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Power Quality Improvement and Harmonics Compensation Using Hybrid Filter

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Abstract:

The need for electricity is expanding at an even faster rate in these modern times. In order for the electrical devices to function properly and effectively, a constant supply of high-quality power is required. The most common types of power quality reducing factors include noise, interruptions, variations in voltage and frequency, and so on. These factors all contribute to a decrease in the electrical devices' overall efficiency. Total harmonic distortion (THD) was made worse by the presence of non-linear loads. The existence of harmonics is the primary cause of the problems that lead to the breakdown of insulation, excess heating, and a shortened lifespan for various pieces of equipment. In addition to this, if there is a high THD in the electrical system, it may cause the energy meter to give inaccurate readings. An economic hybrid filter can be employed to reduce the losses caused by harmonics distortion, thereby providing a solution to those issues. This paper provides an in-depth look into the application of this filter for harmonic compensation. By performing simulations with the Simulink tool of MATLAB and validating the results using the experimental setup, it has been determined that using a filter can reduce the total harmonic distortion (THD) of the current by 40.09 percentage points, which will result in better power quality and energy conservation. The IEEE Standard 519-1992 was consulted as a reference when making this determination**.**

Keywords: *Power Quality, Harmonics, Hybrid Filters, Total Harmonic Distortion, Simulink*

1. Introduction

Electricity is the most popular energy form and its supply is heavily required by the modern society. It is hard to imagine a life without electricity supply. In the same way the electric power quality which is being supplied is also very necessary for the better performance of the consumer equipment's or devices. In the power sector, the power quality is the most important term and it concerns vastly to the users and electric power company [1]. The power quality which is being supplied to the users rely on the power ranges of frequency and voltage. If the frequency and voltage of the power supply are changed from those of the standard ones, the quality of the energy is disturbed or impaired. At present, the advancement of semi-conductor devices is a

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matter of days for technology development. By this advantages and development, semiconductor devices have a permanent place in the energy industry to facilitate the overall control of the system. Furthermore, most of the load is also semiconductor built equipment. However, semiconductor devices are characterized by non-linear and drag non-linear current from the source. Semi-conductor devices are also engaged in the conversion of electricity from AC to DC or vice versa [2]. This power transition has many switching operations that can introduce interruption in the current. Because of this interruption and non-linearity, the generation of harmonics disturbs the quality of electricity which is supplied to the end user.

Modern sources of harmonics include all non-linear loads such as power electronic equipment including Adjustable Speed Drives ASDs, switched mode power supplies, and data processing equipment. Harmonics and reactive power are the root causes of a number of issues, including the distortion of the supply voltage, the excessive heating of transformers, a power factor that is too low, an excessive current, the failure of the control system, the loss of insulation, and the destruction of electronic devices. Because of this, each and every one of these problems presents a significant challenge for the electrical system. Therefore, the reduction of risk is extremely important for both the customer service and the customers. The presence of harmonics is the primary factor that contributes to the aforementioned issues, and filtering out harmonics is the approach that should be taken to address these concerns [3]. Therefore, harmonics compensation is absolutely necessary in order to maintain the high quality of the electric power.

Recently, the loads mostly used in industry or commercially cause the harmonics generation. The current harmonics disturb the voltage of system which gradually upsets the performance of system and provides unwanted circumstances like insulation failure, control system failure, electrical and mechanical fluctuations in the alternator, overheating problems and unpredictable protection behavior etc. These above all the mentioned problems are serious for the electrical system, so harmonic mitigation is essential for the consumers and utility purposes [4].

The purpose of this paper is to discuss ways in which the persistent risk of system losses that is associated with harmonics in line currents can be mitigated. The primary goal is to minimize the amount of power that is wasted by operating the shunt active power filter at a very low switching frequency. On the other hand, this contributes to an increase in the total harmonic distortion. This can be accomplished through the utilization of a hybrid filter, which is a cost-effective strategy that combines active and passive filter arrangements. When compared to the shunt active filter, which accomplishes the same goals at a higher switching frequency, this method yields sinusoidal source current with unity power factor at a lower switching frequency. This allows to obtain these results at a lower cost. As a consequence of this, the strength of the active filter is diminished, and the drawbacks of the passive filter are alleviated. There are two distinct parts to this method that can be utilized. The electrical quality is improved thanks to the elimination of low-order harmonics by the APF and the elimination of higher-order harmonics by the passive filter. The overall cost is brought down without any corresponding loss in efficiency.

2. Power Quality And Harmonics

Power systems are intended to work at a frequency of 50 or 60 Hz. Nevertheless, particular kinds of non-uniform loads generate current and voltages among frequencies which are whole number multiple of the essential frequency. These frequency mechanisms famous as harmonic contamination and is possessing contrary outcome on the power scheme grid [5]. This is usually a customer determined problem. So, power attribute delinquent is expressed as "any amount of established in current, voltage or frequency deviations that effect in harm, distressed, loss or broken of end user appliances."

2.1. Power Quality Issues

Energy efficiency is influenced by any disparity in current, voltage or frequency. Common problems that affect the instrument's variability are power system faults, variation in frequency, Power surges, Improper grounding affect, blackouts or brownouts, Transients and electrical line noise. The effects of these problems are the harmonics production. Harmonics reduced power quality and could damage the end user devices. These harmonics causes insulating failure, underground cable heating, increase losses and reduce the equipment's life etc.

2.2. Harmonics Creation

Pure sinusoidal waveforms can be found in true waveforms of phase or line currents and voltages. This indicates that it is made up of a fundamental frequency of exactly 50 Hz in its purest form (as is the case in Pakistan). Nevertheless, the actual waveform is made up of numerous sine waves operating at a variety of frequencies, with one operating at the power frequency and being referred to as the fundamental component. The other frequencies that are not quite as dominant are referred to as the harmonics [6]. The value of a specific frequency that is compounded of the basic frequency is known as the harmonic component, also referred to simply as the harmonic. The magnitude of the harmonic component is greatest at frequencies that are close to the fundamental frequency, and it begins to decrease as higher orders of the fundamental are achieved.

In a normal alternating system, voltage varies by sinusoidal at a certain frequency typically 50 or 60 Hz. When a connected load to the system is linear, it pulls a current which is sinusoidal in nature and has same frequency such as voltage. When a connected load to the system is non-linear in nature like a rectifier then drag current is also non-sinusoidal. The resulting waveform of current is complicated which depends on load type. The equipment's used in offices like printers, fax machines, personal computers and rotating machines in industry are other examples of nonlinear loads [7].

I. *Static Converters*: These devices are made up of thyristors and gate firing apparatus. A number of different parameters, including as asymmetry, inaccuracy in thyristor firing times, switching timings, and inadequate filtering, all contribute to the modification of the amplitudes of the distinctive harmonics. In the case of thyristor bridges, one might also notice a shift in the harmonics as a function of the thyristor phase angle.

II. *Lighting*: Lighting systems that use discharge lamps or fluorescent lamps can generate harmonic currents. These types of lamps are used in fluorescent lighting. In some circumstances involving contemporary compact fluorescent lighting, a third harmonic ratio can possibly go above one hundred percent. The neutral conductor therefore carries the sum of the third harmonic currents of the three phases, and as a result, if it is not suitably sized, it may be subjected to dangerous overheating.

3. Effects Of Linear And Non Linear Loads

In the past, the vast majority of loads were linear, which means that when they were connected to a sinusoidal voltage, these devices would produce a sinusoidal current. When connected to a sinusoidal voltage, the majority of loads in use today behave in a non-linear manner (for example, power electronics such as rectifiers, frequency converters, switched mode power supplies, electronic lamps, and so on). This means that these devices produce non-sinusoidal currents, as depicted in Fig. 1. These currents are made up not only of the basic current but also of currents of higher frequencies, which skew the sinusoidal waveform in an undesirable way.

Current harmonics are the primary factor in the generation of voltage harmonics [8]. Unless the non-linear load is also pumping power, it will not directly cause voltage harmonics to occur on its own.

The system shows the waveforms of two different loads. One is non-linear and other one is linear. As we can observe that non-linear load current is not smooth. In fact, this wave has a great deal of harmonic contents. On the other hand, the linear load current waveform is far smoother and consists of the fundamental frequency component only [9].

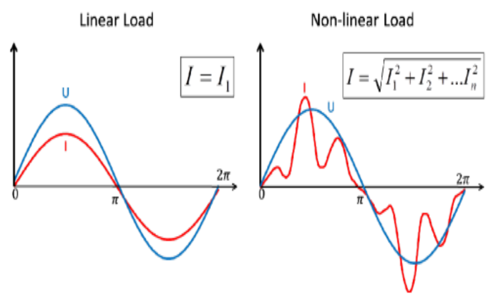

Figure 1: Comparison of linear and nonlinear loads in time domain

Total Harmonic Distortion, more commonly known as THD, is a standard measurement of a signal. It is defined as the ratio of the total of all harmonics components to the value at the fundamental frequency. The THD for the current can be found in the case of the power system in the equation 1

$$\text{THDi} = \frac{I_{\text{harmonic}}}{I_{\text{fundamental}}} \times 100\% \qquad (1)$$

The above equation can be expand in given form,

$$\text{THDi} = \frac{\sqrt{\sum_{j=2}^{\infty} I_j^2}}{I_1} = \frac{\sqrt{I_2^2+I_3^2+I_4^2 \ldots\ldots I_n^2}}{I_1} \qquad (2)$$

Where In is the root mean square RMS value of the nth harmonic and j=1 is fundamental frequency. Therefore, the THD can be decrease by increasing $I_{fundamental}$ or by decreasing $I_{harmonic}$.

4. Effects Of Harmonics On Power Quality

When a load that is not uniform is connected, a sinusoidal source will produce a distorted current in the circuit. Harmonics are present in the current that has been distorted. A voltage droplet for each separately harmonic current forms whenever that current's harmonic passes through the supply impedance. The amount of voltage twisting is affected by the current as well as the impedance of the supply. Harmonics cause disruptions in the quality of the electric power. Harmonics can have unfavorable effects on quality, including but not limited to the following: computer system failures, hasty motor exhaustions, buzzing in telecommunication cable lines, and warmness of transformers [10]. These are just a few examples of the kinds of problems that quality drawbacks can carry into household and engineering industry. A relatively minor problem with quality might prevent the entire industry from functioning normally.

Noise is a chief problem associated with the harmonics. Capacitors are seen to overheat with the production of harmonics. The current increase in the system is one of the major issues of power scheme harmonics. This is the predominant opportunity for third harmonic that causes strong growth in the current of zero order, thereby raising the current fluctuations in neutral.

5. Harmonics Filteration Techniques

There are many problems that disturb electrical systems like transients, noise and voltage sag etc. These problems resulting in harmonic production and affecting the power quality supplied to the end user. Harmonic frequencies may occur in waveforms of voltage or current those are multiple members of the fundamental frequency which do not contribute to the supply of active power. For this purpose filters are utilized at PCC in which load is associated to the power supply. The performance of system is increased by using that filters. Filters are used to overcome the problems produced by harmonics. For this, various filter techniques are available in the literature. Passive filters are used initially, but they are highly relying on parameters of system. In addition, the system encryption is suitable for filtering a particular sequence of events. Thus, in order to address the drawbacks of passive filters the use of active filters is necessary [11]. Various types of filters are available for this objective. The complete sketch is shown in the given Fig. 2.

5.1. Pasive Filters

Harmonic currents can be mitigated with the help of passive filters, which are made up of a collection of passive elements such as resistors, capacitors, and inductors that are tuned to a particular frequency. There have been no addition of any active components, such as operational amplifiers, at any point. The harmonic current is redirected to ground by the passive filters, which also generate a path with low impedance for the particular harmonic frequency.

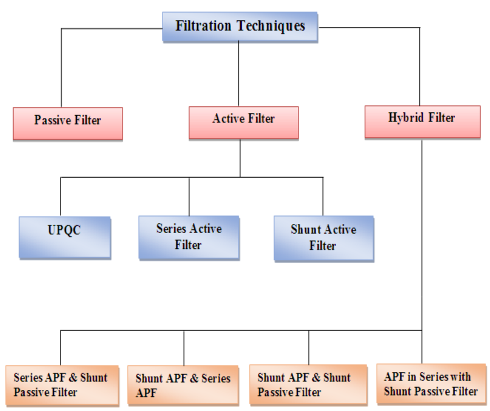

Figure 2: Classification of filters

Therefore, passive filters enhance the voltage and current of the supply system without the adverse effects that are caused by the harmonics produced by non-linear loads. A resistor, an inductor, and a capacitor are the three components that make up the single tuned passive filter. By creating a path with low impedance, the inductor and the capacitor are intended to reduce the impact of a particular order of frequency. In comparison to the design of an active filter, the construction of a passive filter is extremely straightforward and cost-effective [11]. Formulas have been provided, and those will serve as the basis for the filter parameters that will be designed for the proposed work.

Reactive Power (KVAR) = KVA*sin (cos-1(PF))

Filter Reactance

$$X_{fil} = \frac{KV^2\,(1000)}{KVAR}\,\Omega \qquad (3)$$

Capacitive Reactance

$$X_{cap} = \frac{X_{fil} * h^2}{h^2 - 1}\,\Omega \qquad (4)$$

Inductive Reactance

$$X_L = \frac{X_{cap}}{h^2}\,\Omega \qquad (5)$$

Harmonic Frequency

$$f_h = \frac{1}{2\,\pi\sqrt{LC}} \qquad (6)$$

Where h is harmonic order, L is inductance and C is capacitance.

The passive filters have some drawbacks which are given below:

- Due to occurrence of passive elements, these filters are massive and too heavy. These filters restrained the harmonics which are usually low order.
- Oscillation or reconciliation problem that affects the stability of the power system's network.
- Filter features are influenced by the frequency deviation in the energy system and tolerances in components cannot be realized in an environment with varying frequency.
- The filter is loaded when the size of the harmonics in the AC lines rises.
- The impedance of the power supply disrupts the compensation functions of LC filters.

5.2. Active Power Filters

In recent years, due to advancements in switch technology, the study of active power filters has become an increasingly popular research topic. When dealing with high levels of power, the cost of magnetic and capacitive components can become prohibitively expensive. Recent years have seen the development of high frequency switching devices with high current and voltage ratings. Some examples of these devices include the metal oxide semiconductor field effect transistor (MOSFET) and the insulated gate bipolar transistor (IGBT). These are primarily made up of power electronic switching devices like thyristors and IGBTs, both of which are incredibly fast and have a large switching capacity respectively. These filters perform their primary function during run time by sensing the variations in load currents at each point in time and injecting signals to cancel out the effects of harmonics if they are present [12].

In the design of active filters, current or voltage pulse width modulation inverters make up the active filter. These are preferred over the conventional passive filter due to the fact that these have the capacity to overcome the disadvantages associated with the passive filter. This is the primary reason for their widespread use. However, it is important to note that passive filters have limitations. They are designed for fixed reactive power compensation at specific tuning frequencies, making them unsuitable for variable load applications. The variation in load impedance can affect the tuning of the filters, potentially reducing their effectiveness. Despite this drawback, the simulation results demonstrate that the passive filters perform satisfactorily in meeting the reactive power demand [13].

High-parameter active filters provide stability to the power system. By having sufficient capacity to compensate for the harmonic currents, they prevent voltage distortions, improve power factor, and maintain system stability. This is particularly crucial in sensitive applications where stable and high-quality power is essential. Designing active filters with high parameters allows for future expansion and modifications to the power system. It provides the flexibility to handle increased loads or changes in the harmonic profile without the need for immediate upgrades or replacements. This helps in future-proofing the power system against potential changes or growth [14].

It is important to note that the selection of active filter parameters should be based on a thorough analysis of the power system, including harmonic content, load characteristics, and system requirements. Professional engineering expertise and proper sizing calculations are necessary to ensure that the active filter parameters are appropriately determined for optimal performance and cost-effectiveness [15].

Active compensations currently have the ability to overcome the drawbacks that are associated with passive filters. Additionally, the power factor of the power systems improves thanks to the active power filter's contribution. Both in its steady state and in its transient state, it demonstrates excellent compensation properties. In comparison to passive filters, the initial investment and ongoing expenses associated with these filters are significant. Nevertheless, when used by themselves, active filters run into the following issues:

It is difficult to construct a large rated current source with a rapid current response. The control system is complex, and its performance against high frequency harmonics is ineffective. The initial cost and the ongoing cost are both high.

This shortcoming was remedied by the development of a novel strategy known as a "hybrid filter," which is a combination of a passive filter and an active filter.

5.3. Hybrid Filters

The hybrid filter is a combination of active and passive filters in a single device. This configuration is effective because it takes advantage of everything that both filters have to offer. New and improved characteristics of passive filters can protect against the damage caused by shunt and series resonances. Therefore, hybrid filter topologies can use the benefits of both passive and active power filters, which include the ease of use and lower cost effectiveness of passive filters, as well as the higher performance of active filters. They are solutions that can control current variations and distortions while also compensating for harmonics at a low cost as simulation is performed to validate it in Fig. 3. Additionally, they can control current variations. These filters eliminate the issues that were caused by the use of both filters. Therefore, the primary goal of hybrid APF is to improve the filtering performance of high-order harmonics while also providing a cost-effective mitigation of low-order harmonics. Because of this, both work together to produce a much more pure sinusoidal waveform in the line currents that they generate. It is important to point out that the topology of the passive and active filters in hybrid filters can take either the form of a series or a parallel configuration, as appropriate.

6. Simulation

The Simulink model of a hybrid filter for the electrical power quality is composed of a power factor correction (PFC) filter, an active filter, an energy storage device such as an electrolytic capacitor, an inductor and a switch mode power supply (SMPS). The PFC filter eliminates current harmonics while the active filter eliminates voltage harmonics. The switch mode power supply provides a pulsed dc voltage and current. The inductor acts as a buffer and the capacitor helps in stabilizing the output voltage. The control system for the SMPS is responsible for controlling the switching of the MOSFET switches and hence controlling the output voltage.

The analysis revealed that substantial harmonic currents still reached the mains supply even after the introduction of an LC-

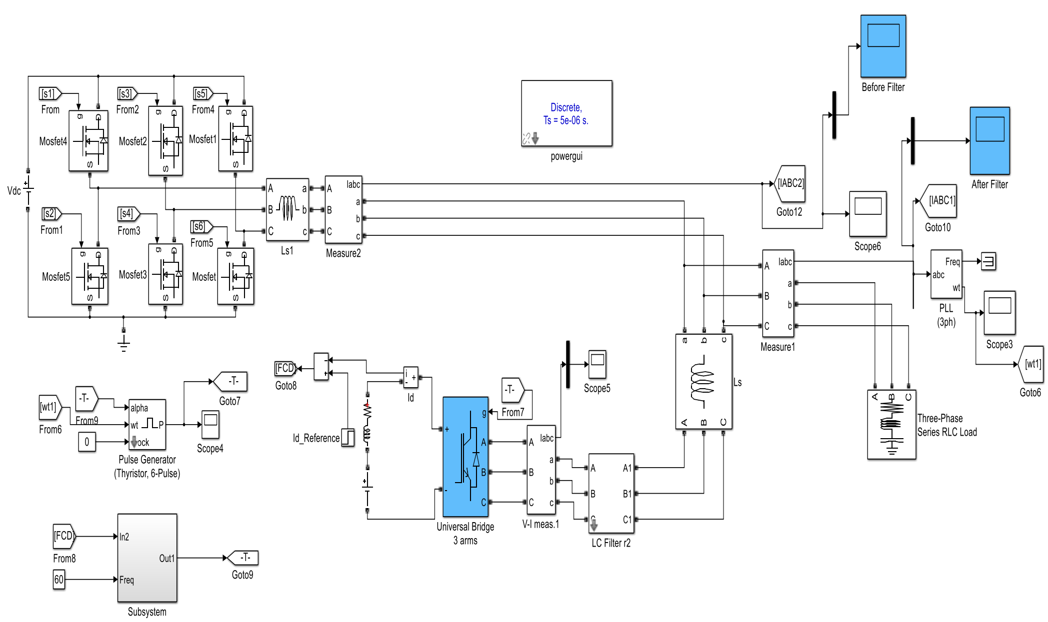

Figure 3: Hybrid filter block diagram in Simulink

passive filter. Fig. 4 depicts the sinusoidal wave of source current, whose frequency spectrum analysis displays minimal harmonic components. This suggests that hybrid power filters are effective in the elimination of harmonics from non-linear loads as shown in Fig. 5.

7. Hardware Setup

The experimental setup used for the mitigation of current source harmonics is shown in Figure 6. This hardware setup of the hybrid active filter for harmonics mitigation involves the combination of a passive filter and an active filter with system parameters shown in Table. 1. The passive filter is used to reduce the harmonic current levels, while the active filter is used to reduce the harmonic voltage levels. The active filter is composed of a single-phase voltage source inverter (VSI) and a DC capacitor. The VSI is used to inject a compensating current into the system to reduce the harmonic voltage levels. The DC capacitor is used to store the energy generated by the VSI and to provide a stable DC voltage source for the VSI. The hybrid active filter is connected to the point of common coupling (PCC) of the system, and it is controlled by a microcontroller. The microcontroller is used for monitoring the system, calculating the compensating current and controlling the VSI.

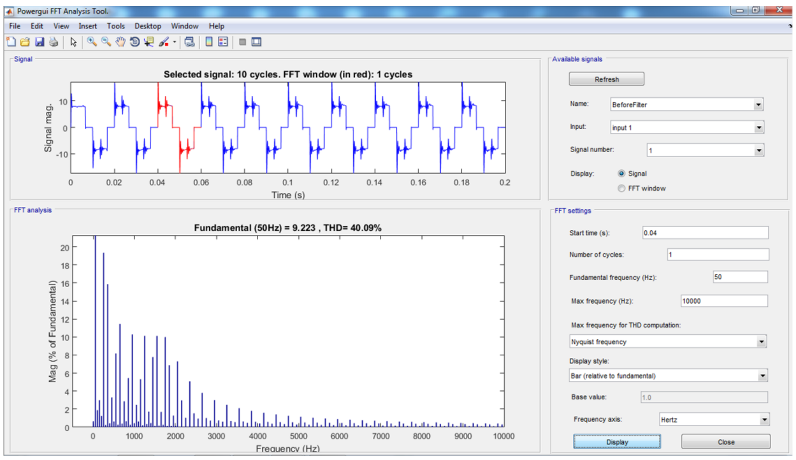

Figure 4: FFT analysis before filtration

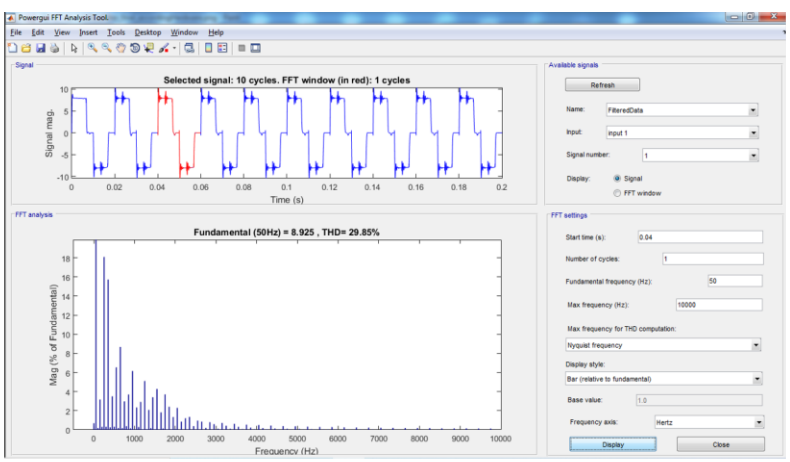

Figure 5: FFT analysis after filtration

TABLE I
SYSTEM PARAMETERS

Parameters	***Values***
Source Voltage	400 V
Frequency (f)	50 Hz
Load Resistance R_L	0.1k Ω
Load Capacitance C_L	100mF
Tuned Passive Filter	C_{f5}=50µF, L_{f5}=8.1mH C_{f7}=20µF, L_{f7}=8.27mH C_{f11}=20µF, L_{f11}=8.27mH
Filter Coupling Inductance	2.5 mH
Active Filter Parameter	Cd=1500µF, L_{af}=10mH
DC Capacitor	C_{dc}=3.5µF
Sampling Time	0.2 µs

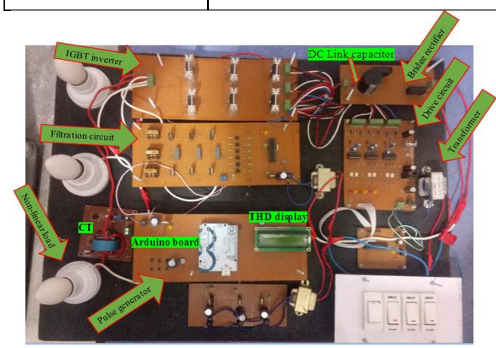

Figure 3: Hardware implementation

8. Results & Discussion

The examination of the results exhibited that the present waveforms were a long way from the sinusoidal waveform, because of the harmonic currents that were added to the power supply system by the non-linear burden. At the point when the filtration circuit was employed, the resulting waveforms was

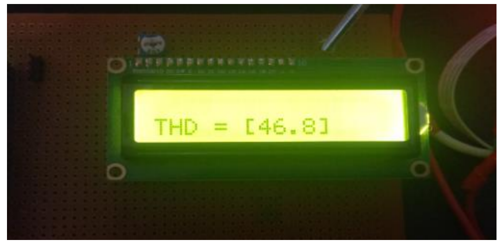

Figure 4: THD value without filter

improved, and distortion effect was decreased by utilization of the recommended filter scheme as seen in Fig 5.

Figure 5: THD value after filtration

8.1. Digital Storage Oscilloscope Results

The hardware setup is tested in the power electronics lab of University of Engineering and Technology UET. Figure 9 shows the output waveform without filter circuitry, Harmonic distortion can be visualized in the display of digital oscilloscope.

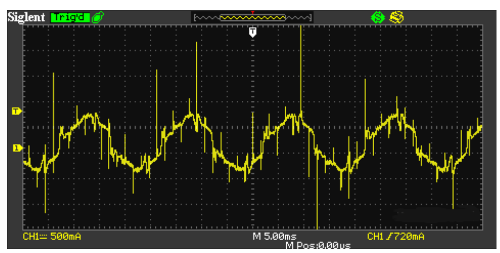

Figure 6: Waveform without using filter

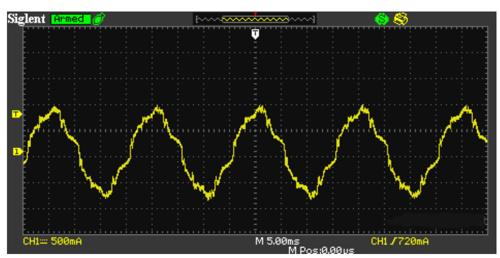

Figure 7: Waveform after filtration

The key component of our discussion is the power ratings of the MOSFET which must be utilized for the active power filter; it must be incredibly high and this necessity has caused us to design the hybrid active power filter. The results acquired from using the hybrid active power filter are shown here for you to look at. Once more, it is evidently clear that the amount of harmonic current in this situation is not of significance. Nevertheless, MOSFETs are typically low-noise and low-distortion, so they can be used effectively to generate very low harmonics. However, the overall performance of the filter will depend on the design of the circuit, so it is important to consider the filter's design parameters when considering harmonics that may be generated.

The THD value recorded from the hardware set-up was 46.8% prior to filtration. When the filtration circuit was active, this decreased to 35.8%. This was due to the fact that the components used were less efficient and in-expensive and so the software and hardware results did not match. This shows that this hardware set-up is a basic version and not the most efficient. If more standardized devices or components were used, the same results could be achieved.

$$\mathrm{PF} = \frac{1}{\sqrt{1 + \left(\frac{\mathrm{THDi}\ \%}{100}\right)^2}} \tag{7}$$

If the value of current harmonics decreases then the value of power factor is improved towards unity. The power factor can be calculated from above equation.

9. Conclusion

The findings of the simulation indicate that the application of the filter will reduce the power loss, and as a result, will contribute to the reduction of both energy consumption and the cost of the electricity. The quantity of power generated is now the single most important factor in the energy industry, despite the fact that the demand for electricity is expanding at an alarmingly rapid rate. Voltage stabilization and an improvement in power quality are both necessities for the devices of today. Harmonics compensation and power factor improvement are therefore required solutions for the aforementioned issues. The installation of the precisely rated filter protection device at the load centers is the primary responsibility of the companies that supply electricity. In addition to this, they are required to conduct routine inspections and maintenance.

According to the findings of this study, it is possible to enhance the quality of electricity by utilizing both active and passive filters in conjunction with one another. As a consequence of this, it is believed that the hybrid filter, which consists of a passive filter connected in shunt and an active filter connected in series, is a worthwhile financial outcome to enhance the quality of the power and reduce the losses in the power structure. The findings of the simulation suggested that utilizing the filter would result in an increase in the power factor as well as a reduction in the power losses caused by harmonic distortion. Although, Harmonic compensation often involves complex algorithms and calculations. When using a hybrid filter to compensate for harmonics, the complexity can increase further as multiple filtering techniques are combined. This increased complexity may require more computational resources and processing power, making real-time implementation more challenging. Moreover, hybrid filters used for harmonic compensation typically involve several parameters that need to be tuned and optimized. Finding the optimal values for these parameters can be time-consuming and may require expertise in the underlying filtering techniques. Improper parameter tuning can lead to suboptimal performance or even instability in the compensation process. Hence, there is always a room exist to further improve and enhance the efficiency of the filter. It's important to note that the drawbacks and shortcomings mentioned above are not inherent to all hybrid filters for harmonic compensation. They may vary depending on the specific combination of filtering techniques, the characteristics of the harmonics, and the implementation details.

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