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Simulation and Analysis of Shunt Active Power Filter for Power Quality Improvement

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***Abstract*— In this paper the drawback associated with ac mains in AC-DC power supply feeding to a nonlinear load is solved by three-phase shunt active power filter(SAPF). This paper presents simulation and development of SAPF for mitigation of the power quality problem at ac mains in AC-DC power supply feeding to a nonlinear load. Simulations using MATLAB for a system with a SAPF have been carried out under steady state conditions and performance of PI controller based SAPF and AC-DC power supply feeding to a Nonlinear load (without PI controller) is compared. Harmonic contents of the source current has been calculated and compared for the different cases to demonstrate the influence of harmonic extraction circuit on the harmonic compensation characteristic of AC-DC power supply feeding to a nonlinear load. Simulation results obtained shows that the performance of compensator is found to be better than without compensator.**

***Keywords*— Shunt active filter, harmonics, active power**

I. Introduction

Recently, wide application of nonlinear and time-varying devices has led to distortion of voltage and current waveforms in ac networks. Consequently, harmonics, sub-harmonics and inter-harmonics are often present in voltage and current spectra. Pollution has been introduced into power systems by nonlinear loads such as transformers and saturated coils, due to its nonlinear characteristics and fast switching, Most of the pollution issues are created due to the nonlinear characteristics and fast switching of PE equipment. Approximately 10% to 20% of today's energy is processed by PE equipment, due to the fast growth of PE equipment capability. A race is currently taking place between increasing PE equipment pollution and sensitivity, on the one hand, and the new PE-based corrective devices, which have the ability to attenuate the issues created by PE equipment, on the other hand.

Increase in such non-linearity causes different undesirable features like low system efficiency and poor power factor. It also causes disturbance to other consumers and interference in nearby communication networks. The effect of such non-linearity may become sizeable over the next few years. Hence it is very important to overcome these undesirable features.

Active power filters are now seen as a viable alternative over the classical passive filters, to compensate harmonics and reactive power requirement of the non-linear loads. The objective of the active filtering is to solve these problems by combining with a much-reduced rating of the necessary passive components.

Various topologies of active power filters have been developed so far [1]. The SAPF based on current controlled voltage source type PWM converter has been proved to be effective even when the load is highly non-linear [2- 4]. Most of the active filters developed are based on sensing harmonics [5-7] and reactive volt-ampere requirements of the non-linear load and require complex control. A new scheme has been proposed in which the required compensating current is determined by sensing load current which is further modified by sensing line currents only.

However, the conventional PI controller was used for the generation of a reference current template. The role of the DC capacitor is described to estimate the reference current. A design criterion is described for the selection of power circuit components. A detailed simulation program of the scheme is developed to predict the performance for different conditions and simulink models also has been developed for the same for different parameters and operating conditions.

II. Mathematical Formulation

A. *Principle of operation*

The shunt active filter shown in Fig. 1 is a current controlled voltage source inverter (VSI), which is connected in parallel with the load. It is controlled in such a way to generate the required reactive and harmonic currents of the load.

SAPF injects a current equal in magnitude but in phase opposition to harmonic current. In this case the SAPF operates as a current source injecting the harmonic components generated by the load but phase shifted by 180°. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the SAPF can also compensate the load power factor [8-12]. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor.

It is controlled to draw / supply a compensating current i_c from / to the utility, so that it cancels current harmonics on the AC side, and makes the source current in phase with the source voltage.

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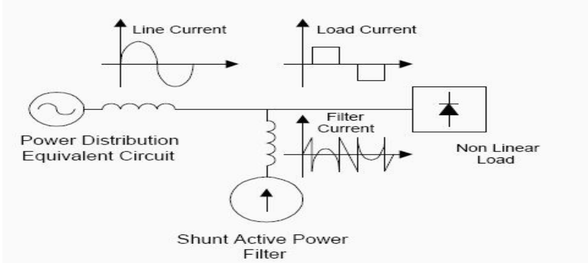

Fig 1 SAPF basic compensation principle

B. System Configuration

Fig.2 shows the system that was implemented in a simulator for electromagnetic circuits. For simplicity, a three phase three-wire system is considered [13,14] (there are no zero sequence current components). The SAPF generates the compensating currents i_{ca}, i_{cb} and i_{cc} to compensate the load currents i_a, i_b and i_c in order to guarantee sinusoidal, balanced, compensated currents i_{sa}, i_{sb} and i_{sc} drawn from the network. This goal is achieved even under non-sinusoidal system voltages. For three-phase ungrounded system only two current sensors could be used, since i_c=-i_a-i_b. The measurement of the active filter currents (i_{ca}, i_{cb} and i_{cc}) is needed only in the PWM current control, and the dc voltage measurement is used in the dc voltage regulator.

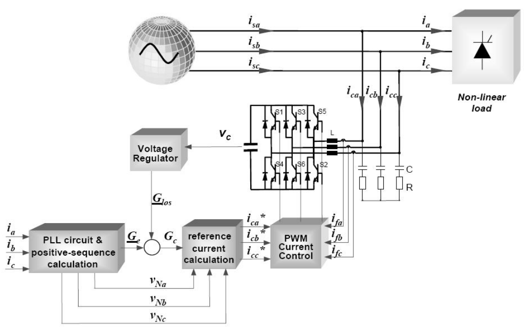

Fig 2 System configuration.

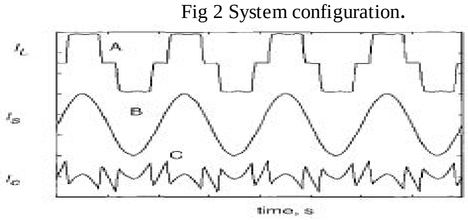

Fig 3 SAPF-shapes of (A) load, (B) source and (C) desired filter Current wave forms.

C. SAPF Control Circuit

There are three main parts to be considered for using the shunt active power filter as shown in Fig. 4. The first is the harmonic detection method to calculate the reference currents of the shunt active power filter. There are many methods to calculate the reference currents such as the instantaneous power theory (PQ), the synchronous reference frame (SRF), the a-b-c reference frame, the synchronous detection (SD) and the DQ axis with Fourier (DQF), instantaneous active and reactive current component I_d - I_q method(DQ). In this project, the DQ is selected for the harmonic detection because this method provide the fast calculation time in which it is suitable for the real time application.

The second part is the structure of SAPF. The voltage source inverter (VSI) with six IGBTs is used for the shunt active power filter. The last one is the control technique and control strategy to control the compensating currents (i_{cu}, i_{cv} and i_{cw}). There are many techniques to control the compensating currents such as the hysteresis current control, the delta modulation control, the fuzzy logic control and the pulse width modulation control [15,16]. The pulse width modulation (PWM) with PI controllers on DQ frame is used in this paper as shown in Fig.4. Therefore, the details of PI controllers design with the PWM technique [17] for the current and voltage loops on DQ frame are presented.

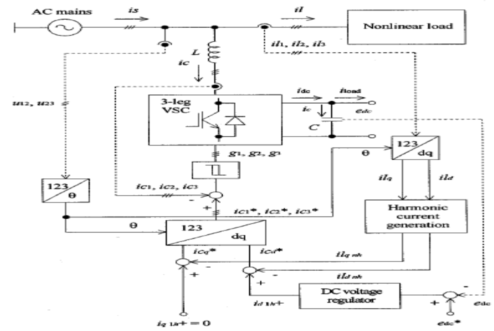

Fig.4. Control block diagram of the shunt inverter

Finally, Fig.4 shows the controller developed for the shunt compensator. The system load currents are detected and then transformed into synchronous d-q-0 reference frame with the sine and cosine functions calculated using a PLL (Phase Locked Loop).

$$V_{sdqo} = T_{abc}^{dqo} V_{sabc} \quad \text{......(1)}$$

$$T_{abc}^{dqo} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

With this transformation, the fundamental positive sequence components are transformed into dc quantities in d and q axes, which can easily be extracted by low-pass filter (LPF). All harmonic components are transformed into ac quantities with a fundamental frequency shift.

$$i_{ld}=\overline{i_{ld}}+\tilde{i}_{ld} \,,\; i_{lq}=\overline{i_{lq}}+\tilde{i}_{lq} \quad \text{........... (3)}$$

Where $i_l = i_s + i_c$ .... (4)

Where i_l is the nonlinear load current, i_s is the source current and i_c is compensating current. The control strategy guarantee balanced and sinusoidal source current at unity power factor.

Reference current components in the d-axis and q-axis are expressed in (5).

$$i^*_{fd}=\tilde{i}_{ld} \,,\; i^*_{fq}=\tilde{i}_{lq} \quad \text{.................... (5)}$$

In this situation, system currents are

$$i_{sd}=\overline{i_{ld}} \,,\; i_{sq}=\overline{i_{lq}} \quad \text{................. (6)}$$

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If correction of power factor considered, reference current components and system currents are expressed in (7) and

$$i^*_{fd} = \overline{i_{ld}}\ ,\ i^*_{fd} = i_{lq}$$

$$i_{sd} = \overline{i_{lq}}\ ,\ i_{sq} = 0 \ldots\ldots\ldots\ldots\ (7)$$

As shown in Fig. 4, reference currents are then inversely transformed into a-b-c reference frame. The output compensatory currents of the shunt compensator are obtained by a PWM Hysteresis current control.

III. Simulation Results

A. *Fixed diode rectifier load*

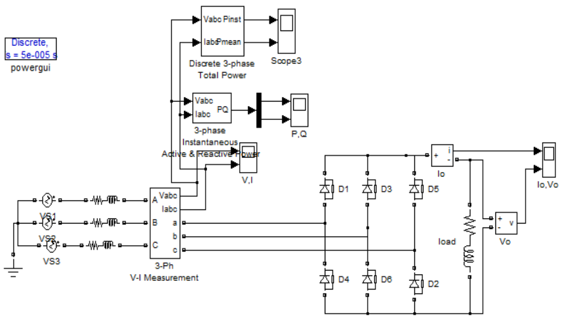


Fig 5 3-Phase source driving a diode

Reactive Power (KVAR) = 8

ActivePower(Kw) =4

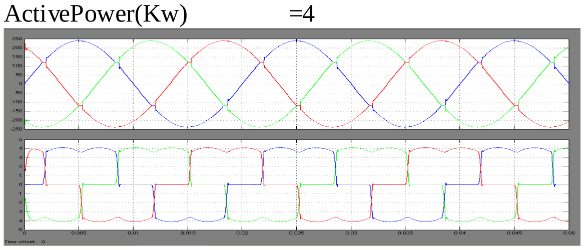


Fig 6 Input Voltage and Current Wave

THD value of current waveform is 28.95

B. *Dynamic diode rectifier load*

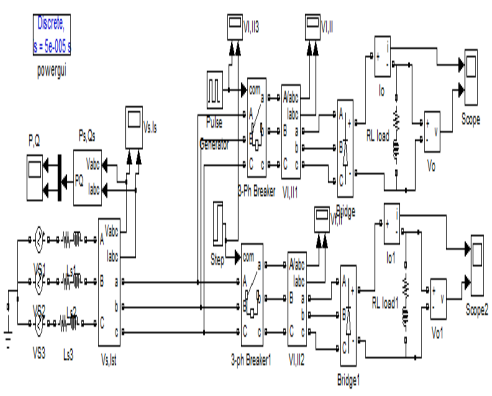


Fig 7 Dynamic Diode Rectifier Load

Active Power (kw) =8

Reactive Power (kVAR) =4

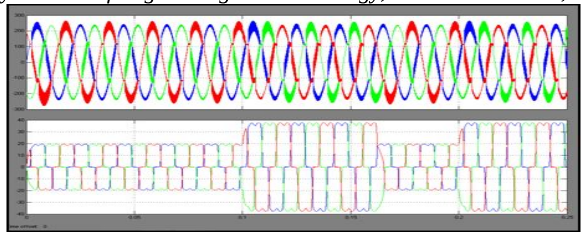


Fig 8 Voltage and Current Waveforms

THD value is 24.56%.

C. *Fixed Thyristor load*

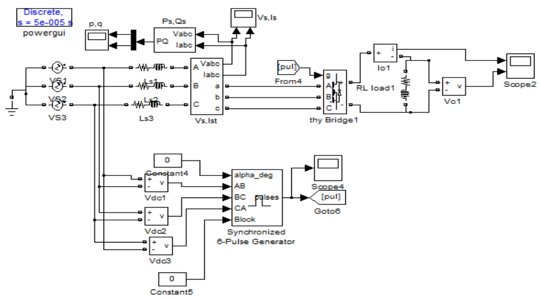


Fig 9 Fixed Thyristor Load

Active Power (kw) = 9

Reactive Power (KVAR) = 5

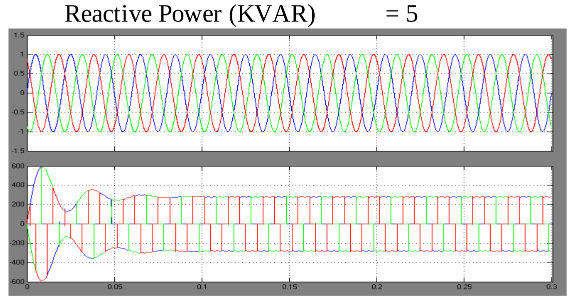
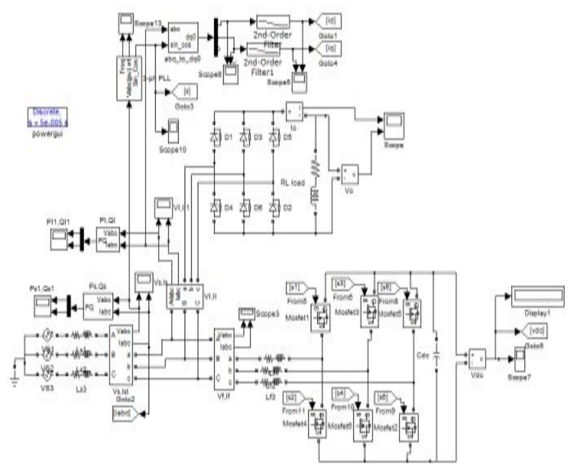


Fig 10 Voltage and Current Waveforms

D. *Diode rectifier load with SAPF Control Strategy*



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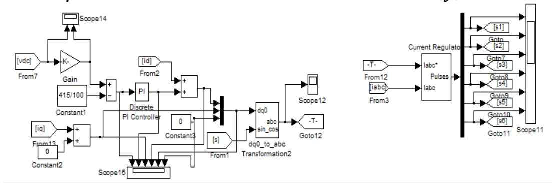

Fig 11 Diode rectifier with SAPF

Active Power (kw) =4

Reactive Power (kVAR) =2.5

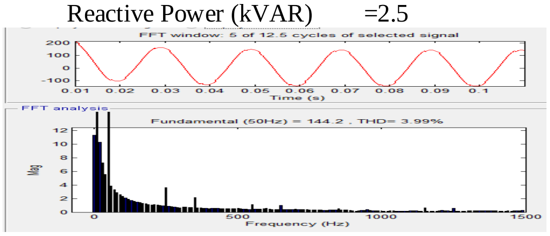

Fig12 THD Values of current waveform for diode rectifier with APF

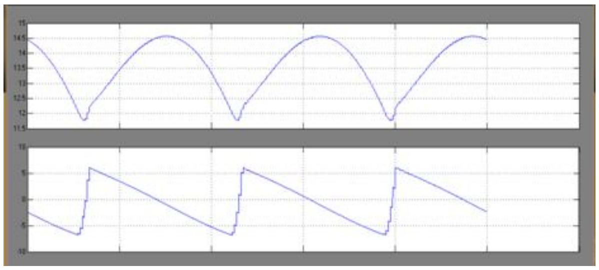

Fig13 I_d & I_q harmonics for rectifier load with APF

From the above THD value of Current it is clear that with Shunt APF control method Current wave forms distortions reduced to 3.99 % which is allowable range when compared to IEEE standard 5 % . Thus supply current distortions are greatly reduced from 28.95 % for fixed diode rectifier load to 3.99 % with SAPF control strategy.

E. Thyristor load with 3-phase SAPF

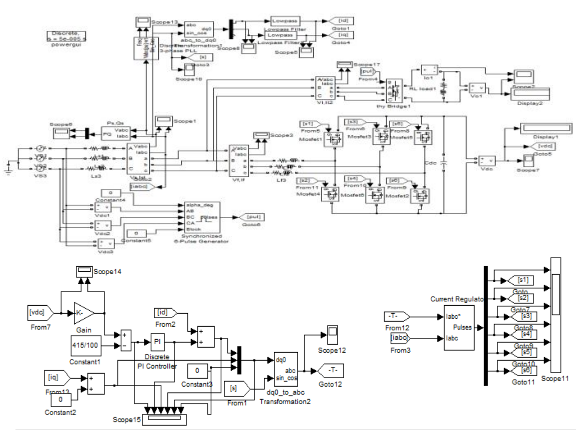

Fig14 Thyristor load with SAPF

Active Power (kw) =5

Reactive Power (kVAR) =2.5

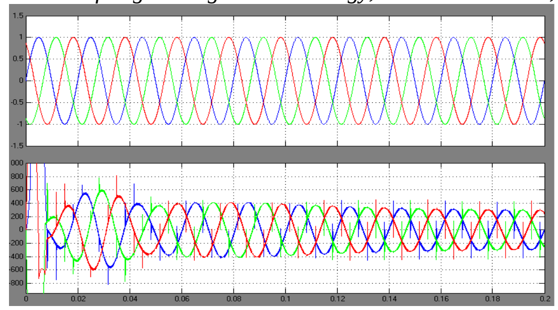

Fig15 Voltage and Current Waveforms for Thyristor converter with APF

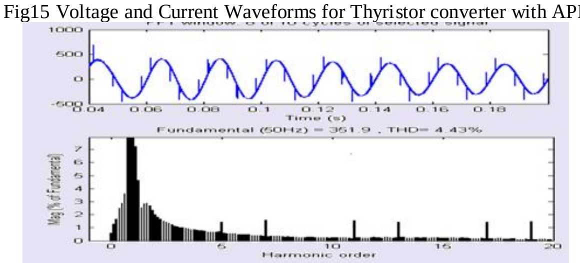

Fig16 THD Values of current waveform for Thyristor converter with APF

Thus supply current distortions are greatly reduced from 28.47 % for fixed thyristor rectifier load to 4.43 % with SAPF control strategy.

F. Dynamic diode load with 3-phase SAPF

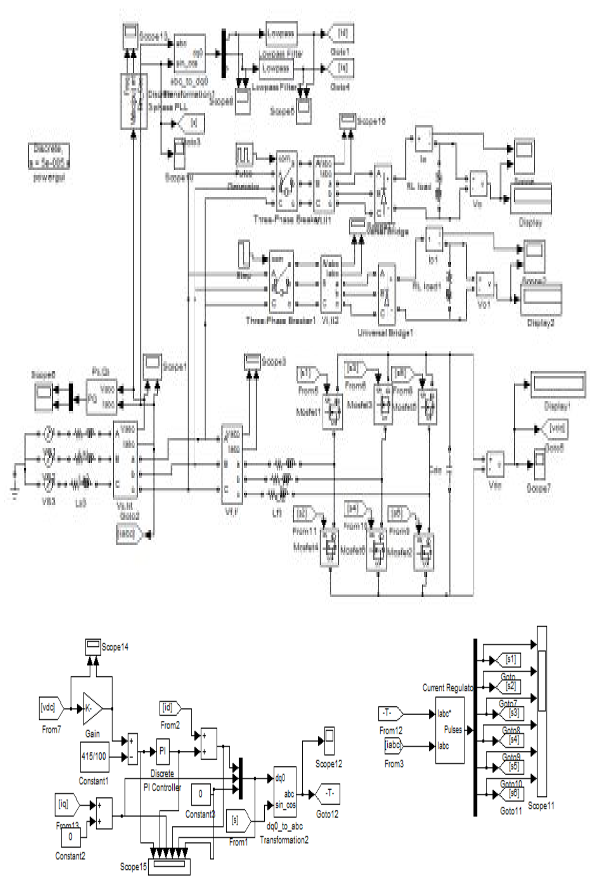

Fig17 Dynamic load with 3-phase SAPF

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Active Power (kw) =6
Reactive Power (kVAR) =3

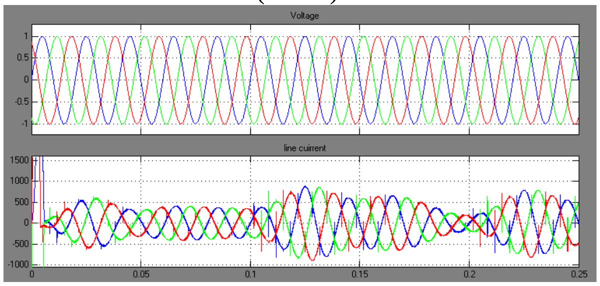

Fig18 Voltage and Current Waveforms for dynamic diode loads with APF

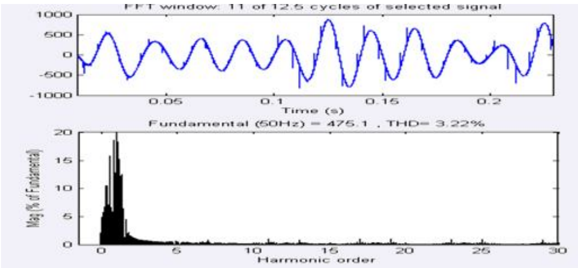

Fig19 THD Values of current waveform for dynamic diode rectifier with APF

Thus supply current distortions are greatly reduced from 29 % for fixed thyristor rectifier load to 3.22 % with SAPF control strategy.

The compensator is switched ON; optimum values (K_p and K_i) are found to be 1 and 10, respectively. From the wave forms it is clear that harmonic distortion is reduced after connecting compensator. Compared to PI controller gives better harmonic compensation.

The system studied has also been modelled using simulink and performance of PI controller is analysed. A diode rectifier with R-L load is taken as non-linear load. The THD of the load current is 28.95%.

Table1 gives the comparison of the magnitudes of the harmonic currents present in the source current before and after compensation.

TABLE I
COMPARISON OF MAGNITUDES OF CURRENT HARMONICS

Order of harmonics	Before % of Total RMS THD=28.95%	After % of Total RMS THD=3.77%
1	96.7	99.8
5	21.6	3.6
7	9.4	0.7
11	7.3	1.6
13	4.4	0.7
17	3.4	1.7
19	2.2	0.7

Table.2 gives the comparison of the magnitudes of the harmonics present in the voltage at the point of common coupling (PCC) before and after compensation.

TABLE III
COMPARISON OF MAGNITUDES OF VOLTAGE HARMONICS

Order of harmonics	Before % of Total RMS THD=5.61%	After % of Total RMS THD=3.1%
1	99.9	100
5	3.4	0.8
7	2.4	0.9
11	2.0	0.6
13	1.1	0.1
17	1.3	0
19	0	0

Table. 3 gives the comparison of the magnitudes of the harmonic currents present in the source current before and after compensation.

TABLE IIIII
COMPARISON OF MAGNITUDES OF CURRENT HARMONICS

Order of harmonics	Before % of Total RMS THD=24.56%	After % of Total RMS THD=3.22%
1	97.11	99.1
5	19.51	4.6
7	12.9	2.7
11	6.12	1.6
13	6.1	0.7
17	4.3	1.9
19	2.3	0.7

Table. 4 gives the comparison of the magnitudes of the harmonics present in the voltage at the point of common coupling (PCC) before and after compensation.

TABLE IIV
COMPARISON OF MAGNITUDES OF VOLTAGE HARMONICS

Order of harmonics	Before % of Total RMS THD=7.62%	After % of Total RMS THD=3.1%
1	98.9	99.7
5	4.6	1.8
7	3.4	0.9
11	2.6	0.6
13	1.9	0.1
17	1.3	0
19	0	0

IV. CONCLUSIONS

A SAPF has been investigated for power quality improvement. Various simulations are carried out to analyse the performance of the system. PI controller based SAPF is implemented for harmonic and reactive power compensation of the non-linear load. A program has been developed to simulate the PI controller based SAPF in MATLAB. It is found from simulation results that SAPF improves power quality of the power system by eliminating harmonics and reactive current of the load current, which makes the load current sinusoidal and in phase with the source voltage. The performance of PI controllers has been studied and compared.

A model has been developed in MATLAB SIMULINK and simulated to verify the results. The PI controller based SAPF has a comparable performance to the Without PI controller in steady state.

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