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*Growth of Power Electronics: The Effort Required to Mitigate the Harmonics*

Khalid Alexander Tayani

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Department of Electrical and Computer Engineering

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Growth of Power Electronics: The Effort Required to Mitigate the Harmonics

Harmonic Filtering

Khalid Alexander Tayani
Department of Electrical and Computer Engineering
UMKC
Kansas City, Missouri
Dr. Faisal Khan – Adviser

Abstract—Power Electronic (PE) devices are welcomed and have improved human lives substantially, but the harmonics produced are a bane to our power systems. This paper details the growth of PE devices and the effort required to mitigate its harmonics. A special filter is studied and experimented to minimize the Total Harmonic Distortion (THD) of nonlinear loads. Nonlinear loads are created from PE equipment which may be used to convert energy from AC and DC power forms. Experiments are performed with a parallel-passive filter (PPF). The PPF consists of an inductor and capacitor in series to act as a low impedance bridge to the flowing, damaging harmonics in our power distribution networks. This paper proves the PPF may be used to mitigate distortion of current waveforms and minimize THD percentages, saving the lives of various electrical equipment.

Keywords— harmonics; filter; power; electronics; nonlinear; voltage; current; distortion; parallel; passive; active; hybrid

I. INTRODUCTION

Harmonics are oscillations where each oscillation is an integral multiple of the same fundamental frequency. In lenient terms, harmonics are simply the product of the fundamental frequency and the specific integer of each harmonic oscillation, ranging from zero to infinity [1]. For example, the United States has a fundamental frequency of 60 hertz, and the fifth harmonic associated with this fundamental frequency would be equal to 300, or the product of 60 and 5. There are even harmonics and odd harmonics. A man by the name of Jean-Baptiste Joseph Fourier discovered a technique to write an equation for the distorted sine wave created by harmonics. This technique proves all even harmonics to zero out, where only odd harmonics remain. Odd harmonics are the bane of our power systems, most specifically the fifth and seventh harmonics, and must be filtered out to mitigate distortion of sine waves in the power distribution networks.

Power Electronic (PE) devices create these harmonics. PE devices are classified by the nature of current entering and leaving each device. These devices are used for controlling voltage and power levels. They are used in circuit theory, electrical machines, control systems, logic electronics, microprocessors and microcontrollers [2]. There are four possible forms of conversions and inversions, once again all depending upon the nature of alternating current (AC) and direct current (DC). An AC to DC device consists of phase controlled devices such as mobile and laptop chargers. A DC to AC device consists of inverters including voltage, current, and frequency components to alter the speed control of motors, both synchronous and induction. A DC to DC device is labeled as choppers pertaining to voltage, including trolley cars or DC chargers, or infamous converters such as the buck and buck-boost converters used to step up/down voltage levels. Lastly, AC to AC devices consists of AC voltage controllers, depending upon the frequency, such as variable frequency drives (VFDs) controlling the speed of both induction and synchronous motors if there is no change in frequency, and cycloconverters if there is a change in frequency [2]. All of these types of PE devices are sources of harmonic current distortion, negatively affecting various power equipment.

PE devices can be classified as nonlinear loads, meaning the current does not follow the same sinusoidal voltage. Nonlinear loads, harmonics, cause stress, and are mostly thermal [3]. They cause distortion of current waves, which results in line losses, equipment damage, increased power costs, wasted energy, increased utility current requirement, component overheating including distribution transformers and generators and wires, reduced utility power factor, and equipment malfunction [4]. This begs the question, how much is too much? There is something called Total Harmonic Distortion (THD), and is referenced to indicate how large this THD percentage must be to specific types of loads. This standard is titled IEEE 519. It provides compliances for both voltage and current distortions. This paper will focus primarily on the current distortions.

The max THD for hospitals and airports, according to IEEE 519, is only 3%, where the max THD for dedicated systems such as converter loads is 10%. Adding nonlinear loads, PE devices, to critical loads including hospitals results in higher THD, and must be reduced. To reduce the THD of a system, engineers must install either passive and/or active filters to act as a bridge or block to mitigate harmonic current distortion, or act as a cancellation method to eliminate such harmonics.

II. OVERVIEW OF PASSIVE AND ACTIVE FILTERS

A. Passive Filters

Passive filters are bridges and/or blocks to mitigate harmonic current distortion. They can be aligned in either a series or parallel configuration. Passive filters offer low or high
impedance pathways to turned frequencies in the power flow from the source to the load. A common example of a passive filter, and the one that is specifically experimented, is the single-tuned notch RLC circuit (R for resistor, L for inductor, and C for capacitor). This filter is to be aligned in a parallel configuration to the load of the circuit, and will essentially be a low impedance branch consisting of series-resonant LC circuit [5]. The filter will take in a single tuned frequency, allowing only the flow of the fundamental current to supply the load of a distribution network. In other words, the filter acts as a spider web and traps in the unwanted harmonic currents exceeding frequencies of 60 hertz, and keeps those harmonic currents in a closed loop where they can be kept away from harm. This filter is to be discussed more in depth later on.

B. Active Filters

Active filters provide and inject harmonic cancelling currents. These types of filters are much more expensive and are higher maintenance than the passive filters. They consist of PE equipment as well, such as switches, diodes, and insulated gate bi-polar transistors (IGBTs) to minimize THD [3]. The configuration is designed to supply a current with the same amplitude and opposite phase of the harmonic current, thus cancelling and mitigating harmonic current distortion. In other words, this active filter can be nicknamed as a current-source inverter to block harmonic current flow, or the flow of currents that are not of the fundamental frequency of 60 hertz [5].

III. GROWTH OF POWER ELECTRONICS

PE devices are efficient conversion of energies. They control voltage levels, current levels, and frequency. These changes results in nonlinear loads, where the current does not follow the same sinusoidal voltage. This causes harmonic distortion, resulting in much loss and equipment damage. So why are they growing?

PE devices provide much benefits. They allow for our laptops, cell phones, solar panels, machines, batteries, and industrial processes to be sustainable and energy efficient. They provide cost and space saving, reduced maintenance, longer life cycles, much lower environmental impacts, overall better performance, better control, flexibility, and improved reliability to various equipment/systems needing energy conversions [6].

The global market for PE devices is rapidly increasing. This kind of technology is the only one that can deliver efficient and flexible control of electrical energy, where in 2007 power electronics were the sole contributor to one trillion dollars in sales related to hardware electronics [6]. There are several specific areas of growth: power supplies, motors drives, home appliances, lighting, renewable energy sources, future electricity networks and automotive and aerospace areas as well. Consumers themselves have grown accustomed to PE devices without even knowing it, where there is a dominant share in laptops, smart phones, televisions, computers, LCDs and DVDs as well as gaming consoles such as PlayStation and Xbox and Nintendo [7]. The market is expected to grow from $12.9 billion in 2015 to $20.0 billion by 2022 [7]. This rapid increase has been mainly due to the developments of semiconductor devices and microprocessor technology. These result in supplying the high demand of higher efficiency, faster switching, and minimal power loss in many of these applications.

This rise will ultimately result in a very low power quality. Filter techniques such as the passive and active filter designs must be implemented to reduce harmonic distortion created from the growth of PE devices. However, with the growth of PE devices rapidly increasing, other means besides the basic addition of either a passive or active filter must be mentioned, as there are critical loads that require a very low THD percentage. The solution to minimize THD as much as possible and provide high power quality is such: the passive and active filter can both be used simultaneously to completely eliminate harmonics as well as provide power factor correction as a bonus. These are called hybrid filters, a combination of both active and passive implementation. These filters can be aligned in either a shunt or series configuration. Both arrangements allows for the following: no harmonic resonance, dynamic voltage regulation, VAR compensation, and minimization of total system cost [5]. These solutions are very ideal moving forward. According to IEEE 519, there are critical loads that must have a solid power quality to maintain sustainability. The hybrid filter design, though most expensive, is the greatest solution thus far to help mitigate and even eliminate the harmonics being created from the growth of these PE devices.

The hybrid filter is indeed the answer to mitigating harmonic distortion. The passive filters compensate for the active filter’s unwanted high fundamental current/voltage rating as well as the VARs being produced. Passive filters are entrapments of the harmonic distortion, and are tuned using simple RLC components. This paper demonstrates the use of using a single-tuned notch filter, and because of its shunt configuration, is nicknamed the parallel-passive filter, or PPF.

IV. PARALLEL-PASSIVE FILTER

The PPF is the filter specifically studied in this experiment. It consists of an inductor and capacitor in series, and is parallel to the load at the point of common coupling, or PCC, which is the reference point used in distribution networks. It is defined as the node between the utility and customer where multiple electrical loads or customers may be connected. In other words, it can be the node including the low-voltage distribution transformer and a house/building.

The PPF single-tuned notch filter is tuned to a specific frequency. It cannot be tuned to multiple frequencies. That is titled a double-tuned frequency, and is not studied in this particular experiment. The PPF can be tuned to the fifth or seventh harmonic. The fifth harmonic is 300 Hertz, and the seventh harmonic is 420 Hertz. The filter is designed as follows:
the inductor and capacitor are tuned to create a resonant frequency where the reactance of both the reactor and absorber can essentially be eliminated or set to zero, and at this point the filter acts as a purely resistive type load. This filter creates a high impedance to the fundamental frequency and creates a very low impedance to the tuned frequency. The mathematics is as follows:

\[ Z = R + jX \]  
(2)

\[ jX = (XL - XC) \]  
(3)

\[ XL = 2 \pi f L \]  
(4)

\[ XC = \frac{1}{(2 \pi f C)} \]  
(5)

According to Equation (2), the impedance is equal to the resistance summed with the reactance. The resistance comes internally from the inductor and capacitor, as these components are non-ideal. However, this circuit is simulated using MATLAB, and for the simulation experience such as MATLAB/SIMULINK, the components are considered ideal and there needs to be a resistor in series to simulate the internal resistance of these two devices. According to Equation (2), once the reactance zeros out, there will then only be a pure resistive value. This pure resistive value must be less than the source impedance. Current, by nature, travels to the path with the least resistance. Therefore, theoretically, the fundamental current of 60 Hertz will bypass the filter, seeing it as a high impedance pathway and will travel only to the load. Contrary to the nature of the fundamental current, the harmonic current will travel into the filter tuned to that specific harmonic frequency, say 300 Hertz, where the frequency cancels the reactance and allows the current to only see a pure resistive pathway, where the value of that resistance is much smaller than the source impedance. This is again due to the internal resistance value of the inductor and capacitor being very little. Equations (3), (4), and (5) proves this theory, as discussed with actual values in the simulation experience.

V. SIMULATION

The simulation experience taught much on how to trap harmonics in our power distribution systems. Using MATLAB/SIMULINK and the library tools it came with, the software may test the PPF with many different component values to get a sense of how the filter behaves accordingly. The filter ultimately shorts the harmonic current, preventing the flow of harmonic currents to the load and source [8].

To simulate a PE device, an AC voltage source with a tuned frequency of 300 Hertz is supplied, simulating the fifth harmonic component. Only odd harmonics cause distortion in the sinusoidal waves, and the third harmonic is of little distortion added, and is neglected in the simulations. The fifth and seventh, 420 Hertz, are the two main culprits of harmonic distortion in our power systems. The equivalent circuit of a low-voltage, 120 Volts, 60 Hertz current with the fifth harmonic current source added to a purely resistive load is shown in Figure (1).

\[ \text{Figure 1} \]

The PPF filter is absent in the circuit above. The voltage level of the 5th Harmonic Source and Fundamental Voltage Source are both 120 Volts. All this does is change the peak-to-peak amplitude of the current being measured across the resistor R3, having a value of 10 Ohms. The current reading is measured in Figure (2).

\[ \text{Figure 2} \]

As shown, there is much harmonic current distortion, and is only being caused by the fifth harmonic. To theoretically minimize the amount of distortion presented by the fifth harmonic, the PPF filter will be tuned to 300 Hertz to trap this harmonic component. The mathematics is as follows with reference to Equations (2), (3), (4), and (5). The tuned frequency, \( f \), will be 300 Hertz. The capacitance, \( C \), will be 1000 microfarads. The capacitance is arbitrary chosen due to the lab research materials on hand. With a capacitance of 1000 microfarads and a tuned frequency of 300 Hertz, these values can be plugged in Equation (5) and achieve a capacitive reactance of 0.5305 Ohms. To cancel the reactance of both the inductor and capacitor, Equation (3) must achieve the same
value of the capacitive reactance for the inductive reactance. Therefore, XL is set to equal 0.5305 Ohms is plugged into Equation (4) with a tuned frequency, f, of 300 Hertz to solve for L, the inductance. This gives a value of 0.281 millihenrys, and sets XL equal to 0.5305 Ohms, same as XC. Looking at Equation (3), since XL and XC are now both equal, this sets jX to be zero, which creates a purely resistive load to the filter, where according to Equation (1), the impedance Z is now only equal to the internal resistance, R, of both the inductor and capacitor.

The tuned frequency is nicknamed the resonant frequency and creates an extremely low impedance for the filter, where the resistor value will be tiny and much less than the source impedance. The filter now acts as a low impedance bridge to frequencies equal to a tuned 300 Hertz, or the fifth harmonic source in these simulations. The fundamental current with a frequency of 60 Hertz will bypass this filter. Why is this? If 60 Hertz is plugged into Equations (4) and (5) with the same inductance of 0.281 millihenrys and the same capacitance of 1000 microfarads, Equation (3) will give jX a value of -2.546. What does this imply? Well, there needs another equation, Equation (6), as shown below.

\[ R^2 + jX^2 = Z^2 \quad (6) \]

Plugging in -2.546 for jX results in the calculated magnitude of the impedance, Z, equal to 6.485 Ohms. This is much larger than the source impedance. The fundamental current of 60 Hertz will not bother with this high impedance path. Contrary to the fundamental current, the harmonic component of 300 Hertz will allow the math to create jX to be zero, ultimately allowing the magnitude of Z in equation (6) to be very low to act as a low impedance bridge.

Be a resistor tied with an inductor in series to the voltage sources. The value of the resistance is equal to 5 milliohms, and the value of the inductor is equal to 0.5 millihenrys. These values are arbitrary chosen to simulate a low source impedance.

\[ \begin{align*}
\text{Resistance (Ohms)}: & \quad 0 \\
\text{Inductance (H)}: & \quad 2.81E-4 \\
\text{Set the initial inductor current} & \quad \checkmark \\
\text{Capacitance (F)}: & \quad 1.0E-3
\end{align*} \]

Figure 3

The parameters are set according to Figure (3). These are the parameters previously described. They set the reactance of jX in Equation (2) to be zero, and allows for a low impedance bridge to harmonic components equal to 300 Hertz. The same circuit as Figure (1) is implemented, with the addition of the PPF in parallel to the resistive load. This a low voltage application, where only 120 Volts is set to both the 5th Harmonic Source and the Fundamental Source. There will be a minor addition, the addition of a source impedance. There will

Figure 4

Figure (4) is the equivalent circuit of adding a PPF in parallel to the 5th Harmonic and the Load. The PPF is being added at the point of common coupling, or PCC. This PCC is the node right after the inductor Ls, and right before the Load of 10 Ohms, and is the point of pathway into the PPF. The PCC is the point in our power systems between a distribution transformer and a house/building. Many electrical components may be installed at this node, a filter being one of them. See the results of the before and after of adding this PPF. The scope will present the Fundamental Voltage source of both Figures (1) and (4), which will be identical, and will present the current traveling through the resistive Load in both Figures (1) and (4), where theoretically, one will be distorted, and the other will be cleaned up.

Figure 6
Figure (6) displays the current going across the Load of 10 Ohms in the bottom two outputs. The top output represents the 120 Voltage Source, where the middle output represents the same output presented in Figure (2) caused by the 5th Harmonic Source, and the bottom output represents that same current measurement with the addition of the PPF, displaying a pure sine wave in phase with its voltage source. This is the desired result for cleaning up the current, and mitigate the distortion of the 5th Harmonic Source.

The two main culprits, as previous stated, are the fifth and seventh harmonic. These two are normally caused by PE devices, and must be mitigated. The PPF single-tuned filter can only eliminate one harmonic component; therefore, another PPF single-tuned filter must be installed at the same PCC, in parallel across the load. The harmonics caused by the fifth and seventh produce much distortion, as shown in Figure (8) below.

The mathematic to tune the seventh harmonic are similar to tuning the fifth harmonic. The same 1000 microfarad capacitor is used; therefore, the inductance value is the only difference in the two filters. The reactor must have an impedance equal to that of the capacitor so the reactance of both devices cancels out, creating a pure, low resistive pathway to the current with a specific tuned frequency. The inductance was calculated to be 0.1435 millihenrys. Table B shows the values of the reactor and capacitor values used to tune each harmonic source. Figure (10) displays the outputs with the addition of the seventh harmonic source and its filter used to mitigate the distortion created from it.

One can easily imagine the kind of damage and power losses that can be sustained when operating with the current shown in Figure (8). This current is supposed to represent a pure sinusoidal wave, however, because of the addition of both the fifth and seventh harmonic sources in Figure (7), this distortion is horrific and must be taken care of. To mitigate both of these harmonic distortions, it is required to add another PPF tuned to 420 Hertz to trap the seventh harmonic current while the PPF tuned to 300 Hertz traps the fifth harmonic current. The circuit is shown in Figure (9).
The results displayed in Figure (10) outline the great use of the PPF to mitigate single specific harmonic distortion. To highlight the impedance and frequency relationship of this filter, a graph displayed below details the creation of a low impedance pathway to suck in and trap the current carrying the fifth and seventh harmonic frequencies.

![Impedance graph](image)

*Figure 11, courtesy of Rooh Ul Amin Shaikh, Abdul Basit Lashari, Irfan Ansari "Harmonics Analysis and Mitigation Using Passive Filters"*

The final piece of the puzzle comes the quality factor, or Q factor of the filter. The quality factor is the nature of the bandwidth in reference to the center, or resonant frequency. This determines the efficiency of the filter. Since this is a designed notch filter, the cutoff or resonant frequency depicted in Figure (11) at 300 Hertz is the center frequency. There is a lower cutoff frequency and higher cutoff frequency. To mathematically represent the quality factor of a notch filter, the equation is represented below in Equation (7).

Quality Factor = (f’ high – f low) / f center \hspace{1cm} (7)

The equation above may be implemented when working with MATLAB/SIMULINK and plotting the dB vs frequency scales. However, a simpler formula will be implemented since there is a capacitor and inductor in pure series. This equation is represented below in Equation (8).

\[
Q = \frac{1}{(1/QL + 1/QC)} \hspace{1cm} (8)
\]

\[
QC = \frac{1}{(2\pi\times300\times C\times R_c)} \hspace{1cm} (9)
\]

\[
QL = \frac{(2\pi\times300\times L)}{R_l} \hspace{1cm} (10)
\]

Equation (8) is calculated using Equations (9) and (10). The resistance of the capacitor Rc and the inductor Rl may be neglected. This calculation is set for the fifth harmonic, or 300 Hertz as depicted in the equations. After using the values for the inductance and capacitance shown in Table B, the calculated Q factor may be determined. The Q factor is calculated to be 94.3, unitless.

The Q factor is basically a depiction of energy. A Q factor of 94.3 means the filter oscillates well and provides a good amount of energy stored over the energy lost. The filter is in great position to filter out unwanted frequencies within its spectrum.

VI. LAB RESULTS

The materials consist of the rated capacitor and inductor shown in Table B for the fifth and seventh harmonics, as well as an advanced function generator to generate both the fundamental frequency and the harmonic components. A load of 6.25 Ohms is also connected. The node connected to the filter and load is designated as the PCC, or point of common coupling.

The first challenge possessed was to overcome the reason for why there was no current flowing through the circuit shown in Figure (13), where the sources are generated by the advanced function generator. Dr. Khan recommended an amplifier to increase the peak-to-peak value of the current.

The amplifier provided is titled LP-2020A Digital Amplifier and is manufactured by LEPAI. It is a two channel 20 Watt output power amplifier. The exterior design is configured below in Figure (A):
MATLAB/SIMULINK does not have the appropriate block diagram to successfully display the Amplifier within the circuit. It must be assumed moving forward that the input of the Function Generator will be connected to the Amplifier in a parallel configuration, where the positive and negative terminals of the Function Generator enter the L Channel of the Amplifier and the L Speaker Output then goes directly to the circuit, shown in Figure (12), where that output is connected to R1, 4 Ohms, the PPF filter, and the load of 6.25 Ohms.

Beforehand, the filter was not registering and bringing in hardly any current. The amplifier did indeed help produce a solid, amplified input signal simply by adjusting a volume control knob used to alter the L Channel output voltage of the amplifier.

The resistors R3 – R6 in Figure (13) each have a value of 25 Ohms with a power rating of 100 Watts. The resistor R1 has a value of 4 Ohms with the same power rating. This gives R total to be 10.25 Ohms, where the resistors in parallel have a total resistance, Rt, of 6.25 Ohms, and the resistor in series, R1, has a resistance of 4 Ohms.

\[ \frac{1}{R_t} = \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_6} \quad (11) \]

Since the harmonic component added is the fifth harmonic, the inductor value must be in range of 280 microhenrys. The selection of a 222 microhenry was used for this experiment. The value is a tad off, but after further examination of altering the frequency to comply with a single-tuned filter of 222 microhenry, the results do not vary whether the frequency is the fifth harmonic component or the exact single-tuned frequency defined by the filter. The only difference is a less distorted waveform.

Figure (13) displays where the filter was first installed. The resistor R1 must be connected before the filter, otherwise the voltage potential across the input and output ports of the filter will not change and no filtering will occur. There must be a voltage drop to have a clear distinction in the input and output ports so the filter behaves accordingly and does not zero out due to the transfer function shown in Equation (12).

\[ V_{out} = V_{in} \frac{1}{1 + j\omega C_1 R_1} \quad (12) \]

The equivalent circuit is shown below in Figure (14).

The current was measured through Rt. The sine waves provided by the scopes are displayed by the following figures. As seen, the distortion is still present. The passive filters are used to mitigate harmonics and not eliminate them. The job to eliminate harmonics is done by the active filter. If passive filters were perfect at filtering harmonics, then there would be no need for expensive active filters.

The figures to be displayed will first show the distorted waveform without the addition of the filter. The objective moving forward is to calculate the THD before and after the addition of the filter using Equation (13).

\[ THD = \frac{I_2^2 + I_3^2 + \ldots + I_n^2}{I_1^2} = \frac{\sum_{i=2}^{n} I_i^2}{I_1^2} \quad (13) \]
These results are much different than the simulation experience. Therefore, an engineer must try different techniques and connections to try his/her hardest to achieve desired results. Although the THD was mitigated, the desire to achieve a more pure sinusoidal waveform was present. Therefore, the circuit was transformed to put the inductor in series with the resistor R1 and connect the capacitor in parallel to the load. The circuit is displayed in Figure (19) on the following page, where the single-tuned notch filter is transformed to form a low-pass filter where frequencies below 300 Hertz will bypass the filter and flow straight to the load.
As a result of changing the configuration of the filter from a single-tuned notch filter to a low-pass filter, the THD is minimized only slightly where the waveforms look less distorted.

The RMS of the current was simply calculated by taking the peak-to-peak value shown in the figures and divide that value by root two. The reason for a higher THD for the seventh harmonic is due to the fact that it includes the fifth harmonic, so according to the formula represented in Equation (13), the numerator will include both the fifth and seventh harmonic current components, increasing the value of the numerator and providing a higher THD percentage.

VII. CONCLUSION

The results of the lab are a bit disappointing compared to the simulation experience. Though the results proved to be only adequate, the lessons learned are plentiful. The lesson of learning to match each component’s power rating is essential as well as configuring connections of parallel and series by determining the configuration of a device’s input and output ports, and using the correct power cords and cables are also essential in metering and generating. If no resistor is added in series before the use of the filter, the voltage across the input and output ports of the filter will be identical and the filter will not act at all. This is due to the transfer function, Vout / Vin equaling a value of one, where the filter then simply zeroes out. These lessons are fundamental, where it is always good to experience and get used to understanding the fundamentals of electrical engineering before one may start designing and experimenting with various components, equipment, power supplies, etc. There is also a self-resonating frequency components like the capacitor and inductor have in them. Must always operate away from the self-resonating frequency. Also, using a multi-meter to measure current and voltage levels at different points of a circuit can help diagnose what issues are present, and then comes the approach of treating the circuit like a puzzle and focus on the surrounding connections to help solve the problems and issues at hand.

Never treat the ways of a conclusion to the means of an end. The passive filter was proved in this Thesis to only mitigate harmonics, and not eliminate them. Filters will continue to advance substantially and will be implemented exponentially. Power Electronics are a beautiful wave of technology. Design techniques such as the passive and active filter may help these wonderful devices flourish, and although the harmonics produced are plentiful, the lives of humans are much simpler and the planet earth may be saved by these devices, because without PE devices, renewables may not exist. Thank you to Fourier for the start, though much is to come.
Acknowledgment

The lessons learned from Power Electronics are extensive and of course practical and useful for the future. Electrical engineering is based around power and the electronics supplying/receiving that power. If the decision was to go with a different route for the Thesis, the class of Power Electronics taught by Dr. Khan would have never entered my thought. I have learned much in this class, such as the practical uses for transistors, switches, diodes, capacitors, inductors and many configurations including transformers related to isolated and non-isolated converters. Harmonics, filters, and the approaches to solving such problems will not be forgotten moving forward into my career. There is much to keep to review and practice moving forward from this Thesis project as well as the PE course taught at UMKC by Professor Khan.

Thank you to Dr. Faisal Khan very much for the experience, the knowledge, and the motivation to work hard and achieve and most importantly, learn. I loved the PE class discussed and taught by you, where I learned more in this class than I did in three full semesters here at UMKC. That’s a sign of a truly wonderful instructor.

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-Khalid

References