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POWER QUALITY ANALYSIS AND IMPROVEMENT USING SHUNT ACTIVE POWER FILTER

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ABSTRACT

The presented paper explores the evolving landscape of power quality in contemporary power systems, focusing on the surge of non-linear loads and the ensuing harmonic distortions. This study explores the integration of SAPF with PQ theory to enhance harmonic mitigation capabilities and improve overall power system performance. Simulation-based study and modelling of Shunt Active Power Filter (SAPF) based on six IGBT Voltage Source Inverter (VSI) with hysteresis controlling scheme is done to compensate load current harmonics at point of common coupling (PCC) to improve the power quality. Execution of the proposed Shunt APF and the prowess of the proposed control scheme are demonstrated through MATLAB simulink. The paper provides a comprehensive understanding of power quality challenges, offers a nuanced approach to harmonic mitigation, and demonstrates the effectiveness of SAPF with PQ theory in enhancing power system reliability.

Keywords:- SAPF, Filters, THD, IGBT, PCC, PQ

INTRODUCTION

With the world entering a new era of power electronics, the widespread presence of non-linear loads has given birth to distorted waveforms in power system. In an increasingly electrified world, the quality of electrical power is of paramount importance. Power quality refers to the conformity of electrical supply to the ideal standards required for safe and efficient operation of electrical equipment. It encompasses various parameters, including voltage stability, frequency regulation, harmonics, voltage sags and swells, transients, and interruptions [1]. Many definitions for power quality have been proposed. In IEEE Std. 1100-2005 (2006) "Power Quality" is stated by "The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment in a manner and compatible with the premise wiring system and other connected equipment."

Ensuring adequate power quality is the fundamental concern for utilities, industries, and consumers alike, as it directly impacts the reliability, efficiency, and safety of electrical systems. Electronic devices are extremely sensitive to even tiny fluctuations in power quality, which can result in failures, data damage, and costly downtime. Power quality difficulties in industries can result in production losses and reduced product quality, reducing competitiveness in the global market. Furthermore, power quality is critical to the stability and efficiency of modern power grids, especially when renewable energy sources and distributed energy resources are integrated on a massive scale.

Since power quality is so crucial in the modern world, standards have been defined to set a bar for power quality in industrial and residential places. Many aspects of electrical power quality are defined and specified by power quality standards. These standards help to ensure that the voltage and current sent to electrical equipment meet specific parameters, therefore avoiding malfunctions, damage, and safety concerns. The standards that are to be used in power quality studies are IEEE 1159, IEEE 519, EN 50160 and IEC 61000 series. All of these standards offer us a level we have to always surpass to ensure good power quality.

There have been attempts to further improve these standards like expanding the voltage THD limit to a total of four limits namely low frequency weighted THD, high frequency weighted THD and even voltage harmonic components THD [2].

HARMONICS

Basically, harmonics are current or voltage waveforms whose frequencies are integer multiple of fundamental frequency. Nowadays, by means of modern equipment, harmonics up to 63rd can be measured. But the most regularly found harmonics are between 3rd to 25th [3].

There are many causes of harmonics in a system. Harmonic voltages in medium-voltage networks can result from the effect of equipment connected to low-, medium-, or high-voltage networks [4]. For this reason, any given piece of equipment can only produce part of any compatible harmonic voltage level, reducing their efficiency and creating other problems as well [4]. As a result, harmonics play an important part in the deterioration of power quality rating.

The harmonics present in a system are often quantified by the system's Total Harmonic Distortion (THD). The total harmonic distortion (THD) of a system is described as "a measure of the distortion or impurity present in an electrical system's voltage or current waveform due to the presence of harmonics." The expression that follows is used to calculate a system's THD:

$$\frac{\sqrt[2]{\sum_{N=2}^{\infty} V_N^2}}{V_{1(rms)}}$$

Measurement of harmonics can be done through several means, such as Fast Fourier transform. A two part study by Y. Baghzouz about time varying harmonics shows us the problems associated with computation of non-steady state harmonics, summation of time-varying harmonics, harmonic power flow calculations and applications. First part of this study reviews potential complications with time-varying harmonic measurement and concludes that the Fast Fourier Transform (FFT) has many shortcomings such as multiple peaks in probability densities. The study also presents that by decomposing the signal via calculations can minimise this problem to some extent [5].

In the second part of the same article, the summation and propagation of harmonics containing random components are discussed. The research has presented many statistical models to gather data on harmonics in the system [6]. The complexity of such data is hard to analyse with normal means, thus ML models become a fitting method to analyse them.

The efficiency of the harmonic distortion power specified in IEEE standard. 1459-2010 utilised for harmonic source detection is examined in the work written by Chang-Song Li [7] It demonstrates how finding the source of harmonics can be done effectively using the relationship between instantaneous power and apparent power. Additionally, harmonic power that cannot be precisely measured by the approach in [7] can be introduced by a non-linear load at the customer end.

International harmonic standards IEC 61000.3.6 and IEEE 519 Establish standards for the voltage harmonics in the power system [2]. The standards mentioned supply restrictions on VTHD and individual harmonics. Limits between h=2 and h=40 are frequently examined, which means that meeting standards typically necessitates meeting 40 different criteria. The arbitrary nature of the restrictions in current standards is highlighted by the significantly varying harmonic limits in IEC and IEEE standards for similar harmonics.

LOW FREQUENCY HARMONICS: Due to their high resistance to high frequency harmonics, inductive loads often exhibit low harmonic currents and I2R losses. In contrast, inductive loads are perceived by harmonics of low frequency (which is generally h≤13) as having a low impedance, resulting in larger harmonic currents and higher I2R losses [2].

Low frequency harmonic voltages and currents are limited in power systems to control excessive heating losses in synchronous and induction motors [2].

HIGH FREQUENCY HARMONICS: Harmonics of high frequency (which is generally h>13) mostly have negative effects on capacitor currents. Such capacitors could be found in the loads of customers, such as small switch node power supply, or they could be a component of power system network power factor correction equipment [2].

MITIGATION OF HARMONICS

Since there exist many methods for the mitigation of harmonics, the harmonic mitigation strategies are divided into three groups, including passive harmonic filters, active harmonic filters, and hybrid harmonic filters. Tuned harmonic filters, converter circuits using greater pulse numbers, and series reactors are components of passive filters. There are two main parts in this technique: a capacitor and an inductor. An L-C circuit is created by connecting these parts in series. This is done in order to prevent harmonic currents from entering the system and to direct the flow of harmonic power through the low impedance circuit while the Passive Power Filter is always connected in shunt (parallel) with the load [8]. Active Harmonic Filter generally functions by monitoring the load current, filtering the fundamental frequency, analysing the frequency, and then injecting a reverse current to reduce harmonic distortion [8]. This filter typically removes harmonics up to the 50th order and can achieve values of 5% or less. The controller portion of the Active Harmonic Filter is its primary component. There are two steps in the Active Harmonic Filter control method. The first stage is for performing a fast fourier transform to calculate the amplitude and phase angle of each harmonic order [8]. In the second step, the filter controller directs the filter to inject the inverse waveform in order to remove the harmonics [8]. Passive Harmonic Filter uses fixed compensation, which is less effective for filtering harmonics; whereas, Active Harmonic Filter uses the power converter switching method, which produces effective results but is more expensive [8]. As a result, the hybrid harmonic filter (HHF), a filter that combines Active Harmonic Filter and Passive Harmonic Filter approaches, was created. Effective solutions for the issues of reactive power and harmonic currents have been devised, including the hybrid harmonic filter (HHF) architecture [8].

In a demonstration of the difference between Active and Passive power filters that involves the use of PQsine active power filters. Various types of electrical loads with the APF were tested, and with many applications and trends, both cases' results were studied in detail [9]. The conclusion was found that active filters are better than passive filters due to multiple reasons such as adaptability, precision and improved power factor [9].

Also on the basis of their connection with the load power filter is classified as : Series and Shunt Power Filter.

A highly sophisticated electrical tool used to lower harmonic distortion and fix power factor issues in power systems is called a series active power filter. With the load or distribution line that needs harmonic correction, these are connected in series. As a result, they are excellent for dealing with voltage-related harmonics and reactive power problems. Continuous voltage waveform sensing takes place at the connecting location. It recognizes voltage distortion brought on by harmonic currents moving through the impedance of the distribution line. Based on the observed voltage distortion, this generates compensating currents that are injected in series with the load or distribution line. These compensating currents are designed to counteract fluctuations in reactive power as well as harmonic components associated with voltage. The series active power filter ensures that the voltage waveform becomes more sinusoidal and balanced by introducing compensatory currents to fix it. Reactive power compensation is another service that series active power filters can offer, which improves the power factor of the system. Voltage supply of order of 3 msec or lower is maintained under transient condition with the help of control response, which ensures safety [10]. The main purpose of series APF is to ensure that the sensitive loads are protected from voltage sags as well as voltage swells [10].

Another electrical device known as a shunt active power filter (SAPF) is utilised in power systems for improvement of power quality and elimination of harmonic distortion. It actively compensates for harmonic currents and reactive power in real time and is parallel-connected to the load it is protecting. Shunt active power filters may alter power factor and are excellent at removing harmonic distortion brought on by nonlinear loads. The shunt APF continuously keeps track of the current waveform at the connecting location. It recognizes harmonic frequencies and their magnitudes. Based on the detected harmonic content, the shunt APF generates compensatory electrical currents that are 180 degrees out of phase with the recorded harmonic currents. These adjusting currents negate the harmonic components [11].

PROBLEM IDENTIFICATION

Nonlinear loads, in the past, were mainly found in heavy industrial settings and were managed by experts due to their harmonics issues. However, today, we’re seeing a significant increase in the usage of non-linear loads in various sectors, including home. Non-linear loads are devices that don’t draw current in proportional to the applied voltage, causing distorted current waveforms. They can affect power quality, leading to problems like flickering lights and equipment issues. Examples include electronics devices like computers and industrial equipment like variable frequency drives. Managing these loads is crucial for maintaining stable power quality. One common type of distorted current is a pulse waveform with a high crest factor, often caused by equipment like SMPS (switched mode power supplies). These devices pull current in short, high-intensity bursts that can cause voltage distortion, making the supply voltage look like it’s clipped or flat-topped.

Following is the simulation we created to show how non- linear loads affect the power quality of a system.

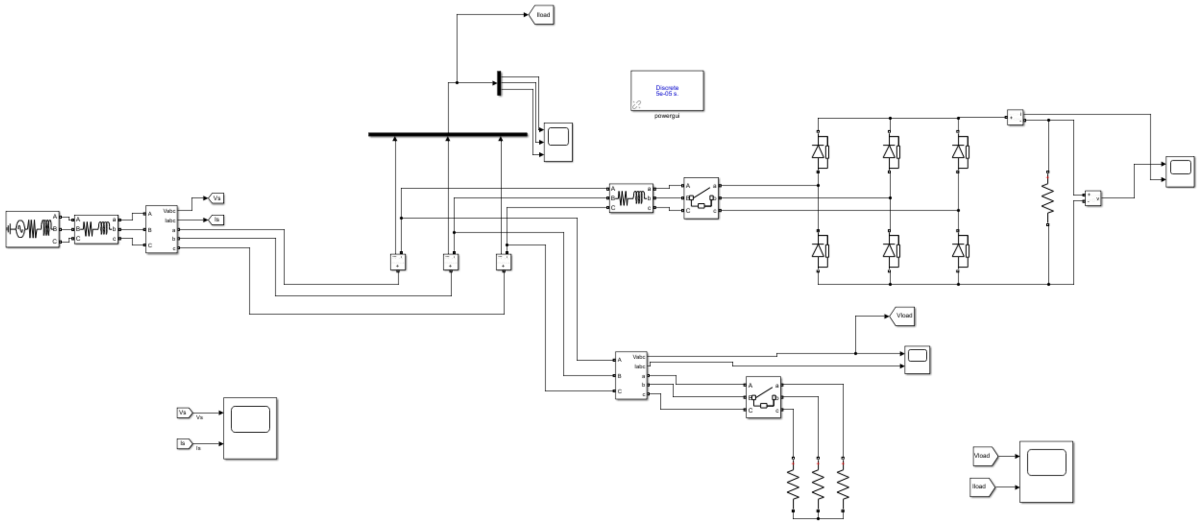


Figure 1. transmission system with balanced and unbalanced load and rectifier as non-linear load

A rectifier load and an unbalanced 3-phase load is connected to a 3-phase transmission line. From this simulation we get the following waveform.

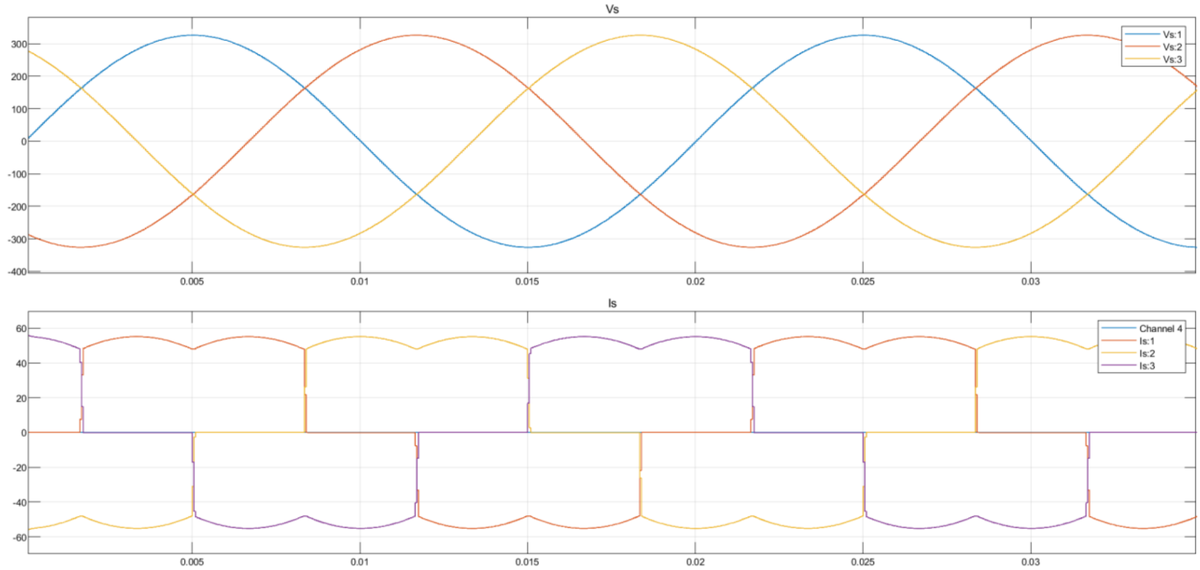
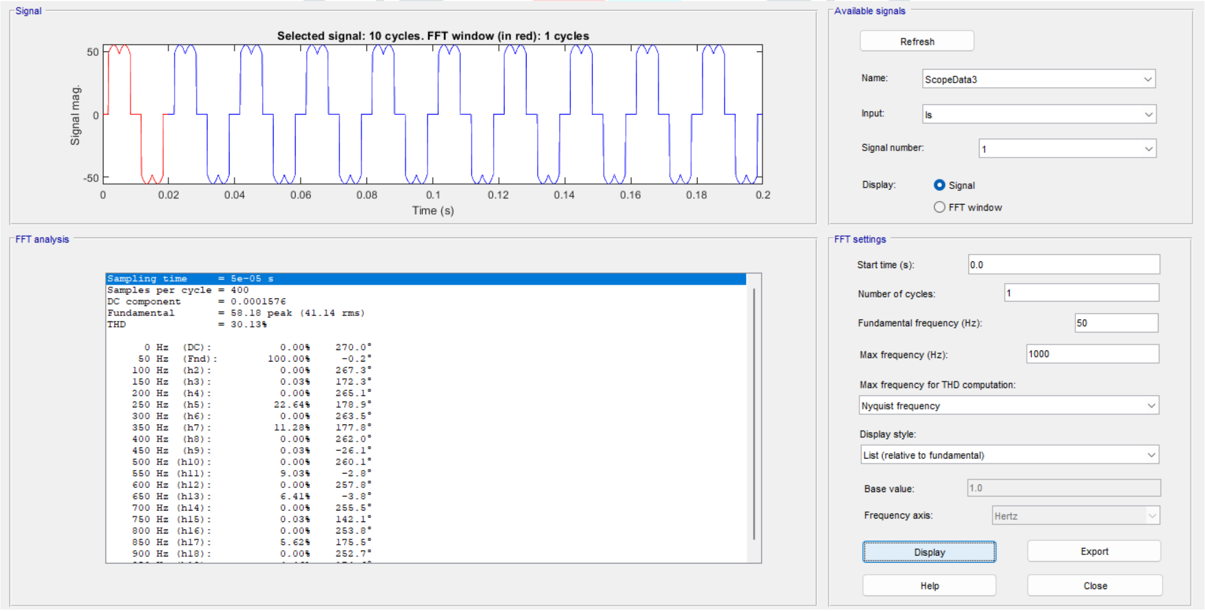


Figure 2. Waveform of source voltage and source current containing harmonics

Thus the current contains harmonics. The FFT shown below gives us the data of the harmonics produced due to the inclusion of nonlinear loads. A Total Harmonic Distortion (THD) of 30.13% relative to the fundamental frequency of 50 Hz is obtained.



```
Sampling time     = 5e-05 s
Samples per cycle = 400
DC component      = 0.0001576
Fundamental       = 58.18 peak (41.14 rms)
THD               = 30.13%

     0 Hz  (DC):          0.00%    270.0°
    50 Hz  (Fnd):       100.00%     -0.2°
   100 Hz  (h2):          0.00%    267.3°
   150 Hz  (h3):          0.03%    172.3°
   200 Hz  (h4):          0.00%    265.1°
   250 Hz  (h5):         22.64%    178.9°
   300 Hz  (h6):          0.00%    263.5°
   350 Hz  (h7):         11.28%    177.8°
   400 Hz  (h8):          0.00%    262.0°
   450 Hz  (h9):          0.03%    -26.1°
   500 Hz (h10):          0.00%    260.1°
   550 Hz (h11):          9.03%     -2.8°
   600 Hz (h12):          0.00%    257.8°
   650 Hz (h13):          6.41%     -3.8°
   700 Hz (h14):          0.00%    255.5°
   750 Hz (h15):          0.03%    142.1°
   800 Hz (h16):          0.00%    253.8°
   850 Hz (h17):          5.62%    175.5°
   900 Hz (h18):          0.00%    252.7°
```

Name: ScopeData3
Input: Is
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 3. FFT analysis representing the %magnitude of individual harmonics distortion relative to fundamentals

Thus we can say for sure that non linear loads create harmonics in the electrical system. The electrical system develops harmonics when nonlinear loads, such as SMPS and other devices, are used. Waveforms of voltage and current get distorted due to harmonics, which are multiples of its fundamental frequency (50 or 60 Hz (USA) in power systems, for example).

These harmonics can cause a number of problems in power distribution networks. As is well known, the primary factor contributing to power quality deterioration is said to be the harmonics' existence; nonlinear loads are the source of power quality decline. In summary, undesired electrical distortions known as harmonics can negatively affect electrical systems in a number of ways. They cause inefficient machinery, such as motors, which wastes energy and performs poorly. When harmonics interfere with the system's native frequencies, they can also lead to voltage instability and perhaps cause device damage. They also reduce the power factor, which raises the possibility of increased electricity bills. Harmonics may also produce electromagnetic interference, which can interfere with communication networks and electrical devices. Regulatory bodies impose harmonic limitations in order to prevent these problems; noncompliance with these standards may result in fines and penalties.

PROPOSED METHODOLOGY

A 400V, 50 Hz three-phase source is used to act as the source of the transmission line. A rectifier load is connected to the system to simulate the non-linear loads common in household, residential and commercial places. An unbalanced three phase resistive load is also connected to the system to simulate how unbalance affect the power quality of a system. These loads are responsible for creating harmonics in the system. The term used to describe the cumulative effects of all the harmonics on a voltage or current waveform in a network is Total harmonic distortion (THD).

$$THD(\%) = \frac{\sqrt[2]{\sum_{N=2}^{\infty} I_N^2}}{I_{1(rms)}}$$

The non-linear loads generate harmonics, resulting in total harmonic distortion (THD) of 30.13%. To mitigate the harmonics of our system, a shunt APF is coupled to the transmission system at the PCC.

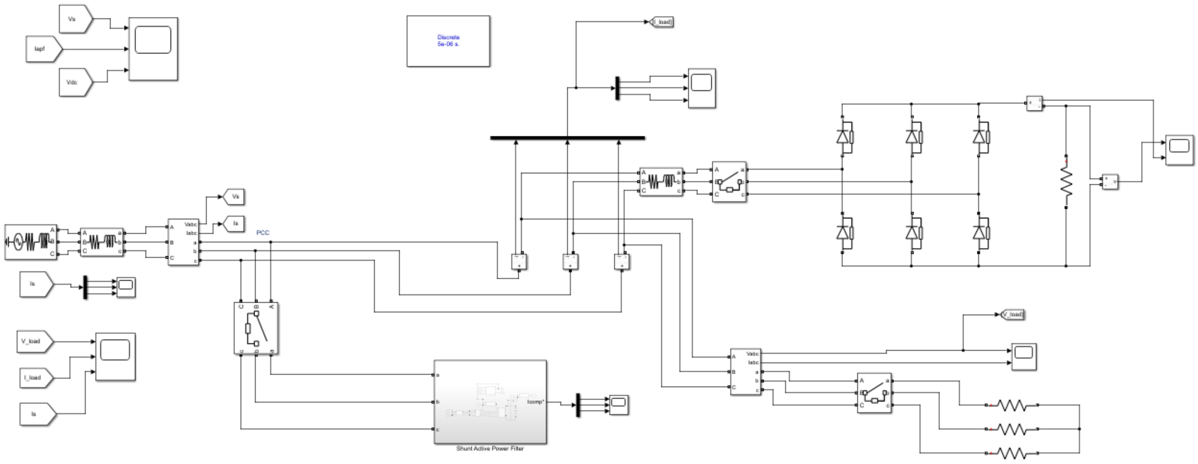


Figure 4. Proposed model for improvement of power quality

The Shunt APF harmonic mitigation stands out because it is primarily dependent on the method used to calculate the reactive power and harmonics of the current, along with the compensation control. The PQ theory and harmonic current compensation methods used in PWM-based voltage source inverters have a big influence on the harmonic current compensation efficiency.

The current flowing can be expressed as:

$$i_S = i_L = [i_{fL} + i_H] - i_C + i_{dc}$$

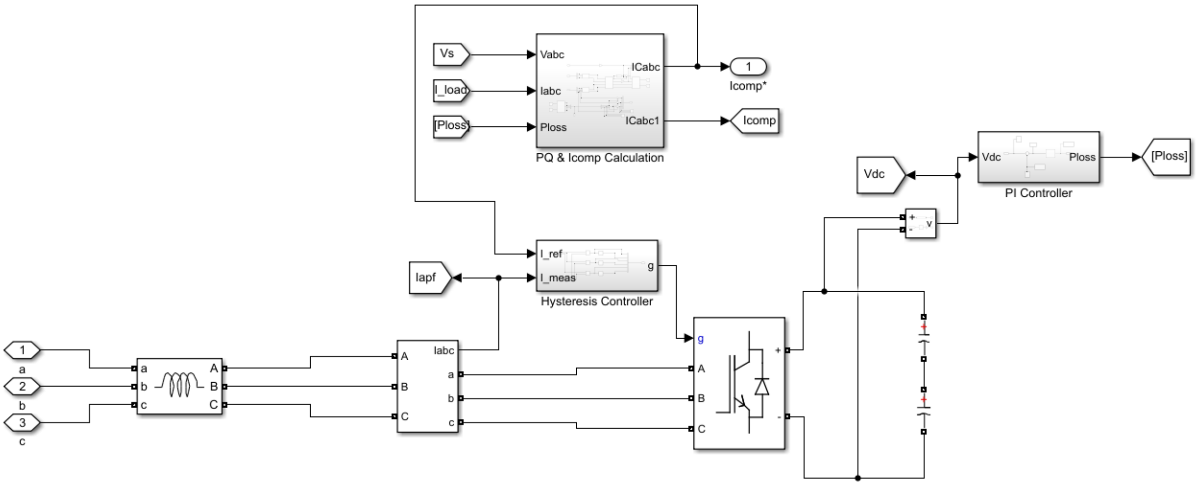


Figure 5. proposed model of Shunt APF

DC-link capacitor operation changes the current in the system to sinusoidal with fundamental frequency (50 Hz). Maintaining a constant value of DC-link voltage is crucial, therefore in the DC-link voltage control loop, a proportional-integral (PI) controller is utilised, which also corrects the harmonics in the current efficiently and also calculates compensation current. It uses a reference voltage value of 850V and compares it with the voltage existing across the DC-link, giving the value of energy consumed and maintaining the value via the DC-link loop, so the current becomes:

$$i_S = i_L = i_{fL} + i_{dc}$$

PQ theory depends on Clarke's Transformation which is basically transformation to an oscillatory ***0-□-□*** coordinate from a-b-c coordinates which is stationary, and in our research paper we are neglecting zero sequence values because of the load.

The transformation from a-b-c coordinates to □-□ co-ordinates of three phase current and voltages by the use of Clarke Transformation is done by the following formulae:-

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Then, for the three-phase system, we have calculated the value of fundamental instantaneous active power and reactive power as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

After this, the fundamental instantaneous active and reactive power, P and Q, will show a DC signal in □-□ frames, and harmonic-infused P and Q will show up as ripples.

Then inverse Clarke Transformation is used to create reference current ***i_ref*** using the retrieved harmonic components.

The oscillating bits of P and Q were extracted using a low pass filter (LPF). The complex sum of P and Q may be written in the □-□ coordinates by:

$$P = \overline{P} + \widetilde{P}$$
$$Q = \overline{Q} + \widetilde{Q}$$

Where, $\overline{P}$ = DC part of P. (related to fundamental component of active current convention)

$\widetilde{P}$ = AC part of P. (The instantaneous real power's AC component causes harmonics to appear. It is related to those harmonics)

$\overline{Q}$ = DC part of Q. (reactive power is generated from fundamental voltages and fundamental current component, it is related to that reactive power)

$\widetilde{Q}$ = AC part of Q, and related with harmonic currents due to AC components' instantaneous reactive power (harmonic current is generated by the AC component, it is related to that harmonic current)

The compensated currents in □-□ coordinates are calculated with neglecting zero sequence value. By these values in □-□ coordinates we will calculate the values in a-b-c coordinates using inverse Clarke Transformation:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} \widetilde{P} \\ \widetilde{Q} \end{bmatrix}$$

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

The switching signal for the Voltage Source Inverter (VSI) is generated by the use of the hysteresis controller with the values obtained above. The actual current is compared to the reference current, and the switches of VSI are switched on and switched off with the error, to keep the actual current within the hysteresis band. These inverters give the necessary compensation to the transmission line. The above process continues in the DC-link loop and thus reduces the harmonics.

RESULT

The below waveform shows the compensation current obtained for the compensation of harmonics current.

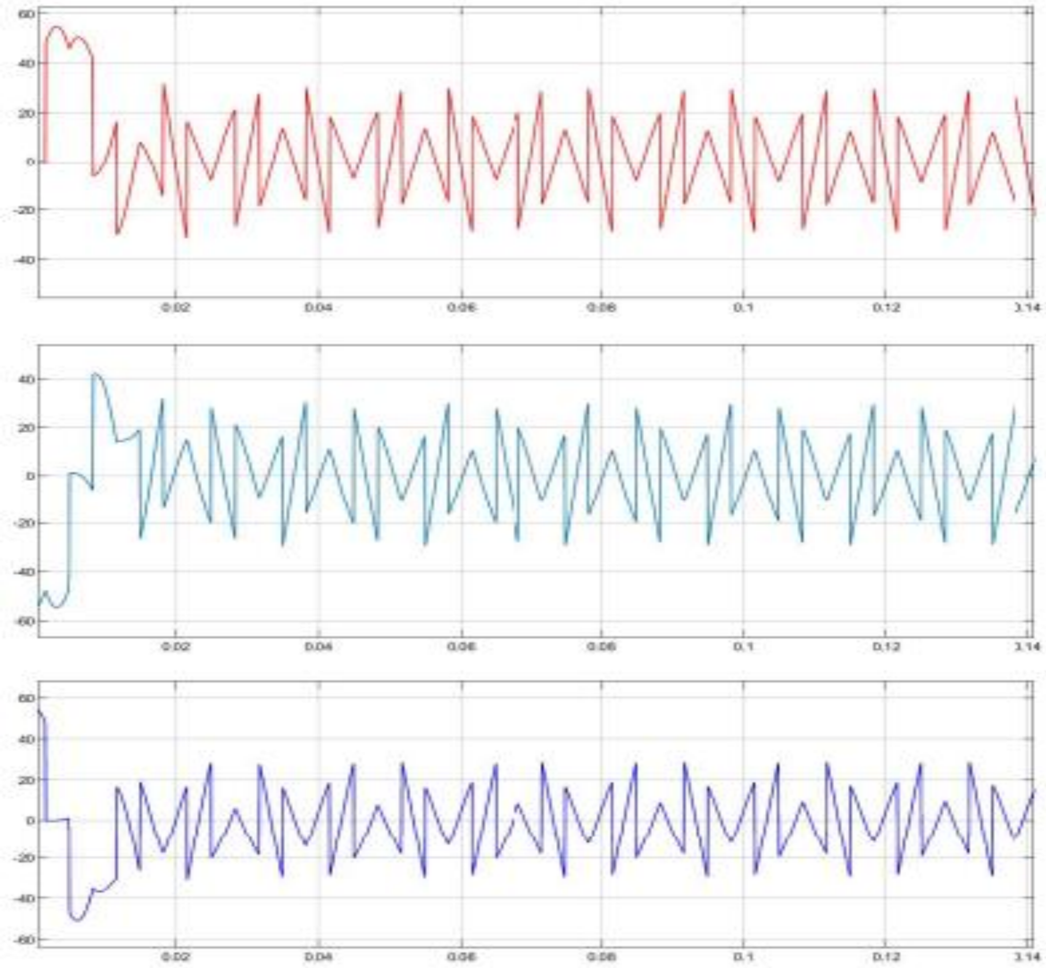
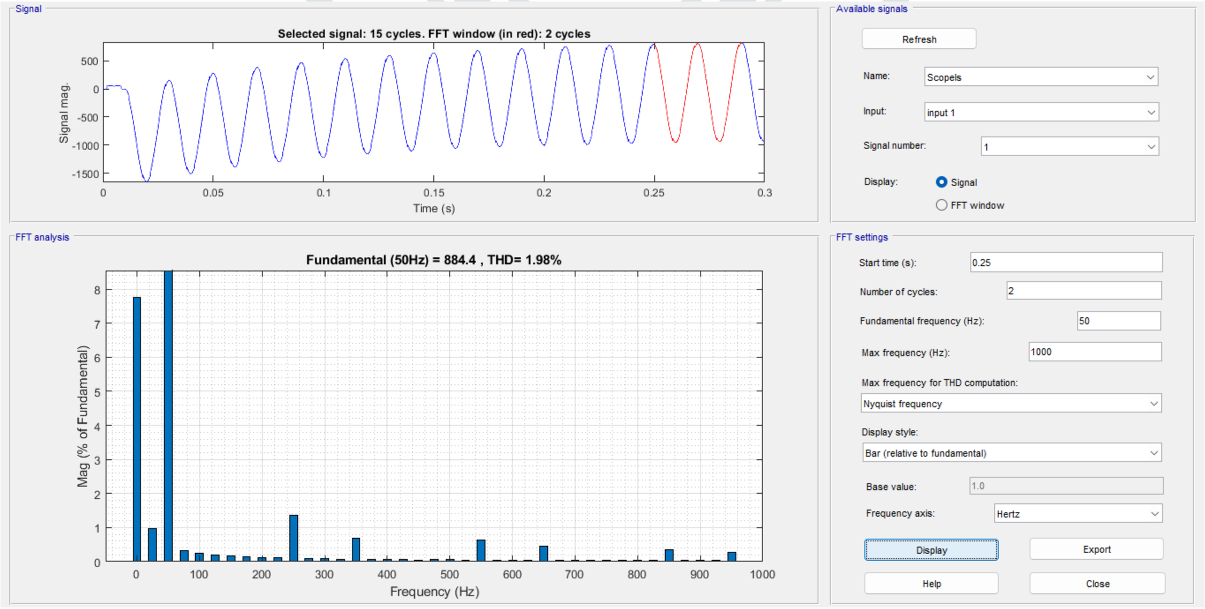


Figure 6. Waveform of compensation current



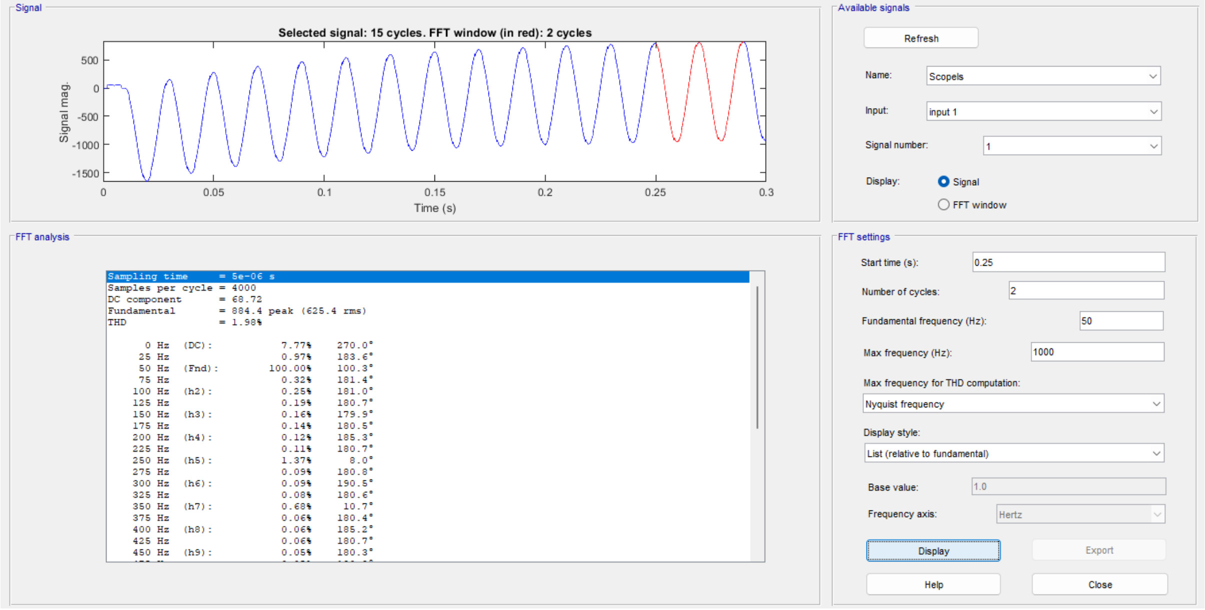
Selected signal: 15 cycles. FFT window (in red): 2 cycles

Fundamental (50Hz) = 884.4 , THD= 1.98%

Name: Scopels
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.25
Number of cycles: 2
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 7. FFT analysis representing the magnitude of harmonics relative to fundamentals



```
Sampling time      = 5e-06 s
Samples per cycle = 4000
DC component      = 68.72
Fundamental       = 884.4 peak (625.4 rms)
THD               = 1.98%

      0 Hz  (DC):          7.77%    270.0°
     25 Hz                 0.97%    183.6°
     50 Hz  (Fnd):       100.00%    100.3°
     75 Hz                 0.32%    181.4°
    100 Hz  (h2):          0.25%    181.0°
    125 Hz                 0.19%    180.7°
    150 Hz  (h3):          0.16%    179.9°
    175 Hz                 0.14%    180.5°
    200 Hz  (h4):          0.12%    185.3°
    225 Hz                 0.11%    180.7°
    250 Hz  (h5):          1.37%      8.0°
    275 Hz                 0.09%    180.8°
    300 Hz  (h6):          0.09%    190.5°
    325 Hz                 0.08%    180.6°
    350 Hz  (h7):          0.68%     10.7°
    375 Hz                 0.06%    180.4°
    400 Hz  (h8):          0.06%    185.2°
    425 Hz                 0.06%    180.7°
    450 Hz  (h9):          0.05%    180.3°
```

Name: Scopels
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.25
Number of cycles: 2
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 8. FFT analysis representing the %magnitude of individual harmonics distortion relative to fundamentals

By the use of the proposed Shunt APF that is coupled in shunt configuration to the load, i.e. to the point of common coupling (PCC), the filtered source and load current waveforms are obtained. The FFT analysis shows that the inclusion of the Shunt APF has resulted in a decrease in Total Harmonic Distortion (THD) of the system. The THD before the inclusion of Shunt Active Power Filter was 30.13% of the fundamental value, which has been reduced to 1.98% of the fundamental value. Thus there is a 93.43% decrease in the THD of the system from its initial value. Also, the individual harmonic components were also mitigated by following magnitudes from their respective initial individual values - 5th harmonics by 93%, 7th harmonics by 94% and 11th harmonics by 94%.

CONCLUSION

Under the influence of balanced and unbalanced non-linear loads (rectifier and unbalanced three-phase resistive load), the THD was mitigated from 30.13% to 1.98% by the use of proposed Shunt APF according to FFT analysis, which is 93% improvement from its initial value. The system is able to mitigate low order harmonics efficiently, evident from the 93% and 94% mitigation in 5th and 7th harmonics respectively, which were the major harmonic components responsible for low quality of power. Thus the system's power quality is improved.

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