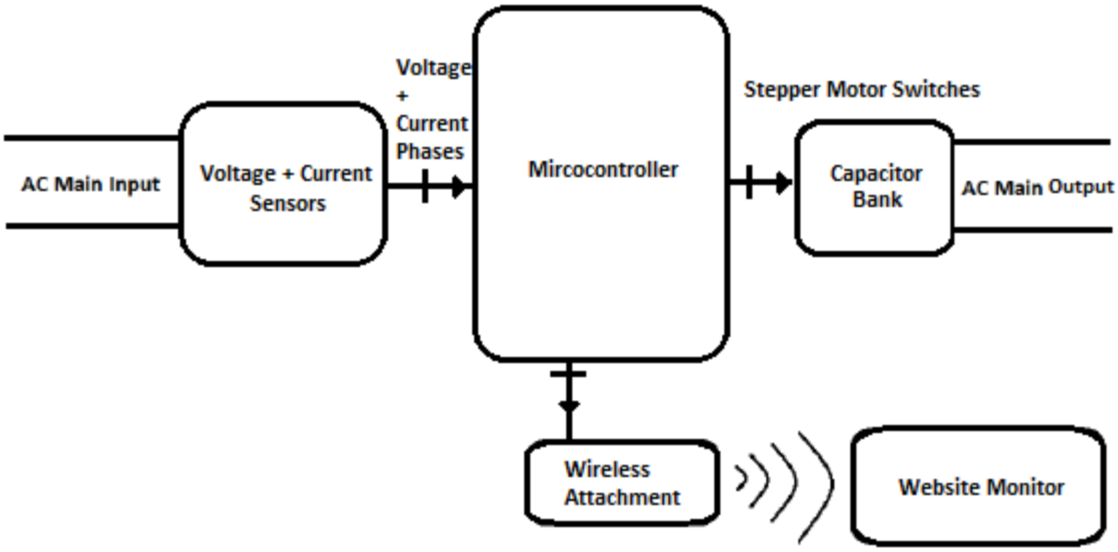


Figure 6- Block Diagram

The device delivers:

- Corrected power within a 5% differential to a desired power factor
- Wirelessly monitor the device, sending data every second
- Calculate and correct power every second
- Easy installation

3.2. Functional Specifications

The power factor corrector is a product that has the ability to correct power factor of a wide range of appliances and will be able to be monitored wirelessly and display this data online.

Functional Specifications

- The device can work with a limit of 10A.
- Since the voltage is 120V and the amps are 10A, the maximum amount of complex power that the device will have to work with is 1200 VA.
- Supplies connections between capacitors and microcontroller through thyristors switches, or different ways reliable enough.
- Corrects power factor within 2% of appliances maximum power factor.
- Provides corrections to the power factor, with updates as often as every 1 s.
- Uses Arduino algorithm to calculate required capacitance to correct power factor.
- Uses Arduino-shield-based 802.11b wireless communication to provide display information.
- Provides a web-based display that includes: uncorrected power factor, corrected power factor, current, and power usage.

3.3. Physical Specifications

· Has dimensions: 8" x 7" x 3.5"

· Power correction device components contained in metal casing to shield from interference and increase safety and aesthetics.

· Capacitor bank contained within metal casing connected to switches (relays).

· Use Arduino-board attachable components for 802.11b wireless communications

Parameter	**Specification**	**Units**
Corrected pf threshold	5%	pf
Maximum Weight	10	lb
Dimensions	1x1x.5	ft
pf corrected	0 to 350	VAR
Operating Voltage	85 to 120	V
Operating Current	3 to 10	A
Operating Temperature	32 to 90	ºF

Table 1- Power Factor Correction Requirements

The test plan for the device will be developed as follows:

Customer Requirement / Constraint	**Test Procedure**
1. Corrects pf to within 5% of motors maximum pf	Simulate a load that matches motor's load and use a wattmeter, ammeter, and voltmeter to measure the pf
2. Calculate and correct pf every second	Simulate a load that can be changed in less than a second and measure the pf using a wattmeter, ammeter, and voltmeter
3. Dimensions of box does not exceed 1' x 1' x 0.5'	Use a ruler and measure dimensions
4. Wirelessly transmits data over WiFi receiving at 802.11b/g networks at a distance of 10 meters	Operate device 10 meters away from a receiver at 802.11 b/g
5. Runs at a range of voltages from 85V to 120V	Operate two test of the device with voltage conditions at 85V and 120V. Use a voltmeter to measure voltage
6. Runs at a range of currents from 3A to 10A	Run two test of the device with current conditions at 3A and 10A. Use an ammeter to measure current
7. Can correct pf of appliances from a range of 0 VAR to 490 VAR	
8. Works in single phase AC systems	Operate device in single phase
9. Weight does not exceed 10lbs or 4.5 kg	Use a scale and measure weight
10. Runs continuously without battery change for 6 months	Using an accelerated test, calculate the power usage/second of the device and

	compare to maximum power usage/second of battery to support 6 months
11. Can operate at a targeted temperature range of 32F to 90F	Operate two test of the device with temperature conditions at 32^oF and 90^oF

4. Design Results

4.1. System Design

4.1.1 Design Overview

The Smart Power Factor Corrector has three main subsystems. The sensor subsystem is used to determine and send to the microcontroller the phase shift between the sinusoidal voltage and current of the main line as well as the magnitude of the current. The second subsystem is the microcontroller. This subsystem takes the information from the sensors and calculates the power factor and reactive power of the load. Then the microcontroller outputs signals used to connect capacitor banks to ground and correct the power factor. The last subsystem transmits the data, such as power factor and power usage, via WiFi so that we can view the data online. This is done with the Arduino WiFi shield that attaches to the Arduino.

Figure 6 gives a visual block diagram of the subsystems connected together. The main feature of the Smart Power Factor Corrector is to keep the power factor at a preset value and to check and update the correction every second. A major concern of the project is the switching of capacitors and the arcing that occur if the capacitors are not fully discharged. With the capacitors we are using, no problems with discharging the capacitors are supposed to appear, the capacitors will fully discharge in a short time. We use the metal box to completely isolate the low and high voltage parts to ensure voltage does not jump over and damage the equipment and to prevent from any accidental contact between the user and the electrical parts of the device that may injure a non-qualified user.

We tried to make this box as small as possible to be easily integrated into a household environment however, the smaller we make the box, the greater the chance of voltages jumping to other areas of the device. To remedy this, we decided to make the box dimensions at 8''x7''x3.5''. This allows the device to be of a modest size but allow for the integrity of the box to be intact.

4.1.2 System Design

We can calculate the power factor of any appliance by measuring the phase difference from the voltage signal and the current signal. For us to find the phase difference between the voltage and current, we must determine when the voltage and current signals go from a high to a low. The Arduino has hard time determining the difference from a high and low value. To make the calculated power factor value more accurate and precise, we want to convert the current and voltage signals into square waves. To do this, we use two comparators that allow us to change the reference value and convert the voltage and current signals into a square wave. This makes the 2.52 V value from the current sensor into a zero. We start the program timer when a positive voltage switches to negative voltage and end the program timer when the current sensor senses a negative to positive current change. This gives us a time delay that is converted into a power factor value. We then add capacitance using switches to reduce the time delay to a specific time. We are using a 16-channel relay at the output of the microcontroller. By adding relays at the end of the microcontroller, we safely keep the AC voltage and DC values of the microcontroller separated. A 16-channel relay gives us 16 switches that we set in parallel.

4.2. Sensor Subsystem

4.2.1 Overview of Sensor Subsystem

The subsystem will provide signals indicating the difference in phase between the sinusoidal voltage and current to the microcontroller. The sensor subsystem will first step down the voltage and current from the 120V and up to 20 A to the limits of the microcontroller which are 5V and 50 mA.

The voltage is brought down to 4V with resistors that step down the voltage and are then sampled. The step-downed voltage goes into a comparator and then into the microcontroller. The current signal is detected with the ACS712 Breakout. This device handles current up to 20A and outputs an analog voltage output signal that varies linearly with sensed current [13]. This allows for us to know when the voltage and current pass through zero and the microcontroller accounts for that time difference. Figure 8 shows a simplefied block diagram of the sensor subsystem.

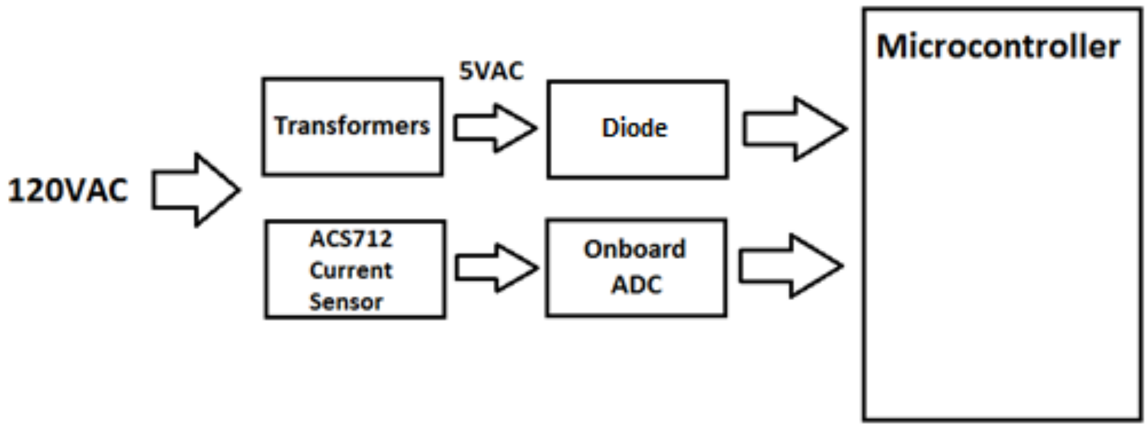


Figure 8- Sensor Subsystem Block Diagram

4.2.2 Detail Design of Sensor Subsystem

The voltage sensor circuit we used is given as figure 9. The current sensor will be connected in series with the load (R1 and L1) of figure 9. We are using a 96mH inductor to simulate the load of the appliance. What we want to get is a signal that gives only positive values since the microcontroller can receive positive voltages. Figure 10 shows a completed connection sensor subsystem diagram. The current sensor, ACS712, will be connected in series with the load. The output of the current sensor will be connected to the Arduino analog pin A5. This will allow the Arduino to calculate the max current of the system as well as when the current is zero. The delay time for the current signal is 10 microseconds.

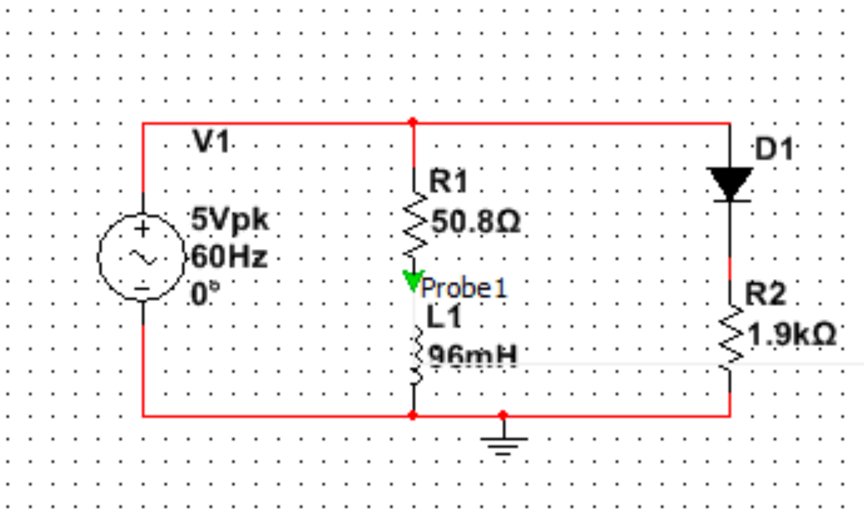


Figure 9-Voltage Sensor Multisim Diagram

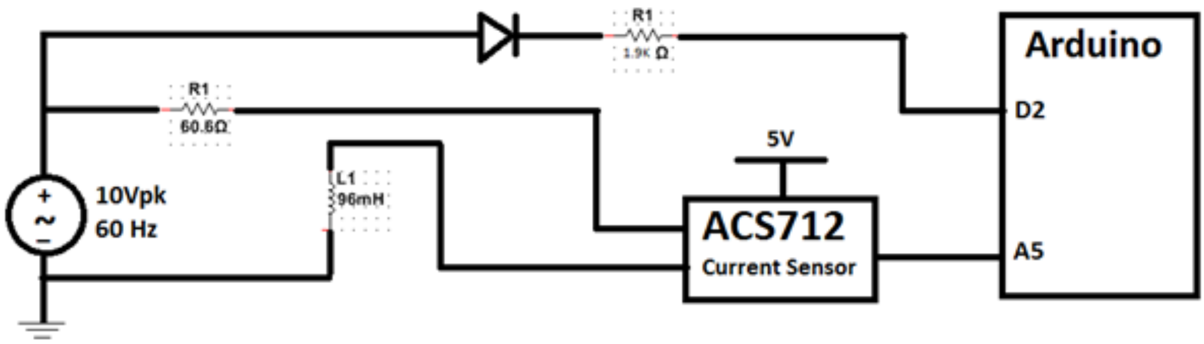


Figure 10- Complete Input Sensor Design

4.2.3 Evaluation of Results for Sensor Subsystem

Figure 11 is the voltage before and after going into a comparator. The voltage out of the comparator goes to zero when the values are not positive and will send out a high when about zero voltage. Figure 12 shows the current going into the current sensor and the voltage value the current sensor is outputting. We conclude from Figure 12 that if the current sensor sends a voltage value of 2.5519 or higher, then it is receiving a positive current.

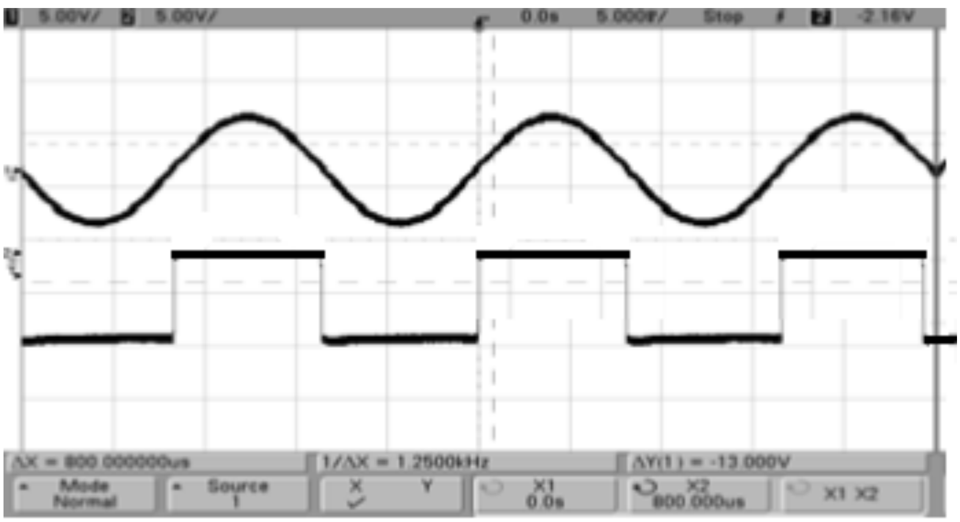


Figure 11- Voltage Signal of Comparator

I	Vout	Iin	2/25/2014
0	2.55	0	
0.1	2.533	0.2	
0.2	2.5292	0.4	
0.3	2.5003	0.6	
0.4	2.4825	0.8	
0.5	2.465	1	
0.6	2.4509	1.2	
0.7	2.4337	1.4	
0.8	2.4185	1.6	
0.9	2.4028	1.8	
1	2.386	2	

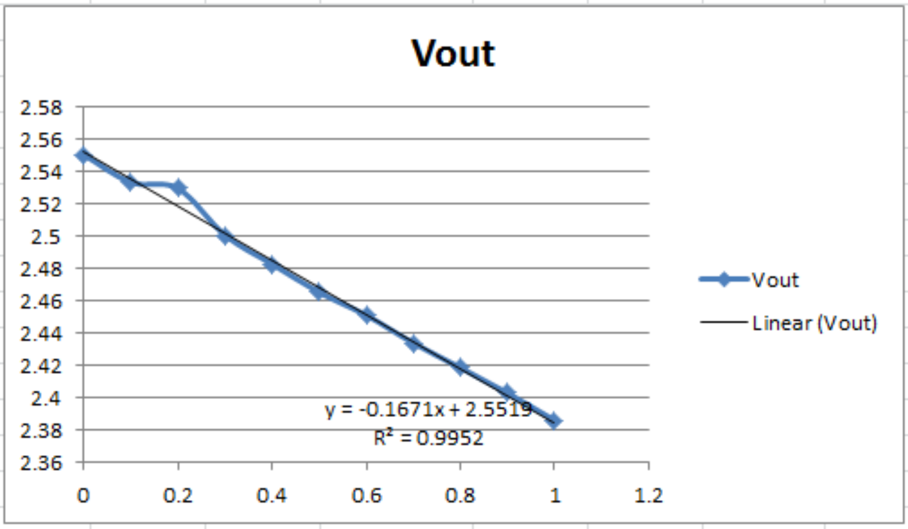


Figure 12-Current Sensor Input vs. Output Results

4.3. Microcontroller Subsystem

4.3.1 Overview of Microcontroller Subsystem

The microcontroller uses the data from the sensors and calculates the power factor and reactive power of the load. The microcontroller needs to be able to control switches that turn on and off switches to the capacitor banks.

The microcontroller chosen by the Smart Power Factor Team is the Arduino Uno rev 3. The reason we chose the Arduino over other microcontrollers is because of the large number of configurable input/output ports and the easily attachable Arduino Wi-Fi shield. The power factor is easily calculated by having the time delay and frequency of the signal. The reactive power is then calculated using the power factor and the magnitude of the power of the load. With the reactive power, we are able to find the amount of capacitance needed to correct the power factor. The microcontroller turns the switches on and off to vary the capacitance needed by using a multiplexer and a 16 channel relay system.

Schematic of the circuit design is seen in the appendix D.11.

Important Specifications:

- Arduino Uno rev3 [14]
    - Flash Memory32 KB (ATmega328) of which 0.5 KB used by boot loader
    - SRAM2 KB (ATmega328)

○ EEPROM1 KB (ATmega328)

○ Clock Speed16 MHz

○ 10 bit ADC

We tested the microcontroller using a low voltage demo, 10 Volts peak to peak, to ensure the algorithm works correctly in a safe environment.

4.3.2 Detail Design of Microcontroller Subsystem

Figure 14 shows a detailed algorithm program we are using with the microcontroller. The algorithm focuses on the inputs of the microcontroller. The step down ratio of the transformers is known so that we are able to calculate the actual value of the current and voltage of the main power line. The algorithm also takes into effect the phase change of the voltage and current comparators to accurately calculate the power factor. The onboard Arduino 10-bit ADC is used and allow us to record data for a set amount of time and then process the phase difference and calculate the power factor. The outputs of the microcontroller are the switches and the wireless transmission. The wireless transmission is done through the Arduino shield which has pre-written code. The code also takes into account how long the capacitor needs to discharge its electrical energy to prevent arcing.

The output circuit is seen in Figure 13. The Arduino has a max amount of inputs and output. To have 16 individual switches, we need to use a multiplexer because of the limit of output pins the Arduino supports is six. Pin D4 through D7 sends out a 4 bit signal into the multiplexer that is interpreted as a number from 0 to 16. The multiplexer turns on a number of switches proportional to the number it receives from the Arduino. A 16-channel relay is for our 16 switches, because it allows us to safely separate the high voltage from the low voltage.

Figure 14 shows the microcontroller block diagram. The input signals will trigger an interrupt, which will run an interrupt service routine. The interrupt service routine will calculate the time delay and the power factor at that moment. When the microcontroller is not running the interrupt service routine, it will be controlling the output control signals that determine if the relays are on or off.

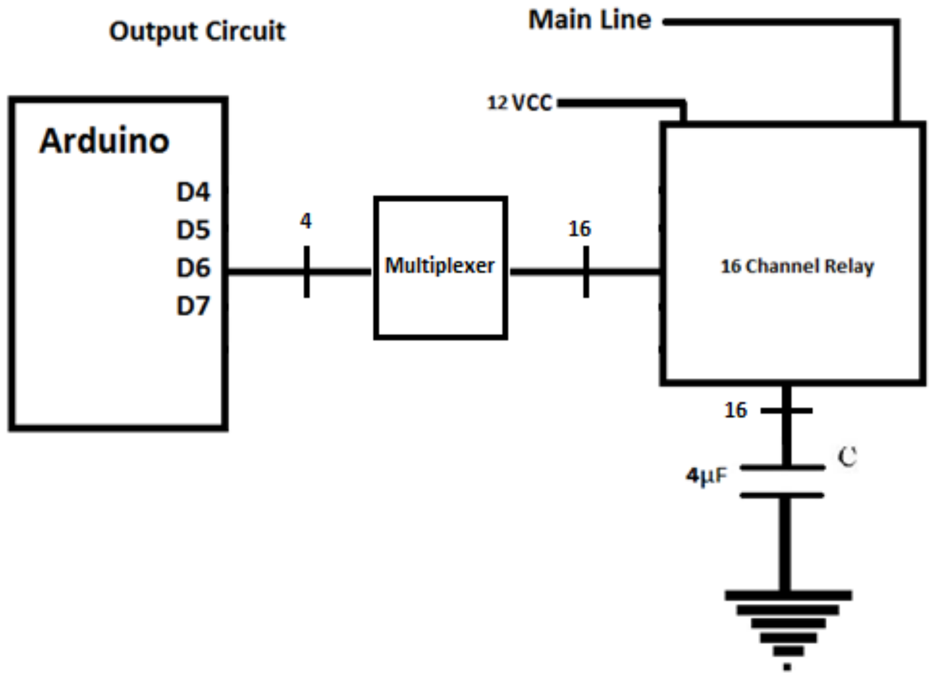


Figure 13-Output Diagram including Arduino

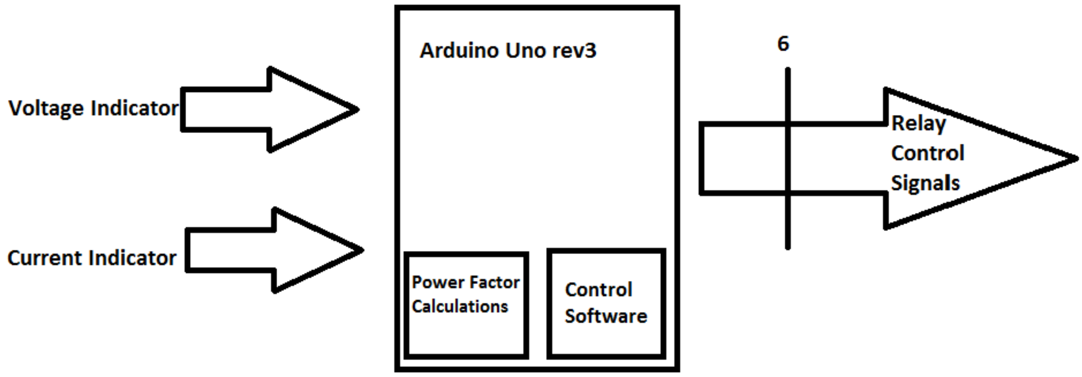


Figure 14- Microcontroller Subsystem Block Diagram

4.3.3 Evaluation of the Microcontroller Subsystem

We are still debugging the combined circuit and cannot test the algorithm until debugging is complete.

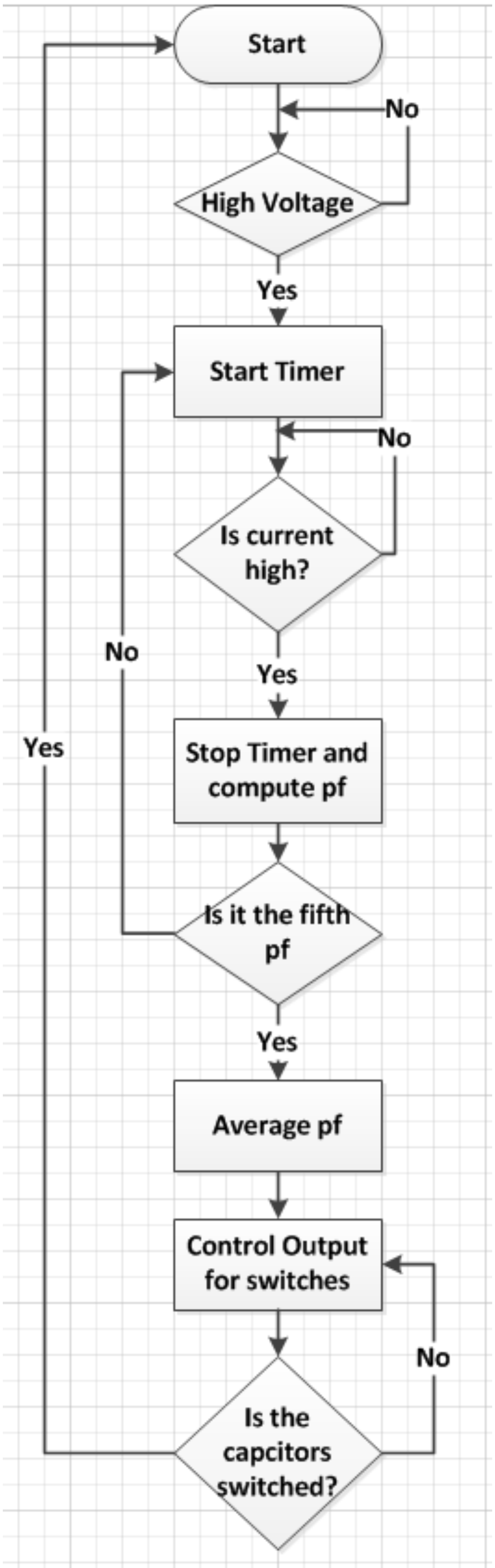


Figure 15- Microcontroller Algorithm

4.4. Transmitting Data Subsystem

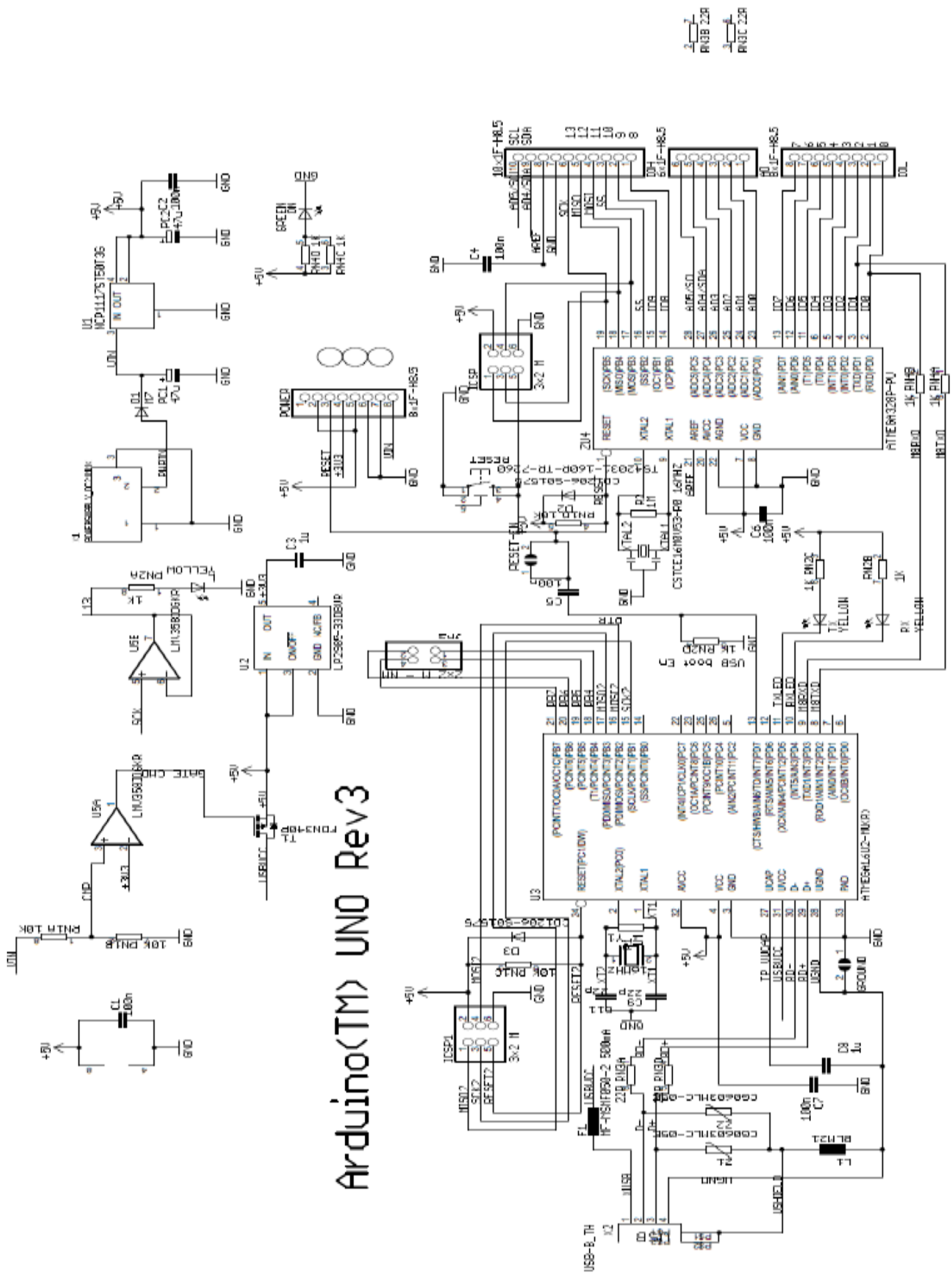
4.4.1 Overview of Transmitting Data Subsystem

The Smart Power Factor Corrector may be in an area not easily accessible and therefore we need a way to remotely view the data. The device needs to be able to send out calculated power factor and current readings.

The easiest way is to attach an Arduino WiFi shield to the device. The shield allows for easy access to the internet and also comes with its own software. We easily use it to send power factor, current, and power usage.

4.4.2 Detail Design of Transmitting Data Subsystem

The Arduino Shield data sheet is at it is shown:


Arduino(TM) UNO Rev3
ATMEGA328P-PU
ATMEGA16U2-MU(R)

Important Specifications:

- Arduino Shield [15]
  - Connection via: 802.11b/g networks
  - Encryption types: WEP and WPA2 Personal
  - Connection with Arduino on SPI port
  - On-board micro SD slot
  - Mini-USB for updating WiFi shield firmware

4.4.3 Evaluation of Transmitting Data Subsystem

As the project was developed, for questions of time, the transmission of the data to a different system as a computer will be left for a future improvement of the initial project.

This improvement will be based on the development of a tool from which the user will be able to decide the power factor that wants to have in the device, and to control and monitored the control of the power factor in real time.

5. Design Plan

5.1. Stage 1- Research

Safety procedures and standards needed to be met. The protection of shunt capacitor banks is an important aspect to protecting both the customer and the device itself. Researches on safety procedures were developed. The following information was found.

Related with security procedures, the major causes of injury and fatality are shocks and electrocution from improper use and shocks and electrocution to utility workers from improper connection to structures. In order to deal with these problems have to take in consideration the use of a ground terminal, grounding mean the connection of an electrical circuit or equipment to reference ground. In this project this is not just a point of reference; the terminal block is physically connected to the metal box to charge the entire box with zero volts. This method is commonly used to avoid damage caused by direct contact with the operator, or to prevent from the risks that can be caused by wires that are accidentally in contact with the case.

Another fact to take in account is the circuit breakers. In order to protect our internal circuit and the current sensor, currents over 10 A have to be avoided. In general, these kinds of devices include a fuse that can avoid this kind of problem. In the project, the connection between the networking and the metal box is made by the use of a power socket with a fuse of 10 A.

5.2. Stage 2- Design

We started by designing a device that corrects the power factor at lower levels of current and voltage. By completing a prototype in steps, we slowly can transition safely to high voltage appliances.

The initial design used a Schmitt trigger and inverter for the voltage sensor. It was a big concern to find only the positive voltages of the main line. Combining those to components would give us those results. Many problems occurred with the Schmitt trigger and inverter. This was due the mixing of AC and DC signals and this created inconsistent data results. It was around March 18th when it was decided to switch to a diode. The diode gave us the same results. At first it was thought that it could not use this as an alternative because it would be working in higher voltages and currents. That was until it was found out that there are diodes that can work at the same specifics as our device. It was while working on the program when it was noticed that it was needed to change the sinusoidal signals from sinusoidal waves to square waves. On April 29th, it was tested the voltage signal using a comparator instead of a diode and found the results to be exactly what it was needed for the program.

Along with the initial voltage sensor, it started off with a design that used a voltage transformer to measure the voltage at lower voltages and to feed the Arduino. It was found voltage transformers to increase the budget and found out around the end of March that the voltage could be step down and get the same results using a step down resistor instead of transformers, saving space and money. Batteries are used to feed the Arduino, so the transformer was not needed anymore.

The last and final design change deals with the switches. Initially we thought logic gates would be able to separate the DC and AC voltages. This also caused mixing of the DC and AC voltages and would not work with our design. From March 20th to April 1st we worked with a 16-channel relay system that prevents mixing of AC and DC voltage. This became part of our final design.

From the second week of April up to the end, the work has been focused on debugging the program. A problem arose in the low voltage demonstration where the current sensor is only changing a few millivolts because the change in the current is only about 50 mA. This has caused the problem of not being able to debug the program because the change in the output of the current sensor is so small that the data collected is unreliable. However, this problem will not exist with the higher voltage because the current sensor output will vary by a few volts.

5.3 Stage 3- Prototype Construction

The prototype used the Agilent 33250A Function Generator to supply the 5V peak-to-peak 60 Hz sine wave. Four 24 mH inductors were connected in series with a 50 Ω resistor to simulate the inductive load. The IN4742 diode is connected in parallel with the load. A 1.9 kΩ resistor is placed after the diode. The resistor value was chosen to be large enough so that 99% of the current still goes through the load but small enough to decrease power losses. The node where the resistor and diode meet is connected to the Arduino D2 port. The ACS712 current sensor is connected in series with the load. The output of the current sensor is connected to the Arduino A5 port.

The output circuit has the Arduino D3-D6 ports connected to the SainSmart 16-Channel Relay as control signals. The relay's neutral port is connected in parallel to the load. The normally open port of the relay is not connected. The normally closed port of the relay is connected to capacitors that will be connected to ground.

Currently for the low voltage prototype, we have all the necessary hardware configured. Our progress is working on debugging the code and possibly having to find a way to increase the RAM of the Arduino if the code cannot be condensed.

5.4. Stage 4- Testing

The voltage sensor circuit used is given as Figure 11. The current sensor will be connected in series with the load (R1 and L1) of Figure 11. We used a 96 mH inductor to simulate the load of an appliance. What we want to get is a signal that gives positive values only since the microcontroller only reads positive voltages. Figure 13 shows that if the current sensor is giving off a value of 2.5519 V, then the current at that time is zero.

For the low voltage demo, we have tested and confirmed all parts are working as intended. This includes the diode, current sensor, Arduino input and output ports, and the 16-channel relay. The test circuit has been properly tested to ensure that it is simulated an inductive load and we measure the time delay with an oscilloscope.

5.5 Documentation/ Final Device

The construction of the final device was followed in order to accomplish the objectives and by using all the feedback obtained from the testing prototype.

This final device is built in a metal box, which is connected to the ground to avoid any risk for the consumer in case he touches the box. The box will be sold completely closed so that the consumer will not access involuntarily to the inside of the box so that risks can be avoided from contacts with wires and other parts of the device.

Initially the box was covered with paint, but in order to be able to connect the box to the ground and to put the whole box to ground potential, the paint was removed.

In order to remove the paint, the substance used for it was acetone. Once the paint was removed, the box was connected to the ground using the screws used to fix the outputs for the load.

The connection of the box to the ground was checked thanks to a voltmeter, observing that the entire box was at the same potential.

Figure 16 is a general overview of connections.

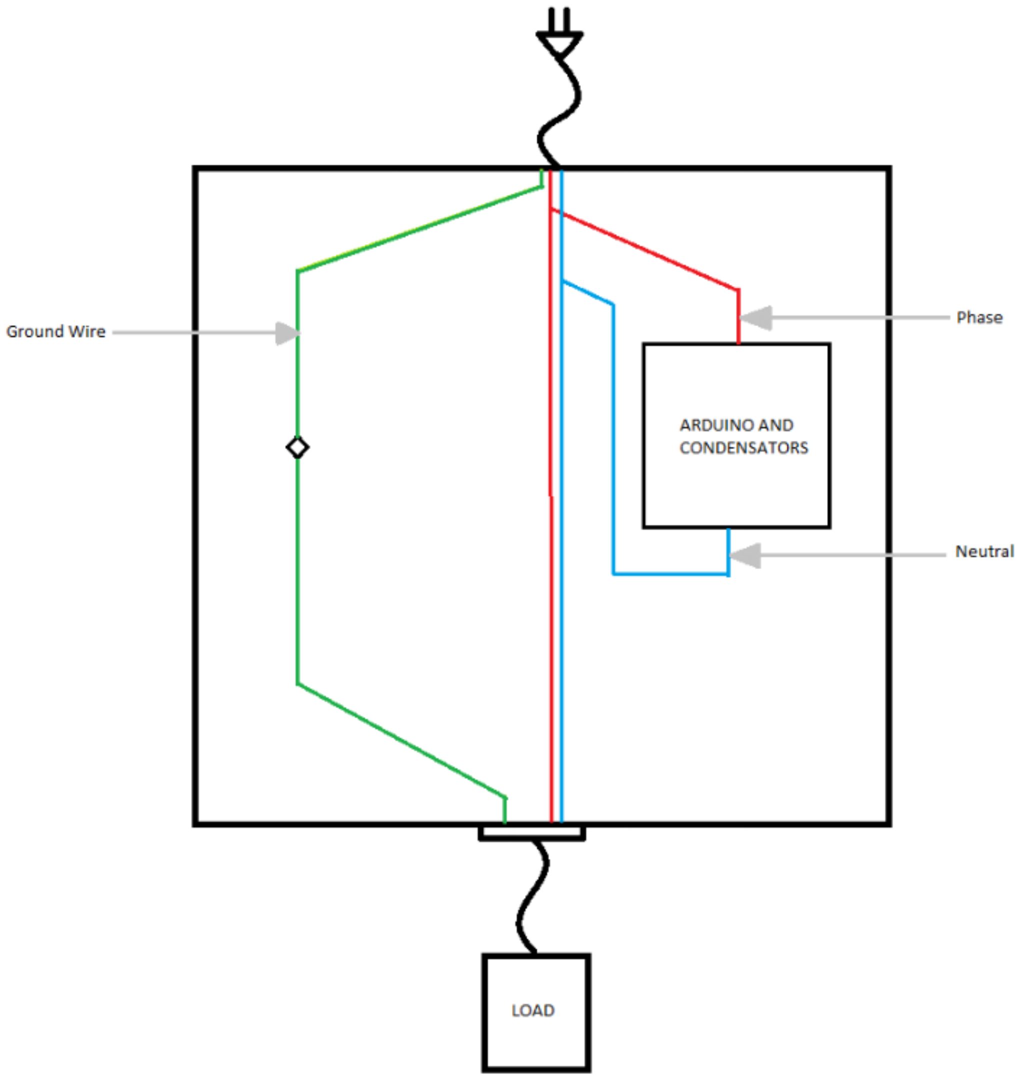


Figure 16- General Overview Connections

The device is built according to the US regulations, so as a consequence the wires follow a color code:

-Protective Earth: Green Wire

-Neutral: White wire

-Line, Phase: Black Wire

The box can be connected to the network through a power socket with a switch that includes a fuse for safety reasons. The switch is a circuit breaker that will interrupt the connection between the line connections in case that it is opened.

As it is explained ahead, the device also includes a current sensor that cannot work with currents that overpass 10 A, so to protect the current sensor from over currents a fast acting fuse of 10 A is included in the power socket. In case that the current overpasses 10A, the fuse will work and it will act as a circuit breaker. This fuse is a glass fuse with a capability of interrupting up to 200 A and with capability of working with voltages up to 250 V. It consists on filaments of 5 x 20 mm of copper

Figure 17 shows the fuse that is being used. Figure 18 shows the power socket with the circuit breaker switch.

Figure 17- Fast Acting Fuse

Figure 18- Power Socket with Switch

The current is measured using a current sensor that, as it is explained in section 4.2.2, provides a voltage proportional to the current as an output. As the input is a wave, the output will be a wave too.

The current sensor is based on the Hall effect to measure the current. The Hall effect is the production of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current. It is an electromagnetic phenomenon. It is related with the induced electromagnetic fields produced by the current going into the sensor. The voltage induced is proportional to the current that is traversing the current sensor.

It is only needed the values of the induced voltages related with specific currents to be able to know the current using the output voltage as it is shown in figure 12 and it was tested in the prototype phase.

Figure 19- Visual Of Current Sensor

The voltage is measured using the step down resistors (R1=100kΩ and R2=3.48kΩ) to be able to measure it with the Arduino. The voltage, once it has been already stepped down, goes directly inside the analog input of the Arduino.

The resistor values are higher than usual because of two different reasons. The first one is that we do not want the wave of the voltage to be affected so the resistance used to step down the voltage has to be much greater than the resistances expected in the main line. The other reason is that the kind of resistances that are used cannot work with more than 0.25W or otherwise they will burn. So knowing that the voltage of the source is a 120V, the total resistance connected in parallel is 103.48 kΩ. With this in mind, the current going through the resistances is:

$$I = V/_R$$

$$I = 120/_{103480} = 1.15964437 \text{ mA}$$

And the power being consumed by each resistance:

$$P = I^2 \cdot R$$

-R1 (100kΩ)

$$P_1 = 0.0015964437^2 \cdot 100000 = 0.134477\ W$$

-R2 (3.48kΩ)

$$P_2 = 0.0015964437^2 \cdot 3480 = 4.6798\ mW$$

As it is shown, both consumptions of the resistances are smaller than the 0.25 W that it is set as their functional limit.

The specific value of these resistances is the result of wanting to have a voltage of 4V going to the analog port of the Arduino. The Arduino is prepared to handle up to 5V of voltage, but the voltage work is 4 to avoid any risk by using the limitations of the Arduino.

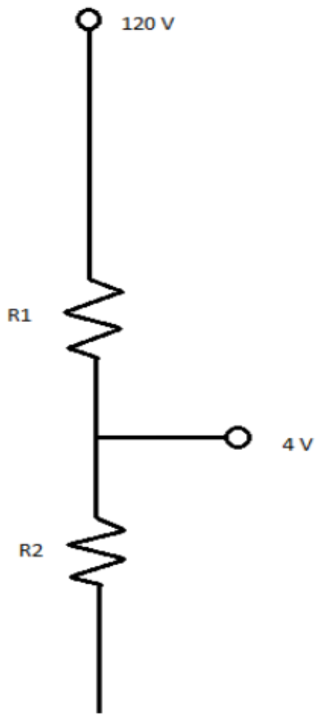


Figure 20- Step Down Resistance Circuit

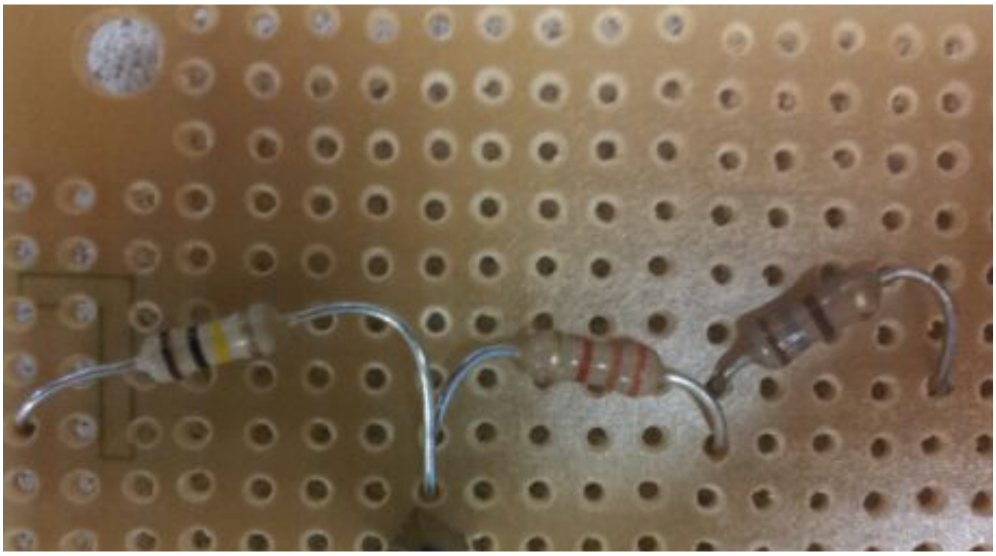


Figure 21- Visual Of Step Down Resistor

All the information is received by the Arduino that works with this information and that connects the capacitors that are connected in parallel thanks to the relays.

The total capacitance is calculated using a worst-case scenario situation. Since the voltage from the network is 120V and the limit of current is 10A, then the maximum apparent power is:

$$S = U \cdot I^*$$

$$S = 120 \cdot 10 = 1200\ VA$$

So the maximum apparent power that the device will be able to work with will be 1200 VA. Now, with this apparent power, then it is necessary to consider the worst power factor expect to be corrected. This power factor is .6, and the Arduino is programmed to correct it as close to .92 as possible. So:

-Without correcting power factor:

I=10A		S=1200 VA
V=120V	→	P=720 W
pf= 0.6		Q=960 var

-Correcting the power factor:

I=10A S=1200 VA

V=120V P=1104 W

pf=0.92 Q=470 var

This implies that for changing the power factor from 0.6 to 0.92, 490 var must be produced by the capacitors.

These results can be interpreted in two different ways. The first one is that for the same amount of current, the costumer is obtaining much more active power, that is, electrical power that can be transformed in mechanical power, heat…

The other way of understanding it is that for producing the same work, less current is produced. If we had a power factor of 0.6, to produce 720 W the system required 10 A. but if the power factor is 0.92, then the current needed is:

P=720W S= 782.61 VA

pf=0.92 Q=306.72 var

$$I = \frac{782.61}{120} = 6.52\ A$$

So the efficiency is improved drastically.

To correct the power factor from 0.6 to 0.92 as it is already shown, 490 var need to be produced by the capacitors. Using the following equation, the capacitance needed can be calculated.

$$C = \frac{Qc}{V^2 \cdot 2\pi \cdot f}$$

Using the values:

$$C = \frac{490}{120^2 \cdot 2\pi \cdot 60} = 90.26\mu F$$

The relays act as switches connecting the capacitors depending on the signal sent to them by the Arduino. The relays provide us six switches and we have six steps of capacitances of values 40μF, 20μF, 20μF, 5μF, 2.5μF and 2.5μF.

Figure 22 is the output outlet for the metal box. Figure 23 is a visual picture of the 16-channel relay.

Figure 22- Output Outlet

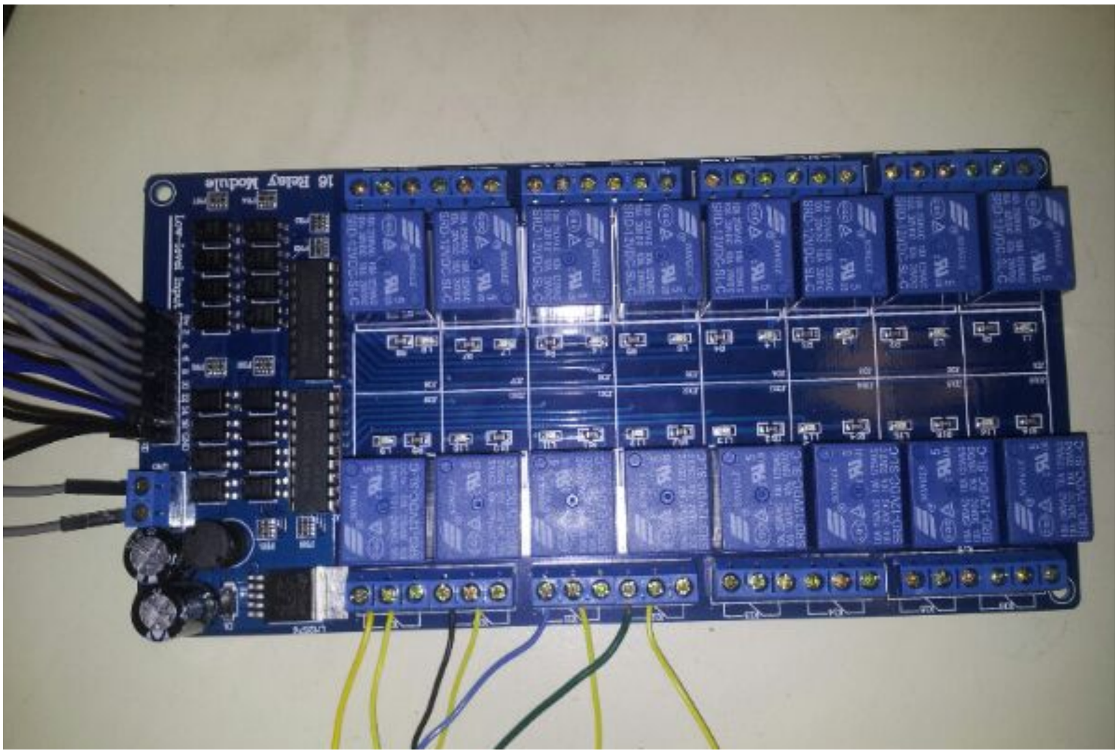


Figure 23- Visual of 16-Channel Relay

As it is shown in the figure 22, the box is prepared to be able to connect two different loads, but the only requirement, due to the limit of 10A of current, is that the total loads do not overpass the 1200VA.

Figure 24 is a visual of the Arduino uno rev3.

Figure 24- Visual of Arduino uno rev 3

The capacitors used to produce the reactive power needed are built to work with voltages up to 250V and their size is one of the constraints in the size of the metal bow. As can be observed in figure 25, the size of this kind of capacitors supposes a great limitation in terms of optimizing the space in the box.

Figure 25- 50 µF capacitor

The connections inside the box will be done with wires prepared to handle 10A. These wires will have a short circuit, so the section of the wire has to be of 1.5 mm.

Other additional tools are used to do the parallel of the connections and all the derivations

The code used in the Arduino to work is:

```
/* Smart Power Factor Corrector
  University of San Diego
  ELEC491W EE Senior Design
  Date Started: 10/31/2013
  Last Revision: 2/27/2014

  This program will allow the Arduino to calculate the power factor of a line and
then correct the power factor by
  switching on capacitors that are in parallel with the line.

  Inputs: Main Line Voltage
        Main Line Current

  Outputs: Switches
         Send out data via Wi-Fi

 The program will sample and calculate the power factor of the main line. The
power factor
 will then be averaged and the program will calculate how much reactive power
to correct. The capacitance needed will
 be achieved by turning switches on and off.
 Switchs' Capacitances:
 Switch1 = 40 uF
 Switch2 = 20 uF
 Switch3 = 20 uF
 Switch4 = 5 uF
 Switch5 = 2.5 uF
 Switch6 = 2.5 uF
*/
//initalizing variables
int input1 = 2; //Voltage Input pin assignment (Digital Input)
int input2 = A5; //Current Input pin assignment (Analog Input)
int pf = 0; //Variable to store power factor
int switch1 = 4; //Pin assignments for switches
int switch2 = 5;
int switch3 = 6;
int switch4 = 7;
int switch5 = 8;
const int frequency = 60; //Frequency of 60 Hz
const int pi = 3.14159265; //Pi
const int voltagemax = 7.07106 //10 over root 2
const int root2 = 1.414 // square root of 2
long StartTime = 0; //variables for time delay loop
```

```
long EndTime = 0;
long timedelay = 0;
long phaseshift = 0;
int val = 0; //variable to store values from current sensor
long starttimeloop = 0; //loop variables for max current loop
long endtimeloop = 0;
int maxcurrent = 0; //Variables for calculations
int currentrms = 0; //Variable for current rms
int phase = 0;
int Q = 0; //Variable for reactive power
int capneeded = 0;
int loopstart = 0; //loop control variable

void setup()
{
 //declare input pins
  pinMode(input1, INPUT);
 //declare output pins
  pinMode(switch1, OUTPUT);
  pinMode(switch2, OUTPUT);
  pinMode(switch3, OUTPUT);
  pinMode(switch4, OUTPUT);
  pinMode(switch5, OUTPUT);

}
void loop()
{
 val = analogRead(input2);
 if(input1 == '1') //Loop will start when voltage is zero and stop when current is
zero
 {
 loopstart = '1';
 unsigned long StartTime = micros();
 while(loopstart == '1')
 {
  if(val == '520') //Value from ACS712 datasheet that corresponds to zero
current
  {
   unsigned long EndTime = micros();
   timedelay = EndTime - StartTime;
   phaseshift = timedelay * 2 * pi * frequency;
   pf = cos(phaseshift);
   loopstart = '0'; //stop loop
   delay(17); //Wait for 17 ms, one cycle at 60 Hz
  }
 }
 starttimeloop = micros(); //Loop to find peak current
 endtimeloop = starttimeloop;
```

```
 while ((endtimeloop - starttimeloop) <=17) // do this loop for up to 17ms, one cycle, to find max current
{
 if (val > maxcurrent)
  maxcurrent = val;
{

endtimeloop = micros();
}
}
 maxcurrent = (maxcurrent*.0293)-15.269; //Calculated equation to go from output voltage of ACS712 to sensed current
 currentrms = maxcurrent/root2 // Go from peak current value to RMS value
 phase = acos(pf); //calculations for reactive power and corrective capacitance
 Q = voltagerms*currentrms*sin(phase);
 capneeded = Q/(voltagerms*voltagerms*2*pi*frequency);
 capneeded = capneeded*1000000; /Changes capacitance needed to integer from micro
 if(capneeded >=4) //Control loop for switches
 {
  digitalWrite(switch1,HIGH);
  digitalWrite(switch2,HIGH);
  digitalWrite(switch3,HIGH);
  digitalWrite(switch4,HIGH);
  digitalWrite(switch5,HIGH);
  digitalWrite(switch6,HIGH);
 }
 else if(capneeded <4 && capneeded >= 3)
 {
  digitalWrite(switch1,LOW);
  digitalWrite(switch2,HIGH);
  digitalWrite(switch3,HIGH);
  digitalWrite(switch4,HIGH);
  digitalWrite(switch5,HIGH);
  digitalWrite(switch6,HIGH);
 }
  else if(capneeded <3 && capneeded >= 2)
 {
  digitalWrite(switch1,LOW);
  digitalWrite(switch2,LOW);
  digitalWrite(switch3,HIGH);
  digitalWrite(switch4,HIGH);
  digitalWrite(switch5,HIGH);
  digitalWrite(switch6,HIGH);
 }
  else if(capneeded <1 && capneeded >= 0)
 {
  digitalWrite(switch1,LOW);
  digitalWrite(switch2,LOW);
```

```
  digitalWrite(switch3,LOW);
  digitalWrite(switch4,HIGH);
  digitalWrite(switch5,HIGH);
  digitalWrite(switch6,HIGH);
 }
  else if(capneeded <.037 && capneeded >= .01)
 {
  digitalWrite(switch1,LOW);
  digitalWrite(switch2,LOW);
  digitalWrite(switch3,LOW);
  digitalWrite(switch4,LOW);
  digitalWrite(switch5,HIGH);
  digitalWrite(switch6,HIGH);
 }
 else
 {
  digitalWrite(switch1,LOW);
  digitalWrite(switch2,LOW);
  digitalWrite(switch3,LOW);
  digitalWrite(switch4,LOW);
  digitalWrite(switch5,LOW);
  digitalWrite(switch6,LOW);
 }
}
```

6. Adaptability to the European market

6.1 Technical Adaptation

The product that was built for the project would need to adapt to be able to work in European countries due to the differences that exist between European and American electrical networks.

There exist both of electrical differences between both markets, but most of them are related with the transportation of the electrical energy and the legislation of each country. The differences that affect are project are those that are related with the voltage and the frequency with which each house receive the electricity.

In US, the houses are fed with voltages of 120V and a frequency of 60 Hz. But in most countries of Europe, the houses are fed with 220V and a frequency of 50 Hz. These changes have a huge impact in the project; because the reactive power produced by the capacitors will change and the power factor of the consumptions tend to be worst with higher voltages, as it is shown in figure 26.

This last change is good for this project, because it implies that in the European market can exist a bigger demand for this product, due to the bigger saving that it can produce in comparison with the US market.

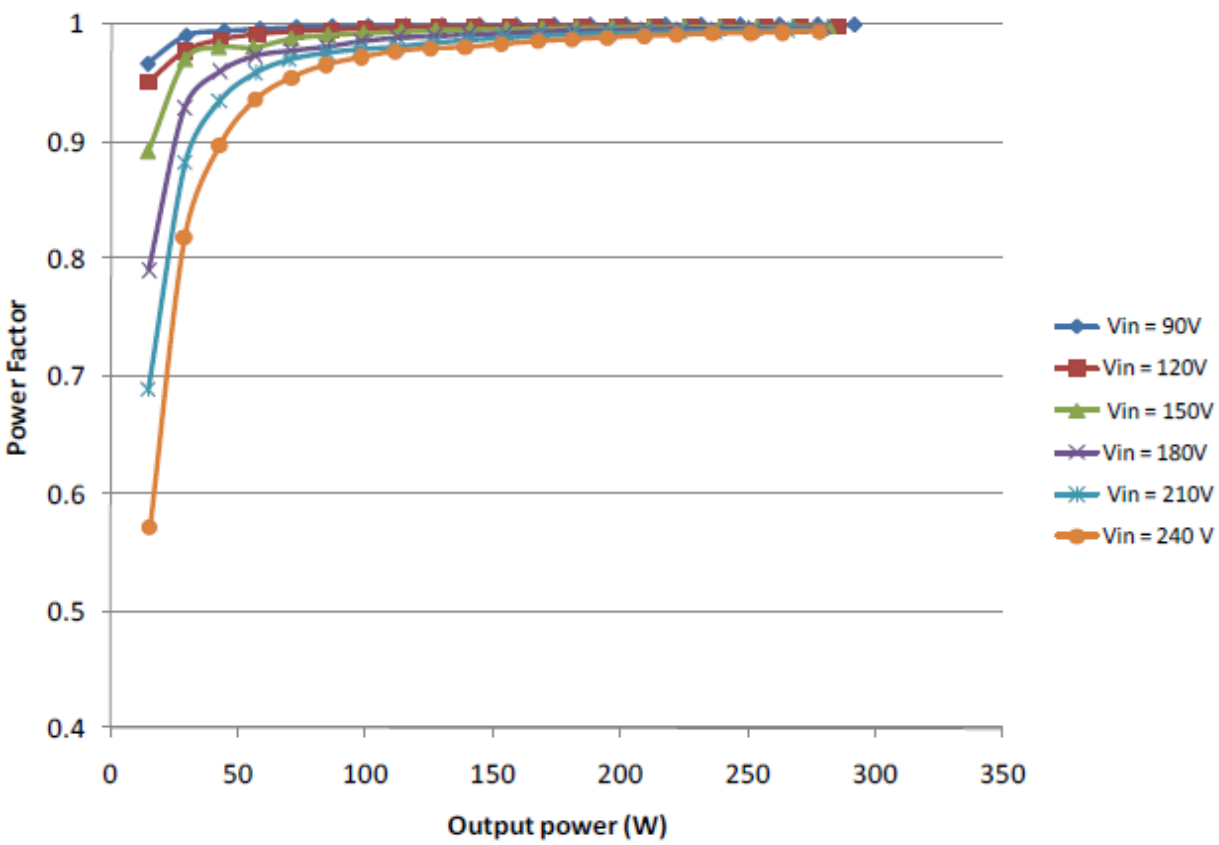


Figure 26- Power factor comparison

As it can be observed in figure 26, the voltage in relation with the power factor is especially relevant in low power consumptions. This is important for the product because it is designed to work in low consumptions such as household appliances.

So if the product were working with the same current sensor then the limitation of the current would still be 10A, but know the voltage is 220V. So the limit of the consumption of the loads changes drastically.

$$S = U \cdot I^*$$

$$S = 220 \cdot 10 = 2200 \text{ VA}$$

So now to change from a power factor of 0.6 to a power factor of 0.92, the amount of reactive energy that has to be produced by the capacitors is completely different.

Without compensation:

U=220V	→	S=2200 VA
I=10A	→	P=1320 W
pf=0.6	→	Q=1760 var

With compensation:

U=220V	→	S=2200 VA
I=10A	→	P=2024 W
pf=0.92	→	Q=862.22 var

The same considerations can be obtained from the European model. More active power can be obtained with the same current, or to obtain the same active power, less current is needed.

For correcting the power factor of this example, the capacitors would have to produce about 900 var. these implies that the capacitors need to be changed from those of the American version of the product. Knowing that now the voltage is 220V and that the frequency is 50 Hz instead of 60 Hz, we can use the following equation:

$$C = \frac{Qc}{V^2 \cdot 2\pi \cdot f}$$

Using the values:

$$C = \frac{900}{220^2 \cdot 2\pi \cdot 50} = 59.19\mu F$$

As it is shown, to compensate more amount of energy in the European network, less capacitance is needed. The current model works with six relays that work as switches, so the total capacitance of 60 μF is divided in six different steps. These steps are divided in two steps of 20μF, one of 10μF, another one of 5μF and two of 2.5μF.

The security measures would be the same as the American model, this is, the fuse to protect rom current over 10A and the box connected to the ground.

Another thing that would need to be changed are the step down resistances. Since the working voltage is bigger, then the resistances have to be bigger in order to avoid that they consume more than a quarter of watt.

To reduce the voltage to 4V at the input of the Arduino, it will be used two different resistances of the same type as the American model, this means, resistances that cannot consume more than a quarter of watt. So as a consequence, the resistances that would be used would be the first one of 200 kΩ and the second one of 3.7037 kΩ.

As it was checked for the American model, lets check for the European model that the use of these resistances is correct:

$$I = {}^{V}/_{R}$$

$$I = {}^{220}/_{203704} = 1.08 \text{ mA}$$

And the power being consumed by each resistance:

$$P = I^2 \cdot R$$

-R1 (200kΩ)

$$P_1 = 0.00108^2 \cdot 200000 = 0.23328\, W$$

-R2 (3.7037kΩ)

$$P_2 = 0.00108^2 \cdot 3703.7 = 4.3199\, mW$$

So both resistances suit in the project design.

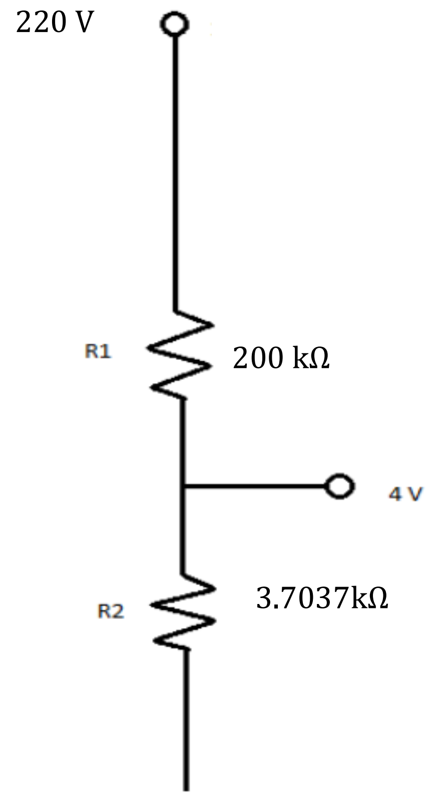


Figure 27- Step-down resistances (European model)

6.2 Regulation Adaptation

There are several things that need to be adapted and to be concerned about when developing the product for a different country. The regulation that will be presented is from Spain.

At first, the color code that must be followed in the wires is different from the American one. It is at follows:

-Protective Earth: Green-Yellow Wire

-Neutral: Blue wire

-Line, Phase: Black, Grey, Brown Wire

Besides the color regulation, in order to deploy a product in the Spanish market, it would have to follow all the regulations for low voltages.

7. Future Improvements

For future improvements of the device, the main idea is to solve those limitations imposed by the current hardware being used.

The first of these limitations is easy to solve since in the market already exists alternatives to the hardware being used. By this I am referring to the Arduino. The model of Arduino used in the first model had only one analog input. This forced an alternative solution to measure the current. In the first model, a current sensor based on the Hall effect was used, and it provided a voltage as an output. This voltage was sent to a comparator, and then the Arduino through one digital input received the information. If a model of Arduino with more than one analog input could be used, then the comparator could be eliminated, using the voltage from the current sensor as an input in the Arduino.

Another improvement that could be done would be the amount of capacitors being used to correct the power factor. With the current model, only six gates are being used, due to the limited quantity of outputs in the Arduino. This problem could be solved using new Arduino models. Or a different alternative is using multiplex doors; one of the objectives established but that was not accomplished. As many capacitors as the Arduino is using, the more precise the correction of the power factor would be.

One great improvement would be to be able to work with a current sensor that was not limited to 10A. The limitation of 10A is the cause of the limitation on the load, and by improving this limitation, the device could be designed to correct more reactive power than it is currently.

The box was built in a metal box. An improvement in the construction of the device would be to build the device using an aluminum box instead of a metal box. The reason is the oxidation that suffers the current box.

Finally, the device was designed to be connected to one or two loads. This suppose a problem for the costumer, since for each device he wants to control the power factor, it implies the acquisition of a device, which implies a lot of expenses. The future of the project would be to make a power factor correction of the entire house or of certain rooms, saving money to the costumer and creating a more attractive product.

8. References

[1] Marinko Stojkov; Kruno Trupinic; Darko Poleto, "Reduction Of Power And Voltage Losses In Low Voltage Networks By Reactive Power Compensating", Proceedings Of The18th International Conference On Electricity Distribution, 2005.

[2] Dixon, J.; Moran, L.; Rodriguez, J.; Domke, R., "Reactive Power Compensation Technologies: State-Of-The-Art Review", Proceedings of The IEEE, Vol.93, No.12, Pp. 2144-2164, 2005.

[3] (No Author), "Design It Right: Power Factor Correction A Guide For The Plant Engineer", Eaton Powering Business Worldwide, 2010.

(accessed Nov 26, 2013

http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/sa02607001e.pdf)

[4] Agrelo Regueira; Juan Luis, "Sistema De Compensación De Potencia Reactiva, De Especial Aplicación En Viviendas", Endesa S.A.E Patent, 2013.

[5] Stone David W, "Reactive Power Compensation Control System", Patent 3754184, 1972.

[6] Arnold P Kehrli; John A Diaz De Leon II; Douglas C Folts, "Reactive Power Compensation To Minimize Step Voltage Changes And Transients", Patent 06900619, Nov. 1999.

[7] IEEE Standards 1-2000, "IEEE Recommended Practice— General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation", Institute of Electrical and Electronics Engineers, Inc., 2001.

[8] IEEE Standards 18-2012, "IEEE Standard for Shunt Power Capacitors", Institute of Electrical and Electronics Engineers, Inc., 2012.

[9] IEEE Standards 1459-2000, "IEEE standard definitions for the measurement of electric power quantities under sinusoidal, non-sinusoidal, balanced and unbalanced conditions", Institute of Electrical and Electronics Engineers, Inc., 2000.

[10] IEEE Standards C37.26-2003, "IEEE Guide for Methods of Power-Factor Measurement for Low-Voltage Inductive Test Circuits", Institute of Electrical and Electronics Engineers, Inc., 2003.

[11] IEEE Standards C37.99, "IEEE Guide for the Protection of Shunt Capacitor Banks,", Institute of Electrical and Electronics Engineers, Inc., 2013.

[12] National Fire Protection Association, “National Electrical Code: 2008”, Article 460, 2007.

[13] “Fully Integrated, Hall Effect-Based Linear Current Sensor with 2.1 kVRMS Voltage Isolation and a Low-Resistance Current Conductor”, Allegro Datasheet.

(accessed Nov 26, 2013 https://www.sparkfun.com/datasheets/breakoutboards/0712.pdf)

[14] “Arduino Uno”, Arduino Online Product Information

(accessed Nov 26, 2013 http://arduino.cc/en/Main/arduinoBoardUno)

[15] “Arduino WiFi Shield”, Arduino Online Product Information

(accessed Nov 26, 2013 http://arduino.cc/en/main/arduinowifishield)

Documento II: Presupuesto

American Budget

Quantity	Description	Price ($)
1	Arduino Uno Rev 1	30 $
1	16-Channel Relay	21.95 $
1	Metal Box	11.5 $
1	Current Sensor	9.95 $
2	Capacitor SPRAGUE 2µF, 250V	7 $
2	Capacitor 20 µF, 250 V	40 $
1	Capacitor 40 µF, 250 V	22 $
1	Capacitor 5 µF, 250 V	7 $
-	Miscellaneous	40 $
	TOTAL:	194.4 $

European Budget

Quantity	Description	Price ($)
1	Arduino Uno Rev 1	30 $
1	16-Channel Relay	21.95 $
1	Metal Box	11.5 $
1	Current Sensor	9.95 $
2	Capacitor SPRAGUE 2μF, 250V	7 $
2	Capacitor 20 μF, 250 V	40 $
1	Capacitor 10 μF, 250 V	10 $
1	Capacitor 5 μF, 250 V	7 $
-	Miscellaneous	40 $
	TOTAL:	177.4