Reduction of Harmonic Distortion in Off-Grid Renewable Energy Systems

Ahmed Habib
Jacob Lamb
Zach Ulibarri

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1. Executive Summary

The Pure Wave team's primary goal is to reduce the level of total harmonic distortion (THD) which is common in the power systems of off-grid homes. Although this objective has not changed, the method by which the team will be performing this task has changed since the original project proposal was submitted on December 7, 2012.

A new design, the shunt active power filter, is being pursued by the team due to its potential to significantly reduce harmonics. Although this new design is more expensive than the active third harmonic filter design previously accepted by the team, the shunt active power filter has the potential to be much more effective. Furthermore, only one shunt active power filter will be required for a system, whereas an active third harmonic filter would have been required for each non-linear load on a system. Parts provided at no cost by Northern Arizona University and M.S. Kennedy will ensure that the cost of constructing a prototype remains within budgetary constraints. Although the team has a final filter design, detailed in section 5.1.5, no method for controlling the filter has been decided upon. The team has several different ideas for how the transistors in the design can be controlled and simulations designed to determine which idea is the most effective are being created.

Significant changes from the originally submitted proposal can be found in the attached document. Specifically, the system diagram, found in section 2, has been modified to a shunt filter configuration to better demonstrate the final device being created by the team. Furthermore, the research survey, found in section 3, has been changed to reflect research conducted by the team since the end of the fall 2012 semester. This new research includes data on shunt active power filters as well as component costs found at various vendors. Mechanical specifications, found in section 4.1, have been changed to allow for a single device which reduces harmonics for an entire system. Design descriptions, found in section 5.1, have been updated to include subsection 5.1.5, detailing the shunt active power filter design. Design constraints, found in section 5.2, have been modified to reflect research which indicated component prices are higher than initially estimated. Furthermore, the manufacturability constraint, also found in section 5.2, was modified to include details about the manufacturability of a shunt active power filter design. Subsection 5.3.2 was added to the document to show the process by which the team determined the shunt active power filter to be superior to the active third harmonic filter. The team's budget, found in section 6, was modified from the original version to show which parts have been purchased and which parts have been supplied at no cost by various sources. A comprehensive test plan is included in section 7 of this document. The project schedule, found in section 8, has been modified to reflect delays in completing various tasks. Finally, because a signed acceptance document was never received, a modified acceptance document, found in section 11, has been included in this document.

2. Problem Definition

Off grid energy is frequently used in remote locations where it would be prohibitively expensive to connect to a conventional power grid. However, many of these systems experience problems when non-linear electrical devices that use pulse width modulation (PWM) to deliver power are connected to the system. Even when off grid systems use pure sine wave DC to AC inverters, PWM devices often create harmonic distortion in the voltage and current on the system's power lines. This distortion is also present in grid-connected power systems, but is much less apparent, as the strength of the grid often forces the signals back to near sine wave operation.

Since many inverters produce a sinusoidal waveform which is roughly 60 Hz, the 2nd harmonic component is 120 Hz, the 3rd harmonic component is 180 Hz, and the nth harmonic component is n*60 Hz. Ideally a power supply produces an undistorted 60 Hz pure sinusoidal voltage waveform, but several common household appliances, such as computer switched –mode power supplies and laser printers, draw power in brief pulses thereby distorting both current and voltage waveforms. Said another way, many common household loads (particularly those that use PWM) will create harmonics on the voltage and current waveforms when they draw power. Furthermore, these non-linear loads only create odd-integer harmonics. Total harmonic Distortion (THD) is used to quantify the amount by which a voltage signal is distorted. A large THD value indicates that a large portion of the voltage or current is not operating at the fundamental frequency, but rather an integer multiple of it.

Total harmonic distortion is an important concept to consider when designing electrical systems, as a high THD can cause increased temperatures in electronics thereby shortening their lifespan. Other consequences of a high THD include lower efficiency, an increase in core temperature of electrical motors (causing damage), damage to power systems, and potential interference with telecommunication devices if the harmonics exist at the same frequency as the transmission frequency. Thus, understanding and mitigating THD levels is essential if one wants to get the most from an off grid system. To this end, the team will be creating a device which reduces the voltage and current harmonics produced by a load. The device must work reliably with all common household appliances, be easy to use, and be safe for households with pets and children. Such a device would save the user money and benefit any off grid home by reducing THD, thereby increasing the lifespan of electrical devices and increasing power quality and efficiency in the off-grid system. Figures 1, 2, and 3 show how the system will reduce THD on the power lines in the off-grid system.

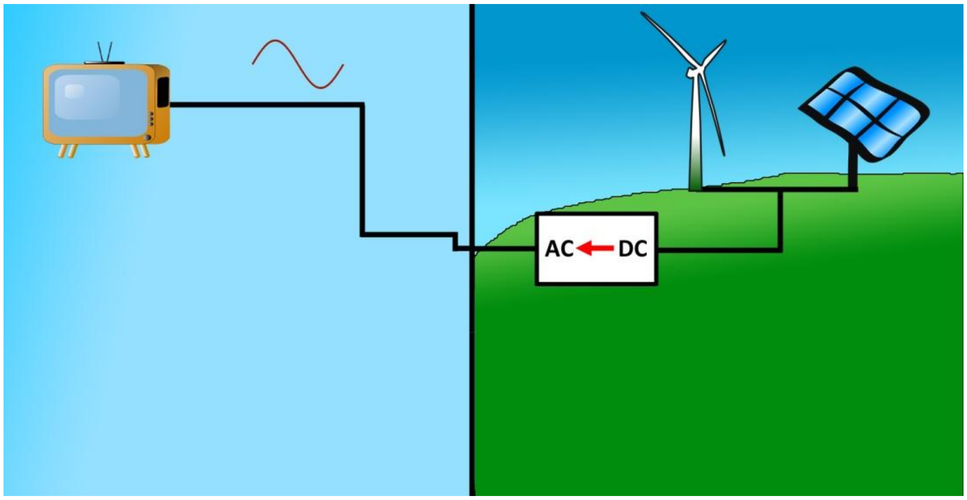

Figure 1: In normal operation, off grid inverters supply a pure sine wave to electronic devices.

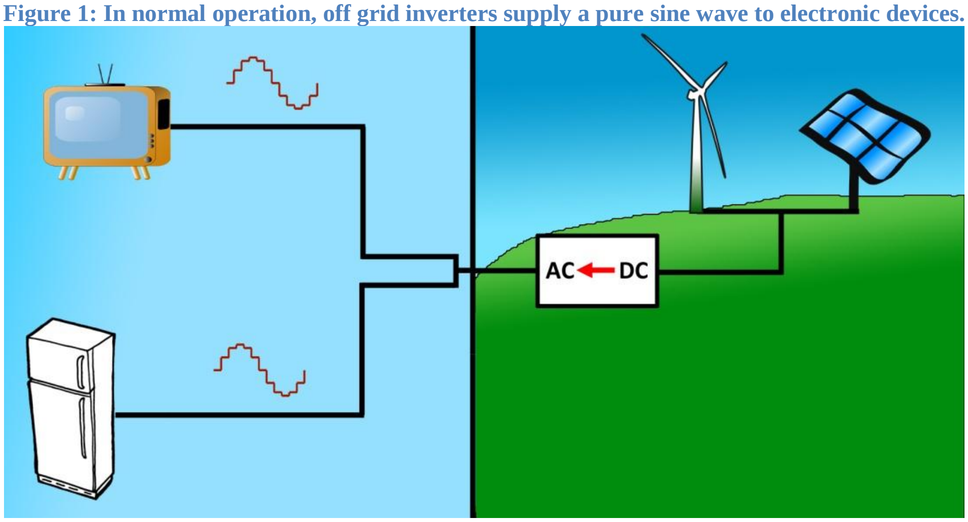

Figure 2: When non-linear loads are connected to the lines, the sine wave is distorted, resulting in diminished efficiency for other devices.

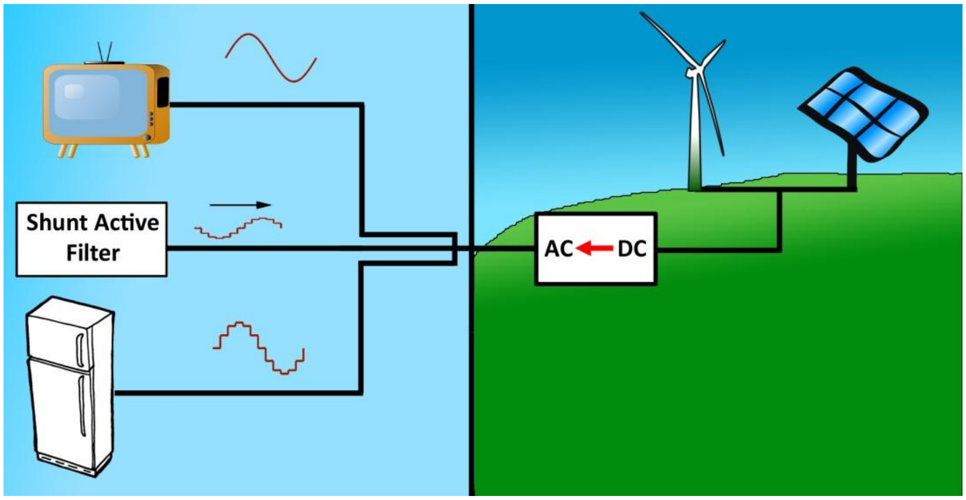

Figure 3: A shunt active power filter measures the distortion on the line and injects equal and opposite currents. The devices on the line then receive clean, filtered power.

3. Research Survey

Since the team's last research survey submittal on November 6, 2012, a significant amount of time has been spent researching filtering techniques. Although there are several filtering techniques readily available, the team investigated how filtering could be done both effectively and inexpensively. The method of frequency spectrum analysis was investigated, and the specific filtering techniques researched were unified power quality conditioners, passive filters, and active filters.

Although the voltage signals generated by power sources have always had harmonic components, the magnitudes of these harmonics were generally minimal, and their effects negligible, until the use of non-linear loads became common place in the 1960s. Non-linear loads draw current from the power source in a way which is not proportional to the voltage of the supplied waveform, often times drawing energy in short bursts, or pulses, of varying width instead [1]. A common technique for drawing power in such pulses is called pulse width modulation (PWM). It is noted, however, "An unfortunate side effect of their [PWM devices] usage however, is the introduction of harmonic distortion in the power system... These harmonics flow through the power system where they can distort the supply voltage, overload electrical distribution equipment (such as transformers) and resonate with power factor correction capacitors among other issues" [2].

The tendency for devices utilizing pulse width modulation to distort the voltage waveform supplied by a power source is well known, and the issue is addressed by several sources. IEEE standard 519 suggests that a voltage signal's total harmonic distortion (THD) is less than or equal to 5%, and that the largest single harmonic is less than or equal to 3% of the fundamental voltage. IEEE provides a partial justification of these limits, stating "Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences” [2]. Although compliance with this standard is voluntary, many efforts have been made to reduce the THD of systems. A simple observation provides an easy to implement method for controlling THD: "The key to controlling harmonic distortion is limiting the current pulses. This has been accomplished through the use of inductor coils, which may also be called reactors or chokes, on the input of the drive. The inductance of a coil creates a back electromotive force (emf), or voltage, as the current pulse passes through it. This reduces the rate of the current pulse" [3]. While the effects of this simple technique can be significant, and the improvement can be made without impacting the performance of the load, the THD of a system may still be well above those recommended by IEEE [3].

In addition to these DC link reactors, other techniques are used to reduce THD. The use of a 12 pulse transformer (12 pulse drive) design can reduce THD by approximately 90% by eliminating the 5th and 7th harmonics in the transforming windings [4]. This harmonic elimination holds in theory, but can be difficult to implement practically, as this elimination requires two rectifiers sharing current exactly [5]. If exact matching is impossible or impractical, research shows “a standard six-pulse drive fed from a low pass Matrix Filter provides superior harmonic performance to a twelve-pulse drive in applications with variable loads and line voltage unbalances ranging from 0% to 3%” [5]. It may also be possible to eliminate specific harmonics using trap filters, but these filters “may cause random circuit breaker tripping and blown fuses” [4]. Alternative, situation specific THD reducing techniques also exist, but they may not provide the functionality desired for this project.

One device used for THD reduction approaches the problem by simultaneously handling several different factors which can influence the functionality of a load. The Unified Power Quality Conditioner (UPQC) is a device which uses hybrid filtering techniques to correct several power quality issues. Among its uses, we find UPQC “can be used to compensate various voltage disturbances of the power supply, to correct voltage fluctuation, and to prevent the harmonic load current from entering the power system” [6]. Thus UPQC acts as a harmonic isolator, protecting sensitive equipment from other non-linear loads. It must be noted, however, that UPQC are custom devices which utilize multiple control systems and require several transformers. Therefore, although it appears UPQC can be used to greatly reduce THD and correct a myriad of other power quality issues, the required construction is both expensive and device specific and, as such, this THD reduction method is unsuitable for this project.

A graphical THD representation provides insight into methods which can be utilized to reduce distortion on a power line. Frequency spectrum analysis is used to measure the frequency response of a signal instead of measuring the signal's time response. Using this method, a sinusoidal signal which has a theoretically infinite time response (i.e. the signal is periodic) can be represented via a finite frequency response, making analysis simpler. Since harmonic frequencies are odd integer multiples of the fundamental frequency, frequency spectrum analysis reveals a response which only has non-zero values at 60 Hz, 180 Hz, 300 Hz, etc. The results of frequency spectrum analyses for various household appliances show a characteristic common to many, though not all, residential non-linear loads: the third harmonic, 180 Hz, is the harmonic frequency with the largest magnitude, and therefore contributes most significantly to THD [7,8]. Thus if the contribution of the third harmonic can be minimized, the THD of the system will be greatly reduced. A sample frequency spectrum plot of a 4-bulb CFL lamp connected to a pure-sine wave inverter in an off-grid home is shown in Figure 4. From this figure it is clear that the largest amplitude occurs at the fundamental frequency, 60 Hz. The other frequencies all contribute to harmonic distortion, with the largest component of this distortion coming from the third harmonic, 180 Hz.

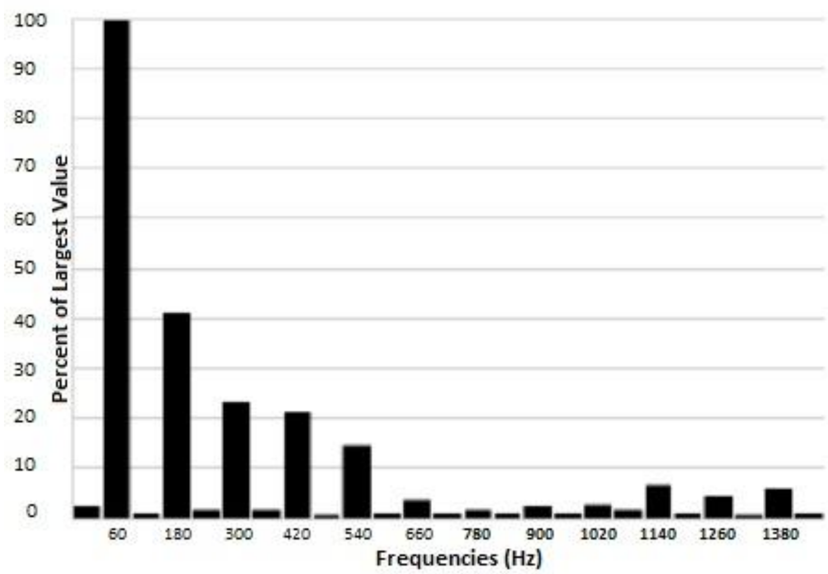

Figure 4: Frequency Spectrum Plot for 4 Bulb CFL Lamp [8]

Passive filters are the most basic way to remove unwanted frequencies from a signal. Passive filters use inductors, capacitors, and resistors tuned to the harmonic frequencies which are to be attenuated. In addition to removing harmonic frequencies, “well designed passive filters can be configured to provide power factor correction, reactive power compensation, or voltage support, […] and reduce the starting impact and associated voltage drops due to large loads” [6]. Furthermore, passive filters are relatively inexpensive and can be easily designed to pass specific frequencies and block others. However, passive filters have several limitations including their large size, variation in performance due to aging, and once a passive filter is installed the performance cannot be easily altered. These limitations led to alternative filters, such as active filter systems, to be sought [6,7,9].

When a filter uses an active component, such as an amplifier, it is called an active filter. Active filters can be specifically designed to remove unwanted harmonics. To do so, “an active harmonic filter injects harmonic current of opposite phase to the non-linear load current so that all harmonic currents are ideally cancelled and only the fundamental current is left to be supplied by the power system” [9]. Using active filtering to reduce THD can be much more effective than passive filtering when waveforms are highly distorted [7]. In addition to filtering unwanted harmonics, specific types of active power filters can be used to perform power factor correction [7,9]. Thus the performance and low cost of active filters [7] make them an effective means of reducing THD.

Research into active filters conducted during the 2012-2013 winter break led to the team finding papers focusing on filters specifically designed to remove harmonics injected by non-linear loads. Simulations run on these filters show the devices are extremely effective at reducing THD [10,11], and a filter designed correctly has “lower cost [compared to] passive filter, because the passive filter is tuned to eliminate a single frequency, but the active filter is suitable for all frequencies" [10]. The filter itself consists of four transistors in an 'H-bridge' configuration, as well as a DC voltage source connected in parallel with a capacitor, forming a DC-link. Hysteresis control methods can be used to control the transistor H-bridge [10,11], and a digital signal processor can be used to implement this hysteresis control. Hysteresis control requires an accurate measurement of the current being supplied to the non-linear load(s), a function which can be performed by Hall probes.

An investigation into component prices using websites such as Digi-key and Newark showed designs which can be used on and off-grid were more costly than originally anticipated by the team. Devices such as the aforementioned transistor H-bridge require driver circuitry for proper operation, and the high voltage drops inherent in devices designed to be used on the grid mean high break down voltages are required for many components, further increasing costs. Preliminary cost research indicated the most expensive component for any active filter design would be the required DC voltage supply with a high voltage output.

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4. Requirements and Specifications

The mechanical specifications section, section 4.1, has been changed significantly since the previous version of this report. Changes in this section account for new research and updated specifications based on new information.

Following is a set of requirements and specifications for the project that ensure the final device will meet the needs of the client, Dr. Allison Kipple. Specifications listed as “ideal” are the performance goals for the team, but may not be feasible. For this reason, “acceptable” specifications are given. All “acceptable” specifications must be met if not exceeded.

4.1 Mechanical

Mechanical specifications have been modified to allow for a larger device. Further, the number of outlets previously listed as a specification is no longer included. Both of these previous specifications were intended to describe a device that would be used in series with an electrical device. Since that time the requirements have been modified to allow for a device that attaches to the power lines rather than individual electronic devices and removes THD for the entire system. This change was approved by the client.

The device created by the team must be able to be connected to an off grid power system. The actual circuit must be contained in an enclosed box, and this box will have mounting brackets attached to help provide a user with more placement options. Since this product is designed for household use, it must be child proof and pet proof. That is, the device should be safe and tamper proof. The specifications for weight and size of the product can be found in Table 1. The upper limit of 3 cubic feet and 50 pounds accounts for the large DC power supply used in active filter designs.

Table 1: Table of mechanical specifications.

	Size	Weight
Ideal	1’x1’x1’	20 lbs
Acceptable	3'x3'x3'	50 lbs

4.2 Electrical

Any appliance which can be plugged into a standard North American wall outlet must operate as expected when the device is being used to reduce the appliance's THD, and as such, the device must handle a wide array of devices. The THD reducing effect of the device must consistently reduce the THD of any appliance attached by at least 25%. In order to protect against current surges, the device will feature a simple fuse as they are less expensive than circuit breakers. A table of additional electrical specifications can be found in Table 2.

Table 2: Table of electrical specifications.

	Voltage Range	Current Range	Lifespan	THD Reduction
Ideal	110-130 V RMS	>30 A	10 Years	25%
Acceptable	115-125 V RMS	>20 A	5 Years	15%

4.3 Environment

The device is designed for indoor use, but should be rugged enough to operate in hot, humid climates as well as cold, dry climates. To ensure proper operation in humid conditions the product must be moisture resistant. Furthermore, minor perturbations (e.g. small vibrations, falls from distances of less than 2 feet) should not alter the functionality of the device.

4.4 Documentation

Documentation provided with the final device will include a user's manual detailing appliances which will benefit from using the device (i.e. which appliances are non-linear loads). In addition, the manual will have safety precautions and a troubleshooting guide. Furthermore, the device will have information regarding input/output voltages, currents, frequencies and any other relevant electrical information imprinted, as is standard with many electrical products. Finally, as mentioned in the mechanical section the device will be designed to be tamper proof, therefore the team expects no maintenance manual to be offered.

4.5 Miscellaneous

If time permits, the team will also give the client a short report on the effect of using capacitors and super-capacitors to mitigate transients in off-grid battery systems, in addition to creating a THD reducing device. The data from this report will be gathered by the team during the spring 2013 semester at various off-grid homes using equipment provided by the client. In order to fully study the topic, testing will be performed at two or more off grid residences. Houses with more modern inverter topologies will be preferred testing sites for this side project.

4.6 Testing

In order to ensure the final product reduces THD, a power quality meter will be used to measure THD for a range of devices with and without the product. The power meter will be supplied by the client and appliances tested will be those commonly found in off-grid households. The devices to be tested are incandescent, CFL, and LED light bulbs, a vacuum cleaner, a laptop, and a microwave oven. These appliances will be supplied by Northern Arizona University and will be tested in the solar shack operated by the engineering department. After the product has been shown to be successful, the appliances may be tested again in an off-grid system.

5. Design

5.1 Design Descriptions

Several different approaches to solving the problem were considered. Brief descriptions of each of the designs are offered below. This section of the proposal has been updated to include section 5.1.5, the shunt active power filter.

5.1.1 Inductive Reduction

Research has shown that placing an inductor in series with a non-linear load can reduce THD. This design is also effective at reducing large surge currents which can be troublesome in off-grid residences. The inductive reduction design uses a minimum of components to achieve some measure of THD reduction. The design would be much better suited to individual appliances during testing, as the component values can be easily changed as required. This would allow a large number of tests to be performed to empirically determine optimum results.

5.1.2 Passive Filtering

Although the inductive reduction technique can be effective, the limited complexity of the design hampers its potential THD reduction, and thus filtering techniques were considered as a more effective alternative. A filter is a circuit that is designed to eliminate certain frequencies of electricity. Specifically, a passive filter uses resistors, inductors, and capacitors to remove undesired frequencies. The passive filter design will be to build a simple filter to eliminate the frequencies that cause the most THD. Two primary sub-designs were considered: the third harmonic filter, and the multiple harmonic filter.

The third harmonic filter is designed to only attenuate the third harmonic frequency of electricity, 180 Hz. By eliminating this frequency, it is believed that THD can be reduced by a large degree without significant effects on the response of the device being filtered, as the third harmonic typically has the largest magnitude.

The multiple harmonic filter is designed to eliminate the third, fifth, and seventh harmonics. This will greatly reduce the THD in the circuit, but may cause large power loss or voltage drop. If voltage drop is an issue, the selected design will be modified to include a microcontroller that boosts voltage to an acceptable level.

5.1.3 Active Filtering

An active filter uses operational amplifiers to remove harmonics. This can make the device smaller or give operating characteristics that would be expensive or dangerous in a traditional passive filter (e.g. large capacitors used in passive filters can present a safety hazard even after the device is powered off). In addition, the active filter can give a gain factor greater than 1, while the passive filter necessarily drops power and voltage. As with the passive filter, both third harmonic and multiple harmonic filters with optional microcontroller voltage boosters were considered.

5.1.4 Unified Power Quality Controller

The Unified Power Quality Controller (UPQC) is a relatively new device typically used in precision-machinery, such as those found in hospitals. This device uses series-active and shunt-active filters in addition to transformers to solve voltage and current harmonics. Given that a large number of components are used in the construction of such a device, this is the most complicated and expensive design considered.

The UPQC is primarily designed to provide high quality power to sensitive loads rather than eliminate the harmonics generated by various devices. For this reason, the existing designs would be modified to better suit the intended goal of the project, which is to isolate devices that cause harmonic distortion from the rest of the power line. An example schematic of a UPQC is presented in Appendix A.

5.1.5 Shunt Active Power Filter

The shunt active power filter is a design being considered after research indicated that it is very effective in countering harmonic distortion. The shunt active power filter uses four transistors in an H-bridge configuration. These transistors are connected to a DC link and a controller to control current on the line via a hysteresis band. That is, the controller compares the waveform on the lines against a clean 60-Hz signal and switches the transistors on and off as needed to inject current into the system.

5.2 Design Constraints

The design constraints that have been updated are cost (5.2.1) and manufacturability (5.2.3). Each modified section contains addendums to previously submitted data.

5.2.1 Cost

Since all designs except the shunt active power filter are intended to be used in conjunction with multiple devices in the home, the device must be made inexpensive enough that the average off-grid home owner would be able and willing to purchase one unit for each device which injects current harmonics, thereby creating harmonic distortion. The shunt active power filter must be made inexpensive enough that one can be purchased by the average off-grid home owner.

The passive and series active filtering designs would likely be very comparable in terms of cost. Although the passive filter requires large inductor and capacitor values for the high cutoffs and low frequencies used, many series active filter designs require power MOSFETs as well as a high DC voltage supply, both of which can be expensive.

The inductive reduction design uses a minimal number of components, and so this design would cost much less than the other THD reducing techniques.

The UPQC design is by far the most expensive of the proposed designs. This THD reduction technique relies on shunt capacitors with large values as well as several transformers and controllers, making the cost of components considerably higher than those used in any of the other designs. The cost of such a device makes it useful only for specialized applications where high quality power is needed, such as in industrial and hospital settings. As such, the cost of the UPQC makes the design unfeasible.

However, research conducted after the last version of this report was submitted indicated that components suitable for grid-level power are considerably more expensive than previously anticipated. Components such as capacitors and inductors must be capable of passing large currents at high voltages. Further, the DC supply required for active filtration must be capable of high voltage and current in order to be effective.

The shunt active power filter will be more expensive than the basic filter designs, but will still be less expensive than the UPQC. However, because only one device will be needed for an off-grid system, its high cost does not render it unfeasible.

5.2.2 Health/Safety

The device is meant to be left in a home unattended, and should therefore be safe in the presence of children and pets. Since the inductive reduction design only uses inductors there is no safety concern with this approach to reducing THD. Both active filter designs are likewise very safe devices, as they can be easily contained in a tamper-proof box. The passive filter design may contain large capacitors which are potentially dangerous even after the device has been unplugged, although it too can be easily contained in a small box. The UPQC design requires the use of large capacitors as well as transformers, which have very high voltage at the terminals. If either of these components became exposed, it would present a significant danger to anyone that might touch the device. For this reason, a very large, tamper-proof container would be needed. Because of the large number of components contained within this box, heat dissipation would be a further problem.

5.2.3 Manufacturability

In order to operate with the desired high cutoff response, the passive filter and inductive reduction circuits would depend on capacitors and inductors. If the values of these components vary, the response of the filter would change. As inexpensive capacitors and inductors are only specified to within 10%, achieving high precision may be difficult when the devices enter production. By comparison, the active filter uses components which can be specified to better accuracy, making the device easier to manufacture. However, since very few components are used in constructing the inductive reduction design, it maintains a slight edge in terms of manufacturability. The UPQC design will feature a large number of precision devices and will need to be custom designed, making it very expensive to manufacture.

Research has indicated that the shunt active power filter design will not require inductors or capacitors specifically tuned to harmonic frequencies. Therefore the shunt active power filter will not require components with low tolerances, and so manufacturing devices will be easier. Components such as the DC supply required for the shunt filter will be expensive but, if purchased from a supplier, will be simple to assemble with the filter. A printed circuit board would make manufacturing the device easier, but designing this piece would initially require a considerable amount of effort.

5.2.4 Social

One significant challenge in making the final product a success is being able to communicate its effectiveness to the average consumer. One might think people living in off-grid homes know more about power than the average person, but this is unfortunately not the case. In order for the device to be profitable, the average user must be able to understand the benefits of using it in their daily lives. In order to effectively communicate how the device will be useful, the packaging must explain, in layman’s terms, how the device will increase the life expectancy and efficiency of every appliance being powered. The nontechnical diagram presented in the problem statement of this document will not be useful, as that explains what the device does from an electrical standpoint, rather than the benefits of the device in terms that the average person would understand. In addition to a brief summary of benefits on the device packaging, a user's manual which provides detailed benefits of using the device must be created and included with the device.

5.3 Design Selection

This section has changed considerably since the initial project proposal was submitted. Although the original selection process has been included for completeness, section 5.3.2 added at the end of this section details changes in the final design selected by the team.

5.3.1 Preliminary Design Selection

Based on the different designs that the team came up with, the third harmonic active filter was originally deemed the best THD reducing method. This decision was made based on the decision matrix presented in Tables 3 and 4. However, since the shunt active power filter has since been considered, a second decision was made that compared the third harmonic active filter to the shunt active power filter. It was decided that the shunt active power filter would suit the client's needs best. Thus, the shunt active power filter was selected according to the decision matrix found in Table 5. Table 3 illustrates the initial design decision.

Table 3: Decision Matrix for Overall Design

Design	Effectiveness (2)	Cost (1)	Safety (1)	Manufacturability (.7)	Size (.5)	Score
Inductive Reduction	1	10	10	10	10	34
Passive Filtering	7	9	6	7	8	37.9
Active Filtering	**8**	**9**	**9**	**9**	**9**	**44.8**
UPQC	10	1	4	1	3	27.2

Each preliminary design was rated in 5 categories. Each design was given a score of 1-10 based on its performance in that category. High scores denote better performance. Each category further has a weight associated with it, which is given in parentheses under the category. For example, cost was considered to be far more important than size, so cost is weighted at one while size is weighted at one-half. The score for each category is multiplied by the weight, and the sum of these gives the score for each design. Because the active filter design received the highest score, it was chosen as the preliminary design.

Effectiveness was selected as the most important category, and so it is weighted twice as much as cost or safety. The UPQC design was given the highest score in the effectiveness category due to its ability to improve power quality in nearly any application. The two filter designs, however, are projected to be effective solutions to the problem, and thus received high scores as well. The inductive reduction method received the lowest score, as it achieves comparatively low THD reduction.

In terms of cost, the active filter and passive filters both received high scores, as detailed in section 5.2.1. The inductive reduction design was given the highest rating, as it uses the fewest number of components.

The inductive reduction design was given the highest safety score as it only features a single inductive element. The active filter was given a high score because it has few dangerous components. It will include capacitors, but these will be of small value and present little danger to any user that may accidentally touch them. The passive design was considered to be slightly hazardous due to the potentially high-valued capacitors and inductors within it. The UPQC design contains numerous dangerous components and as such, received a very poor safety rating. Further detail can be found in section 5.2.2.

Although important, manufacturability was considered to be less important than the three previous categories because manufacturing difficulties will increase unit cost, but not to the same degree as the component cost. The inductive reduction design was once again given the highest score due to its minimal complexity. The active filter received the second highest manufacturability score because it again features a relatively small number of components, as described in section 5.2.3. The UPQC received a very low score due the large number of components and the fact that it must be designed for appliance-specific applications.

Lastly, size was given a weight of one-half because it is not as critical to the device's operation or marketability as the other categories. The inductive reduction design would likely be the smallest to make, so it was given the highest score. The UPQC design's large component list makes it very large in comparison to the other designs, and thus it was given a very low score. The two filter designs were given relatively high scores, as they are not expected to take up a large amount of space. Because the active filter relies on an op-amp in lieu of passive elements, it is predicted to be slightly smaller than the passive filter design.

As the filter design had two sub-designs, third harmonic filtering and multi-level filtering, a second design matrix was created to determine which of these methods would be most suitable for the project. This matrix is found in Table 4. The third harmonic filter was chosen as it scored higher than the multi-level filter. However, the multi-level filter design may still be implemented as a contingency if the third harmonic filter underperforms.

Table 4: Decision Matrix for Filtering Technique

Design	Effectiveness (2)	Cost (1)	Safety (1)	Manufacturability (.7)	Size (.5)	Score
Third Harmonic Filtering	**7**	**10**	**9**	**8**	**9**	**43.1**
Multi-Level Filtering	10	7	7	5	5	40

The third harmonic filter scored highest in cost because it will use fewer components than a multi-level filter. Because of this reduced components list, it will also be smaller and easier to manufacture. It will also be slightly safer owing to the fact that it will have less capacitors. The multi-level filter will be more effective than the third harmonic filter because it will filter out all harmonics rather than just the largest, the third harmonic. This will result in a larger reduction of THD in the system. Thus, the third harmonic filter received higher scores in all categories except effectiveness.

Because the third harmonic active filter design scored the highest across the two design matrices, this is the design that was chosen as the preliminary solution to the problem.

5.3.2 Updated Design Selection

The team extensively researched the shunt active power filter during the 2012-2013 Winter Break, decided to compare the design to the previously selected active third harmonic filter. The two designs were compared using the same criteria initially established to compare designs.

Furthermore, research conducted during the break indicated that the active third harmonic filter would be considerably more expensive and larger than initially expected. This new data is included in the updated decision matrix. The decision matrix evaluating the shunt active power filer and the third harmonic active filter can be found in Table 5.

Table 5: Decision Matrix for Updated Designs

Design	Effectiveness (2)	Cost (1)	Safety (1)	Manufacturability (.7)	Size (.5)	Score
Shunt Active Power	**10**	**7**	**9**	**8**	**9**	**46.1**
Active Third Harmonic	5	10	9	8	9	39.1

While the active third harmonic filter would negate the most prominent harmonic, the shunt active power filter would compensate for all harmonics on the line. For this reason, the shunt active power filter was given a larger effectiveness score than the active third harmonic filter.

The shunt active power filter would be more expensive to construct than the active third harmonic filter, but this increase in cost is mitigated by the fact that only one device would be needed per off-grid system while one third harmonic filter would be needed for each electronic device on the line.

Both types of filters would contain capacitors and inductors of similar values, so both designs were given the same safety score. Additionally, the number of components for each device is similar, so each device received the same manufacturability and size score.

The shunt active power filter scored higher than the active third harmonic filter, and thus it will be the design that is constructed.

Two methods designed to control the shunt active power filters are currently being investigated. The first uses a simple comparator to determine when the transistors should be on or off. This method is unproven but simpler than the alternative, which is to use a digital signal processor (DSP) to control the transistors. Both control methods will be investigated, as approved by the client.

6. Budget

The budget for this project will cover the cost of electronic components used by the team in construction of the prototype as well as travel costs. The proposed budget for the project is $181.82. An itemized list of costs is presented in Table 6.

The client will pay for all costs associated with the project. The team will submit itemized lists of components to the client along with potential suppliers, and the client will then order the components and make them available to the team. Travel costs will be reimbursed to the team by the client upon submission of receipts of fuel bills.

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Table 6: Proposed Project Budget

Item	Unit Cost	Quantity	Total Cost
Hall Probe	$16.35	2	$32.7
Inductor	$2.09	1	$2.09
Capacitor	$7.03	1	$7.03
Controller	$100.00	1	$100.00
Travel			$40
Total Project Cost			**$181.82**

The client has already ordered the hall probes, capacitor, and inductor. The controller has not yet been ordered as its design has not yet been finalized. The $100 estimate is based upon the best information available to the team at this time, and is sufficiently high to allow both previously mentioned control methods to be investigated.

As already stated, the budget includes funds for travel to various off grid homes in the Northern Arizona region. The team will have to travel to these locations to complete the field work portion of the capacitor research as well as to potentially test the final device in an off-grid environment. The total of $40 was chosen as a rough estimate as the team does not currently know how many trips will be made or the distance travelled in each trip. The client will supply the team with a power quality meter for testing purposes when the first prototype device is completed.

Northern Arizona University will supply computers and software for the team to perform design simulations. Specifically, PSpice will be provided by NAU to perform simulations of the device. Additionally, MultiSim will be provided by the team to provide further analysis. Northern Arizona University will supply the team with various electrical devices to be tested in the solar shack. Northern Arizona University will further provide a 120v DC power supply to the team. This DC power supply will be used in the DC link part of the final design.

MS Kennedy will supply the team with two transistor H-bridges at no cost. The two H-bridges have different characteristics such as breakdown voltages, throughput currents, and transistor type. Testing will determine which H-bridge will be used in the final design. These items have not yet been received.

7. Testing

Preliminary simulations are currently being performed in PSpice and MultiSim. Jacob Lamb is using PSpice, provided by Northern Arizona University, to estimate the shunt active power filter's THD reduction ability. Ahmed Habib is using his own copy of MultiSim to perform similar tests.

Jacob Lamb's PSpice simulation is not currently running due to an inability to simulate the transistor H-bridge configuration. It is expected that the simulation will be completed by early March.

Ahmed Habib's MultiSim simulation is similarly is being hampered by inability to simulate H-bridge transistors. This is being overcome by using circuitry meant to mimic the H-bridge. This simulation is nearing completion, but is currently being debugged.

As the device has not yet been constructed, there has not been any testing to date. When the first prototype has been constructed, the shunt active power filter's THD reducing ability will be tested at the Northern Arizona University solar shack. This shack contains solar panels and several wind turbines and can be configured to operate in both on and off-grid setups.

As stated previously, the devices that will be tested are incandescent, CFL, and LED light bulbs, a microwave oven, a vacuum cleaner, and a laptop. These devices will be supplied by Northern Arizona University.

The client has provided a Fluke 43B power quality analyzer. This device is capable of measuring harmonics and transients on a line. The supplied electronic devices will be plugged into the solar shack and their effect on current harmonics measured with this power quality analyzer. The shunt active power filter will then be added to the system to determine its effectiveness in reducing THD for each device. Once individual tests have been conducted, several devices will be connected simultaneously to determine the shunt active power filter's ability to regulate larger arrays of objects, as would be the case in an off-grid home. These tests will be performed by all team members.

Once it has been established that the shunt active power filter is working, it may be tested at actual off-grid homes in the Flagstaff area. Any such additional tests will be performed at the discretion of the client.

The two control methods that are being investigated, direct control and DSP control, allow for contingencies should one method fail. Ideally, simulations should ensure no such issues arise.

8. Schedule

Changes to this section of the report include a modified Gantt chart as well as new details concerning the delays, new tasks, and all incomplete work. This new information can be found in section 8.2.

8.1 Original Schedule

At the time of the writing of the original proposal, the team had completed its initial research to see how other groups have attempted to solve the problem in the past, as well as what level of success each group achieved. It has been noted that active filtering has been used with some success in larger scale applications, and UPQC systems have been very successful in sensitive systems, albeit at a large cost.

The team will continue to research possible solutions to the problems, and will give the client the preliminary parts list over NAU's winter break. The client will order the parts so that the team will be able to begin construction as soon as the spring semester begins.

Ahmed Habib will be in charge of the technical design aspects and will, with the help of the other members of the team, continue to update the designs as new information becomes available and testing begins to offer feedback on the designs.

Jacob Lamb will be in charge of documenting the process and maintaining the website. He will add new information to the website and ensure that all the data received from testing the prototypes is correct and maintained.

Zach Ulibarri will be in charge of writing the report and will be the primary point of contact with the technical advisors and the client. While Jacob and Zach will serve as the primary authors for the final report and any additional documents that will be written over the course of the project, Zach will serve as the primary editor and will compile all individual contributions. All three members will contribute to the field work related to the capacitor research. The report will be primarily authored by Jacob.

A Gantt chart of the proposed project schedule can be found in Figure 5. Additions to the Gantt chart are the new subtasks, filter and controller prototype construction. Further, the dates of the prototype task have been altered to correct for delays, and the capacitor research task has been moved back approximately 1 month.

8.2 Schedule Changes

During the time remaining for this project the team has several tasks which must be completed. These remaining tasks are:

- Test the two control methods and decide which will be used in the final design
- Construct the first prototype
- Test the final design
- Complete of the website
- Prepare the final report and presentation

Progress made on specific tasks is detailed below.

The initial goal of having the first prototype completed by the end of January has not been met. Due to the change in design from the active third harmonic filter to the shunt active power filter, parts were not ordered until February. As these parts come in, initial construction will begin. The final filter design has been completed, but no final control method has been decided upon. At the time of this writing, controller simulations have begun and parts for the filter have been ordered. Construction will begin once all parts have been received.

The first prototype will be constructed by all three team members beginning in early March 2013. All three team members will also built the two filter controllers in March 2013. These two devices will then be tested with the filter prototype to determine which will be the most effective. The final design will be based on the tests performed on the prototype. Once testing has confirmed the device is operational and a control method has been selected, it will be further tested by all team members to ensure that optimum performance has been achieved.

The website has been started, with the splash, team, project description, problem definition, and proposal pages already completed. The website will be completed by Jacob Lamb as more relevant data becomes available. Updating the website will be an ongoing task until the 22^{nd} of April.

All three team members will be writing the final report until it is submitted on May 2nd 2013. This report will contain information about the device, such as its intended function, design, testing methods, and results. Zach Ulibarri will be the editor of the document.

Finally, all three team members will be involved in creating the final presentation. This presentation will be started in April and completed before the UGRADS presentation at Northern Arizona University.

Because the primary focus of the team is the reduction of harmonic distortion in off-grid energy systems, the capacitor research task was moved back to allow the team to focus on prototyping the shunt active filter. The capacitor research field work will be done primarily by Zach Ulibarri and Jacob Lamb. This research will be carried out during March and April, and data received will be forwarded to Ahmed Habib. All three team members will then work together to create the capacitor research report, but the primary author of this report will be Jacob Lamb.

Task Name	Duration	Start	Finish
Research	141 days	Mon 9/3/12	Mon 3/18/13
Design	147 days	Thu 9/20/12	Fri 4/12/13
Simulation	108 days	Thu 11/1/12	Sun 3/31/13
Prototype	**48 days**	**Wed 2/6/13**	**Mon 4/15/13**
Order Parts	1 day	Wed 2/6/13	Wed 2/6/13
Initial Construction	11 days	Fri 3/1/13	Fri 3/15/13
Filter Prototype Construction	5 days	Fri 3/1/13	Thu 3/7/13
Controller Prototype Construction	11 days	Fri 3/1/13	Fri 3/15/13
First Prototype Completed	0 days	Sat 3/16/13	Sat 3/16/13
Final Prototype Completed	0 days	Mon 4/15/13	Mon 4/15/13
Testing	22 days	Sat 3/16/13	Mon 4/15/13
Capacitor Research	**31 days**	**Mon 3/18/13**	**Mon 4/29/13**
Field Work	20 days	Mon 3/18/13	Fri 4/12/13
Capacitor Report	26 days	Mon 3/25/13	Mon 4/29/13
Website	**123 days**	**Thu 11/1/12**	**Mon 4/22/13**
Splash Page	13 days	Thu 11/1/12	Mon 11/19/12
Team Page	20 days	Tue 11/20/12	Sat 12/15/12
Project Description	20 days	Mon 12/17/12	Fri 1/11/13
Design Process	**90 days**	**Mon 12/17/12**	**Fri 4/19/13**
Problem Definition	20 days	Mon 12/17/12	Fri 1/11/13
Proposal	20 days	Mon 12/17/12	Fri 1/11/13
Detailed Design	15 days	Mon 4/1/13	Fri 4/19/13
Testing	57 days	Thu 1/31/13	Fri 4/19/13
Final Product Page	6 days	Mon 4/15/13	Mon 4/22/13
Final Presentation	8 days	Tue 4/16/13	Thu 4/25/13
Final Report	154 days	Mon 10/1/12	Thu 5/2/13

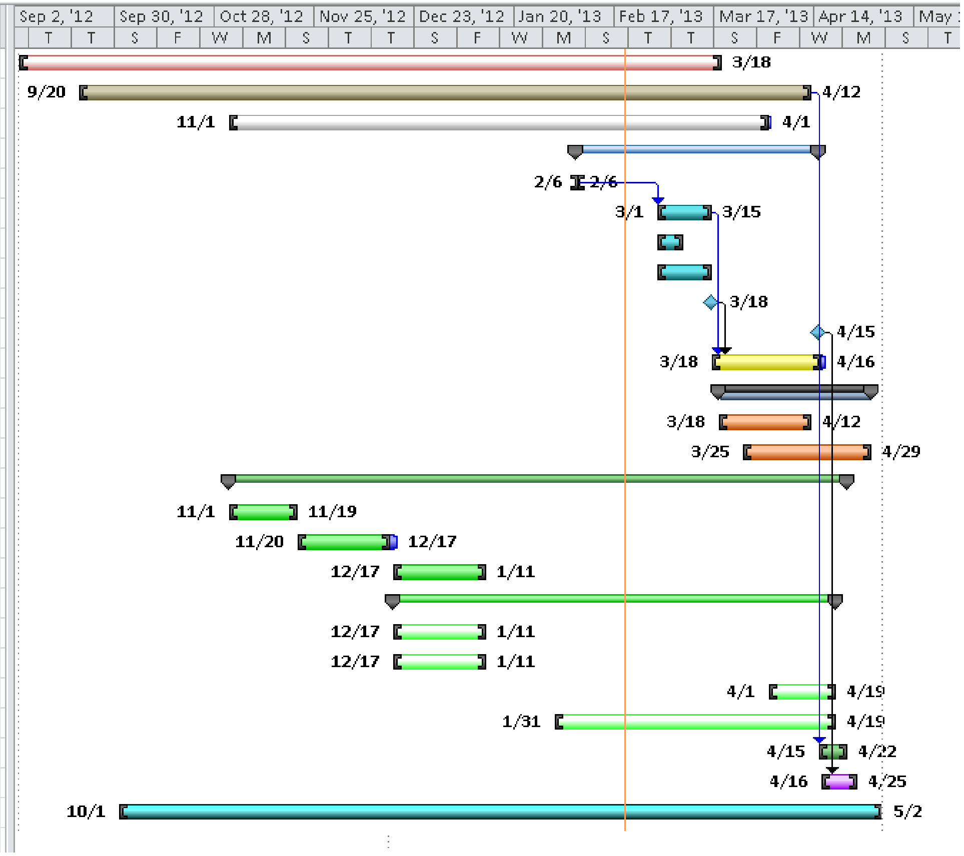

Figure 5: Updated Project Gantt Chart.

9. Deliverables

Several items will be given to the client as deliverables. The final project report will detail the final design and the specifications of the device created by the team. This will include a fair amount of scientific data that explains how the device works as well as how effective it is in terms of the THD reduction across the tested devices. This report will be emailed to the client on May 3rd, 2013.

The other primary deliverable is the prototype device itself. This device will be the test bench used to determine if THD reduction met the required specifications. The prototype will ideally be made to the same specifications as the final product is intended, but may merely be a proof of concept prototype. This prototype will be given to the client on May 3rd, 2013.

Furthermore, if time permits the team will present the client with a short technical report on the methods used to test the effect of capacitors and super-capacitors on battery transients in off-grid systems. This report will be submitted prior to May 3rd, 2013

The team will also create a website showcasing the design process as well as the results of the shunt active power filter. This website will be stored on NAU's servers and will offer basic and technical information on the filter. This website will be completed by April 22nd, 2013.

Lastly, the team will prepare a design presentation that will be given at the NAU Undergraduate Research and Design Symposium on April 26th, 2013. This presentation will give an overview of the system and the results of the shunt active power filter.

10. Appendix A: UPQC Example Schematic

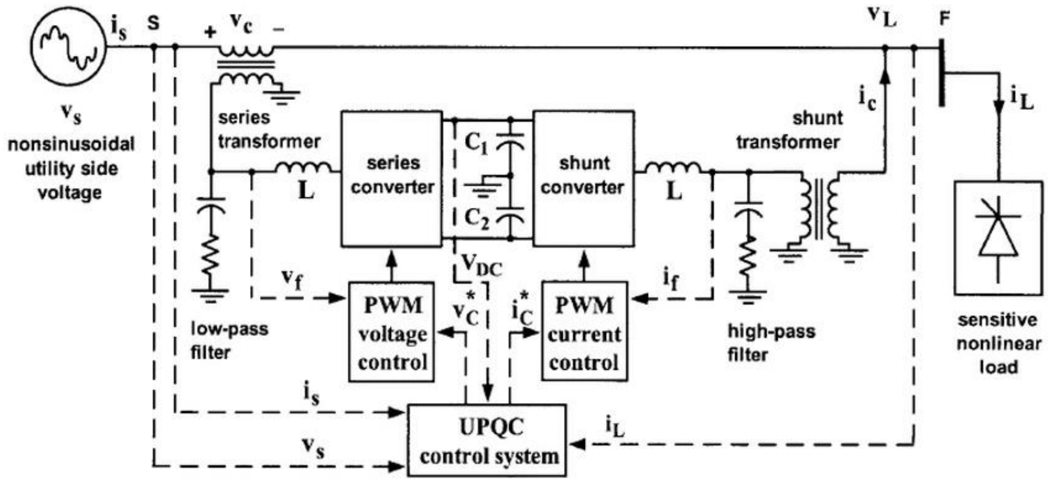

FIGURE 11.2 Detailed configuration of the right-shunt UPQC.

This schematic was printed in *Power Quality in Power Systems and Electrical Machines* by E. F. Fuchs and M. A. S. Masoum. Page 447.

11. Acceptance Document

If all terms and conditions presented in this proposal are acceptable, please sign and return this document before March 15, 2013. By signing the document below, the signer is agreeing to all responsibilities, specifications, and deadlines presented in the proposal. If any changes to this document are required prior to signing, please contact the Pure Wave team leader, Zach Ulibarri, by emailing Zach.Ulibarri@yahoo.com.

Proposal Alterations

After this document has been signed the Pure Wave team is under no obligation to accept any project changes, and, once this proposal has been accepted, any changes to the responsibilities or duties to be performed by the team must be approved by both parties.

Product Ownership

Upon completion of this project, any device or designs created by the Pure Wave team in an effort to resolve the problem presented will become the intellectual property of Dr. Allison Kipple.

Cessation of Duties

Pure Wave team members are no longer obligated to continue work on the project described in this proposal once the proposed project end date, May 3, 2013, has been reached. Any duties performed by team members after this date are voluntary and ownership stipulations described in this document may no longer apply.

Team Signatures

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Name Date

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Name Date

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Name Date

Sponsor Signature

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Name Date