Simplified Control Algorithm Based on IRP Theory for Three Phase Shunt Active Power Filter

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Abstract. In this paper a concept of instantaneous imaginary power (IRP) theory has been proposed for the load compensation of three phase balanced system. In this theory the total power is separated into two components, namely imaginary and real instantaneous power. The instantaneous imaginary power has been considered as zero and dc component of the real power is therefore selected as compensation power reference for compensation of harmonics and reactive power. In the design of active power filter (APF) three current, two ac voltage and one DC link voltage sensors have been used. By using this approach the overall system design becomes easier to accomplish and the implementation cost has been reduced. The model is prepared in MATLAB/SIMULINK and the system with the proposed theory has been tested for non-linear loads. The harmonic analysis of supply side quantities comply with the IEEE 519-1992 recommendations of harmonic standard limits, which validate the implementation of proposed shunt active power theory.

Keywords: Shunt Active Power Filter (APF), instantaneous reactive power theory (IRP), power quality improvement, balance three phase nonlinear system.

1 Introduction

In this present era, the use of power electronics devices has been increased in industrial level of application (i.e. switched-mode power supplies, uninterruptible power supply systems, inverters & high-frequency lighting etc.). These loads are nonlinear in nature. Due to these types of loads the current waveforms are non-sinusoidal in nature and contain high total harmonic distortion (THD). The harmonic distortion of current is representing as distortion factor of current waveform with respect to pure sine-wave [1]. Therefore a number of harmonics are injected into supply system. It creates more severe problem in power system network [2]. Traditionally, passive LC filters have been used to eliminate these harmonics in current. However, these passive LC filters are load dependent, fixed and bulky. They can also cause resonance problems to the system [3]. In order to solve these problems, active power filters (APFs) have been developed and used to mitigate these problems.

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Several control algorithms have been proposed for the controlling of shunt active power filter [4]-[5]. In which most of control circuits are complicated and not easier to implement.

In this paper, the simplified instantaneous reactive power theory has been proposed which uses three current sensing devices, two voltage sensing devices and a DC link voltage measurement device for the controlling of APF. This proposed method is simple and total implementation cost is reduced.

1.1 Instantaneous Reactive Power Theory

Instantaneous reactive power theory deals with instantaneous voltages and currents in three-phase circuits mathematically [6]-[7]. Instantaneous voltage space-vectors v_a , v_b and v_c are transformed into 0-α-β coordinate as follows:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

Likewise, the instantaneous current space-vectors i_a, i_b and i_c are transformed into 0-α-β coordinate.

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

In case of balance system, zero sequence components are absent in the system. Hence the zero-phase sequence components are excluding in three-phase voltages and currents [8]. The simplified form of (1) and (2) may represent as for a balance three phase system

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{\sqrt{3}}{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{3}}{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4}$$

Fig.1 represents the transformation of three phase a-b-c coordinates to two phase α-β coordinates. The a-b-c axes are apart from each other by 2π/3. The instantaneous space vectors, v_a and i_a are placed on a-axis, and their amplitude and (+,-) direction vary with the passage of time. In the same way v_b and i_b are on the b-axis, and v_c and i_c are on the c-axis. Where the α and β, axes are the orthogonal coordinates [9].

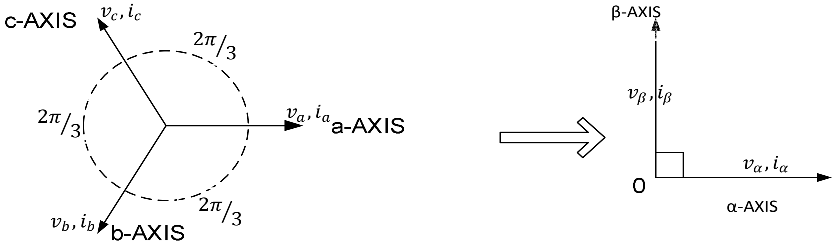

Fig. 1. α-β coordinate transformation

The conventional instantaneous real power on the three-phase circuit can be defined into α-β form as follows;

$$p = v_\alpha . i_\alpha + v_\beta . i_\beta \tag{5}$$

The instantaneous imaginary power space vector ' q ', can be defined by

$$q = v_\alpha \times i_\beta + v_\beta \times i_\alpha \tag{7}$$

This space vector is the imaginary axis vector and is perpendicular to the real plane on the α-β coordinates, In IRP theory the instantaneous real and reactive power can be expressed as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$

Equation (5) shows that the instantaneous power for three-phase system. The instantaneous real power ‘ p ’, will contribute to the instantaneous value of total energy flowing per time unit from source to load or vice versa while the instantaneous reactive power ' q ' represents energy that is being exchanged between the phases of the systems. Rearranging (8) for the calculation of α-β reference current as shown below [10]

$$i^*_{\alpha\beta} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{9}$$

2 The Proposed Method

The control system block diagram of the proposed method for the three phase shunt APF is shown in Fig. 2. It is clear from Fig. 2, in this APF control circuit model only source voltage and current signals are utilized for the calculation of reference current. The hysteresis band current controller generated PWM (pulse width modulation) signal by the comparing between the reference current and the real source current. These PWM signal used to provide the gate pulses of voltage source inverter (VSI).

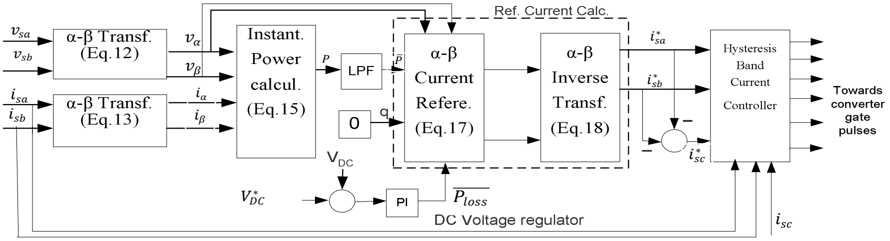

Fig. 2. Control block diagram of the proposed method

In this study, the shunt APF is connected to a three-phase three-wire system, which has sinusoidal and balanced source voltages and a three phase balanced rectifier load connected. In balance condition the sums of the instantaneous source voltages and source currents for a three phase system are zero. Measuring of two source voltages and currents are adequate for the reference current calculations. [11][12] Therefore, the (3) and (4) may represent as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \sqrt{3/2} & 0 \\ 1/\sqrt{2} & \sqrt{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sqrt{3/2} & 0 \\ 1/\sqrt{2} & \sqrt{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} \tag{11}$$

For making the simplified form of transformation (10) and (11) are multiplied with a factor of $\sqrt{2/3}$, and the simplified Transformations are obtained as in the form of (12) and (13).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/\sqrt{3} & 2/\sqrt{3} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/\sqrt{3} & 2/\sqrt{3} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} \tag{13}$$

The instantaneous real ‘ p ’and reactive power ‘ q ’ calculated as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{14}$$

In this proposed method, calculation of the instantaneous imaginary power 'q' is not required which is used in conventional method, since it is no need to draw 'q' from the source. Only calculation of the instantaneous real power 'p' is adequate as shown in (15). Therefore, the proposed control method has been simplified in the calculations of reference currents.

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{15}$$

The ac and dc values of instantaneous real power can be expressed as:

$$p = \overline{p} + \tilde{p} \tag{16}$$

Where '$\overline{p}$' is the dc component of instantaneous real power and '$\tilde{p}$' is the ac component of instantaneous real power.

In this proposed control algorithm, the instantaneous imaginary power is taken to zero (q=0) and a dc component of the real power'$\overline{p}$' is therefore selected as compensation power reference for compensation of harmonics and reactive power. The compensation current references in α-β coordinates are calculated by (15). In order to get the DC part of the instantaneous active power'$\overline{p}$' the signals need to be filtered using 1st order low pass filter with a cut-off frequency at 50 Hz. The low-pass filter will remove the high frequency component and give the fundamental part [10]. The average real power '$\overline{p_{loss}}$' is added to the dc component of the instantaneous real power '$\overline{p}$' to cover the voltage source inverter (VSI) losses of the shunt APF.

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \overline{p} + \overline{p_{loss}} \\ 0 \end{bmatrix} \tag{17}$$

In this study, the compensation current references in the α-β coordinates are transformed back into the a-b-c coordinates by the use of inverse simplified α-β Transformation as given by

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \tag{18}$$

The current reference of phase 'c' is calculated by

$$i_{sc}^* = -(i_{sa}^* + i_{sb}^*) \tag{19}$$

These reference currents utilized for the generation of APF switching pulses by the comparing of the reference current ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) and the actual source currents

(i_{sa}, i_{sb}, i_{sc}).By comparing these currents hysteresis-band current controller generate PWM pulses for controlling of VSI. The switching logics are formulated as follows:

If $i_{sa} > (i_{sa}^{*} + HB)$ higher switch is ON and lower switch is OFF for leg “A” (QA = 0).
If $i_{sa} < (i_{sa}^{*} - HB)$ higher switch is OFF and lower switch is ON for leg “A” (QA=1).

Similar For legs ‘B’ and ‘C’ the switching pulses obtained. Where HB is denoting hysteresis bandwidth and QA is the switching function [11]-[13].

Dc-link voltage regulator is used for a good compensation. The error is found by the comparing of actual dc-link capacitor voltage and reference value. This error is processed in a PI controller which generates additional average real power ‘$\overline{p_{loss}}$’.

3 Result and Discussion

This simulation model has been made for three phase 450V (phase to phase rms voltage), 50 Hz supply system and tested on MATLAB/SIMULINK. The complete simulation model of the proposed theory for the three phase system has been shown in fig.3 it contains three main sections such as load, control circuit, APF. The load circuit is given in fig.4, and the load component is given in the table-1. The three phase nonlinear load is made by using three phase diode bridge rectifier. In beginning only rectifier-I is operated and after 0.2 second rectifier-II is operated and rectifier-I eliminate in system. For opening and closing of the rectifier using three phase breaker and this three phase breaker is controlled by external step signal. In this load model the step signal is set at 0.2seconds. Fig.5 represent’s the APF model, in this model VSI is connected with star connected 3 filter capacitors and 3 series inductors The load side current waveform is shown in fig6. The load is changed at 0.2 second as discussed above in the load model description, before load changes the FFT analysis has done in steady state for 5 cycles at 0.1 second is 39.28% and after load change the FFT analysis has been perform for steady state 5 cycles at 0.25 second THD obtained 20.47% as shown in fig.11. The compensating current waveform is shown in fig7. Fig8. shows the source current waveform its nearly about sinusoidal after load change and before load changing condition. Before load changes THD obtained 4.98% and after load change the THD became 3.46% as shown in fig.12. Fig.9 shows that the capacitor charging and discharging with very high frequency. Fig10. represent’s voltage and current waveform of phase-a it is clear from this waveform that voltage and current are almost in the same phase. Hence power factor is improved and the harmonic analysis of supply side quantities comply with the IEEE 519-1992 recommendations of harmonic standard limits [14].

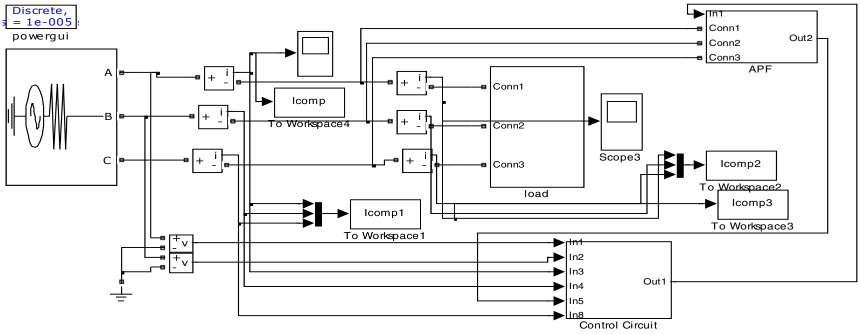

Fig. 3. Complete simulation model

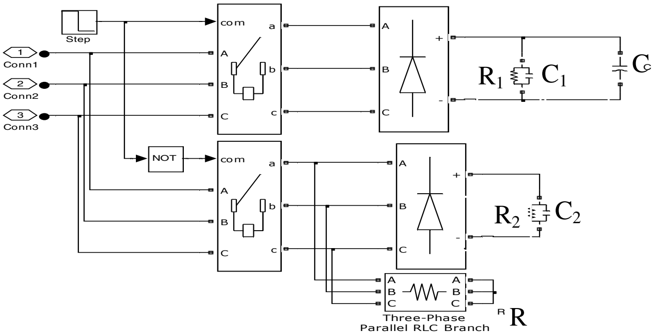

Fig. 4. Load model

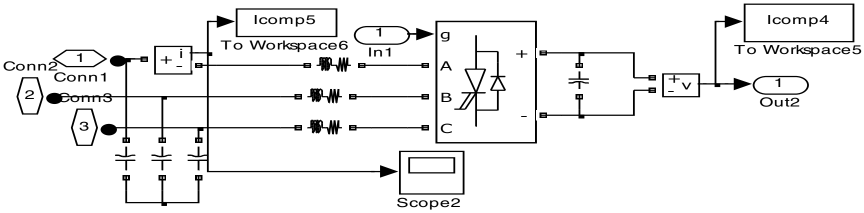

Fig. 5. APF model

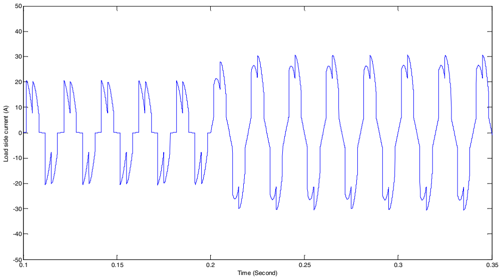

Fig. 6. Load side current

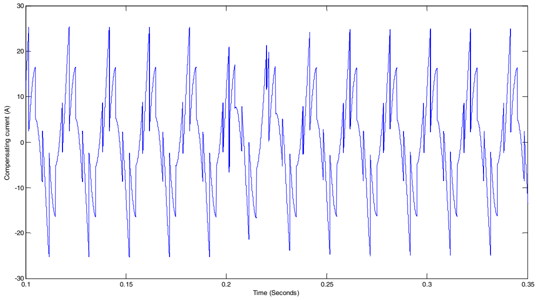

Fig. 7. Compensating current

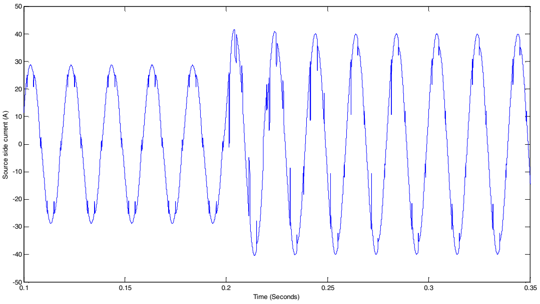

Fig. 8. Source side current

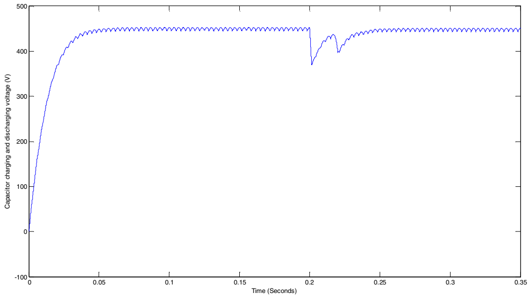

Fig. 9. Capacitor charging and discharging voltage

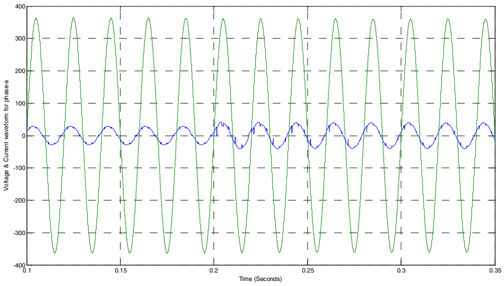

Fig. 10. Voltage & Current waveform for phase-a

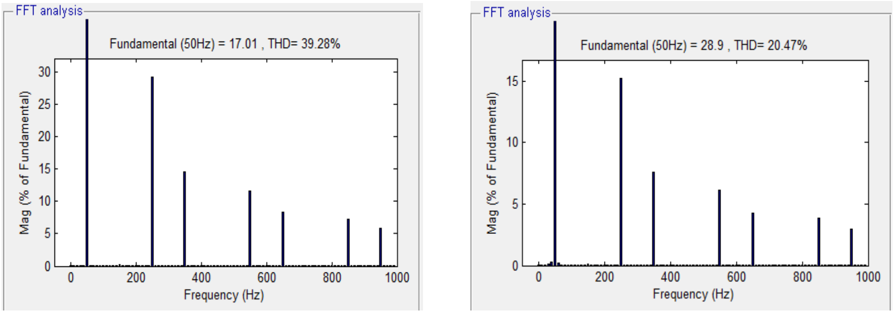

Fig. 11. FFT analysis of THD for load side current before load change 39.28% and after load change 20.47%

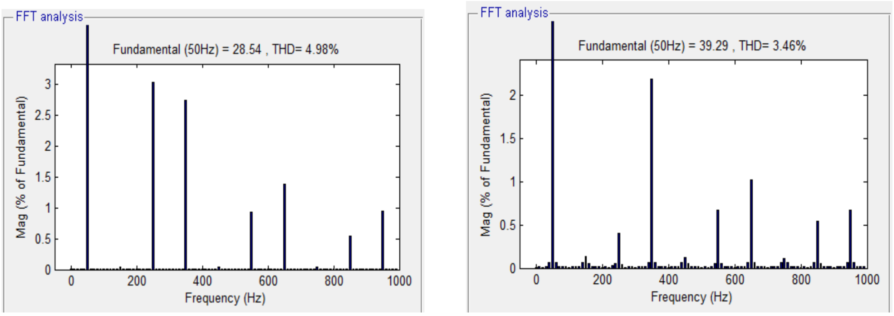

Fig. 12. FFT analysis of THD for supply side current before load change 4.98% and after load change 3.46%

Table 1. Technical Specification of Load

Component	*Quantity*	*Rating for each*
R_1	1	39Ω
C_1	1	46μF
C	1	21μF
R_2	1	39Ω
C_2	1	46μF
R	1	30Ω

R_1,C_1 and C used for rectifier-1, R_2 and C_2 are used for rectifier-2 and R represent's resistance of three phase parallel resistive branch.

4 Conclusion

The modeling and analysis of simplified IRP theory feeding non-linear load has been carried out on three-phase system. The complete system model has been developed in Matlab/simulink. The proposed control strategy has less complexity. 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 there by validate the satisfactory system performance.

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