Application of Generalized Instantaneous Reactive Power Theory for Three-Phase Four-Wire System

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***Abstract*—in this paper a concept of generalized theory of instantaneous imaginary power is proposed for a three-phase four-wire system. Unlike instantaneous reactive power theory in which a complex mathematical transformation is used for controlling action of shunt active power filters. The proposed control strategy is simple and further to reduced its complexity the line current vector is decomposed into two orthogonal components without mathematical transformations. The developed control strategy has been tested for three-phase four-wire system feeding non-linear load. The obtained results show satisfactory performance for a number of actual system conditions such as load changing of non-linear load. The THD (total harmonic distortion) on supply side with shunt active power filter complies with IEEE harmonic standard, which validates the satisfactory implementation of proposed theory.**

***Index Terms*—Shunt Active Power Filter (APF), Generalized instantaneous reactive power theory, poly-phase system.**

I. INTRODUCTION

With the excessive usage of power electronics devices in the industrial applications produce undesired variations in the current known as harmonics. These harmonics produces very severe problems and it does also affect the power quality. A number of theories have been proposed for improvement of power quality in case of nonlinear loads by compensating reactive power of load[1]-[2].

Among them, Akagi et al. [3]-[4] attempted by proposing instantaneous reactive power theory to provide compensation for nonlinear three-phase loads. In this theory, a mathematical transformation, known as α-β transformation is used for compensating the reactive power and harmonics. It has been assigned mathematical transformation instantaneous space vectors that are submitted to an orthogonal transformation. However, this theory is not providing correct compensation for poly-phase systems having phases more than three [5].

In an analogous way, Ferrero et al. [6] used the same transformation of the co-ordinates as Agaki, referring to it as Park's transformation. The theory proposed by Ferrero is valid for poly-phase systems and it has a new transformation matrix. The zero sequence components are treated apart, separate from the overall expansion.

In this paper, a generalized theory of instantaneous reactive power for three-phase power systems is proposed with a three-phase four-wire nonlinear load. The generalized theory is valid for sinusoidal or non-sinusoidal, balanced or unbalanced three-phase systems, with or without zero- sequence currents and/or voltages [7].

II. GENERALIZED THEORY OF INSTANTANEOUS REACTIVE FOR MULTIPHASE POWER SYSTEM

A schematic diagram of a three-phase four-wire power system is shown in Fig. 1.

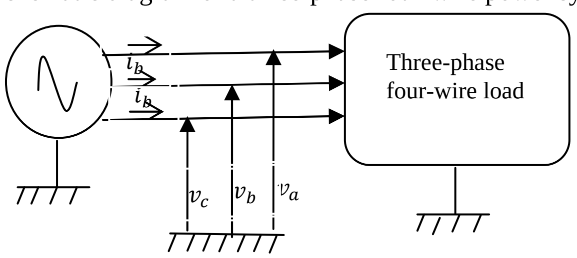

Fig-1 three-phase four wire system

Instantaneous voltages (v_a, v_b, v_c) and instantaneous current (i_a, i_b, i_c) are expressed as instantaneous space vectors, v and i, [8] as,

$$V=\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix},\ i=\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

Fig. 2 shows the three-phase coordinates which are mutually orthogonal, representing phase 'a,' phase 'b,' and phase 'c,' respectively. The instantaneous active power of a three-phase circuit, p, can be given by

$p = v.i$ (2)

Where ".'' denotes the dot product, or scalar product of vectors. Equation (2) can also be rewritten as

$$p = v_a i_a + v_b i_b + v_c i_c$$

The instantaneous reactive power is expressed as,

$q = \|q\| = \|v \times i\|$ (3)

Where "×" denotes the cross product of vectors or vector product.

Where ''‖ ‖'' denotes the magnitude or the length of a vector. Equations (3) can be rewritten as

$$q = \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} v_b & v_c \\ i_b & i_c \end{bmatrix} \\ \begin{bmatrix} v_c & v_a \\ i_c & i_a \end{bmatrix} \\ \begin{bmatrix} v_a & v_b \\ i_a & i_b \end{bmatrix} \end{bmatrix} \quad (4)$$

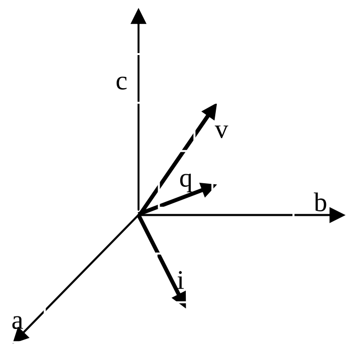

Fig. 2. Representation of v and i in three-phase coordinate system

and q is expressed as,

$q = \|q\| = \sqrt{{q_a}^2 + {q_b}^2 + q_c^2}$ (5)

In turn, the instantaneous active current vector 'i_p', the instantaneous reactive current 'i_q', the instantaneous apparent power's', and the instantaneous power factor 'λ', are defined as

$$i_p = \begin{bmatrix} i_{ap} \\ i_{bp} \\ i_{cp} \end{bmatrix} \stackrel{\text{def}}{=} \frac{p}{v.v} v \quad (6)$$

$$i_q = \begin{bmatrix} i_{aq} \\ i_{bq} \\ i_{cq} \end{bmatrix} \stackrel{\text{def}}{=} \frac{q \times v}{v.v} \quad (7)$$

$s \stackrel{\text{def}}{=} vi$, and

$\lambda \stackrel{\text{def}}{=} \frac{p}{s}$,

Where $v = \|v\| = \sqrt{{v_a}^2 + {v_b}^2 + v_c^2}$ and $i = \|i\| = \sqrt{{i_a}^2 + {i_b}^2 + i_c^2}$ are the instantaneous magnitudes or norms of the three-phase voltage and current, respectively.[9]

III. A Practical Example

A simulation model of three-phase four-wire is developed for the testing and verification of "Generalized Instantaneous Reactive Power Theory". The system uses 381V phase-to phase voltage, 60 Hz three-phase power supply which is connected to a three-phase four-wire nonlinear load. As shown in figure 3, PWM voltage source converter (VSC) is connected for the compensation. This converter is connected in parallel with the load. The control circuit of the compensator is shown in figure 4 and it uses computational circuits for the calculation of instantaneous reactive power of the load, q_L, and the instantaneous reactive components of the load currents, i_{Lq},. Their relations of instantaneous reactive power and reactive component of load current can be expressed as

$q_L = v_s \times i_L$ (8)

$$i_{Lq} = \frac{q_L + v_s}{v_s . v_s} \tag{9}$$

The reference compensation current uses instantaneous reactive components of the load currents as the command current, i_c^* i.e.,

$$i_c^* = i_{Lq} \tag{10}$$

For a three-phase four-wire power system, the source current vector, i_s, the source voltage vector, v_s, the load current vector, i_L, and the compensator current vector, i_c, can be expressed as

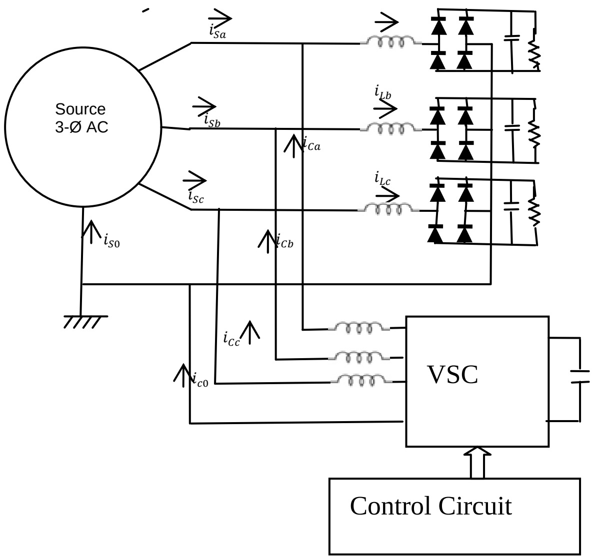

Fig.3- System Configuration

$$v_s = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix}, i_s = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}, i_L = \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix},$$

For the compensation of neutral current compensation control circuit can be design by sum of the three-phase currents of the source, the load and the compensator, the reactive power compensator output current vector, i_c, is controlled by a PWM converter.

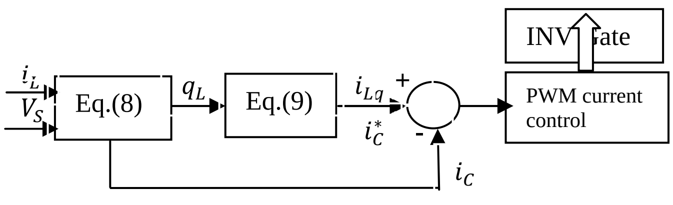

Fig.4-Control system diagram

IV. Simulation Results

The simulations results of shunt active power filter are illustrated using quantities of both load and source side. The fig.5 shows that Matlab/Simulink Model of complete system, it has the three major sections the first one is APF section, second one is nonlinear load section and the last one is control system model section. Fig.6- represents shunt APF model which contains three filter inductors, each phase contain one filter inductor and a dc bus capacitor is connected in dc side. The APF components specifications are mention in table I. Fig.7- represents the model of control circuit of APF, in this model used equation numbers (8) and (9) for the calculation of compensating current and a PWM generator is used for generating thyristor gate pulses. Fig.8- shows the load model in it three full-bridge single-phase rectifiers are used for making three-phase four-wire nonlinear load. The resistances $R_{a1}, R_{b1} and\ R_{c1}$ are connected in star and resistances $R_{a2}, R_{b2} and\ R_{c2}$ are connected parallel with $R_{a1}, R_{b1} and\ R_{c1}$ respectively through the breaker. The connection is shown in fig.8 in beginning the breakers are open and at 0.3 second the breaker are closed. The current waveform obtain in load side is shown in fig.9 load is changed at 0.3 second. The load components specifications are mention in table-II. The FFT analysis in study state has been done for the calculation of THD (Total Harmonic Distortion). To find out THD before load change FFT analysis of load current for 0.1second to 0.3 second for 12 cycle the THD is obtain 41.12% as shown in fig.19 and after load change the FFT analysis done for 0.3-0.4seconds for six cycle THD become 25.23% as shown in fig.20 for phase-a. The compensating current waveform for phase 'a' is shown in fig.10. The source side current waveform is shown in fig.11. This waveform is nearly about sinusoidal in nature and the THD before load change 4.82% as shown in fig.21 and after load change 3.47% as shown in fig.21. The Fig.12 represents the charging and discharging of capacitor for 0 to 0.4 second. Fig.13 represents neutral current before compensation; it has high amplitude and high frequency. Fig.14 is representing the compensating neutral current waveform which has same frequency and nearly about same amplitude of uncompensated neutral current. The fig.15 shows the neutral current after compensation this current ideally zero. Fig.16 depicts the three-phase load side current waveform which is non-sinusoidal in nature and fig.17 shows the three-phase source side current waveform which is sinusoidal in nature and having higher order of harmonics. Fig.18 shows the voltage and current waveform in phase-a. In this figure the current and voltage waveform are almost in same phase hence power factor is improved by using this active power filter.

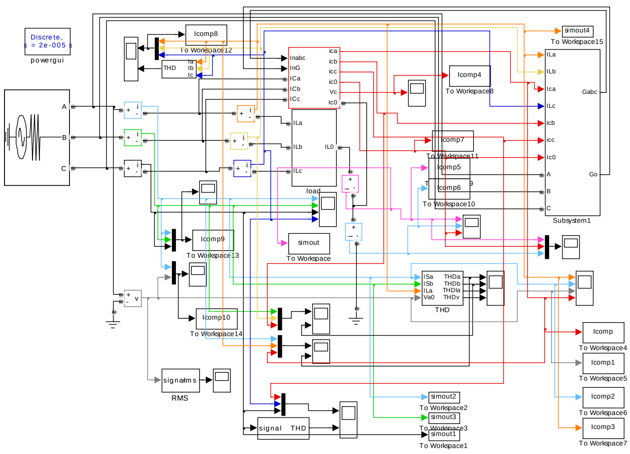

FIG.5- MATLAB SIMULINK MODEL OF COMPLETE SYSTEM

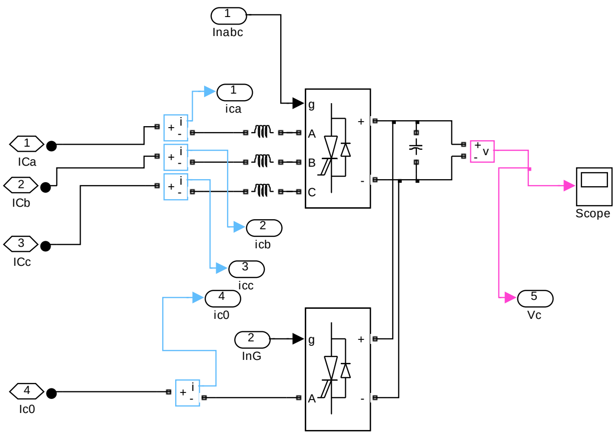

Fig6- Matlab Simulink model of APF

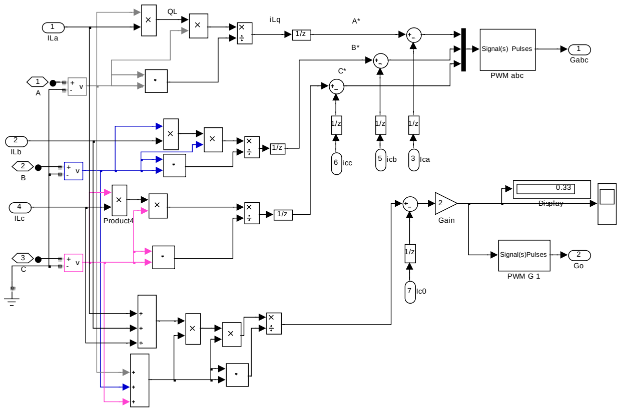

Fig7- Matlab model of control circuit

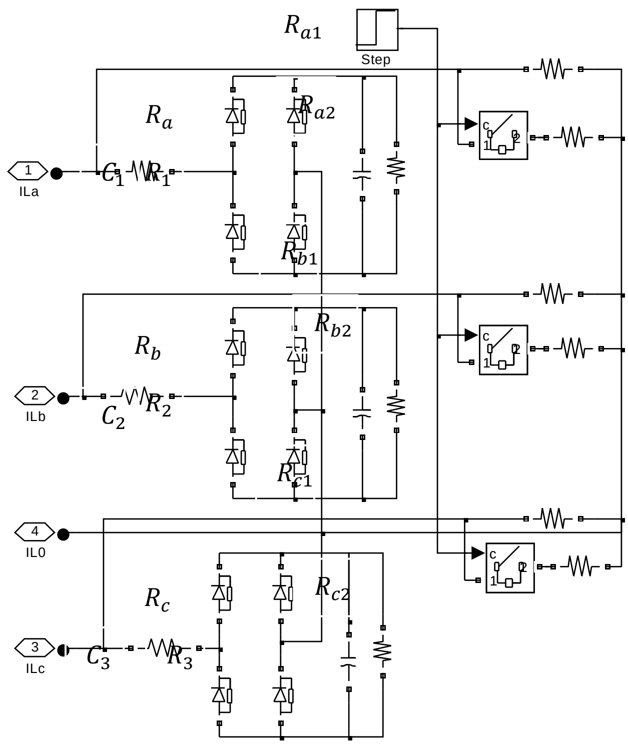

Fig.8- three-phase four-wire load model

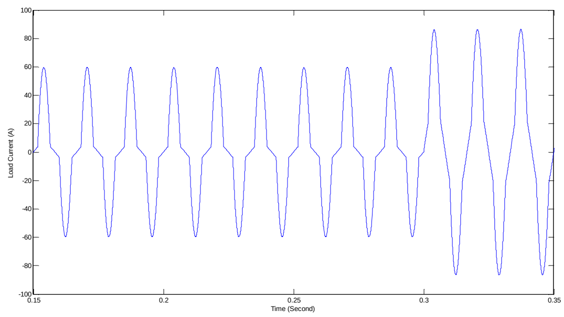

Fig.9-Load side Current Waveform

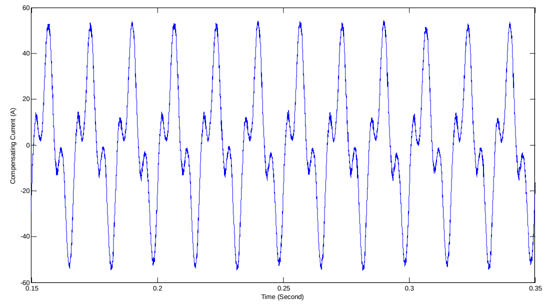

Fig.10-Compensating current waveform

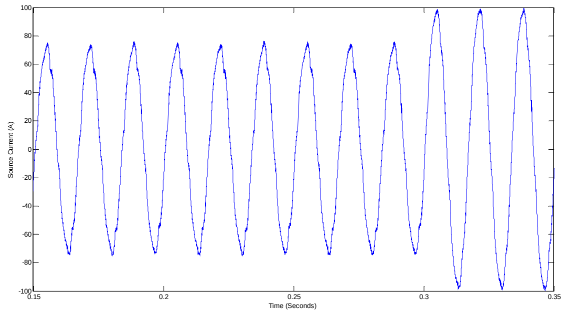

Fig.11-Source-side current waveform

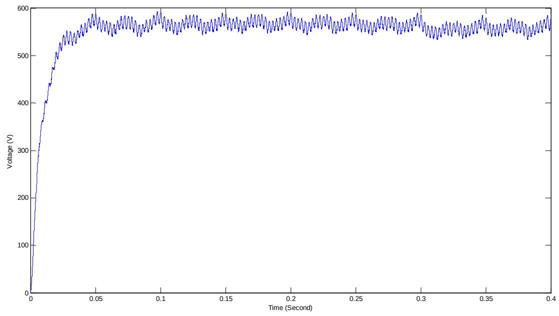

Fig.12-Capacitor charging and discharging voltage waveform

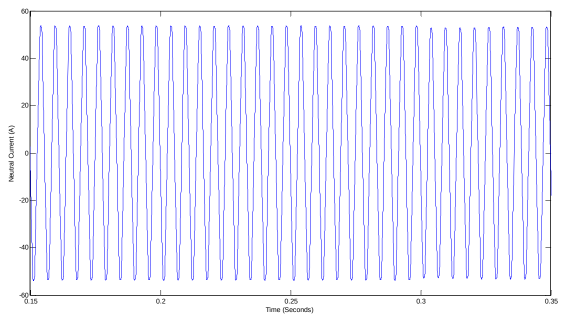

Fig.13-Neutral current waveform before compensation

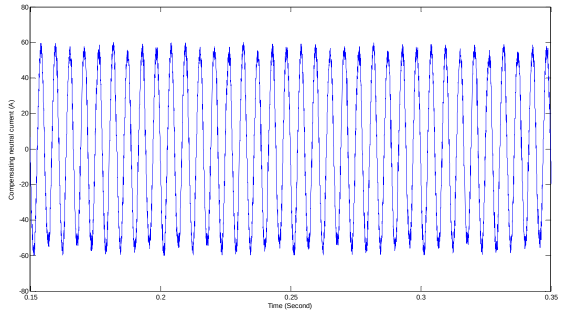

Fig.14-Compensating neutral current waveform

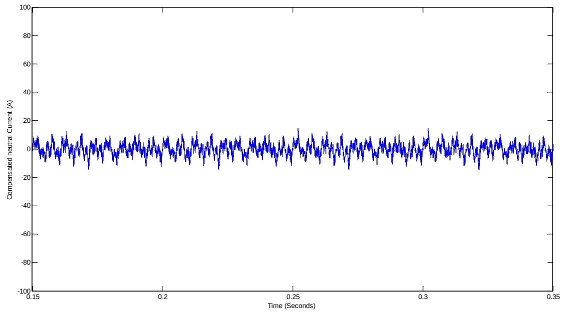

Fig.15-Neutral current after compensation

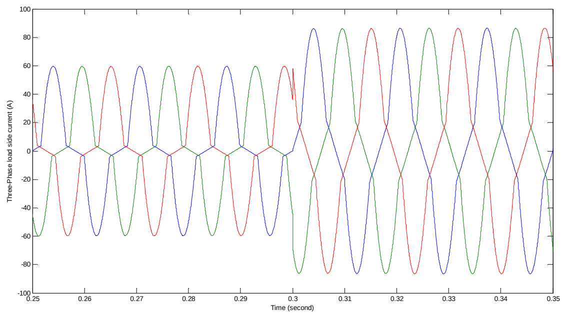

Fig.16-Three-Phase load side current waveform

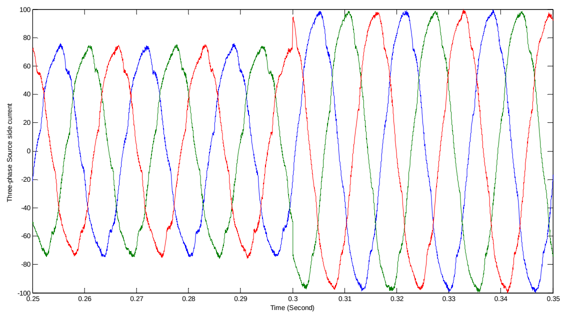

Fig.17-Three-phase Source side current waveform

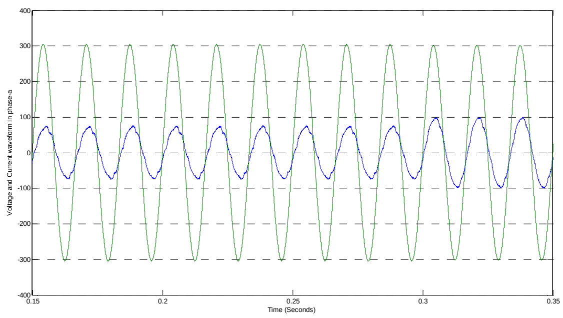

Fig.18-Voltage and Current waveform at phase-a

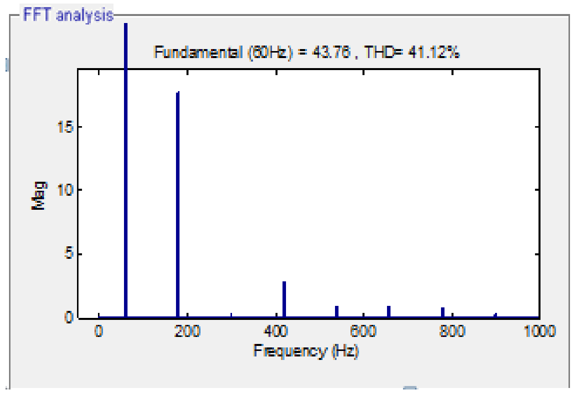

Fig.19-Load Current THD before load change

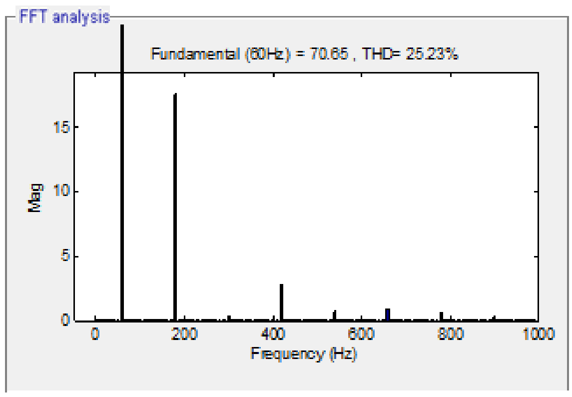

Fig.20-Load current THD after load change

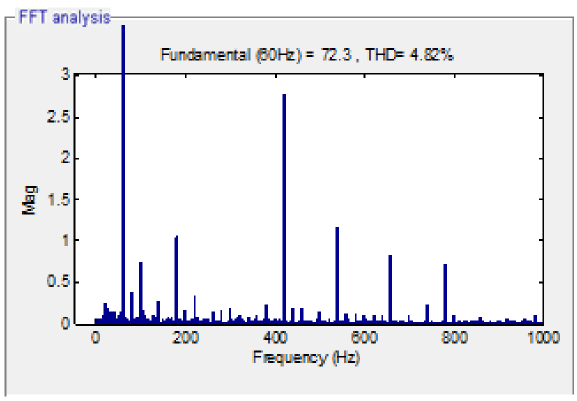

Fig.21-Source current THD before load change

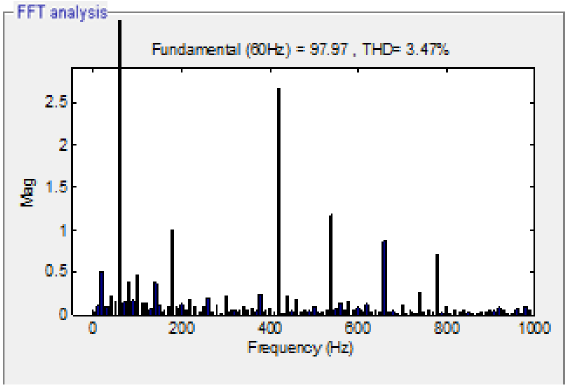

Fig.22-Source current THD after load change

TABLE I: TECHNICAL SPECIFICATIONS OF APF

S.No	APF Specification		
	Component	***Quantity***	***Rating***
1	Filter Inductor	3	6.75mH
2	DC bus Capacitor	1	500µF

TABLE II: TECHNICAL SPECIFICATIONS OF LOAD

S.No	Load Specification		
	Component	***Quantity***	***Rating for each***
1	Capacitor	3	5000 µF
2	Resistance (R_1, R_2, R_3)	3	2.2Ω
	R_{a1}, R_{b1}, R_{c1}	3	50Ω
	R_{a2}, R_{b2}, R_{c2}	3	11Ω

V. CONCLUSION

The modeling and analysis of generalized instantaneous reactive power theory feeding non-linear load has been carried out on three-phase four-wire system. The complete system model has been developed in Matlab/simulink. The proposed control strategy has less complexity and does not need any mathematical transformation. The voltage source converter using this control strategy facilitates enhancement of power quality through reactive power compensation and harmonic suppression for nonlinear load. The THD of system quantities with compensator comply with the IEEE 519 standard, which thereby validate the satisfactory system performance.

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