Estimation and Elimination of Power System Harmonics and Implementation of Kalman Filter Algorithm

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Estimation and Elimination of Power System Harmonics and Implementation of Kalman Filter Algorithm

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of the requirements of the degree of

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By **Anshuman Pradhan**
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Certificate

*This is to certify that the thesis entitled, "**Estimation and Elimination of power system harmonics and implementation of Kalman Filter Algorithm**" submitted by Anshuman Pradhan in partial fulfillment of the requirements for the award of dual degree (B. Tech and M. Tech degree) at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this Project review report has not been submitted to any other university or institute for the award of any Degree or Diploma.*

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Declaration of Originality

I, Anshuman Pradhan, Roll Number 711EE2067 hereby declare that this dissertation *"**Estimation and Elimination of power system harmonics and implementation of Kalman Filter Algorithm**"* presents my original work carried out as a graduate student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am completely aware that in the case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

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ABSTRACT

With the extensive implementation of power circuit devices, mainly rectifier, inverters, switches in power system and manufacturing industries results in serious problem relating to the quality of power. One of the major issues is a production of harmonics for current and voltage causing alteration in output waveform, voltage-distortion, voltage degrading, equipment local heating, etc. Loads which are non-linear such as UPS, SMPS, and speed drives results in production of harmonics in current waveform.These draws in the component of current having reactive power from the bus bar, and thus, causes an imbalance in bus current waveform. Hence to eliminate the problems of harmonics we need to compensate the component of harmonic causing such trouble. With all the existing methods used, one of the method being minimizing harmonic in power utility via SAPF. Hence this Paper suggests a complete analysis of SAPF performance by applying two current control strategies. First being instantaneous active and reactive power theory (p-q) and second being synchronous frame reference theory (d-q) and analyzing their overall performance to select one of the above methods. Harmonic current controller is described and used which provides correct gating signals for the IGBT based inverter nad thus helps in eliminating harmonic components. Also, this Paper explains the Kalman Filter implementation in real life scenario in frequency calculation taking an suitable example.

CHAPTER 1

INTRODUCTION

1.1 Overview

Electronic switches in addition with non-linear appliances/loads results in extensive harmonics problems in utility power because of their intrinsic nature for sucking harmonic currents and reactives powers from AC bus bar. This results in unbalance voltage and currents neutral difficultly in the power system. Voltage and current waveform get distorted because of the existence of harmonics effects the power system gear which is connected to preserve stable and consistent course of power in the power system. Majority of problems arises includes overheating, failure of capacitor, vibration, problem of resonance, power factor degradation, overloading, neutral current, communication interference and lastly power fluctuation. Eliminating harmonics will extrapolate the reliability and stability of the system and thus it will further increase the quality of the power [1] [2]. The solution used for removal of harmonics is the application of SAPF using a current reference method which is created to minimize alteration from the harmonic currents. Shunt active power filter uninterruptedly monitors the harmonic currents and reactive powers propagation in the network and produces reference currents from the inaccurate current waveforms. During the load condition, the frequency of operation can be taken into consideration over a small allowable range from its standard value. When there is a mismatch in frequency of the system from its nominal values, consequences in further change of reactance component which influence differential relay functionality of power system. So frequency involves an important role in controlling, operating and monitoring of any power device [3]. The available frequency estimation techniques are used digitalized samples of current or voltages signals. Frequently, the voltage signals is implementated for estimation of system parameters because it is less distorted than the line current. The voltage signal from the system is measured as purely sinusoidal, the frequency of the system is considered as the time between the two zero crossings. Nevertheless in reality, the restrained signals contains error and thus various methods are present for frequency calculation. Zero crossing method, DFT method, least square error method, Kalman filter are a few examples of the methods used. Other methods for frequency calculation used in the power system are Soft computings techniques, neural network method. SRPF method, fuzzy logic controller, p-q method, neural networks are used to control current. are used in SAPF which is resourceful for eliminating actual harmonic content from the power system [1] [4].

1.2 Motivation for Project Work

Harmonic contamination is generally much more pronounced at lower energy area due to large implementation of nonlinear loads (UPS, SMPS, Rectifier etc.), which is unwanted as it results in abrupt voltages fluctuations and voltages concavity in system. As discussed before, the contamination of power system atmosphere either by arbitrary noise or harmonics or reactive power disruption is because of the fact that there are large use of nonlinear loads and unexpected misalliance in the generation load. Which consequences in the mismatch in fundamental frequency from its reference values and promotes harmonic levels in system linkage which is seriously unwanted. It's a hard assignment to calculate the exact frequency and harmonic amplitudes and voltage in occurrence of arbitrary noises in the system. Though Kalman Filtering algorithm is implemented for estimation of electrical system frequency but then also enough attention has to be paid for frequency estimation in various power system conditions, which is the prime motivation for estimating frequency in different situation of power system.

1.2 Objectives of Project Work

The prime goals behind the thesis are as follows:

- To implement Kalman filter algorithm for system frequency estimation.
- Study and implementation of various control schemes recommended towards exhibiting 3- phase SAPF.
- Modelling and testing 3-phase SAPF with various current control schemes using SIMULINK environment.
- Comparison of various control schemes on FFT analysis platform for harmonic removal in the power system.

CHAPTER 2

INTRODUCTION TO HARMONICS AND SCHEMES TO REDUCE HARMONICS

2.1 Power system frequency estimation:

A power system with no loss parameters is taken into subjection in power environment. For obtaining utmost quality power the measured voltage or current signal must be purely sinusoidal. But in real life scenario, it gets degenerated due to type of source, under voltage, over voltage, variation in frequency and harmonics, nonlinear load and generated load mismatches, etc. Thus, there is a need of rapid and accurate calculation of supply frequency and voltage for improving the power quality in presence of noise and higher harmonics. Most of the technique for calculation of power system parameter is using digitized samples of supply voltage. Basically frequency of a system indicates the time between two zero crossing of voltage signal where the voltage signal is purely sinusoidal. However in reality the signals measured are in distorted form. Hence a number of method is proposed to estimate the frequency. DFT, least square error, Kalman filtering and iterative approaches are one of the few popular technique used in this area. This chapter includes complex LMS, nonlinear LS and RLS has been employed to obtain the power system frequency [5] [3].

2.2 Introduction:

- **Interruptions:** Magnitude of the bus-bar voltage is zero.
- **Undervoltages:** Magnitude of the bus-bar voltage is below its nominal value.
- **Overvoltages:** Magnitude of the bus-bar voltage is above its nominal value.

According to the time these last, these are categorized into four states, very short, short, long and very long.

Transient: Transients in power system are defined as undesirable, quick and short-duration events that create distortions. Their attributes and the waveforms rely on the production of electricity as well as the system parameters for example resistance, inductance and capacitance at the purpose of consideration. "Surge" is frequently viewed as identical with transient.

Interruptions: Interferences occur if the supply voltage (or burden current) abatements to under 0.1 pu for less than 1 minute. Some reasons for intrusion are hardware disappointments, focal glitch and blown circuit or breaker opening.

The contrast among long (or maintained) interference and intrusion is that in the first case the supply is reestablished naturally. Interruptions are typically measured by its length.

- Up to 3 mins is called as a short interruption and
- Longer than 3 mins is called as a long interruption.

Conversely, based upon the standard IEEE-1255[8]:

- Instantaneous interruption occurs between 0.5 and 30 cycles.
- Momentary interruption occurs between 30 cycles and 2 seconds.
- Temporary interruption occurs between 2 second and 2 min.

Interruption which is larger than 2 mins is called as a sustained interruption.

Dips (Sags): Dips are brief length diminishments inside rms voltage somewhere around 0.1 and 0.9 pu. There is no unmistakable definition for the length of list, yet it is as a rule between 0.5 cycles and 1 min. Voltage dips are normally brought on by:

- Heavy load energization such as arc reactor.
- Large induction motors starting.
- Ground to single line faults.

Transformation of loads from one power source to another also results in voltage sags.

Swells: The expansion of voltage greatness somewhere around 1.1 and 1.8 PU is known as swell. The most recognized span of a swell is from 0.5 cycles to 1 cycle. Droops are not as regular as swells and their primary driver:

- When a very big load is switched off.
- When a capacitor bank is charged, or
- The increase in voltage of the un-faulted phases throughout a ground to line fault.

Sustained interruptions: When voltages drops to zero and doesn't increases spontaneously, then it is called as Sustained interruptions. Agreeing to IFC description, if the period iss longer than 3 mins, then it is called long sustained interruption; but based on the IEEE description the period is greater than one min.

- Fault incident in an area of the electrical power system incorporated with no dismissal or by the terminated share out of process.
- Component outrage due to the incorrect intervention of a protective relay.

Interruption in a low-voltage system by no severance is known as Planned (or scheduled) interruption [6] [4].

2.3 Waveform distortion:

Deviation in the form of a steady-state from a proper sine wave of power frequency is called waveform distortion.

DC Offset:

DC Offset is the the DC current and/or voltage component in an AC system.

Harmonics:

Sinusoidal voltages or current with frequencies that are integral multiples of the power system fundamental frequency is called as Harmonics. For example, let 'f' being the fundamental frequency, then , the frequency of n^{th} harmonic is nf.

- Mal-operation of controlling circuits.
- Rotating machines, capacitors, transformers losses.
- Rotating appliances and motors producing noise.
- Telephonic interloping causing series and parallel resonance frequencies (due to the power factor correction capacitor and cable capacitance) consequential in voltage intensification even at a distant position from the changing burden.

Interharmonics:

Frequencies which are not integral multiples of the base/fundamental frequency.

Notching(s):

Line-commutation of thyristor causes an episodic voltage disorder in circuits. This may be known as notching. Notching are observed in the line voltages waveform when typical maneuver of the power automated appliances is carried out or when the current propagates from one phase to other phase. Throughout this notching period, the two propagating phases, reduces the line voltage is restricted only by the system resistance [3].

2.4 Creation and effects of harmonics:

2.4.1 Creation

Up until 1950, all loads were thought to be direct which implies if the voltage contribution to a gadget is a sinusoidal wave, the resulting voltage wave created by the disturbance is additionally a sinusoidal wave. In 1981, makers of electronic equipment changed to an effective kind of inside force supply known as a SMPS. These device changes over the connected voltage sine wave to a mutilated current waveform that looks like substituting current spikes, the first since the load no more display steady impedance all through the connected AC voltage waveforms. Most electrical gear today makes noise. In the event that a gadget changes over AC energy to DC force (or the other way around) as a piece of its enduring state operation, it is thought to be a consonant current-creating gadget. Such gadgets incorporate uninterruptible power supplies, copiers, PCs, and so on.

2.4.2 Effects:

The most serious issue with harmonic is waveform of the voltage mismatch. We could ascertain the connection amongst the basic and misshaped waves by determining the square foundation of the entirety of the squares of the considerable number of music produced by a solitary burden, and after that partitioning this number by the ostensible 50 Hz waveform esteem. We do this by a scientific count known as FFT hypothesis. This technique decides the aggregate total harmonic distortion (THD) controlled inside a non-straight present or voltage wave [7].

Triplen harmonics:

Hardware of electronic type creates greater than one harmonic disturbance. Say for example, PC produces third, ninth and fifteenth sounds. These are known as triplen sounds. They represent a more concerning issue to specialists building originators since they accomplish greater than mutilate voltage waves. They can generate heat to overheat the structure wiring, cause an annoyance stumbling, burn transformer units and causes arbitrary end-client hardware disappointment [7] [5].

Circuit overloading:

Harmonic cause over-burdening of PCs and transformers and overheating of usage hardware, for example, engines. Triplen sounds can particularly bring about overheating of impartial of nonpartisan conduits on 3-stage, 4-wire frameworks. While the principal recurrence and even sounds counterbalance in the impartial conductor, odd-request music are added substance. Indeed, even under adjusted burden conditions, nonpartisan streams can achieve extent as greater as 1.732 times the normal stage current.

This extra stacking causes extra heat, causing separation between the protection of the unbiased electrode. In certain cases, it separates the protection amongst the winding of a transformer. For both cases, outcome is unwanted damage to the circuit. Be that as it may, one can diminish this potential harm by utilizing sound wiring process.

2.5 Methods of elimination of harmonics:

Four of the most suitable solutions include:

- Growing the overall thickness of the neutral conductor.
- Diminishing the burden on the transformer having delta-wye connection.
- Substituting the above with transformer having k-factor winding.
- Connecting a power HF at the source load position.

Among these, first 3 methods are used to manage the problem of harmonics in the power system; but the fourth actually eliminates the problem.

Neutral conductor sizing:

The neutral conductor is distressed by harmonic currents. In a balanced-three-phrase system, these currents don't terminate out and the neutral carries greater current than we expect. When this occurs, it overheats the neutral conductor path.

That is how we ought to twice over the magnitude of the neutral probe for feeders and subdivision circuits helping non-linear loads. Some wiring schemes include a distinct per circuit conductor while others implement a shared neutral doubled over in size.

Transformer loading:

Transformers may be more proficient when supplying direct loads. Be that as it may, the greater part sustains non-straight hardware, creating more iron losses in dry-sort transformers than the basic current. These errors are connected with the loop streams and the hysteresis in the center and skin impact misfortunes in windings. The outcome is transformer overheating and winding protection breakdown.

K-factor transformers:

These transformers vary in construction from standard dry-type transformers. These may sustain harmonic current at close volume resulting to be de-rated. Constructional structures include:

- The primary and secondary windings of each coil are electrostatically shielded.
- The size of the neutral conductor is made as much as twice the size of phase conductor.
- To negate skin effect parallel smaller windings on the secondary are employed.
- To reduce losses inversion of the primary delta winding conductors (in large size units) is done [4] [7].

2.5.1 Harmonic Filters:

The theoretically hazardous effects of harmonic currents created by non-linear loads can be mitigated by a harmonic filter. These currents are drawn and, by the implementation of a series of capacitors, coils, and resistors shunt these to earth. The filter assembly may consists many of those elements, each intended to filter a specific frequency.

We can connect filters one or the other between the circuit we are trying to protect and the load's power supply or amongst the circuit causing the circumstance and its power supply.

Basically there are two kinds of harmonic filters:

- Passive filter
- Active filter

Passive Filter:

These are low-priced compared with most moderating appliances. Within, they can result in the harmonic current to vibrate at its frequency. This results in the harmonic current from rolling back to the power supply and causes problems with the voltage waveforms. The weakness of the passive filter is that it cannot be flawlessly adjusted to grip the harmonic current at a specific frequency.

Active Filter:

These filters can be tuned to the exact frequency of the harmonic current and do not cause resonance in the power system. They can also mitigate more than one specific harmonic problem at the same instance. Active filters can also provide extenuation for other power quality problems such as voltage sags and power line flickering. They use power electronic circuits to replace part of the biased current sine wave coming from the burden, giving the appearance you are using linear loads.

As a result, the active filter provides power factor improvement, which intensifies the efficiency of the load [2] [3].

2.6 Estimation of harmonics:

Keeping in mind the end goal to give the clients and electrical utilities a nature of the force, it is basic to know the sounds parameters, for example, greatness and stage. This is vital for planning the channel for disposing of or lessening the impacts of sounds in the force framework.

Numerous calculations have been proposed for the assessment of harmonic. To get the voltage and current recurrence range from discrete time tests, most recurrence area symphonious examination calculations depend on the DFT or on the FFT techniques [1] [5]. Albeit different strategies, incorporating the proposed calculation in this paper, experience the ill effects of these three issues and this is a result of existing high recurrence parts measured in the sign, however truncation of the grouping of examined information, when just a small amount of the succession of a cycle exists in the investigated waveform, can support spillage issue of the DFT strategy. Along these lines, the need of new calculations that procedure the information, test by test, and not in a window as in FFT and DFT, is of fundamental significance.

One of the techniques is that Kalman Filter. A more hearty calculation for evaluating the sizes of sinusoids of known recurrence implanted in an obscure estimation clamor which can be a measure of both stochastic and signed was presented. Kalman channel can track the sudden and element changes of signs and its music.

CHAPTER-3

LITERATURE REVIEW

3.1 KALMAN FILTER

An essential property of the Kalman filtering process is the recursive processing of the noise measurement data. Kalman filter is primarily is utilized for estimating voltage and frequency fluctuations in power system applications. Dynamic estimation of voltage and current phasors is also done by Kalman filter. This purifying technique is used to get the optimal estimate of the power network voltage magnitudes at different harmonic levels. The Kalman channel is an estimator which is to figure the straight element framework state impacted by Gaussian White commotion, utilizing estimation parameters that are direct elements of the framework state, yet ruined by added substance Gaussian repetitive sound. Kalman channel permits assessing the condition of element frameworks with some writes of sporadic conduct by utilizing these factual data [5] [1].

3.2 Kalman-Filtering Algorithm

The Kalman filter conditions can be isolated into two gatherings: time redesign conditions and estimation overhaul conditions. The time upgrade conditions are responsible for extrapolating forward (in time) the present state and mistake covariance assessments to acquire from the earlier gauges for whenever step. The estimation redesign conditions are responsible for consolidating another estimation into from the earlier gauge to get an enhanced a posteriori gauge. The time overhaul conditions can be considered as indicator conditions, while the estimation redesign conditions can be considered as corrector conditions. In this way, the last estimation calculation goes about as an indicator corrector for taking care of different numerical issues.

For executing the Kalman filter, a numerical model for the framework under thought ought to be in the accompanying state structure:

$$\hat{x}^{-}_{k} = A\hat{x}^{-}_{k-1} + Bu_{k-1}$$

And the measurement (observation) of this system is assumed to occur at discrete points of time in accordance with the relation:

$$Z_k=H\hat{x}_k + V_k$$

Where,

Z_k = measurement of current samples

H = measurement matrix

$\hat{x}_k$ = state to be determined

V_k = noise covariance vector

R = let be known covariance of a white sequence.

Assuming that we have a prior estimate $\hat{x}_{k,}$ and its error covariance matrix P_k; then the general recursive filter equations are as follows:

- Compute the Kalman filter gain, K_k as

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$

- The error covariance is computed for updating

$$P_k = (I - K_k H) P_k^-$$

- Update the estimate with the measurement Z_k as

$$\hat{x}_k = \hat{x}^{-}_{k} + K(Z_k - H\hat{x}^{-}_{k})$$

- Project ahead the error covariance and the estimate

$$P_k^- = AP_{k-1}A^T + Q$$

$$\hat{x}^{-}_{k} = A\hat{x}^{-}_{k-1} + Bu_{k-1}$$

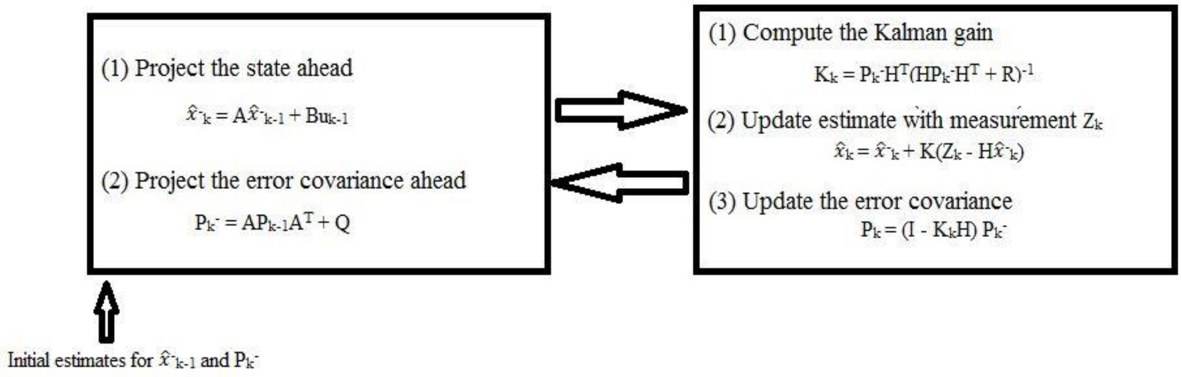

Figure 1 Filter Prediction Estimation cycle

3.3 Shunt Active Power Filter

As the name depicts the shunt active power filter (SAPF) are connected in parallel to the power system network wherever a source of harmonic is present. Its main function is to cancel out the harmonic or non-sinusoidal current produce as a result of presence of nonlinear load in the power system by generating a current equal to the harmonic current but off opposite phase i.e. with 180^o phase shift w.r.t to the harmonic current. Generally SAPF uses a current controlled voltage source inverter (IGBT inverter) which generates compensating current (i_c) to compensate the harmonic component of the load line current and to keep source current waveform sinusoidal.

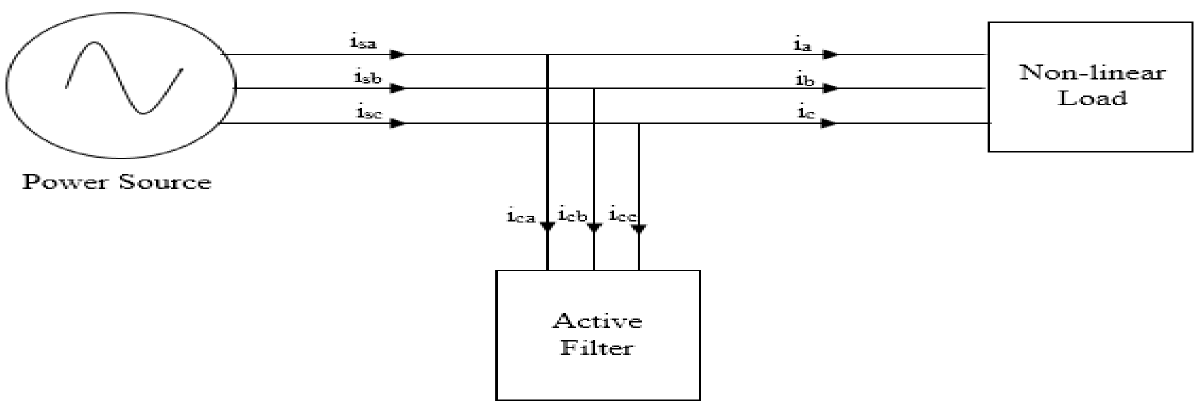

Figure 2 Block diagram representing the location of SAPF

Compensating harmonic current in SAPF can be generated by using different current control strategy to increase the performance of the system by mitigating current harmonics present in the load current. Various current control method [2]-[4] for SAPF are discussed below.

3.4 Instantaneous Real and Reactive Power Theory (p-q method)

This theory takes into account the instantaneous reactive power arises from the oscillation of power between source and load and it is applicable for sinusoidal balanced/unbalanced voltage but fails for non-sinusoidal voltage waveform. It basically 3 phase system as a single unit and performs Clarke's transformation (a-b-c coordinates to the α-β-0 coordinates) over load current and voltage to obtain a compensating current in the system by evaluating instantaneous active and reactive power of the network system.

This theory works on dynamic principal as it's instantaneously calculated power from the instantaneous voltage and current in 3 phase circuits. Since the power detection taking place instantaneously so the harmonic elimination from the network take place without any time delay as compared to other detection method.

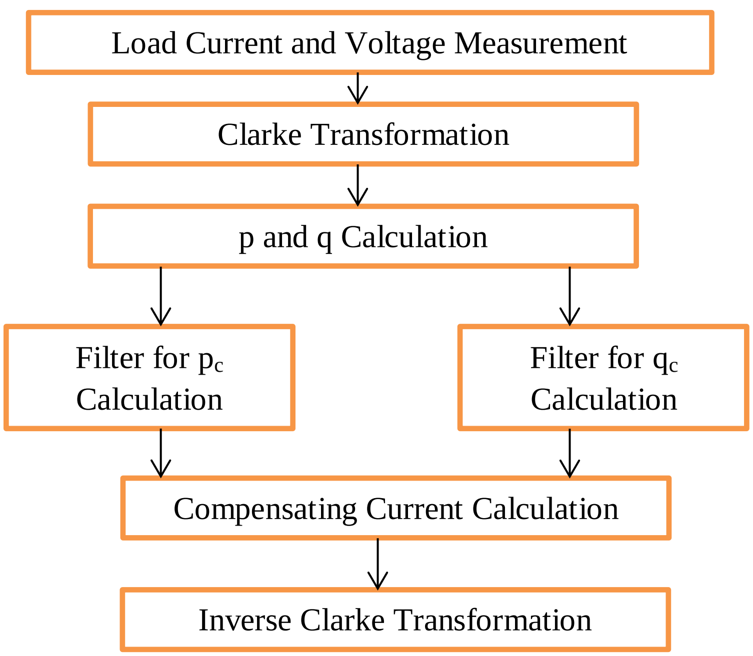

Figure 3 Control strategy of p-q method

Although the method analysis the power instantaneously yet the harmonic suppression greatly depends on the gating sequence of three phase IGBT inverter which is controlled by different current controller such as hysteresis controller, PWM controller, triangular carrier current controller. But among these hysteresis current controlled method is widely used due to its robustness, better accuracy and performance which give stability to power system.

3.4.1 P-Q method Mathematical modelling

The connection between load current and voltage of three stage power framework and the orthogonal directions (α-β-0) framework are communicated by Clarke's transformation which is appeared by the according conditions 1 and 2.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{..........} (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{..........} (2)$$

In orthogonal co-ordinate framework quick power can be discovered by basically duplicating the immediate current with their comparing prompt voltage. Here the 3 stage co-ordinate framework (a-b-c) is commonly orthogonal is nature, so we can discovered quick power as condition 3

$$p = v_a i_a + v_b i_b + v_c i_c \text{..........} (3)$$

From above equations, the instantaneous active and reactive power in matrix form can be rewritten as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \text{...........} (4)$$

The quick responsive force creates a restricting vector with 180o phase shift keeping in mind the end goal to drop the consonant segment in the line current. From the above conditions, yield condition 5.

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2+V_\beta^2}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} P_o + P_{loss} \\ 0 \end{bmatrix} \ldots\ldots. (5)$$

In the wake of finding the α-β reference current, the remunerating current for every stage can be inferred by utilizing the reverse Clarke changes as appeared in condition 6.

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \ldots\ldots\ldots (6)$$

3.5 Synchronous Reference Frame theory (d-q method)

Another method to separate the harmonic components from the fundamental component is by generating reference frame current by using synchronous reference theory. In synchronous reference theory park transformation is carried out to transformed three load current into synchronous reference current to eliminate the harmonics in source current. The main advantage of this method is that it take only load current under consideration for generating reference current and hence independent on source current and voltage distortion. A separate PLL block it used for maintaining synchronism between reference and voltage for better performance of the system. Since instantaneous action is not taking place in this method so the method is little bit slow than p-q method for detection and elimination of harmonics. Figure 4 illustrate the d-q method with simple block diagram.

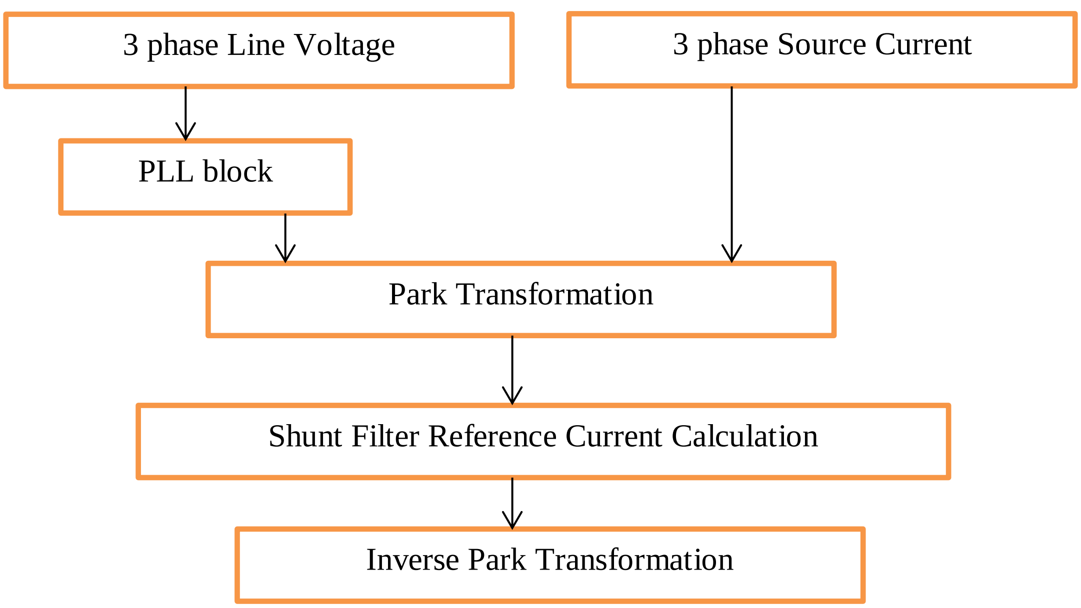

Figure 4 Control strategy of d-q method

3.5.1 D-Q method Mathematical modelling

As indicated by Park's change connection between three stage source current (a-b-c) and the d-q reference co-ordinate current is given by condition

$$\begin{bmatrix} i_{ld} \\ i_{lq} \\ i_{l0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\mu & \cos(\mu - \frac{2\pi}{3}) & \cos(\mu + \frac{2\pi}{3}) \\ -\sin\mu & -\sin(\mu - \frac{2\pi}{3}) & -\sin(\mu + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \ldots\ldots\ldots (7)$$

Where, "µ" is the precise deviation of the synchronous reference outline from the 3 stage orthogonal framework which is a direct capacity of crucial recurrence. The symphonious reference current can be gotten from the heap streams utilizing a basic LPF. The streams in the synchronous reference framework can be deteriorated into two segments given by condition (8) and (9)

$$i_{ld} = i_{\bar{ld}} + i_{\tilde{ld}} \ldots\ldots (8)$$

$$i_{lq} = i_{\bar{lq}} + i_{\tilde{lq}} \ldots\ldots (9)$$

After filtering DC terms ($i_{\bar{lq}}$, $i_{\bar{ld}}$) are suppressed and alternating term are appearing in the output of extraction system which are responsible for harmonic pollution in power system. The APF reference currents is given by equation 10.

$$\begin{bmatrix} i_{fd}^{*} \\ i_{fq}^{*} \end{bmatrix} = \begin{bmatrix} i_{\tilde{ld}} \\ i_{\tilde{lq}} \end{bmatrix} \ldots\ldots (10)$$

With a specific end goal to discover the channel streams in three stage framework which scratchs off the consonant parts in line side, the reverse Park change can be utilized as appeared by condition 11.

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \mu & -\sin \mu \\ \cos(\mu - \frac{2\pi}{3}) & -\sin(\mu - \frac{2\pi}{3}) \\ \cos(\mu + \frac{2\pi}{3}) & \sin(\mu + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{fd}^* \\ i_{fq}^* \end{bmatrix} \quad \ldots\ldots\ldots\ldots (11)$$

3.6 Hysteresis Current Controller

Hysteresis current control method is used to provide the accurate gating pulse and sequence to the IGBT inverter by comparing the current error signal with the given hysteresis band. As seen in figure 5 the error signal is fed to the hysteresis band comparator where it is compared with hysteresis band, the output signal of the comparator is then passed through the active power filter to generate the desired compensating current that follow the reference current waveform.

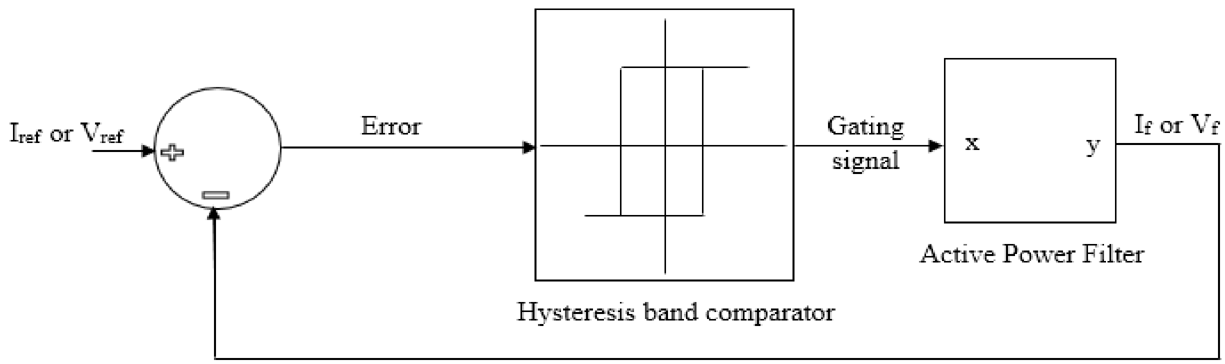

Figure 5 Hysteresis current controller logic

Asynchronous control of inverter switches causes the current of inductor to vary between the given hysteresis band, where it is continuously compare with the error signal, hence ramping action of the current takes place. This method is used because of its robustness, excellent dynamic action which is not possible while using other type of comparators.

There are two limits on the hysteresis band i.e. upper and lower band and current waveform is trapped between those two bands as seen from figure 4. When the current tends to exceed the upper band the upper switch of the inverter is turned off and lower switch is turned so that the current again tracks back to the hysteresis band. Similar mechanism is taking place when current tends to cross the lower band. Thus current lie within the hysteresis band and compensating current follow the reference current.

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Hence, Upper limit hysteresis band= I_{ref} + max(I_e) and where, I_{ref} = Reference Current

Lower limit hysteresis band= I_{ref} - min(I_e) I_e = Error Current

As a result, the hysteresis bandwidth= $2*I_e$.

Thus smaller the bandwidth better the accuracy.

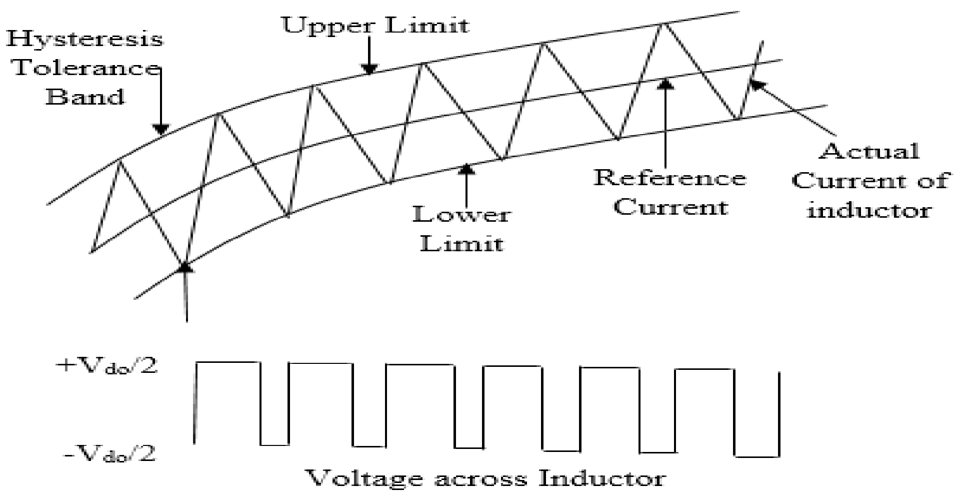

Figure 6 Hysteresis Band

Switching frequency can be easily determined by looking at the voltage waveform of the inductor. The voltage across inductor depends on gating sequence/gating pulse of IGBT inverter which is again dependent on the current error signal of the hysteresis controller. Variable frequency can be obtained by adjusting the width of the hysteresis tolerance band.

CHAPTER-4

MATLAB/SIMULINK MODELLING AND RESULTS

The simulation is carried out in MATLAB in Simulink environment. Suitable source and load are chosen. Two separate control algorithm are devised as p-q and d-q algorithms for generating compensating harmonic currents for the respective models. Figure 8 shows Simulink model with p-q method and figure 9 shows Simulink model with d-q method.

4.1 Simulink model with Shunt Active Power Filter and Non-linear burden

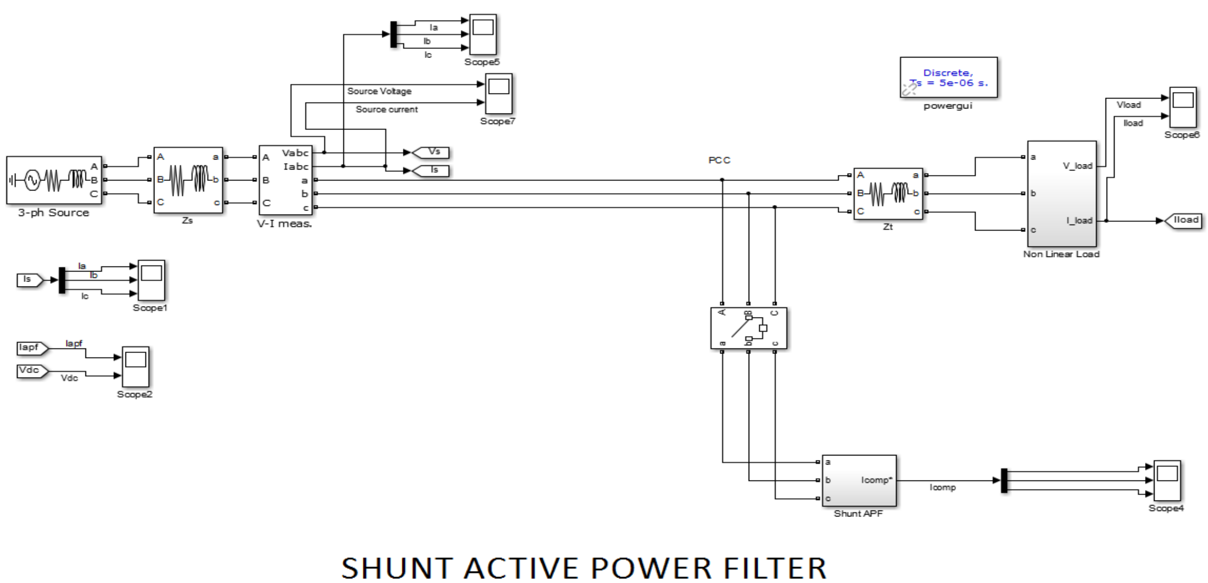

Figure 7 SAPF Filter

4.2 Simulink model of Shunt Active Power Filter with ‘p-q’ method

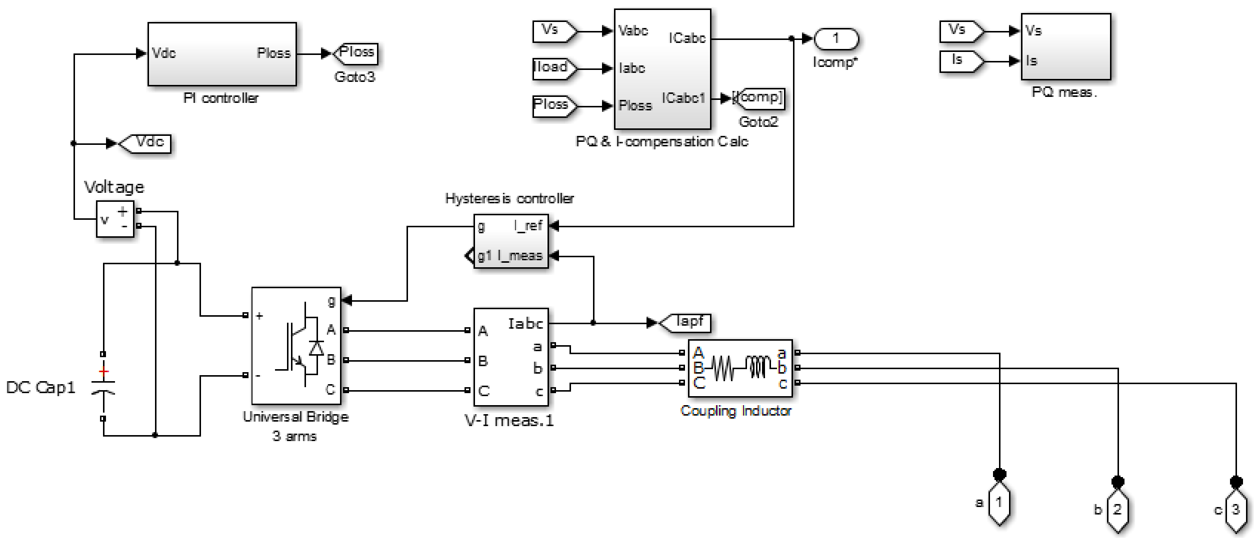

Figure 8 Model of SAPF with p-q method

4.3 Simulink model of Shunt Active Power Filter with ‘d-q’ method

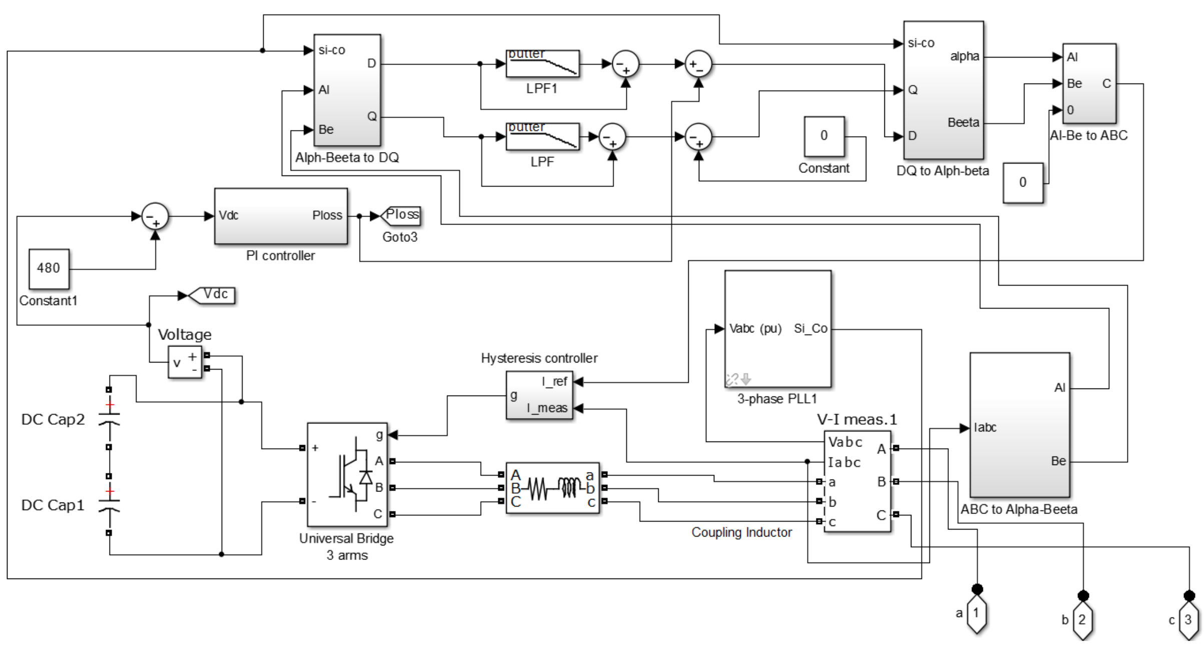

Figure 9 Model of SAPF with d-q method

4.4 Design Parameters for MATLAB Simulation

Simulation is performed on **a balanced Non–Linear Load** consisting of an R-L load and a bridge rectifier as shown below:

- System Parameters

Table.1 SAPF parameter specification

Source Voltage (r.m.s)	400Volt
System Frequency	50Hz

- Active Power Filter (APF) Parameters

Table.2 SAPF parameter specification

Coupling Inductance	1mH
Coupling Resistance	0.01Ω
Dc link capacitance	1100µF
Source inductance	0.05mH
Source resistance	0.1Ω
Load resistance	0.001Ω
Load inductance	1µH

4.5 Simulink Results

The simulation results were obtained by in MATLAB/Simulink environment using Sim-power system Toolbox. Here a breaker is used to show the analysis during ON & OFF time of the Active power Filter. A slight distortion in current and voltage waveform is seen during switching of breaker which can be removed by using thermistor in series with DC link capacitor.

4.5.1 Simulink Result with P-Q control strategy

Breaker Transition Time: 0.06 sec **Simulation Run Time**:0.2 sec

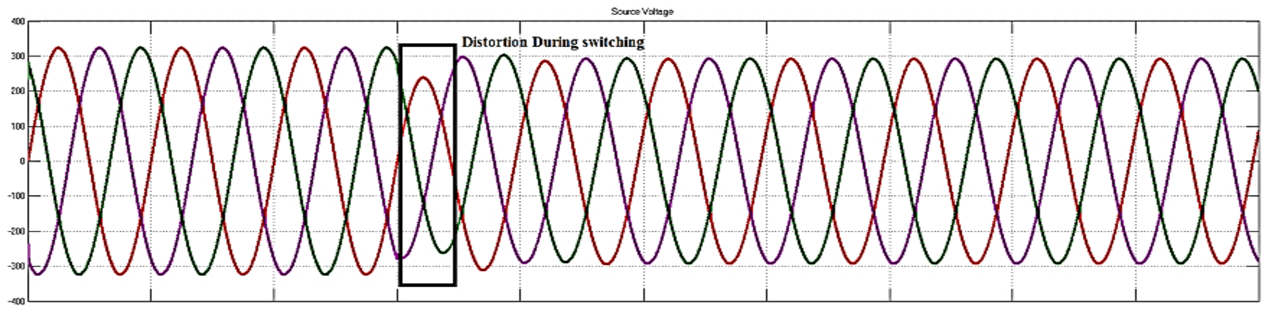

Figure 10 Source Voltage Waveform 'before and after filtering with p-q method'

Figure 10 shows the source voltage waveform before and after using p-q method of harmonic filtration. There is a slight distortion observed which is due to the switching ON of SAPF via a breaker.

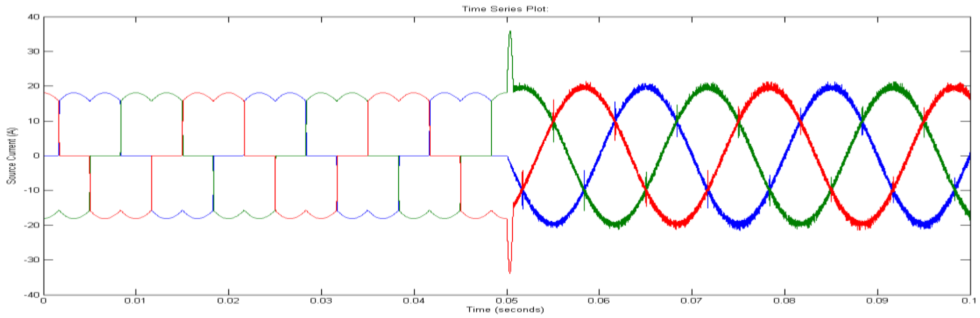

Figure 11 Source current waveform before and after filtering with p-q method

Figure 11 shows the waveform for source current before the use of SAPF and after it is switched ON. We can observe that after switching ON of the SAPF, the current waveform is sinusoidal.

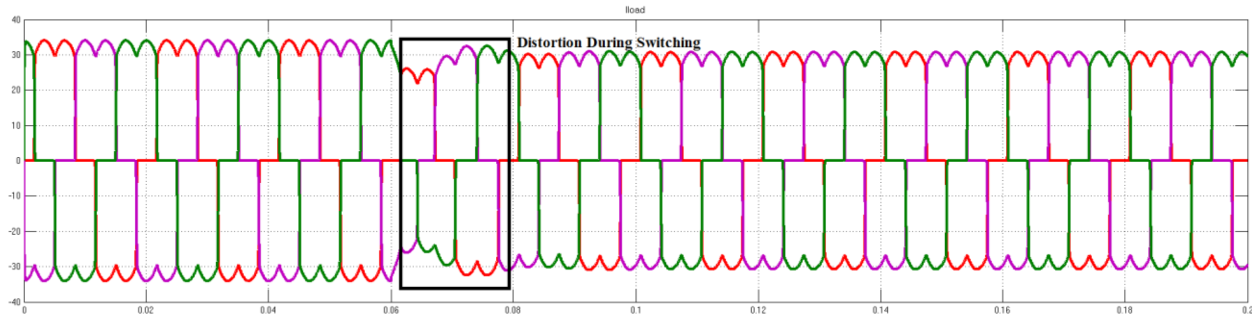

Figure 12 Load current waveform before and after filtering with p-q method

Figure 12 indicates the waveform analysis for the load current before and after switching ON of the SAPF. As we know load current will not change by the use of a filter as it depends on the type of load.

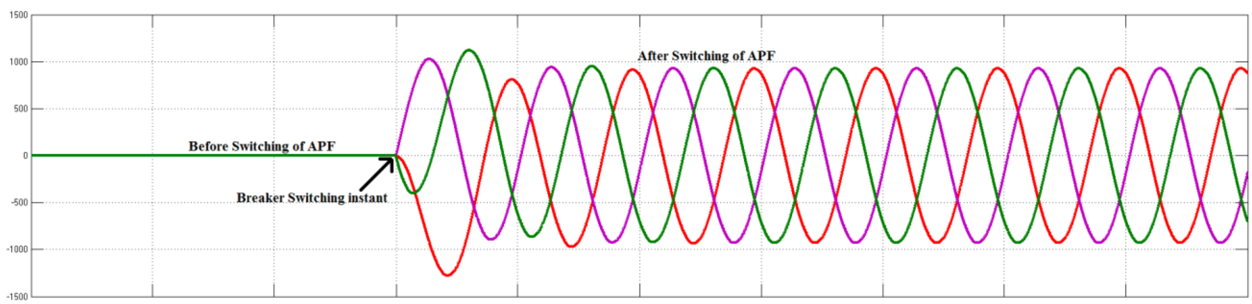

Figure 13 APF Current Waveform before and after filtering with p-q method

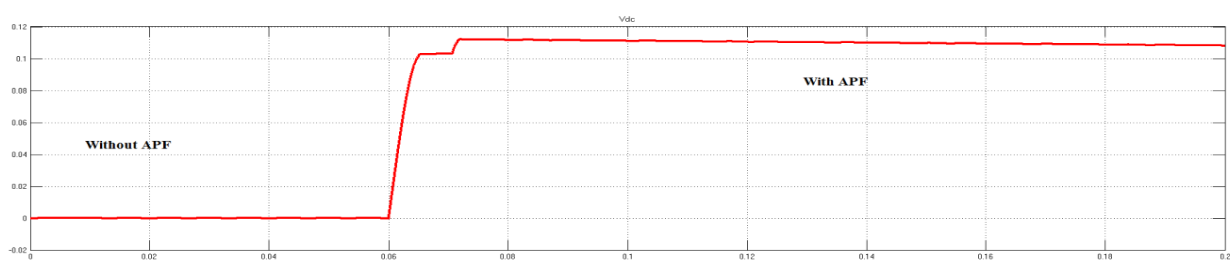

Figure 14 DC link Voltage Waveform before and after filtering with p-q method

Figure 14 shows the building up of DC link voltage used in the SAPF circuit. Once the breaker is switched ON, DC voltage starts to build up.

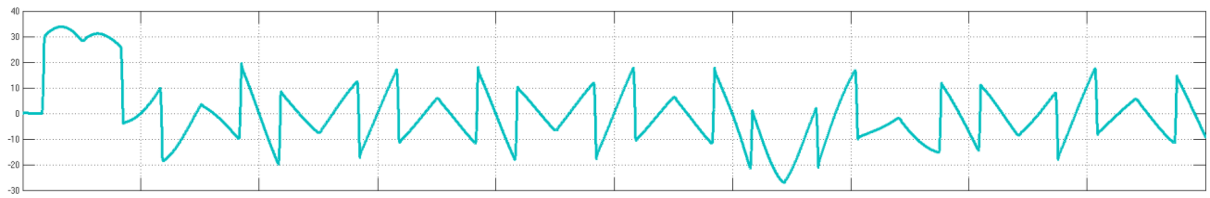

Figure 15 Compensating Current Waveform

Figure 15 shows the waveform for the magnitude of compensating current provided by the SAPF to make the current purely sinusoidal.

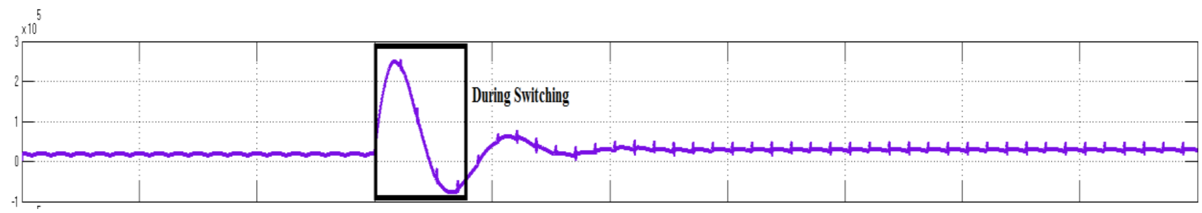

Figure 16 Active Power Waveform

Figure 16 shows the waveform for the active power before and after the operation of SAPF.

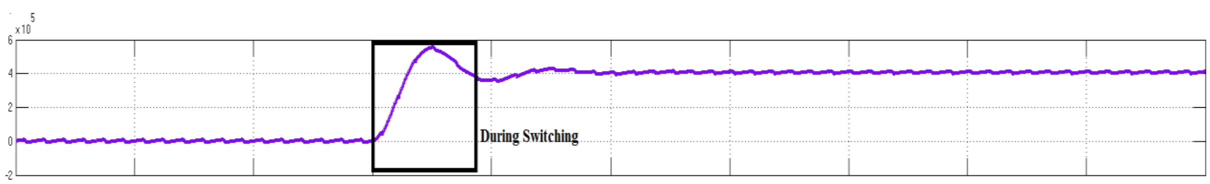

Figure 17 Reactive Power Waveform

It can be observed from the fig. 17 that reactive power increases in the system as the SAPF supplies this reactive power.

4.5.2 Simulink Result with D-Q control strategy

Breaker Transition Time: 0.06 sec **Simulation Run Time**: 0.2 sec

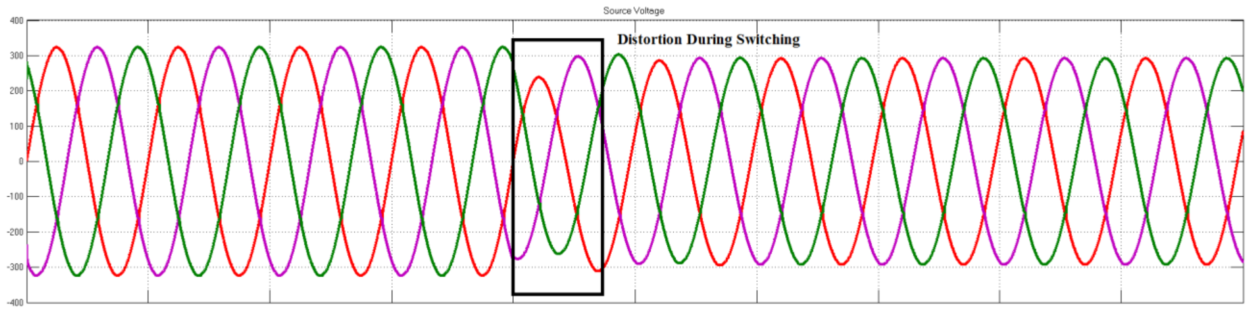

Figure 18 Source Voltage Waveform before and after filtering with d-q method

Figure 18 shows the source voltage waveform before and after using d-q method of harmonic filtration. There is a slight distortion observed which is due to the switching ON of SAPF via a breaker.

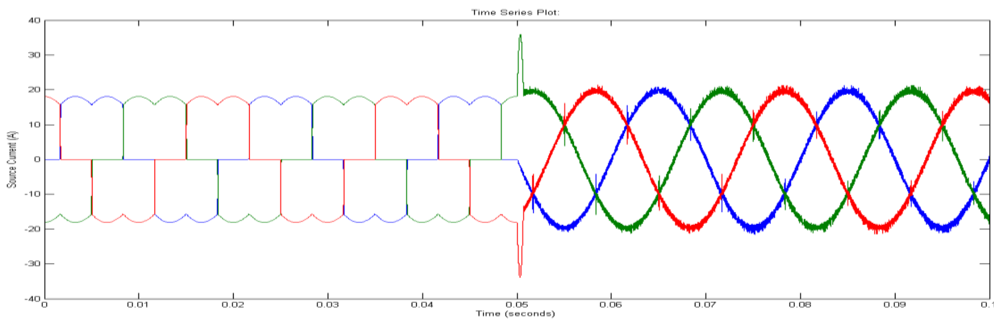

Figure 19 Source Current Waveform before and after filtering with d-q method

Figure 19 shows the waveform for source current before the use of SAPF and after it is switched ON. We can observe that after switching ON of the SAPF, the current waveform is sinusoidal.

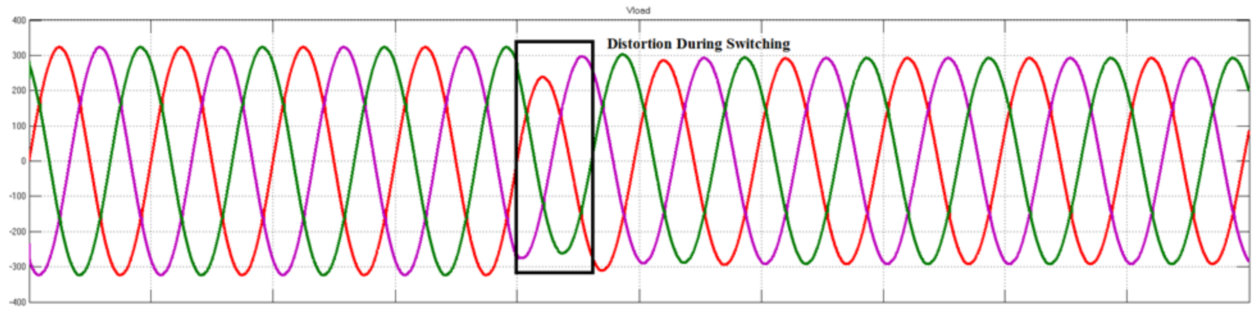

Figure 20 Load Voltage Waveform before and after filtering with d-q method

Figure 20 indicates the waveform analysis for the load voltage before and after switching ON of the SAPF. As we know load current will not change by the use of a filter as it depends on the type of load.

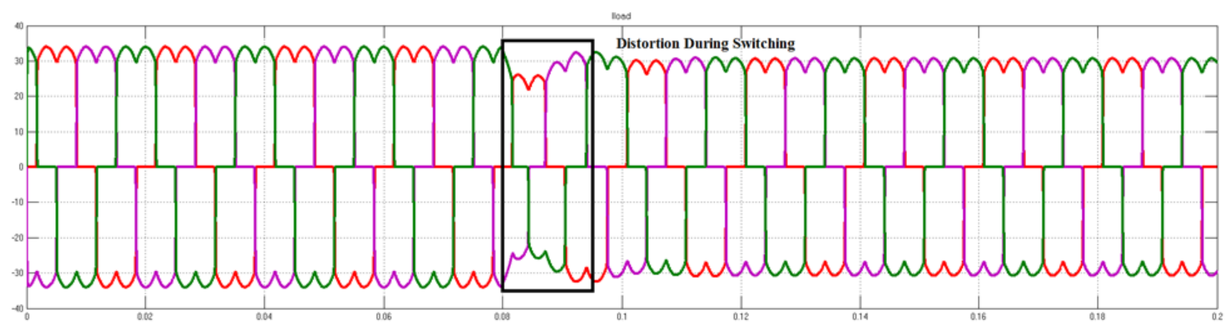

Figure 21 Load Current Waveform before and after filtering with d-q method

Figure 21 indicates the waveform analysis for the load current before and after switching ON of the SAPF. As we know load current will not change by the use of a filter as it depends on the type of load.

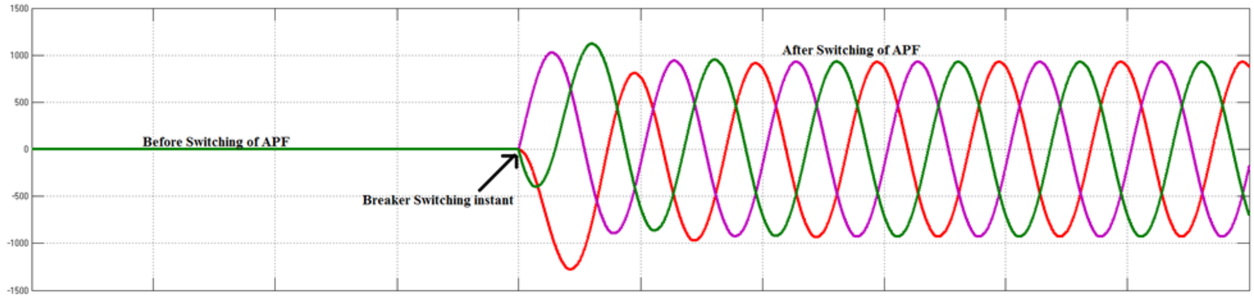

Figure 22 APF Current Waveform before and after filtering with d-q method

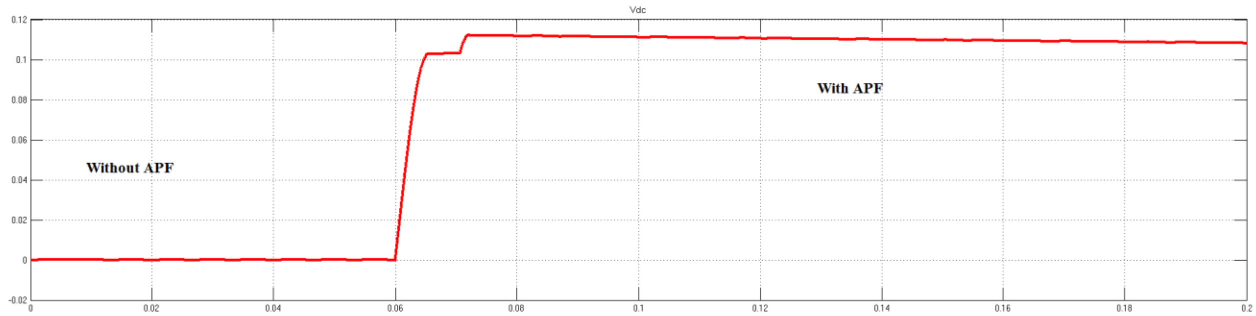

Figure 23 DC link Voltage Waveform before and after filtering with d-q method

Figure 23 shows the building up of DC link voltage used in the SAPF circuit. Once the breaker is switched ON, DC voltage starts to build up.

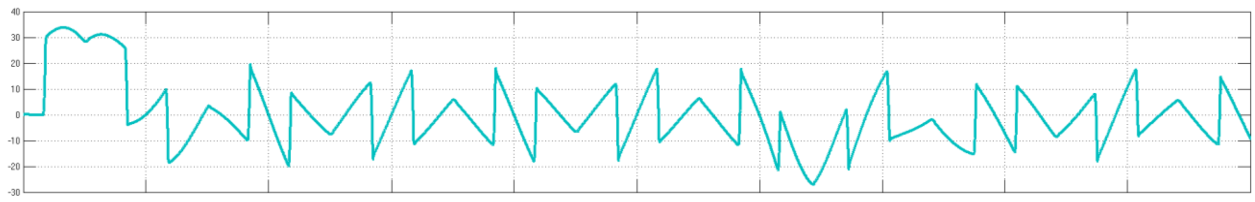

Figure 24 Compensating Current Waveform

This waveform shows the magnitude of compensating current provided by the SAPF to make the current purely sinusoidal.

4.6 FFT Analysis

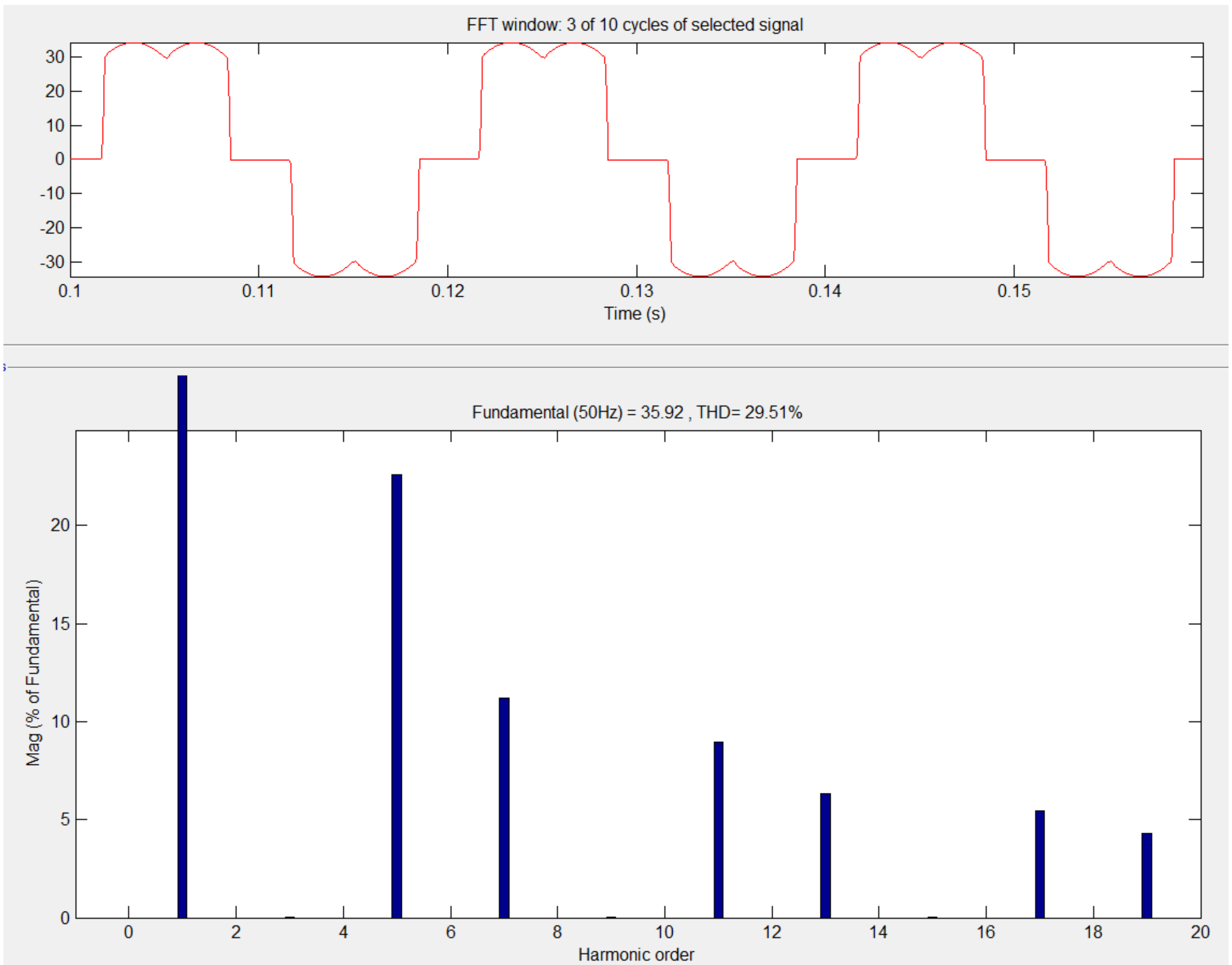

Figure 25 FFT analysis for source current without APF

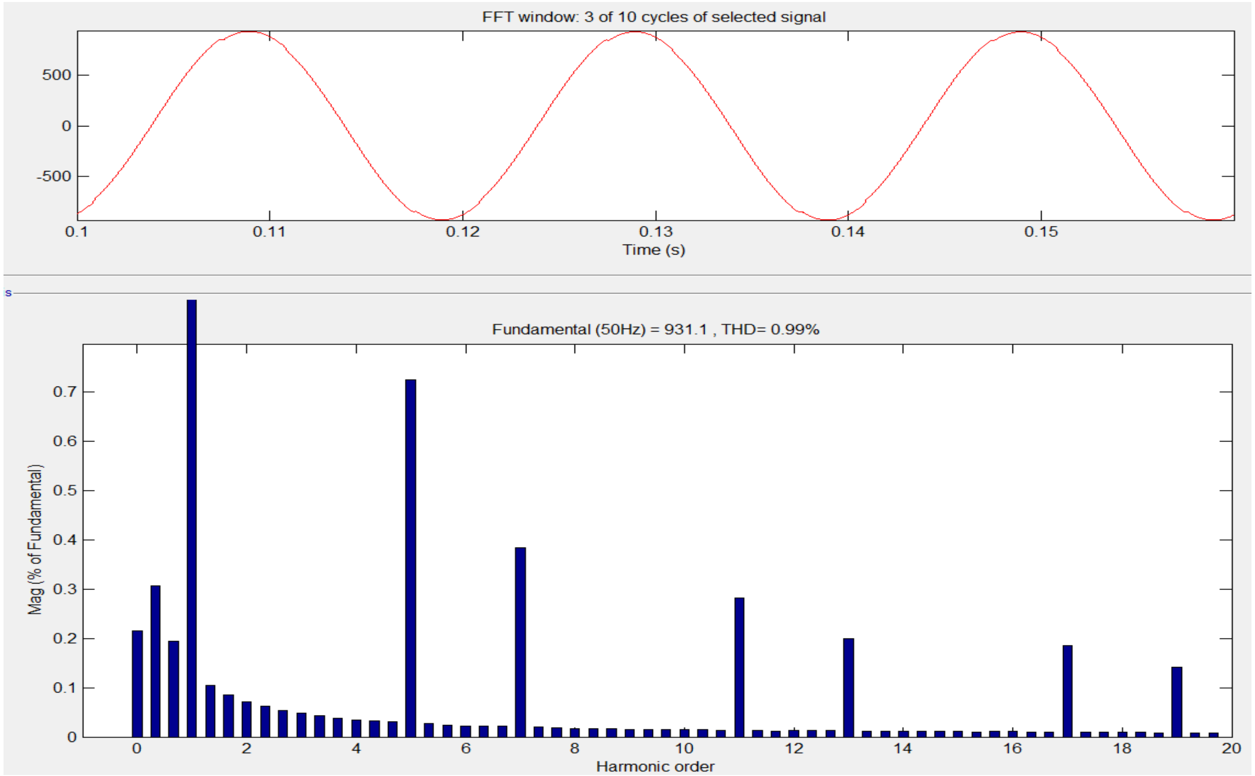

Figure26 FFT analysis for source current with 'SAPF using p-q method'

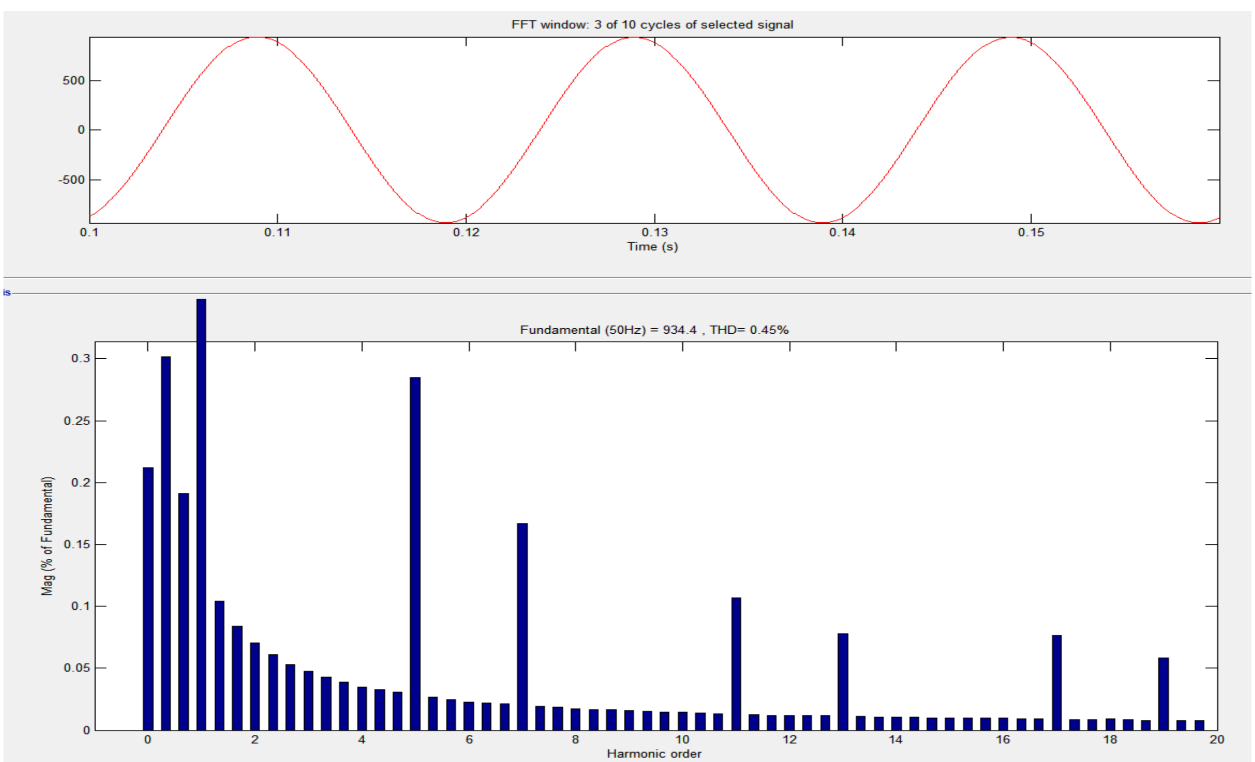

Figure 27 FFT analysis of source current with APF using d-q method

4.7 Comparative Analysis

The comparative analysis between system without SAPF and with SAPF using p-q & d-q current control method based on FFT analysis is shown in table 3 and 4. Table 3 shows the % of individual harmonics distortion w.r.t fundamental present in the system and table 4 shows the Total Harmonic Distortion (THD) of the system before and after using filter. As seen from the table 3 and 4 the system with SAPF having d-q control strategy gives the better result as compare to the system without filter & SAPF with p-q control strategy.

Table 3 Harmonic component as % of fundamental frequency component

Harmonic Order	**System without SAPF**	**System with SAPF using 'p-q' method**	**System with SAPF using 'd-q' method**
3rd order	0.03%	0.09%	0.06%
5th order	23%	0.75%	0.28%
7th order	11%	0.35%	0.16%
9th order	0.03%	0.04%	0.03%
11th order	9%	0.30%	0.12%
13th order	7%	0.26%	0.08%
15th order	0.03%	0.01%	0.01%
17th order	6%	0.24%	0.08%
19th order	5%	0.17%	0.07%

Table.4 Total Harmonic Distortion of System with and without filter

System	**System without SAPF**	**System with SAPF using 'p-q' method**	**System with SAPF using 'd-q' method**
% THD	29.51%	0.99%	0.45%

4.8 Graphical Depiction Of Results and Comparisons

Graph shown in figure 28 shows the efficiency of Kalman Filter. This graph shows how Kalman filter estimates and predicts frequency or voltage. Blue line being the test signal which is pre-calculated and known. Red line is the estimated signal after the Kalman filter logic is applied to the system. It is observed that the estimated signal correctly follows the test signal. The slight mismatch arises due to the presence of noise in the system.

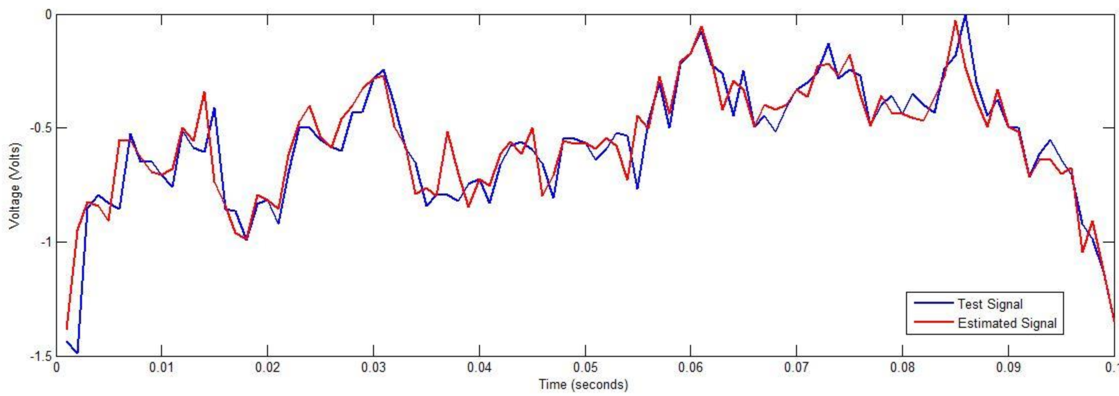

Figure 28 Kalman filter

Graph shown in figure 29 and figure 30 summarize the performance of the distribution system without and with shunt active power filter using ‘p-q’ & ‘d-q’ current control strategies.

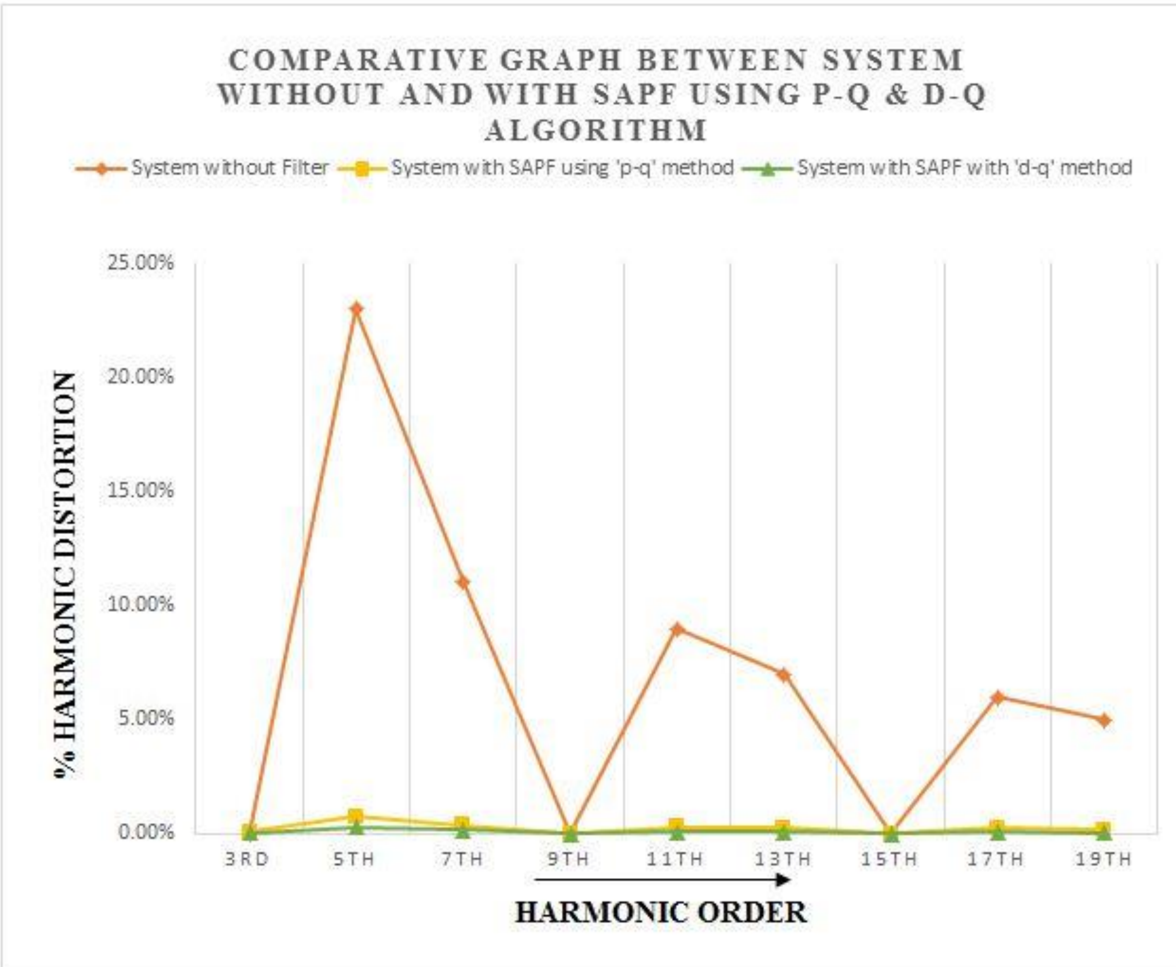

Figure 29 Comparative Graphical analysis between System without and with SAPF

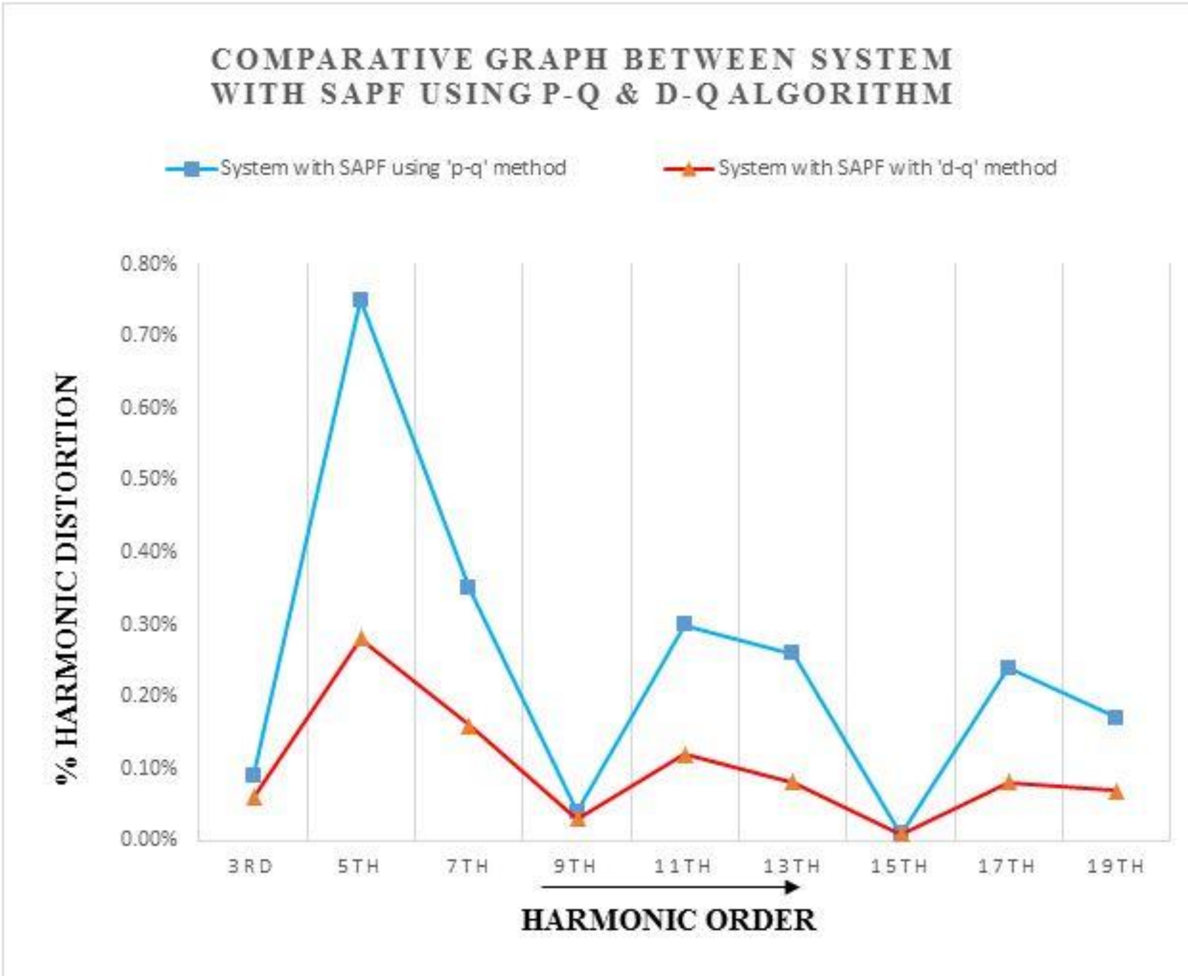

Figure 30 Comparative Graphical analysis between p-q and d-q method

CHAPTER-5

CONCLUSIONS

5.1 Conclusion and Scope for future work

The Kalman Filter is basically a recursive estimator and its algorithm is also based on the least square error. Since all the algorithms produce a noisy estimate of the filter taps, we need a low pass filter which would then process this noisy signal. The filter bandwidth of this filter should be so chosen that it compromises between eliminating the noise from the noisy estimate and preserving the original signal. This feature is only provided by the KF. But one limitation of KF is that it cannot be used for non-linear systems. It obviously unmistakable from the FFT examination of the MATLAB/SIMULINK model of the circuit with and without channel that the symphonious segment present in the source is remunerated with utilization of channel. Further it is additionally seen that consonant is repaid to a more noteworthy degree while utilizing d-q control system rather than p-q i.e. the THD of source current is nearly decreases significantly while utilizing the d-q strategy.

Physical implementation of Kalman filter can be done although MATLAB simulation is already in progress. Experimental results can correctly depict the effectiveness and differences between p-q and d-q methods.

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