Shunt Active Power Filter Design

Group - S13

Members

Harshvardhan Srivastava - 17EE10058

Param Budhraja - 17EE32002

Sanyog Jayant Pohare - 17EE35012

Shailesh Mishra - 17EE35014

Shreyase Rangamani - 17EE35015

Power Apparatus and System Design Lab
Department of Electrical Engineering
Indian Institute of Technology Kharagpur

31.03.2021

Contributions

1. Harshvardhan Srivastava - Non-linear load, calculations (system parameters), report compiling(Shunt Active Power Filter), code for inverse pq-theory, connection

2. Param Budhraja - Controller, pq theory design, report compiling (calculation, pq Theory), code for inverse pq-theory, low pass filter, connection

3. Sanyog Jayant Pohare - Controller, hysteresis band controller, overall connection, Kp-Ki calculation, calculation(system parameters, coupling inductor), report compiling(Results)

4. Shailesh Mishra - Three-phase inverter, Kp-Ki Calculation, output block, report compiling (Introduction, Implementation, Results, Discussion), code for pq-theory, connection

5. Shreyase Rangamani - Controller, pq theory design, report compiling (Implementation, Discussion, Conclusion), calculation, code for pq-theory, low pass filter, connection

1 Introduction

Due to the advancements in the semiconductor technology, the usage of power electronics devices at the end user side is increasing day-by-day. A large amount of harmonic current gets injected into distribution system due to this increasing usage of nonlinear loads and power electronic devices like electric arc welders, switching power supplies and speed drives. Harmonic currents lead to numerous issues in distribution systems like higher power losses, electronic equipment operational failures, voltage distortion. Harmonic currents lead to heating of the motor and may also cause voltage stress and corona in case of power lines [1].

Therefore, the design of reliable power filters that mitigate current and voltage harmonics to meet the power quality requirements of the utility grid is a necessity for present-day power systems. Shunt Active Power Filter(SAPF) is one such flexible possible solution. In this report, the designing of a SAPF using *pq* theory for the compensation of harmonic currents has been presented. The calculation of various components of the filter for its design has been explained thoroughly. The results after the compensation of the harmonic currents have also been presented.

The rest of the report has been outlined as follows: Section 2 gives a brief description and working of Shunt Active Power Filter (SAPF). Section 3 explains the *pq* theory and how it is used to calculate the reference compensating commands. In section 4, the calculation for obtaining the various parameters of the filter has been done. In section 5, the implementation of the SAPF on MATLAB Simulink has been described. Section 6 discusses the results obtained from the simulation. In section 7, we discuss the implications obtained from the implementation and the results. The report has been concluded in section 8.

2 Shunt Active Power Filter (SAPF)

Shunt active filters generally consist of two distinct main blocks:

1. Pulse-width modulation (PWM) converter (power processing) : PWM Controller has the responsibility for processing the power that is drawn from the power system and providing the compensating current for it.

2. Active filter controller (signal processing) : The filter is responsible for processing the signal in real time to determine the instantaneous compensating current required for the specific load .

The VSI that we have implemented consists of a voltage fed inverter with a current controller and an active filter controller to act on the changing current instantaneously . The shunt active filter controller works in a closed-loop manner, continuously sensing the load current i_l and calculating the instanta-neous values of the compensating current reference $i_c^* = i_0$ for the PWM inverter.

Another very important aspect of the SAPF is the Hysteresis Controller . It ensures that the output current that is generated are based on reference current values . Based on the error b/w the 2 inputs and the reference value , signals are generated .

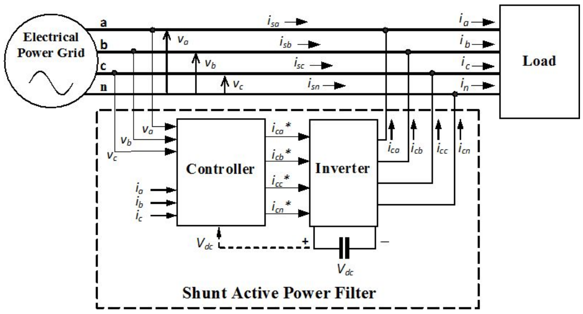

Figure 1: Shunt Active Power Filter with PWM Inverter and Active Controller Shown

The DC Voltage Regulator on the inverter side consists of energy storage element namely Capacitor . The aim of the capacitor is to supply the real power difference between load and source during the transient periods.

3 *pq* Theory

The *pq*-theory was proposed in [2] by Akagi, Kanazawa and Nabae. It is a time domain technique used to calculate compensating signals.In this technique to calculate the compensating signals simple algebraic calculations and transformations are used which gives it an added advantage of simplicity. We convert the three phase voltage and current signals in the a-b-c coordinate to α-β-0 coordinate using the Clarke transformation (also known as $\alpha\beta 0$ transformation). The transformation equations are as follows

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

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \tag{2}$$

An advantage of using $\alpha\beta 0$ transformation is the separation of zero sequence components. The instantaneous zero sequence power p_0 is given by $p_0 = V_0 i_0$ and the instantaneous power components p and q are given by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

In general when the load is nonlinear the power can be divided into oscillating and average components. We denote the average component using $\bar{\cdot}$ and oscillating component using $\tilde{\cdot}$. For example, $\bar{p}$ is the average value of instantaneous real power and $\tilde{p}$ is the oscillating component of the instantaneous real power. Among all the power components of the *pq*-theory only $\bar{p}$ and $\bar{p_0}$ are desirable.

The dc link capacitor is required to compensate $\tilde{p}$ and $\tilde{p_0}$. The instantaneous reactive power is compensated without any contribution from the capacitor and because of this the size of capacitor doesn't depend on the amount of reactive power to be compensated. We calculate the α and β component of the reference compensation current, in α-β-0 coordinate, by

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} - \bar{p_0} \\ q \end{bmatrix}. \tag{4}$$

The $'0'$ coordinate reference compensation current is given by $i^*_{c0} = i_0$ and is used to compensate the zero sequence current. Finally, to obtain the reference compensation current in the *a*-*b*-*c* coordinate use inverse Clarke transformation

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{c0} \\ i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix}. \tag{5}$$

The inverter uses these reference currents to produce compensation currents which are injected in the power system.

Figure 2 represents the steps that are needed for calculation of currents using *pq* theory.

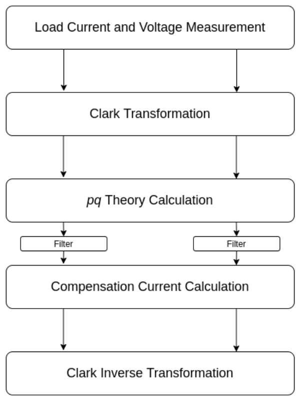

Figure 2: pq theory calculation

4 Calculation

4.1 Circuit Parameters Calculation

The three phase voltage supply has line to line voltage $V_{LL} = 400V$ and has a frequency of $50Hz$. We take the rms value of load current $I_{load} = 10A$ which gives us the value of load resistance $R_{load} = 40\Omega$. We assume the value of load inductor $L_{load} = 0.5H$. The rms value of the rectifier input current is calculated as $I_{Lrms} = 0.816 \times 10 = 8.16A$. The fundamental component of rectifier input current has a magnitude of $I_{L1} = 7.79A$. The value of harmonic current $I_h = \sqrt{I^2_{Lrms} - I^2_{L1}} = 2.43A$. The rating of SAPF is calculated using $S = 3V_{ph}I_h = 2.1kVA$. The value of DC bus voltage V_{DC} is calculated using

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} = 653.2V \approx 700V.$$

The value of the DC bus capacitor is calculated using second harmonic ripple voltage at the DC bus as

$$C_{DC} = \frac{I_d}{2\omega V_{DC,ripple}},$$

where I_d is the active filter supply current, $V_{DC,ripple}$ is the maximum DC link ripple voltage and $\omega = 2\pi f$. The value of C_{DC} is calculated to be $226.93\mu F$ and a capacitor of value $500\mu F$ is selected.

4.2 Calculation of K_p and K_I

There's a PI controller in the P_{Loss} block. Here, we describe how the K_p and K_I of the controller is obtained.

$$\frac{V_{Cap}}{V_{DC}} = \frac{\frac{K_p.K_I}{C}}{s^2 + \frac{K_p}{C}.s + \frac{K_p.K_I}{C}} \tag{6}$$

Since this transfer function is second-order transfer function, K_p and K_I can be obtained by equating equation (6) to a general second-order transfer function.

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{7}$$

Therefore, K_p and K_I are:

$$K_p = 2\zeta\omega_n C \tag{8}$$

$$K_I = \frac{\omega_n}{2\zeta} \tag{9}$$

5 Implementation

In this section, the simulation has been explained thoroughly. The implementation has been done on MATLAB Simulink. Figure 3 shows the whole simulation which has multiple subsystems. The simulation consists of the following subsystems.

1. Voltage Source
2. Non-linear Load
3. Compensating Current Block
4. Hysteresis Band Controller
5. Coupling Inductor
6. Three-Phase Inverter
7. PLoss Calculation Block

Each of these components has been explained thoroughly in this section.

5.1 Voltage Source

The voltage source considered here is a star-connected, *3-phase*, 4 wire system. The specifications of the voltage source are:

$$V_{L-L} = 400V \qquad f_S = 50Hz$$

5.2 Non-linear Load

Figure 4 shows the implementation of the non-linear load. The load is a 3-*phase*, 3 wire diode rectifier operated R-L load. Each diode is equipped with a snubber circuit. This kind of load leads to a step shaped load current wave-form on all of the three phases. This leads to harmonic components in the grid current without the action of Active Power Filter. Moreover, since the load is inductive, the power factor of the load is also less than 1.

$$R_{load} = 40\Omega \qquad L_{load} = 0.5H$$

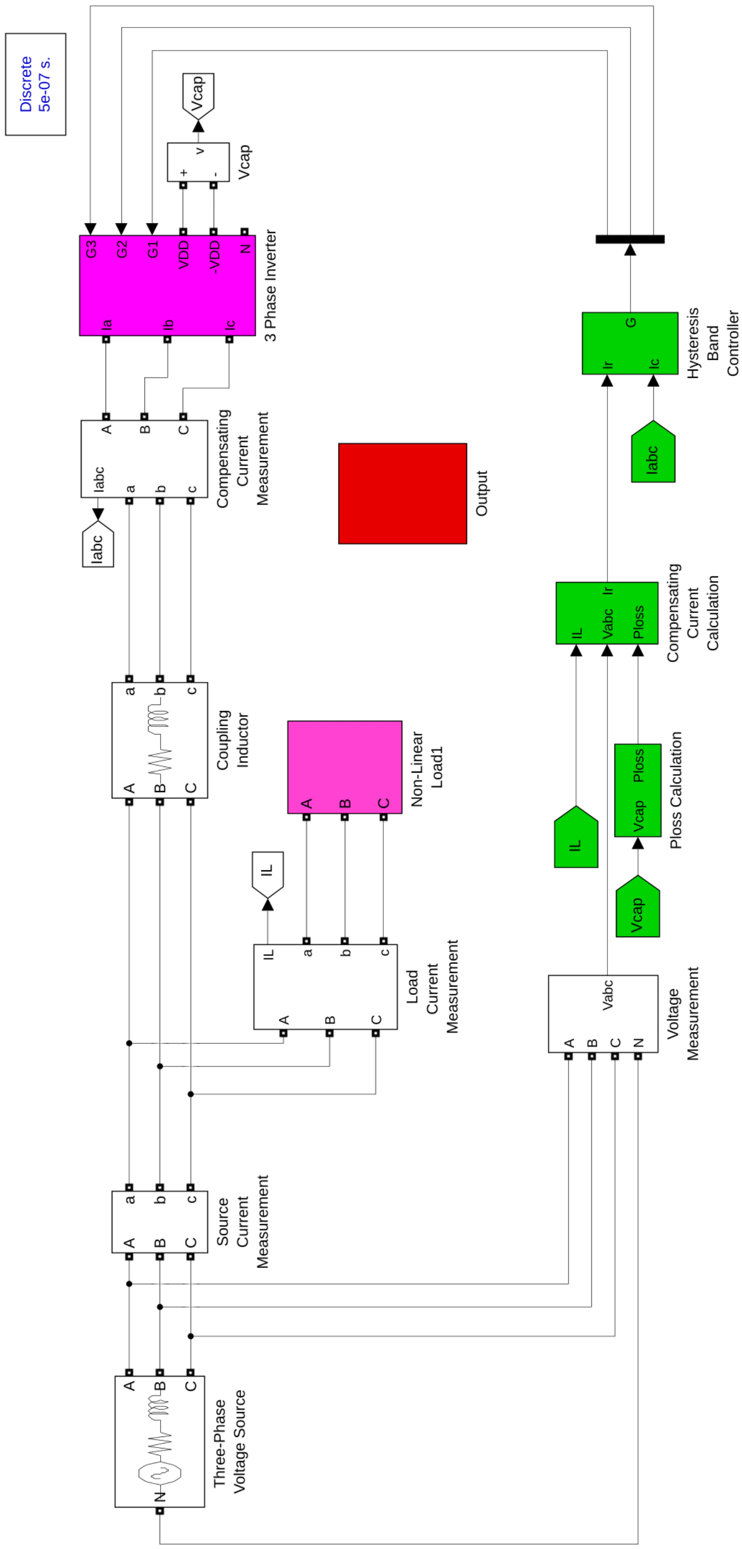

Figure 3: Whole simulation

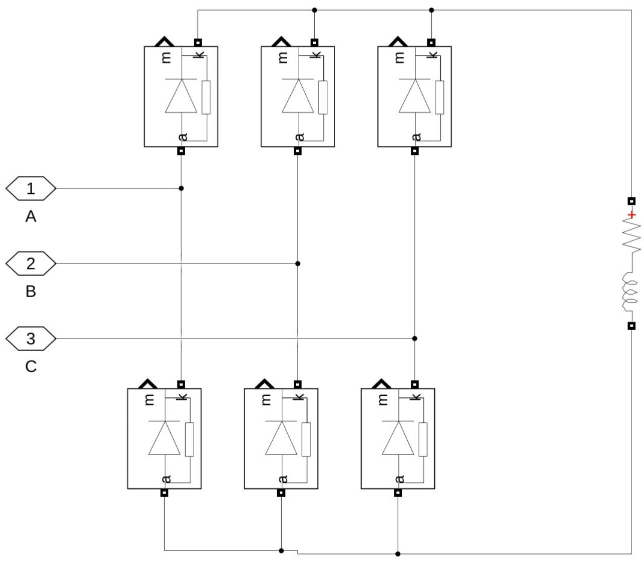

Figure 4: Non-Linear Load

5.3 Compensating Current Block

Figure 5 shows the block for obtaining the compensating current which will be added to the total current. This block implements the *pq*-theory. This block takes the power loss coming from the PLoss Calculation Block because of capacitor losses, the voltages of all the three phases and the load current as the input and gives the total current as the output.

The source voltages and the load currents which are accepted in the input are transformed from three phasor coordinates into the $0-\alpha-\beta$ coordinates using the Clarke transform. The instantaneous real and reactive powers are calculated using the currents and voltages obtained in the transform domain. The instantaneous power is then split into two components - Mean power (p_0) and Alternating power. The Mean power is calculated using a high order Low-Pass filter. The PLoss component is added to the Alternating power and this Total Alternating power(p) along with all of the instantaneous reactive power (q) is used to compute the compensation currents in the transform domain, before using the inverse Clarke transform to output the reference phasors for the compensation current.

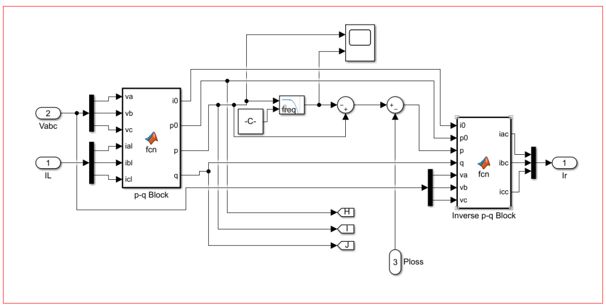

Figure 5: Compensating Current Block

The code for the function inside the *pq* block is written below. This piece of code implements Clarke transformation using equations (1) and (2) and calculates the power components p and q using (3).

```
function [i0,p0,p,q]= fcn(va,vb,vc,ial,ibl,icl)

```

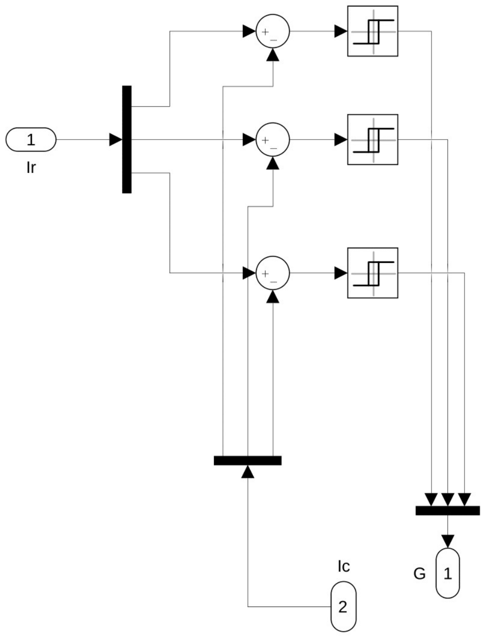

Figure 6: Hysteresis Band Controller

```
v_zero=(va+vb+vc)/sqrt(3);
v_alpha=(va-vb/2-vc/2)*sqrt(2/3);
v_beta=(vb-vc)/sqrt(2);
il_zero=(ial+ibl+icl)/sqrt(3);
il_alpha=(ial-ibl/2-icl/2)*sqrt(2/3);
il_beta=(ibl-icl)/sqrt(2);
i0=il_zero;
p0=v_zero.*il_zero;
p=v_alpha.*il_alpha+v_beta.*il_beta;
q=v_beta.*il_alpha-v_alpha.*il_beta;
```

Here is the code for the inverse *pq* block. It calculates reference compensation currents i^*_{ca}, i^*_{cb} and i^*_{cc} using equations (4) and (5).

```
function [iac,ibc,icc]= fcn(i0,p0,p,q,va,vb,vc)

v_zero=(va+vb+vc)/sqrt(3);
v_alpha=(va-vb/2-vc/2)*sqrt(2/3);
v_beta=(vb-vc)/sqrt(2);
i_zero=i0;
i_alpha=(v_alpha.*p+v_beta.*q)/(v_alpha.^2+v_beta.^2);
i_beta=(v_beta.*p-v_alpha.*q)/(v_alpha.^2+v_beta.^2);
iac=sqrt(2/3)*(i_zero/sqrt(2)+i_alpha);
ibc=sqrt(2/3)*(i_zero./sqrt(2)-i_alpha/2+sqrt(3)*i_beta/2);
icc=sqrt(2/3)*(i_zero./sqrt(2)-i_alpha/2-i_beta*sqrt(3)/2);
```

5.4 Hysteresis Band Controller

Figure 6 shows the hysteresis band controller that has been implemented in the simulation. Hysteresis band controller has been used here for current control. Hysteresis band current has been adopted in this work in order to generate the switching signals of the voltage source inverter.

In hysteresis current control, the current is kept in a predefined bandwidth around the reference current. The actual current ($\mathrm{i_{Sa}}$, $\mathrm{i_{Sb}}$, $\mathrm{i_{Sc}}$) is compared to the reference current ($\mathrm{i_a}$, $\mathrm{i_b}$, $\mathrm{i_c}$) and the VSI switches are turned on and off in accordance with the error to maintain the actual current within the hysteresis band. When the current error exceeds the upper limit of the hysteresis band, the VSI output is switched off or vice versa [3].

$$Band_{Upper} : +0.0001A(error) \qquad Band_{Lower} : -0.0001A(error)$$

5.5 Coupling Inductor

Coupling inductors have been used between grid and the voltage source inverter (VSI). The specifications have been calculated in Calculations (4) section, optimizing between two opposing criteria: reduction of ripple current due to switching of the VSI and adequate bandwidth of the response of the VSI to the reference current signals from the compensation circuit. The specifications of these are:

$$R_{coupling} = 0.0001\Omega \qquad L_{coupling} = 0.0004H$$

5.6 Three-Phase Inverter

A 3-*phase* 3-wire Voltage Source Inverter is the main block of the SAPF. It is composed of three pairs of Power MOSFETs for each phase, each pair operating in a complimentary manner. The specification of the MOSFET used is:

$$I_{Rated,MOSFET} = 10A$$

The AC side of the inverter is connected to the coupling inductor which leads the compensation current towards the voltage source. The output voltage of the inverter is controlled switching the MOSFETS with the gate pulses generated by the Hysteresis Band Controller. The MOSFETs are switched in such a way that when the compensation current is falling below the hysteresis band, the output voltage of the inverter is increased and thus the compensation current flowing through the coupling inductor increases. The reverse happens when the compensation current exceeds the hysteresis band.

On the DC side of the inverter is a DC-Link capacitor with enough capacity to act as a constant DC Voltage Source and supply the zero-mean compensation current. Ideally, the real power supplied by the capacitor is zero. But, practically, the capacitor is also responsible for absorbing and supplying the switching currents of the MOSFETs. Switching leads to some losses and they have to be compensated from the supply voltage, which leads to the PLoss component in the Compensation Current Block.

A suitable value of DC-Link capacitor voltage has been calculated in the Calculations (4) section. The criteria for deciding its value is the reduction of the capacitor voltage ripple due to the flow of compensation current. The capacitor is maintained at a fixed DC voltage such that irrespective of the phase angle of the supply voltage, the capacitor always supplies positive current when the switch connecting a phase with the positive terminal of the capacitor is turned on. The specifications of the Capacitor is:

$$C_{DC-Link} = 500uF \qquad V_{ref} = 700V$$

5.7 PLoss Calculation Block

This block takes the capacitor voltage, V_{cap} and the reference voltage, V_{ref} and gives the power loss as the output.

Due to switching losses of the inverter and other non-idealities, V_{cap} drops with time and does not remain equal to V_{ref}. Hence a PI controller is used to compute a PLoss component using the voltage difference V_{ref} - V_{cap} as the error signal. This PLoss component is used by the Compensating Current Block while computing the reference current. More the voltage drop with respect to the reference voltage, more is the reference current in order to recharge the capacitor. The controller parameters

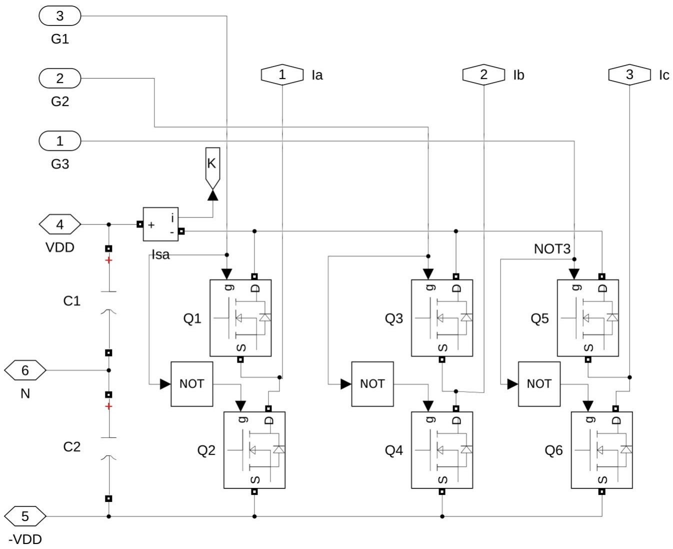

Figure 7: Three Phase Inverter

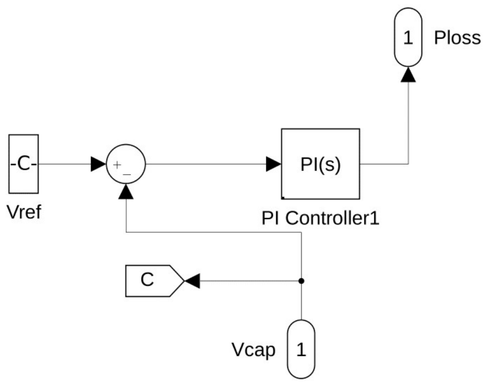

Figure 8: Power Loss Calculation Block

K_{P} and K_{I} have to be calculated such that the voltage correction response in the capacitor is fast, without adding significant high frequency components to the compensation current. The calculation has been shown in 4.2.

6 Results

In this section, various results have been presented. These results imply the performance of the filter designed. Figure 9 shows the p0, the active power(p) and the reactive power(q). It is clear from the graphs that the value of p0 is very small and hence, can be neglected. Also, the magnitude of p is larger than q.

Figure 10 represents the parameters corresponding to phase a. There are very few spikes in a full cycle. This was possible because of the low pass filter.

Figure 11 shows the parameters of all the three phases. As expected, the variation of each parameter is same, only shifted by their phase differences.

Figure 12 shows the capacitor voltage. The capacitor voltage shoots to value more than 1000 volts but it settles down to the desired voltage(700V) very fast (around 0.03 seconds). Therefore,

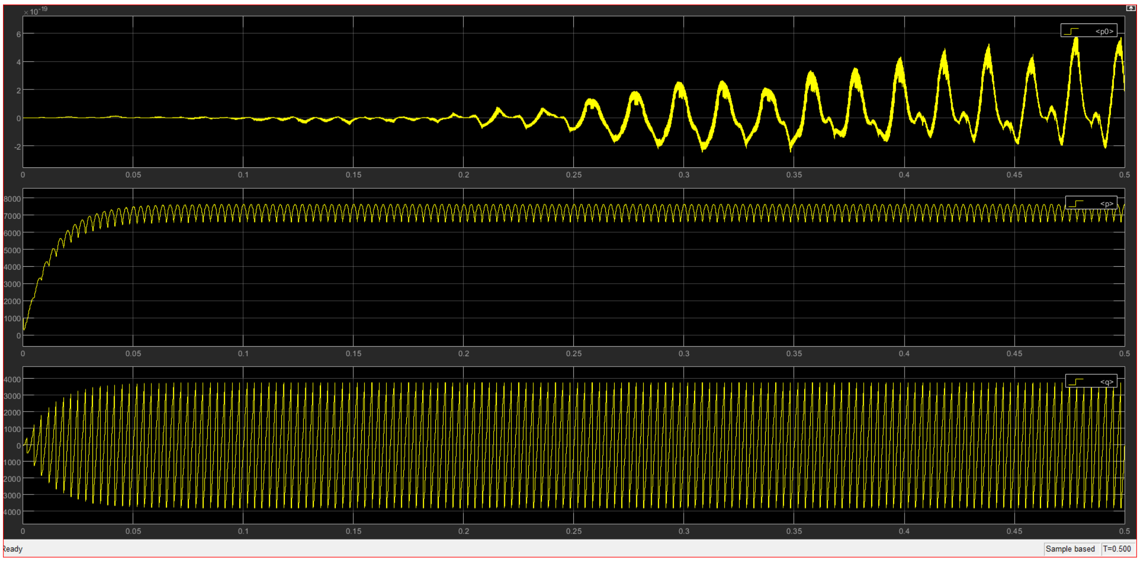

Figure 9: p0, p, q obtained from pq theory

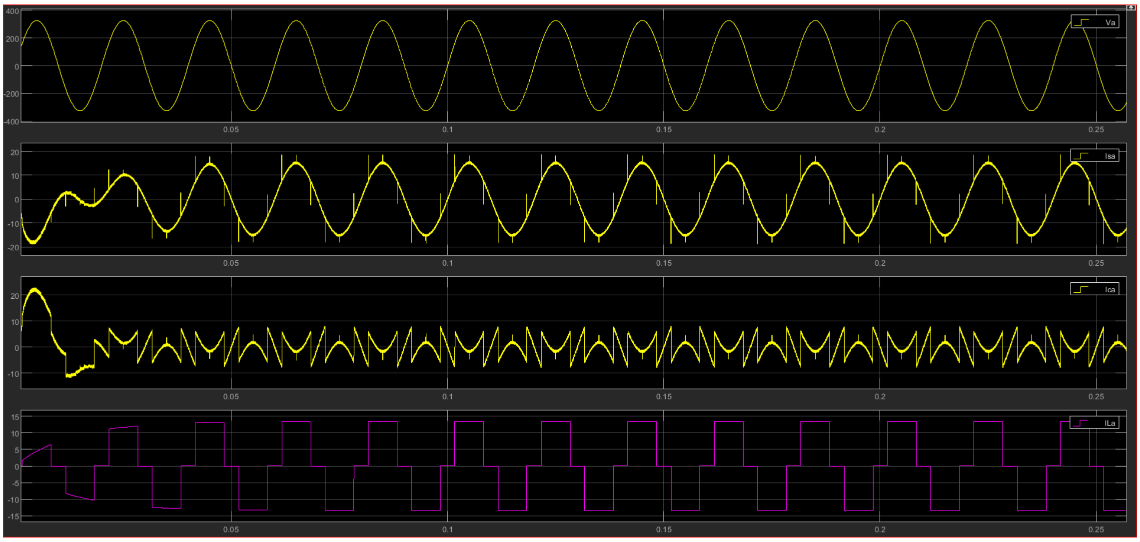

Figure 10: Voltage, Source Current, Capacitor Current and Load Current of phase a

the performance of the controller is as desired.

Figure 13 shows the total harmonic distortion(THD) because of the designed filter. From the results, it is evident that the value of THD is way less than 5%. Therefore, the designed filter's performance is really good.

7 Discussion

In this section, we describe the important implications obtained from the results and the implementation. They are as follows:

1. **Switching frequency of the Voltage Inverter**: The voltage inverter is poperated by the hysteresis band controller. Hence the switching frequency of the inverter is not controlled by a deterministic gate pulse, but indirectly by the bandwidth of the R-L values of the coupling

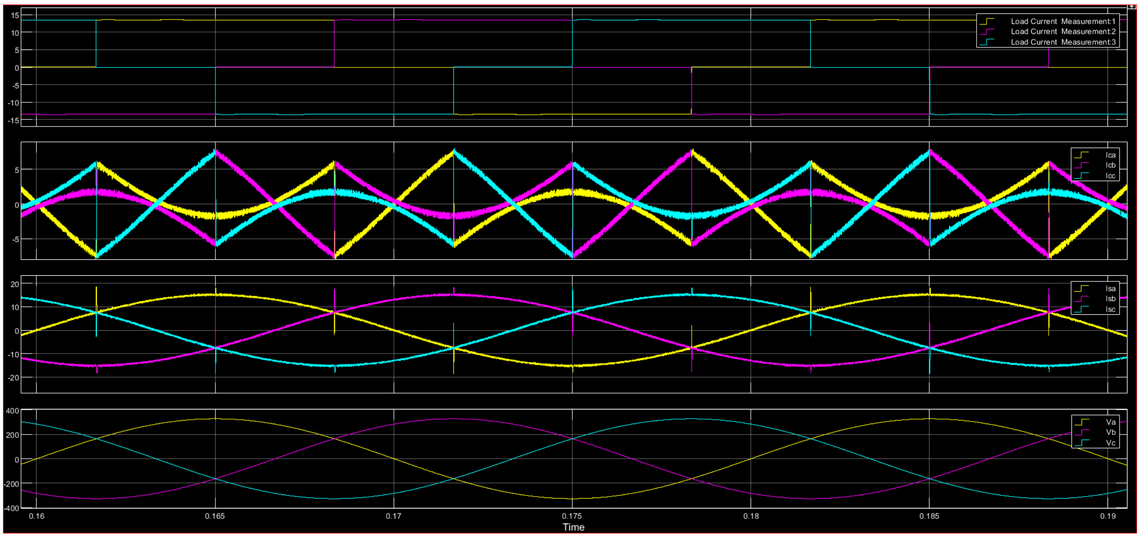

Figure 11: Load Current, Capacitor Current, Source Current and Voltages of all the three phases

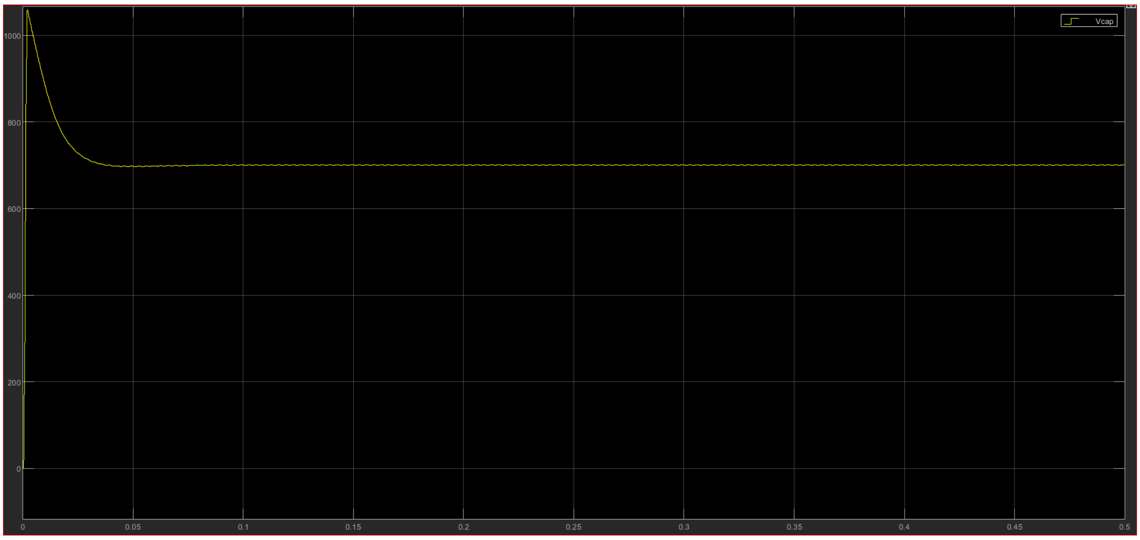

Figure 12: Capacitor Voltage

circuit and the hystereses band values.

2. **Load Rating of the Inverter**: The maximum load that can be connected across a SAPF is limited by both the current limit of power electronic switches and the capacity of DC-Link capacitors. For industrial applications with larger loads, where Power Filtering is also needed more, SAPF has to be connected on a load-by-load basis rather then directly connecting one to the point of common coupling. Hence a mass-producible and a rugged design of the SAPF is beneficial from the economic point of view.

3. **Low Pass Filter**: The low pass filter mentioned in 5.3 has been obtained using the low-pass filter offered by MATLAB. The cut-off frequency is chosen to be 50 Hz, thus filtering the oscillating real power for current compensation. We have not designed the low-pass filter on our own. The low-pass filter coefficients can be designed using the directions provided in [3].

4. **Spikes in Line Currents**: The line currents show a current spike whenever there is a diode

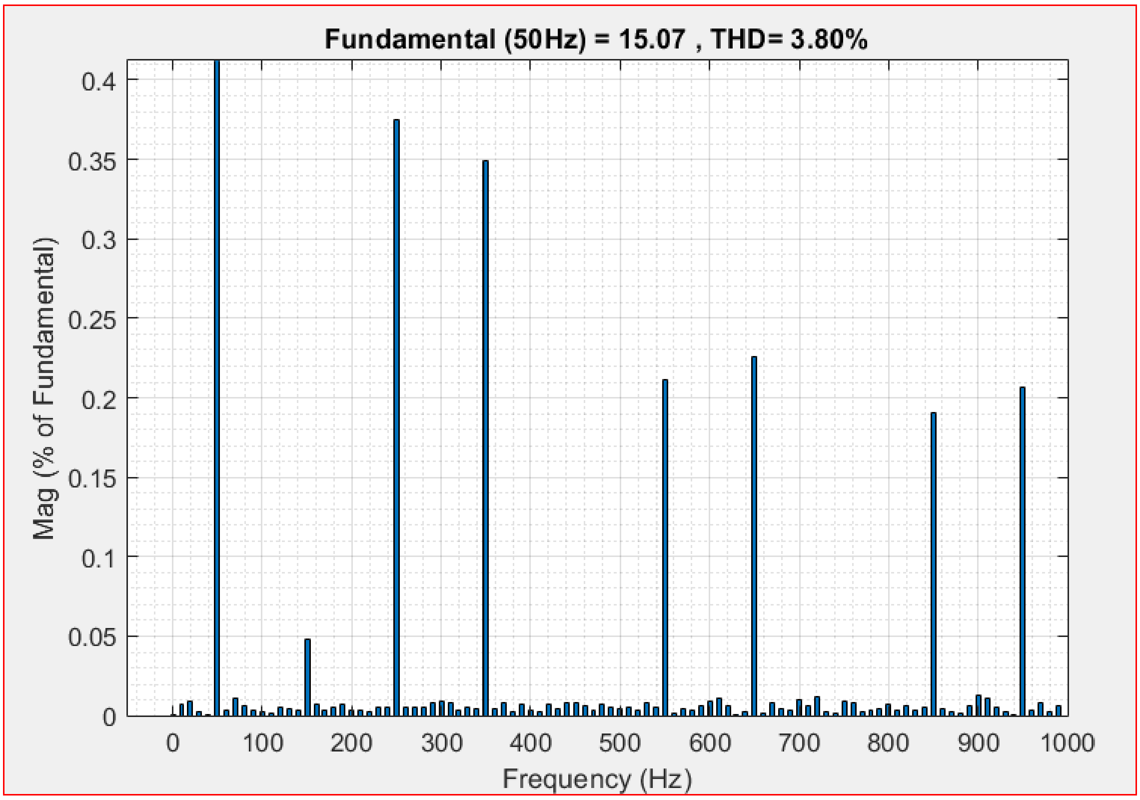

Figure 13: Total Harmonic Distortion

commutation in the non-linear load. This is because the compensation current cannot change immediately like the current of the load, due to the presence of the coupling inductor. The value of the coupling inductor had to be fine tuned to minimize this current spike.

8 Conclusion

The designed Shunt Active Power Filter simulation is working according to the design expectations. The observed THD in the line currents is less than 5 %, as targeted by the design requirements. The line currents are visibly free from both harmonic components and lagging current. The choice of capacitor capacity is also proven correct as there is nearly no ripple voltage.

References

[1] I. . W. Group *et al.*, "Ieee recommended practices and requirements for harmonic control in electrical power systems," *IEEE STD*, pp. 519–1992, 1992.

[2] H. Akagi, Y. Kanazawa, and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," *IPEC, Tokyo, Japan*, pp. 1375–1386, 1983.

[3] A. A. Imam, R. Sreerama Kumar, and Y. A. Al-Turki, "Modeling and simulation of a pi controlled shunt active power filter for power quality enhancement based on pq theory," *Electronics*, vol. 9, no. 4, p. 637, 2020.