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Enhancement of Power Quality in Domestic Loads Using Harmonic Filters

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ABSTRACT This study deals with the mitigation of current harmonics, which is primarily important to alleviate power quality problems in modern times. Current harmonics produced by different widely used loads have been evaluated and related parameters have been tabled. Using the data obtained, a non-linear load was modelled to serve as the test load. Different mitigation solutions and techniques were studied to select an appropriate filter design for domestic single-phase application. The Active Power Filter (APF)'s steady-state and dynamic output was evaluated with reference current extraction techniques like PQ and SRF theories in Simulink. For a fair comparison, various parameters related to the filter design were kept identical between the tests conducted; and to test the dynamic performance, a highly inductive load was connected halfway through simulation. The reactive power compensation offered by the filter was studied by using various waveforms and parameters are investigated and tabulated. The study was carried out to identify a reference current extraction technique that yields the best performance and understand the implementation of the same to identify inherent issues that can sometimes be overlooked because of their simplicity and ease of implementation. The performance of two commonly used reference current extraction techniques were analyzed by subjecting it to highly non-linear and highly inductive loads that were modelled based on various loads that were analyzed.

INDEX TERMS Harmonics, active filter, power quality, SMPS, THD, SRF-theory, PQ-theory, VFD.

I. INTRODUCTION

Back when commercial power generation and distributions started, a major part of the load that was experienced by the grid was linear because it mainly comprised of resistive loads such as incandescent lights, heating elements, motors etc. Industrialization was driven by motors; and demanded better control techniques and solutions [1]. Speed control of motors was achieved by varying the voltage across the motor with the help of resistors, auto-transformers or tap changing transformers. In the case of household appliances, many devices depended on small step-down transformers to reduce the voltage to a suitable level. With the invention of diodes and transistors, a new era of electronics was born. The introduction of these new devices was widely accepted, and people started switching to these devices due to benefits in terms of cost, efficiency and overall compactness. It should be noted that any device that makes use of semiconductors are non-linear which means that the current drawn by these loads are non-linear [2]. In the past 15-20 years, the world has witnessed a major shift towards smart devices, energy-efficient lighting, and various advancements in the field of power control. Some of the well-known major shifts in technologies were- incandescent light bulbs to fluorescent lights

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to LED-based lighting, transformer-based wall adapter and power supplies being phased out with Switched Mode Power Supplies (SMPS), and bulky transformer-based or resistive motor control being phased out with power electronics-based motor control techniques [3]. This has led to an increase in certain undesirable components being injected back to the grid and these undesirable components are called harmonics. Harmonics are components present in the waveform that are in multiples of the fundamental frequency, these are mainly generated because of the non-linear nature of the switching devices being used and the fast switching involved. Harmonics are power quality issues which are observed in both voltage and current. Some commonly used domestic loads that are being used today which are non-linear and the usage of which is known to rise in future are LED lighting, chargers, TVs, computers, smart refrigerators etc. In an industrial scenario, some common non-linear loads are SMPS, Variable Frequency Drives (VFDs) and Arc Furnaces. When a device draws harmonic currents, the component of the current has to be generated at the source, which means that these harmonic components propagate through all the different power system components between source and load. Harmonics have various negative effects on the grids such as increased losses, affects the operation of sensitive equipment such as measurement devices, reduction in the overall service life of equipment's owing to accelerated ageing and reduction in reliability of the system. The importance of 'Power Quality' is only recently getting recognized in today's societies. Industrial users are penalized based on the scale of the negative footprint they have on power quality and are forced to use devices such as filters to reduce the negative effects they have on the grid and improve the quality of power. Also, there has been a major influx in renewable penetration at domestic level and the harmonic impacts domestic users have on the grid is not given much importance [4]. For current harmonics mitigation, there are three types of filters – passive, active and hybrid power filters. Therefore, this study talks about the negative effects some commonly used domestic loads have on the grid by analysing various waveforms associated with it. Based on the data obtained, a non-linear load was modelled and the results are evaluated using two reference current extraction techniques on a single-phase shunt active power filter. The performance evaluation was carried out in terms of analysing steady state and dynamic performance of the reference current extraction techniques under similar loading conditions. First half of the simulation was carried out using a highly non-linear load and during the second half a highly inductive load was connected along with the highly non-linear load mentioned previously. This methodology was used to mimic the type of loads the filter experiences during its operation, which in practice can vary continuously and at times can be subjected to sudden load variations. This type of sudden variations in a domestic scenario can arise from power hungry devices such as ovens, stoves, heaters, water pumps etc.

A. POWER QUALITY

"The standard of something as measured against other things of a similar kind; the degree of excellence of something" or "a distinctive attribute or characteristic possessed by someone or something" are two definitions that are presented in the result of a simple Google search of the term 'quality'. The term "Power Quality" on the same lines is related to power (in terms of quality of voltage and current). Many definitions are presented in literature; for the utility, it is "the measure of the quality of service provided and the ability of the end-user/consumer to make use of this power in the desired manner". In the perspective of the user, it is "the quality of the power being supplied by the utility that allows them to have a trouble-free experience". The idea behind both utility and the user are that at the end of the day, the user should be able to use the said power to achieve their end-goal with little to no issues [6]. At present, there is no universally accepted definition, but IEEE defines it as "Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment" and IEC defines it as "Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters" [7].

This term is commonly used to assess and discuss the pollution observed in voltage or current at generation, transmission, distribution and utilization with the majority of the pollution being caused at utilization level which propagates throughout the system. Therefore, studies need to be carried out at the utilization level to observe and understand the problem [7]. For example, to understand the effects the consumer has on the grid, the measurements have to be made at the point of connection between the distribution network and the consumer also referred to as the Point of Common Coupling. Based on the [6]–[8], PQ problems are classified as shown in Table 1. Apart from the negative effects mentioned in Table 1, these problems can lead to financial losses owing to loss of manufacturing, failure of equipment, service or repair costs and unexpected downtime [7]. Harmonics is one of many power quality problems that is more prevalent than others owing to the major influx in power electronic devices and conductors. Harmonics are components present in the waveform that are in multiples of the fundamental frequency. This can be observed both in voltage and current, with current harmonics being more pronounced. The non-linear nature of the loads and the switching involved causes the current to be drawn in pulses which can sometimes have sharp rising or falling edges. Current harmonics can lead to voltage harmonics [7]. In general, harmonics are measured/characterized by Total Harmonic Distortion (THD) and is given by the ratio of RMS of harmonic components to the RMS of fundamental component,

$$THD_I = (I_1)^{-2} \sqrt{I_2^2 + I_3^2 + I_4^2 \ldots + I_n^2} \tag{1}$$

In case of light loads, the THD value can often be misleading because the magnitude of the fundamental component

TABLE 1. Causes and effects of power quality problems.

Problems	Category	Causes	Effects
Transients	Impulsive	Lightning strikes, Switching ON/OFF heavy loads	Power system Resonance
	Oscillatory	Line, Capacitor, Load Switching	
Short-Duration Voltage Variations	Sag	Motor starting, Single line to ground faults	Protection devices may false trigger, sensitive equipment malfunction/fail
	Swell	Capacitor switching, heavy load switching faults	
	Interruption	Temporary faults	
Long-Duration Voltage Variations	Sustained Interruption	Faults	Reliability is compromised, increased losses or heating, damage to equipment
	Undervoltage	Switching ON loads, Capacitor de-energization	
	Overvoltage	Switching OFF loads, Capacitor energization	
Voltage Imbalance		Improper load distribution among phases, Single-phasing	Heating of motor
Voltage Flicker		Arc furnaces, Arc lamps	Irritation, Headache and other negative effects in health
Voltage Fluctuations		Load changes	Protection malfunction, light intensity changes
Power Frequency Variations		Faults	Damage to generator and other equipment
Waveform Distortion	DC Offset	Geomagnetic disturbances, Rectification	Increases losses, saturation in transformer, damage to sensitive equipment, accelerated degradation of equipment, EMI, audible noise
	Harmonics	Non-linear loads	
	Inter harmonics	Non-linear loads	
	Notching	Non-linear loads	
	Noise	Arc furnaces, Arc lamps and Non-linear loads	

is low and that of harmonic components might be considerably larger causing the %THD to be high. This might be an insignificant amount of distortion when considering the whole system. Therefore, to avoid this ambiguity the term Total Demand Distortion (TDD) is used. Instead of taking the ratio with respect to the fundamental component, the ratio is taken with respect to the rated current of the system given by IR as,

$$TDD_I = (I_R)^{-2}\sqrt{I_2^2 + I_3^2 + I_4^2 \ldots + I_n^2} \tag{2}$$

But at lower-rated currents, TDD and THD values are not far apart [9]. Some major negative effects of harmonics on the grid are as [8],

1) Increased losses and heating.
2) Derating of the distribution system and excessive neutral currents.
3) Accelerated degradation of power system components and hence reduction in service life.
4) Interference in communication systems and other devices.
5) Failure or Mal-operation of protection systems and capacitor banks.

Various International Standards are given by organisations around the globe that define or recommend certain limits for power quality-related problems. IEEE-519 is one such standard that is related to harmonic pollution limits. IEEE-519 is a set of recommendation and not defined limits. It gives the measure of TDD at the point of PCC and magnitudes of TDD are given based on the rated current of the system. For a small system such as a residential system, the rated current is relatively low and %THD number that can be obtained using measurement devices, with great care, can be used for analysis [8]. To reduce current harmonics being injected back to the grid, various types of power filters are available, mainly classified as passive, active and hybrid power filters.

B. PASSIVE POWER FILTERS

Passive filters are designed using a combination of passive components such as resistors, capacitor and/or inductors with the intention of either directing the undesirable components through a different path and/or by providing a high impedance path for undesirable components to block it. There are various topologies in which the three basic passive components can be connected to get the desired frequency response – some of the popular configuration or topologies are shunt, series, hybrid, single tuned, double-tuned and damped. Fig. 1 shows a broader classification of passive filter [6]–[8]. Based on the type of connection, passive filters can be classified as series, shunt and hybrid.

1) SHUNT PASSIVE POWER FILTERS

Shunt PPFs are connected in shunt or parallel across the load. This provides a low impedance path for harmonic current so that they don't propagate back to the grid. The advantage with shunt PPFs is that the filter need not be designed for the full load system current, hence can be designed just to take up the harmonic current load. The simplest configuration RLC in series. Series resonance is a phenomenon where the minimum impedance is offered by a circuit at a particular frequency called resonant frequency. This nature of the circuit is used to redirect the path of a particular harmonic component to ground. These types of filters are called notch filters/single-tuned filter. The design and choice of components depend on the power rating and the tuned frequency. The designer should

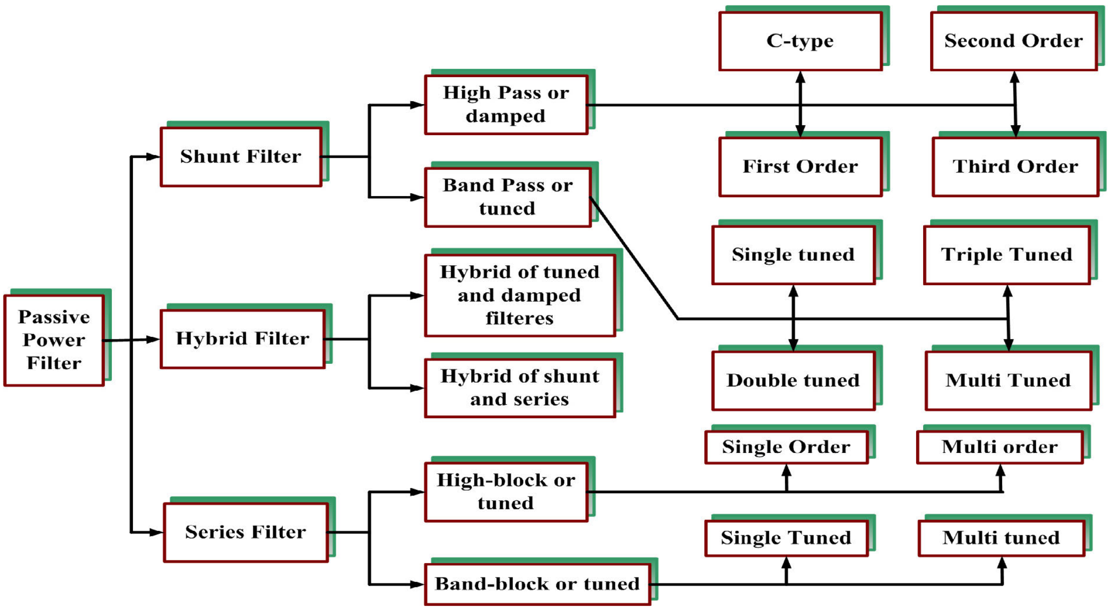


FIGURE 1. Classification of passive filters [2].

make sure that the filter offers high impedance for current at the fundamental frequency, failure to do so causes the filter to overload and unnecessary power loss to take place [9]. It is a common practice to detune the filter to avoid overloading at harmonic frequencies. Multiple tuned filters are made by combining individual single tuned filters to obtain the desired frequency response. High pass filters are used to redirect all high-frequency harmonics which are usually observed in switching converters [9], [10]. Some common configurations of shunt PPFs and its corresponding frequency response are shown in Fig. 2. The major problem with shunt PPFs is resonance, the grid has an impedance that varies continuously with the loads being connected and disconnected and environmental conditions. The grid impedance can interact with the filter impedance to create an undesirable frequency response. This can cause relatively high amounts of currents to flow through the filter causing overloading. In some cases, the current flowing through the filter at resonance frequency can cause the excessive voltage to appear across the filter. This can affect the filter and the system it is connected to [11], [12]. It can also cause poor power factor in light loading conditions because of excessive reactive power injection back to the source [12]. Using multiple tuned filters such as quadruple tuned or more becomes uneconomical and complex. Therefore, multiple tuned filters are usually designed up to triple tuned configurations.

2) SERIES PASSIVE POWER FILTERS

Series PPFs are connected in series with the load. This provides high impedance for harmonic currents and thus blocks them. Similar to shunt PPFs, there are various configurations; some are shown in Fig. 3(a). Series filters in practice aren't preferred over an equivalent shunt filter as the series filters have to be designed to take up entire system's load current and such that it offers low impedance for the fundamental component of current to avoid excessive losses and voltage drop. This makes the design bulkier and expensive. The benefits are less when compared to its shunt counterpart. These types of filters are used in systems with small power ratings.

3) HYBRID PASSIVE POWER FILTERS

These types of filters are a combination of series and shunt PPFs. The best characteristic of both types of filters can be obtained by carefully combining the two in different configurations and some of the configurations can be seen in Fig. 3(b). One such example is a combination of series single tuned passive filter and a passive shunt filter. In this configuration, the passive filter offers the low impedance path to the harmonic current, while at light loading conditions the series filter absorbs the reactive power and thus improves the power factor. Usually, by combining both shunt and series, desired characteristics can be obtained with less components thus making it feasible and hence are commonly used in industries [13].

C. ACTIVE POWER FILTER (APFs)

Passive filters can cater to only certain components of harmonic pollution and in some cases, it is hard to achieve certain harmonic limits with just the help of a passive filter. Active filters make use of power electronic devices and appropriate control techniques to feed the harmonic current required by the load so that only the clean current is drawn by the load. Especially in the case of three-phase systems, there are problems such as load imbalance, poor power factor, excessive neutral current and excessive reactive power. This can be easily reduced with the help of active filters. The increased

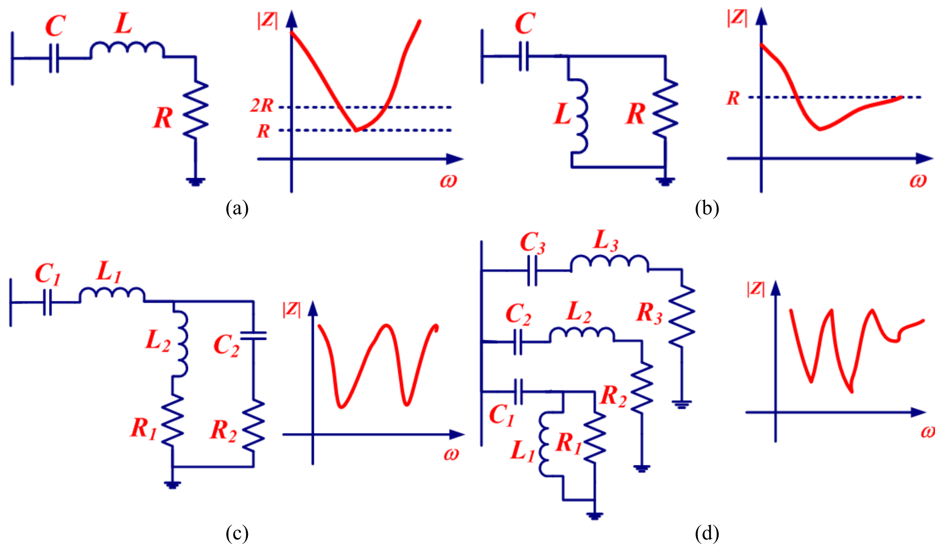


FIGURE 2. Common configurations of shunt passive power filter and its frequency response: a) band-pass: b) high pass: c) double band-pass; d) composite. [2].

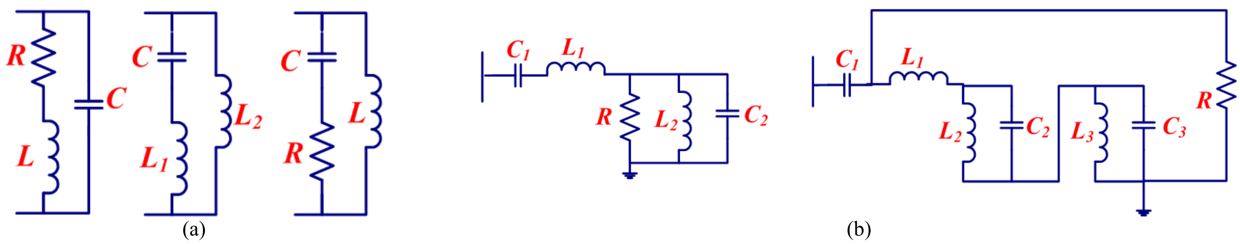


FIGURE 3. Common configurations of passive power filter a) Series filter: single tuned (left), double tuned (middle), high-block (right) b) Hybrid filters: damped double tuned (left), damped triple tuned (right) [2].

severity of power quality problems has forced power system engineers to consider active power filters. Active power filters can be classified as – shunt, series and hybrid. This can be seen in Fig. 4. Shunt APFs are commonly used for mitigation of current harmonics, compensating for reactive power and load balancing in three-phase systems. Series APFs are used for improving the voltage profile and balance terminal voltage. This type of APF makes use of a coupling transformer. Hybrid APFs are usually a combination of the active and passive filter. This configuration is used in high power systems. The passive filter is responsible for bulk filtering and the active filter is responsible for reactive power compensation, improved current harmonic mitigation and load balancing. Series and Shunt APFs cater only for certain power quality issues, hence in some cases, a combination of two active filters are used [1]–[3]. Usually, the inverter stage of active filters can be made of Voltage Source Inverters (VSI) or Current Source Inverter (CSI). VSI's are more popular owing to the simplicity of design and implementation [14].

II. PROBLEM IDENTIFIED

Power electronic devices can be found in almost all devices that are connected to the grid and the harmonic pollution they cause are quite prominent. The use of power electronics has been increasing and hence mitigation of current harmonics is important to maintain a healthy system. Power filters or the design topology/design of power converters need to be modified or changed to reduce current harmonics. Filters can be connected at the point of PCC that can cater to the entire system it was connected to. The filter can be passive, active or hybrid and each has its pros and cons as mentioned in the previous section. Although in literature there are various topologies and techniques mentioned, in the field of single-phase active filters, there are only a few studies related to active filters for domestic appliances. Analysis of performance of such active filters (in terms of steady state and dynamic) while catering to highly non-linear and highly inductive loading conditions are also not widely found in literature.

III. INVESTIGATION STUDIES

A. HARMONIC ANALYSIS OF VARIOUS LOADS

The main objective of this paper is to reduce the current harmonics and hence reduce the problems caused by it. To understand current harmonics and learn about how it is generated, analysis of current harmonics on various commonly used loads was carried out. Current and Voltage waveforms were captured using a 2-channel DSO (Digital Storage

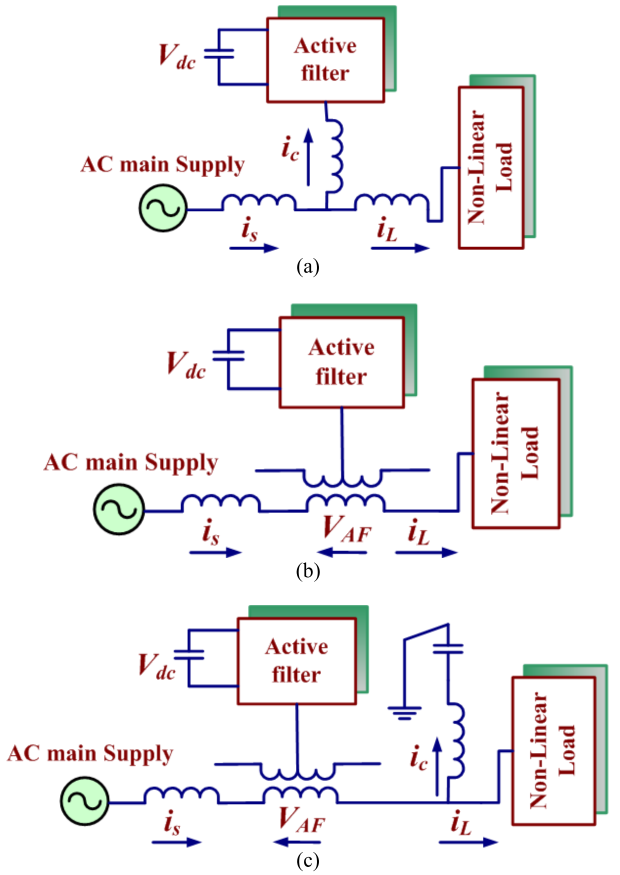


FIGURE 4. Active power filter topologies: a) shunt; b) series; c) hybrid [1].

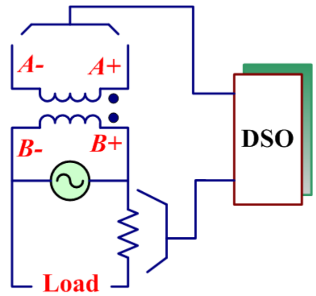


FIGURE 5. Connections for capturing the waveforms using DSO.

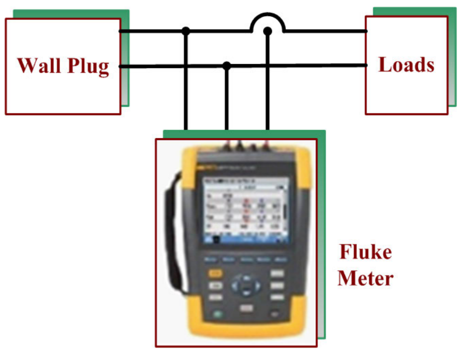


FIGURE 6. Connections used for measuring % THD.

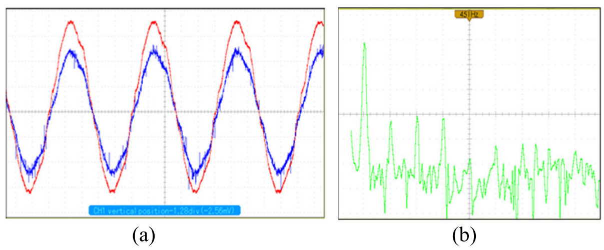


FIGURE 7. Incandescent light bulb (a) current (red) and voltage (blue) waveforms, (b) Fast fourier transform waveform.

Oscilloscope). To keep the measurements simple and safe, the mains supply for the DSO was isolated using a separate 1:1 transformer. The mains voltage was probed with the help of 1:1 transformer. To measure current, a shunt resistor was connected in series with the live wire going to the load. The voltage drop across the shunt resistor is proportional to the current flowing through it, therefore by using a DSO to measure the voltage drop across it is equivalent to visualize the current drawn by the load. The need for a 1:1 transformer for measuring voltage or the need for voltage isolation can be explained with the help of the test setup that was used to capture the waveforms shown in Fig. 5. The voltage drop across the resistor, hence the current is measured by connecting the positive end probe of the first channel to the mains supply (the starting end of the resistor) and the reference/ground clip is connected to the other end of the resistor. But this reference/ground probe is shared by both the channels of the DSO and the reference of a DSO is connected to mains earth. Therefore, using the same reference for measuring the voltages would cause a short. Fluke 434 Series II Energy Analyser was used to obtain %THD (Percentage Total Harmonic Distortion). The test setup employed for the same is shown in Fig. 6.

1) INCANDESCENT LIGHT BULB

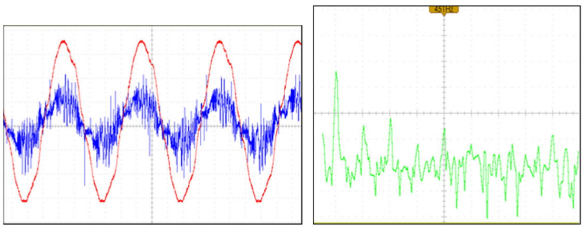
Incandescent light bulbs use a filament usually made of Tungsten enclosed in an inert atmosphere. A sufficient current flowing through it causes it to glow. By nature, the filament is resistive. Therefore, the current and voltage waveforms depict in Fig. 7(a) are sinusoidal and are in phase with each other. This translates into the FFT waveform shown in Fig. 7(b). Apart from the peak at 50Hz which is the fundamental frequency, other harmonic components are not significant hence it can be concluded that there is very little distortion in the current waveform.

2) LED LIGHT BULB

With the shift towards energy-efficient lighting, the usage of LED lights has increased over the years. Usually, these LED lights have an SMPS that provides the constant current supply required to drive the LEDs properly and safely. To understand the general design of the SMPS/Driver, one of the LED bulbs was taken apart and it was found that it uses a single chip solution where the IC takes care of the switching for the conversion and at the same time is responsible for maintaining a good power factor i.e. it had APFC (Active Power Factor Correction) built-in. The current and voltage waveforms and Fast Fourier Transform (FFT) waveform associated with the

TABLE 2. Various parameters for the different loads and analysis.

Load	V_{rms} (Volts)	V_p (Volts)	I_{rms} (Amps)	I_p (Volts)	Freq (Hz)	VTHD (%)	ITHD (%)
GM LED 20W	234.65	321.3	0.4	0.9	51.343	2.835	62.35
CG LED 9W	234.69	321.4	0.3	0.7	51.344	2.82	31.975
SYSKA 7W	234.33	321.5	0.3	0.8	51.344	2.82	66.45
PHILIPS LED BULB 10W	234.56	321.25	0.3	0.7	51.344	2.88	28.86
PHILIPS LED BULB 8W	234.46	320.9	0.3	0.7	51.344	2.86	29.325
SMPS	234.21	320.35	0.4	1.4	51.344	2.925	136.935
MI CHARGER	234.29	320.2	0.3	0.8	51.344	2.935	67.575
SAMSUNG CHARGER	234.38	320.9	0.3	0.8	51.344	2.885	64.82
DELL 45W LAPTOP CHARGER	234.17	320.5	0.35	1.3	51.344	2.93	138.87
INDUCTION STOVE	234.36	320.7	0.3	0.6	51.344	2.88	88.495
VFD(RUN)	233.97	318.65	0.7	3.2	51.344	3.04	189.125



(a) (b)

FIGURE 8. LED light bulb (a) current (red) and voltage (blue) waveforms, (b) Fast fourier transform waveform.

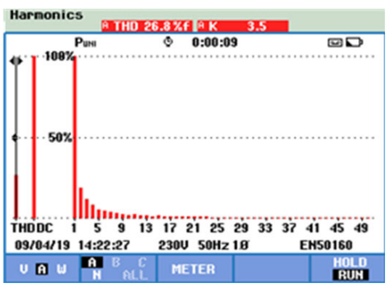
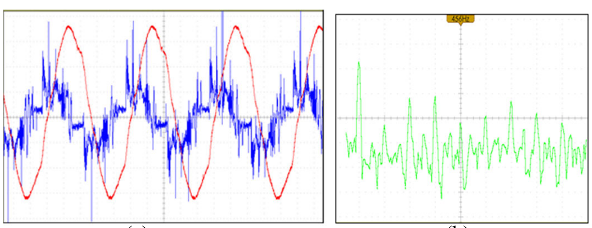


FIGURE 9. Power spectrum of a LED light bulb.



(a) (b)

FIGURE 10. Generic LED light bulb (a) current (red) and voltage (blue) waveforms, (b) Fast fourier transform waveform.

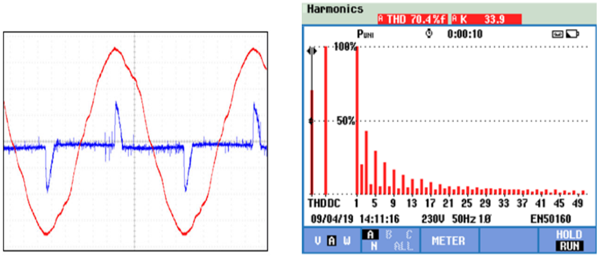
LED lights are shown in Fig. 8(a) and Fig. 8(b). Although there is a significant amount of distortion in the current waveform, it has a roughly sinusoidal shape, as a result, the total harmonic distortion is relatively less. Fig. 9 shows the power spectrum graph.

3) GENERIC LED LIGHT BULB

In the market, as with many other things, fake or generic versions of products are available. Cheap versions of LED light bulbs are a common sight with false claims that lure customers into buying them. The current and voltage waveforms of a generic 3W LED light bulb is shown in Fig. 10(a). The current waveform has high amounts of distortion and there is a visible phase difference between voltage and current (i.e. comparing the zero-crossings of the waveform). The FFT waveform (Fig. 10(b)) shows significant peaks at harmonic frequencies. To further analyse the reason for the distortion, one such example of these LED bulbs was taken apart. Instead of using an SMPS like the branded ones, it employs a capacitor dropper and a rectifier to power the LEDs. The current is limited with the help of a resistor.

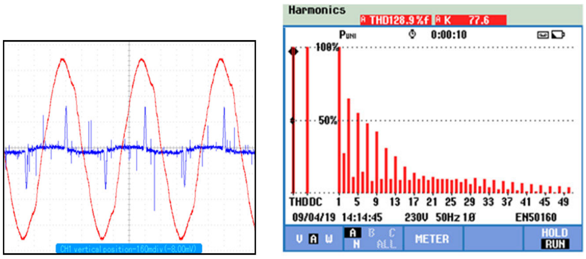
4) SMPS (SWITCHED MODE POWER SUPPLY)

Some of the commonly used devices like mobile chargers, laptop chargers, TVs, PCs etc. make use of SMPS for their power requirements. The reason for its widespread adoption is the power density that can be achieved. High power outputs can be obtained efficiently while achieving a small form factor. The nature of the operation of these SMPS causes current spikes when the voltage is at its peak. Generally, SMPS consists of a rectifier stage and a filter capacitor. When the rectifier is in conducting state, the filter capacitor offers low impedance and the capacitor starts charging which is denoted by the sudden increase in current. These current pulses are often short and at times have a sharp edge. These types of waveforms tend to have high amounts of distortion. In Fig. 11 and Fig. 12 shows the current waveform and the corresponding power spectrum graph of a mobile phone charger and a laptop charger, respectively. There are short pulses of current and have a sharp rising edge. This corresponds to a high %THD which is evident by Fig. 11 and Fig. 12. High-frequency distortion can also be observed and in the case of the laptop charger, there are large spikes in current.



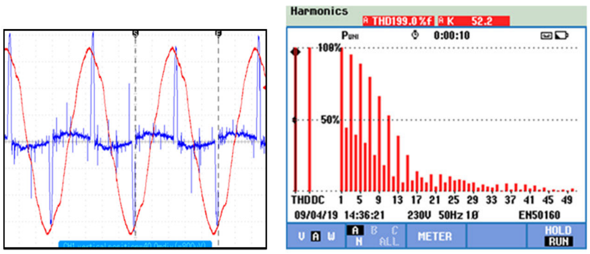
(a) (b)

FIGURE 11. Mobile phone charger (a) current (red) and voltage (blue) waveforms, (b) Power spectrum.



(a) (b)

FIGURE 12. Laptop charger (a) current (red) and voltage (blue) waveforms, (b) Power spectrum.



(a) (b)

FIGURE 13. Variable frequency drive (a) current (red) and voltage (blue) waveforms, (b) Power spectrum.

5) VFD (VARIABLE FREQUENCY DRIVE)

VFDs are common industrial loads that are used to control an induction motor. The supply is of a fixed frequency, therefore, to generate the variable frequency required to drive the induction motor at a required speed, the AC supply is first converted to DC using a rectifier followed by filter capacitors/DC-link capacitors. This DC is then converted back to AC of variable frequency to drive the motor. The VFD that was used for analysis, operated on single-phase AC input and the output was variable frequency three-phase AC. The initial topology is similar to an SMPS and by the nature of the operation, there are large current spikes and high amounts of distortion. Fig. 13. shows the current waveform and the corresponding power spectrum graph of a variable frequency drive.

Various loads were analysed in this study, different brands of LED lights, different types of SMPS, induction stove and VFD. Table 2 shows the various parameters that were recorded during the analysis. Fig. 14 shows the comparison of %THD of the various loads that were analysed. The analysis has given insight into the extent of harmonics pollution caused by some commonly used loads. Amongst all these

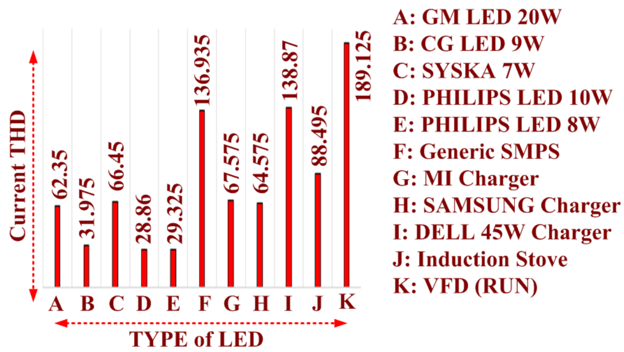


FIGURE 14. %THD (Current) of various loads.

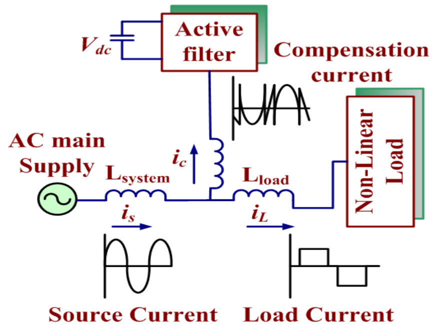


FIGURE 15. Shunt active power filter [1].

loads, VFD has the highest %THD at almost 200% which is followed closely by the SMPS. It should be noted that there are millions of such devices connected to the grid at any given moment. LED lights, although do not have %THD high as the SMPS or VFD, it should not be taken for granted since LEDs are being used to replace all the other conventional sources of lights that were being used and the cumulative effect of them has to be considered. At night, lighting loads make up a considerable percentage of load the grid experiences and hence this study has given much-needed insight to the problem.

B. SHUNT ACTIVE POWER FILTER (SAPF)

The SAPF is commonly used for reducing current harmonics. The compensation is made possible by injecting the harmonic currents 180° out of phase which cancels out the harmonic current. In other words, the harmonic current required by the loads is supplied by the SAPF such that only the clean fundamental current is drawn by the source. SAPFs with the use of an appropriate control technique/scheme can be used for load balancing, power factor correction and reactive power compensation [15], [16]. Fig. 15 shows how the compensation is offered by a SAPF. The important components that make up a SAPF are reference current extraction, inverter, gating signal generator, dc-link voltage control.

1) REFERENCE CURRENT EXTRACTION

To inject the harmonic currents, the inverter needs to be switched appropriately, this is taken care by the gating signal generator which generates gating pulses based on

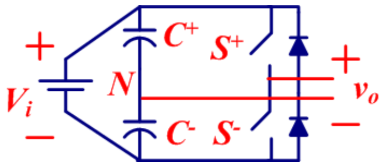


FIGURE 16. Half-Bridge configuration [1].

some 'reference'. This reference current extraction involves the use of an appropriate technique or algorithm to extract the components responsible for the harmonic current from the load current that is being measured. These techniques can be time domain, frequency domain or neural network based. Examples of each are Time Domain – PQ Theory, SRF-Theory, Frequency Domain – FFT (Fast Fourier Transform), STFT (Short Term Fourier Transform), and Neural Network Based – Adaline, Adaptive Filters [9].

Real-time and fast response are two of the most desired characteristics of a reference current extraction technique, therefore time-domain techniques are preferred because of the ease of implementation and relatively less processing power is required. Some commercial units tend to use FFT based techniques since there are dedicated processors and the conversion operation takes place within a short time that is negligible and selective harmonic component elimination is possible [17].

2) INVERTER

Inverters are used to convert DC to AC. There are two main types – Current Source Inverters (CSI) and Voltage Source Inverters (VSI). The two main configurations of single-phase VSI are Half-Bridge Configuration and Full-Bridge Configuration. For this study, Half-Bridge Configuration (Fig. 16) was used for two main reasons – only two switching devices and the gate-drive requirements are less if the hardware is considered. The switches can be MOSFETs or IGBTs. When $S+$ is ON and $S-$ is OFF the output voltage $+v_o$ and when $S+$ is OFF and $S-$ is ON the output voltage is $-v_o$. By switching $S+$ and $S-$ appropriately, the required waveform can be recreated [18]. In the case of SAPF, the source v_i shown in Fig. 16 is not used because the voltage is maintained by drawing some amount of active power from the source.

3) GATING SIGNAL GENERATOR

An inverter consists of multiple switching devices such as IGBT, MOSFETs etc. and these can be connected in different configurations. The switching devices need to be switched appropriately based on the reference current to recreate the compensation current to cancel out the harmonics. This task is taken care of by the gating signal generator. There are various techniques and some commonly used techniques are – SPWM (Sinusoidal Pulse Width Modulation), Hysteresis Current Control, SVPWM (Space Vector Pulse Width Modulation) [17]. Desirable characteristics of a gating signal generator are fast response and close tracking of the reference current [18]. For this study, Hysteresis Current

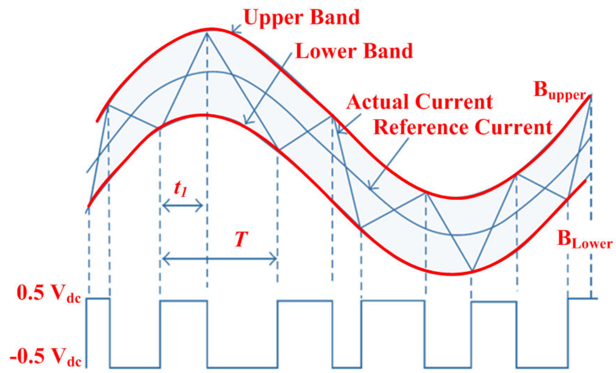


FIGURE 17. Hysteresis current control technique.

Control (HCC) technique was used. The gating signal is generated based on the reference current and the actual current of the inverter i.e. the actual current is kept within a certain error/tolerance band when compared to the reference current. In a fixed band HCC, the band is made by adding the desired current error or tolerance. For example – Assume i_{ref} is the reference current, the tolerance\error band are obtained by adding and subtracting the tolerance, i_t from i_{ref}. This operation can be visualised in Fig. 17, the upper band $(i_{ref}+i_t)$ and lower band $(i_{ref} - i_t)$. Let the actual inverter current be i_{inv}, based on the inverter circuit diagram in Fig. 16 when this i_{inv} is more than the upper band, $S+$ is turned OFF and $S-$ is turned ON, the current starts dropping. When i_{inv} is less than a lower band, $S-$ is turned OFF and $S+$ is turned ON, the current starts rising. The linking inductor which is responsible to reduce the switching noise does not allow the current to drop or rise sharply, but rather it causes it to slowly increase and decrease. This helps the gating signal generator to track the reference current waveform accurately. The linking inductor plays an important role in HCC and failure to choose proper value will affect the performance. If the inductor value is too low the current will rise and drop at a faster rate, in turn, increase the switching frequency and can become unstable. On the other hand, if the inductor value is too high, it might lead to poor tracking, errors and high magnitude current spikes which can damage the inverter [19]. Therefore, it is clear that fixed band HCC does not operate at a fixed switching frequency and is highly dependent on the linking inductor and the grid condition. Various modification to HCC is shown in [19] to constrain the switching frequency. An implementation of HCC for three-phase unbalanced load conditions is shown [20].

4) DC LINK VOLTAGE CONTROL

During operation, switching losses occur due to various factors and the voltage of the DC-Link Capacitor reduces. To ensure proper operation and to maintain good performance, the DC Link voltage needs to be maintained at a certain level. This is done by adding the loss component to the reference current which makes the inverter draw small amounts of active power from the source. To maintain this

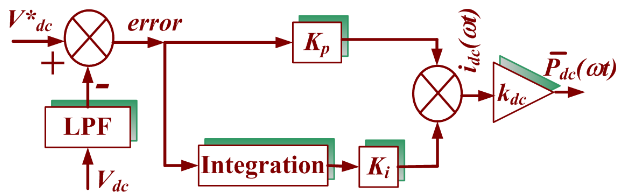


FIGURE 18. Basic block diagram of DC link control loop [8].

voltage, various closed-loop control techniques are used. PI (Proportional Integral) controllers are commonly used for this task. Fuzzy logic-based voltage control loops are proposed to improve the overall performance of SAPF [21]. PI controller-based control loops make use of a reference voltage and the actual voltage to generate an error. This is fed to the PI controller which produces an output that is added with the reference current, as mentioned previously, this makes the inverter to draw the active power required to maintain the voltage. Usually, the measured voltage is passed through a low pass filter to avoid the switching noises of the inverter which can introduce error, but this slightly affects its transient response [22]. Fig. 18 shows the basic block diagram.

C. PQ-THEORY

Instantaneous reactive power theory or PQ theory is the popular time-domain based harmonic current extraction technique that was proposed by Akagi in [22]. This technique involves converting the abc or the phase variables to $\alpha\beta 0$ coordinate system using clarke's transformation. The resultant active power and reactive power calculated using the phase variables in $\alpha\beta 0$ coordinate system are made up of AC and DC components. The DC component is removed by passing it through a High Pass Filter (HPF). After filtering, the components left out are active and reactive power that corresponds to the harmonic current drawn by the load. With the help of inverse clarke's transformation, the necessary compensating current (reference current) is calculated by converting the $\alpha\beta 0$ to abc.

1) THREE-PHASE VERSION ADAPTED FOR SINGLE PHASE IMPLEMENTATION

For this study, the technique originally meant for three-phase systems was altered for a single-phase application. The three-phase implementation can be seen in literature [23], [24]. The other two phases required for the calculation were obtained by phase shifting the voltage and current waveforms by 120° and 240° respectively to create a balanced three-phase system scenario. With the following three-phase quantities obtained, the following calculations were carried out to calculate the compensating current. The single-phase quantities being shifted by 120° and 240°.

$$\left.\begin{array}{l} V_a = V_m \sin(\omega t) \\ V_b = V_m \sin(\omega t + 120°) \\ V_c = V_m \sin(\omega t + 240°) \end{array}\right\} \left.\begin{array}{l} I_a = I_m \sin(\omega t) \\ I_b = I_m \sin(\omega t + 120°) \\ I_c = I_m \sin(\omega t + 240°) \end{array}\right\} \quad (3)$$

The following current and voltage are converted from abc to $\alpha\beta 0$ coordinate system with the help of Clarke's transformation as follows,

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (5)$$

Instantaneous values of active power 'p' and reactive power 'q' are calculated as,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \cdot \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (6)$$

This instantaneous active power 'p' consists of the DC component (fundamental active power) and the AC component (harmonic power) as shown in (7),

$$p = p_{dc} + p_{ac} \quad (7)$$

The reference current required for the compensation is obtained by taking the inverse of (6) by taking into consideration just the component responsible for the harmonics, that is the AC component mentioned in (7). To obtain just the AC component from the instantaneous active power in (7), the DC component needs to be eliminated. This is taken care by a high pass filter. There are losses associated with the system and this causes the DC link voltage to come down over time, to overcome this and maintain the DC link voltage at a set value, the power loss component is added. This component makes the inverter draw some amount of active power from the source and thus compensates for the power loss. This is shown below

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \times \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} p_{loss} - p_{ac} \\ q \end{bmatrix} \quad (8)$$

Inverse Clarke's transformation is used to obtain the abc values of the compensating current from the $\alpha\beta 0$ coordinates as shown,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \quad (9)$$

To obtain the reference current, only phase 'a' is considered because the technique meant for three phase was altered for single phase application. This current is responsible for harmonic current mitigation and reactive power compensation. This is calculated using the final equation shown below,

$$I_a = \sqrt{\frac{2}{3}} \left(\frac{I_o}{\sqrt{2}} + I_\alpha \right) \quad (10)$$

2) IMPLEMENTATION FOR SINGLE PHASE SYSTEMS

Various literatures have proposed PQ-theory for single-phase systems, some of the implementations can be seen in literature [21], [25]. Based on [21], the following equations were used to realise it. The voltage and current that were measured are phases shifted by 90° to obtain the quantities in $\alpha\beta$ coordinate system as follows,

$$\left.\begin{aligned} V_\alpha &= V_m \sin(\omega t) \\ V_\beta &= V_m \sin(\omega t + 90^\circ) \end{aligned}\right\} \left.\begin{aligned} I_\alpha &= I_m \sin(\omega t) \\ I_\beta &= I_m \sin(\omega t + 90^\circ) \end{aligned}\right\} \quad (11)$$

Instantaneous active and reactive power is calculated by,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (12)$$

The Instantaneous active power contains AC and DC components and can be written as,

$$p = p_{dc} + p_{ac} \quad (13)$$

Using an HPF, the dc component of the power is eliminated; the ac component responsible for the harmonic current and the switching losses are considered to maintain the DC link voltage. With the components of interest isolated (the ac component of power), the operation is carried out to obtain the harmonic currents as follows,

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \times \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_{ac} - p_{loss} \\ q \end{bmatrix} \quad (14)$$

The compensating current is obtained by solving for I_α as follows,

$$I_a = \frac{1}{V_\alpha^2 + V_\beta^2} \times \left(V_\alpha . p_{ac} - V_\alpha . p_{loss} - V_\beta . q \right) \quad (15)$$

D. DQ-THEORY/SRF THEORY

DQ Theory also called as Synchronous Reference Frame theory is generally used for inverter regulation, motor control and other specific power-related control applications. This method uses Park's methodology to represent current in terms of the dq reference frame, which includes transforming the AC quantity into components in a synchronous reference frame from which the components of interest are separated by means of filters and the actual current is derived by the transformation of the Inverse Park.

This methodology is explained by the researchers in [23], [24]. The single-phase version of this technique can be seen in [25]. For this study, the three-phase version of this was adapted for single phase application. Similar to the implementation of a three-phase PQ theory-based technique for single-phase application, the single-phase quantities were phase shifted by 120° and 240° to mimic a balanced three-phase system. Further calculations were carried out based on this. To keep the implementation simple, the DQ transformation block available in Simulink was used, similar to the PQ theory. The DC components were eliminated using HPF and the resultant was transformed back to obtain the compensating current using the inverse DQ transformation block. Both the DQ and Inverse DQ transformation blocks is synchronised with a PLL.

E. PERFORMANCE COMPARISON OF PQ THEORY AND SRF THEORY BASED SAPF

Based on the harmonic analysis that was carried out on various loads, it was found that many loads generate %THD greater than 60%. Many studies on SAPFs are conducted with loads that generate %THD around 30-40%. This study compares the performance of PQ Theory and DQ theory based SAPF, two of the most commonly used time-domain techniques under highly non-linear conditions. The steady-state and dynamic performance of a SAPF depends on how fast the extraction technique can respond. Many loads such as VFDs, arc furnaces, heating loads etc are fast-changing loads and continuously vary over time. The control technique should be capable of responding to these changes. Failure to do so may cause problems such as phase difference and inaccurate magnitude which further leads to problems such as a backward current flow that can damage the APF. For a fair comparison of the two techniques, a highly non-linear load was modelled and all the other simulation parameters were kept the same. To test the dynamic performance and the reactive power compensation offered by the SAPF, a highly inductive load was connected halfway through the simulation. The total simulation time was 3 seconds, i.e. the test was conducted for 1.5 seconds with the highly non-linear load and 1.5 seconds with highly non-linear load and a highly inductive load across the supply.

1) MODELLING OF HIGHLY NON-LINEAR LOAD

Loads such as SMPS and VFDs draw current in short pulses and often have sharp rising or falling edge which can be seen in the previous sections where various loads were analysed. A non-linear load was modelled considering these waveforms using simulink. To recreate these waveforms, GTO's in full-bridge configuration were used. They were turned on appropriately when the voltage was close to its peak value, it causes a sharp rising edge when the GTO turns OFF, and it causes a sharp falling edge. By changing the GTO's trigger voltage, a desired amount of %THD can be obtained for testing. For this study, it was set to produce %THD of 115%. The current waveforms and FFT analysis of the non-linear load is shown in Fig. 19(a) and 19(b), respectively.

2) SAPR PARAMETERS

As mentioned previously, for proper comparison of the two extraction techniques, other than the components/blocks responsible for the harmonic current extraction, the rest of the model was kept the same. In this case, both techniques (PQ and DQ) which were originally meant for three applications were utilized for a single-phase application. For generating the gating signal, hysteresis current control technique was used and the PI controller was used for DC link voltage control. The parameters used for the performance comparison is shown in Table 3.

F. PQ THEORY BASED SAPF: WAVEFROMS AND ANALYSIS

Fig. 20(a) depicts the waveforms of the first half of the simulation when only the non-linear load was connected.

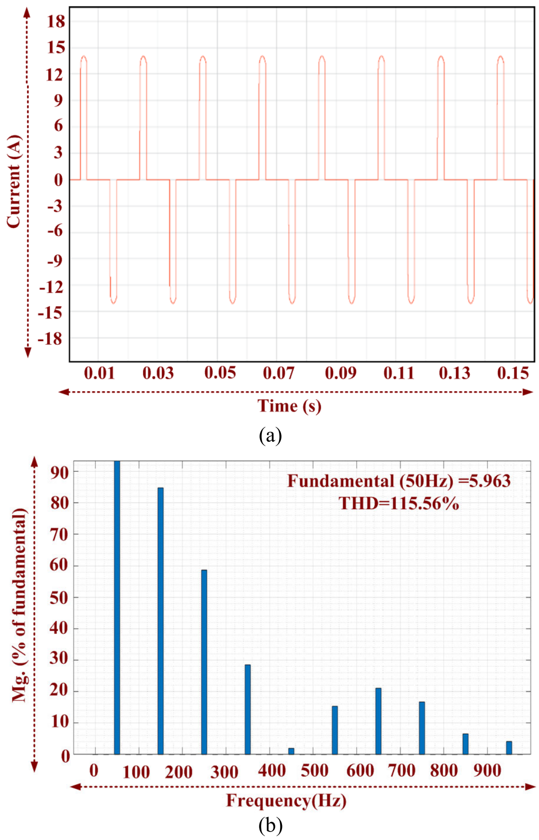


FIGURE 19. Non-Linear load (a) Current waveform of the modelled non-linear load, (b) Harmonic spectrum of the modelled non-linear load.

TABLE 3. Parameters of SAPF.

Parameter	Value
Supply Voltage	230V(RMS)
Fundamental Frequency	50Hz
DC Link Voltage	325V
DC Link Capacitor	3300uF
Inverter Filter Inductor	0.2mH
RL Load (First Half)	R = 23Ω, L = 1mH
RL Load (Second Half)	R = 23Ω, L = 1mH *R = 23Ω, L = 30mH (*Connected directly across supply)

TABLE 4. Comparison table of the harmonic extraction techniques tested with highly non-linear load.

Parameter	No Filter	PQ-Theory Based	SRF-Theory Based
%iTHD	115.56%	4.92%	4.42%
Active Power (Watts)	970W	972W	973W
Reactive Power (Volt-Ampere)	6.778VA	-0.65VA	-0.9VA

The FFT analysis is shown in Fig. 20(b). Fig. 20(c) shows the waveforms when the inductive load is connected.

G. SRF THEORY BASED SAPF: WAVEFORMS AND FFT ANALYSIS

Fig. 21(a) shows the waveforms of the first half of the simulation results with non-linear load and the FFT Analysis is shown in Fig. 21(b). Fig. 21(c) shows the waveforms for inductive load.

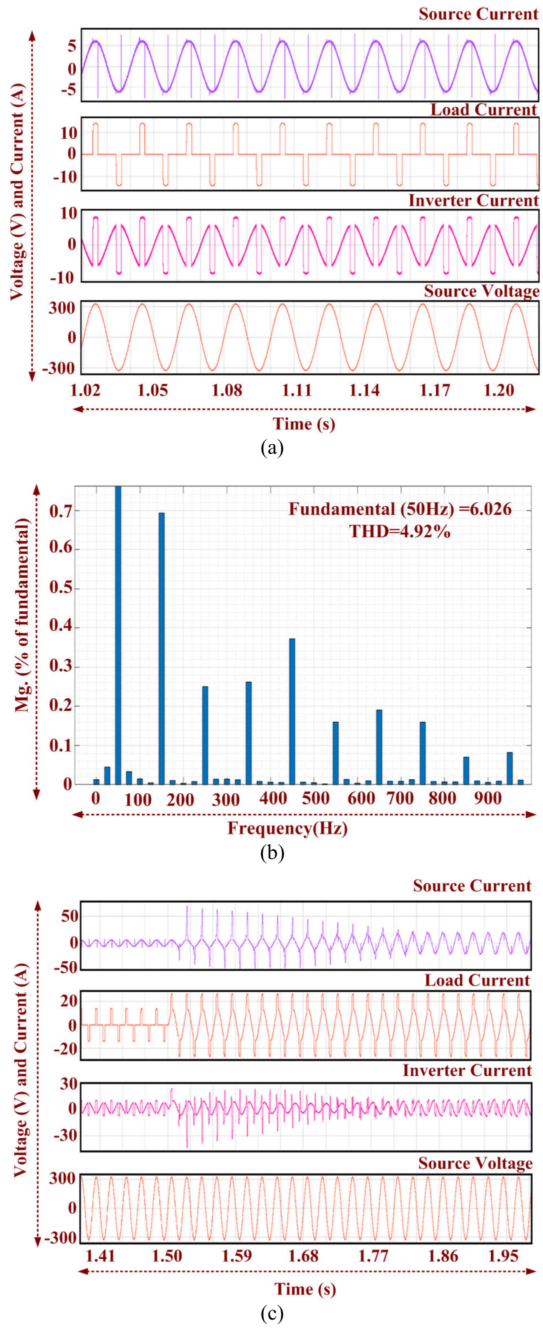


FIGURE 20. Results (a) Source current, load current, inverter current and source voltage waveform (Top to Bottom) of PQ-Theory based SAPF, (b) Harmonic spectrum of source current after filtering (%iTHD = 4.92%) (PQ-Theory), (c) Source current, load current, inverter current and source voltage waveform (Top to Bottom) of PQ-Theory based SAPF when inductive load is connected.

H. COMPARISON

In Table 4, the first half of the simulation results with non-linear load is presented. The percentage of iTHD of SRF-theory based shunt active power filter (SAPF) is relatively better contrary to PQ-theory based shunt active power

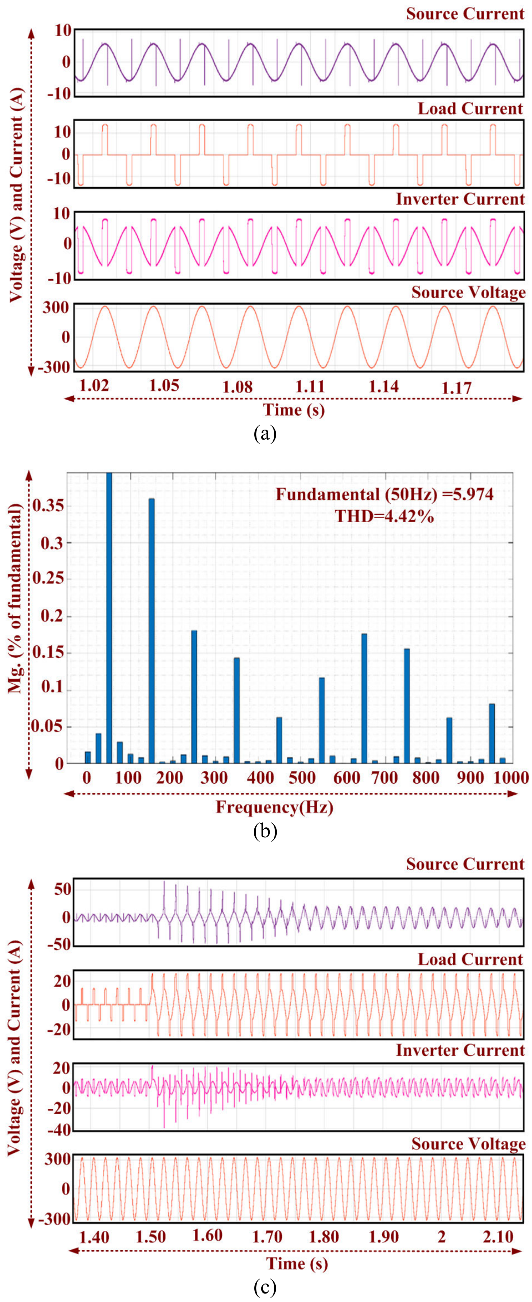


FIGURE 21. Results (a) Source current, load current, inverter current and source voltage waveform (Top to Bottom) of SRF-Theory based SAPF, (b) Harmonic spectrum of source current after filtering (%iTHD = 4.42%) (SRF-Theory), (c) Source current, load current, inverter current and source voltage waveform (Top to Bottom) of SRF-Theory based SAPF when inductive load is connected.

filter (SAPF). Also, the reactive power compensation of both the extraction techniques is quite same. The other half of the simulation results when inductive load was connected across the supply is presented in Table 5. The percentage iTHD reduction and reactive power compensation is same as inferred in the previous case.

Taking a brief overview at the waveforms that were mentioned in the earlier subsections, it can be found that the dynamic and steady-state performance of the SAPF using

TABLE 5. Comparison table of the harmonic extraction techniques after inductive load was connected.

Parameter	No Filter	PQ-Theory Based	SRF-Theory Based
%iTHD	36.76%	1.66%	1.46%
Active Power (Watts)	2938W	2938W	2937W
Reactive Power (Volt-Ampere)	813VA	-0.61VA	-0.9VA

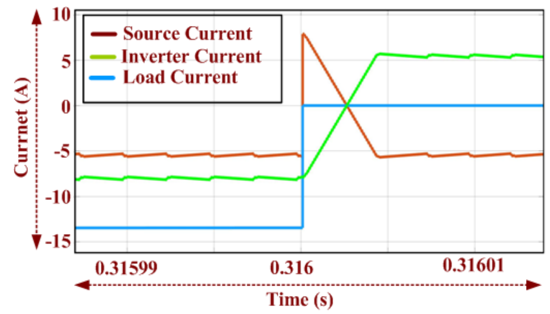


FIGURE 22. Anomality observed in source current waveform.

two different extraction techniques were almost the same. Comparing the source current waveforms in Fig. 20(c) and Fig. 21(c), it can be observed that PQ-Theory based SAPF takes around 15 cycles to stabilize whereas the DQ-Theory based SAPF takes around 10 cycles. The results are quite similar but in terms of implementation and the parameters required for reference current extraction, it should be noted that in PQ-Theory, both, voltage and current values are used for generating the reference current whereas in case of SRF-Theory, only current values are used and voltage is used just for synchronization with the help of PLL Therefore, if the voltage is distorted, SRF theory based SAPF will perform better than PQ-Theory based SAPF. Also, SRF theory based SAPF involves fewer complex calculations and hence the processing required is quite less. Overall, comparing the performance and the benefits, SRF theory based SAPF would be a better option.

I. ANAMOLITY IN SOURCE CURRENT

There are visible spikes in the source current waveforms presented earlier mainly due to the inverter not being able to react to the rapidly changing reference current. Once the reference current decreases rapidly to zero, the inverter remains on for a brief period, after which the current passes back into the APF from the source and induces a current surge. This is expressed in Fig. 22.

IV. CONCLUSION

Power Quality and its importance in the past decades is significantly increasing due to the increased use of power electronic devices. Various domestic loads and their non-linear behavior is studied and the need for mitigation of current harmonics is analyzed. Various reference current extraction techniques were analyzed with the performance comparison of PQ-Theory based and SRF-theory based SAPF. For proper comparison, the parameters of SAPF, highly non-linear load and highly inductive load were considered the same for testing reactive power compensation and dynamic performance. In this comparison, the effective reduction of harmonics at source and the reactive power compensation were analyzed. Also, the steady-state and dynamic performance of the SAPF were studied using two different techniques. Waveforms related to the comparison were captured and the final numbers were tabulated. Based on the results obtained and the parameters involved in implementation it was found that the performance of SRF-theory was noteworthy. With the use of both the techniques, it was possible to reduce the %THD to less than 5% as per the IEEE-519 standard recommendation.

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