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Simulation of Hybrid Active Power Filter with Selective Harmonic Suppression

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Abstract

Active filters are considered as credible solutions to the growing current harmonics in the grid. Shunt Hybrid Active Power Filter when implemented suffers from different transportation delay for different harmonics currents. The method used to extract the harmonics current, plays an important role in the performance of the active filter. Compensating a selected number of harmonics offers several advantages such as optimization of rating, reduced bandwidth of controller, and reduced switching frequency. Here, a shunt hybrid active power filter is implemented with a time-domain selective harmonic detection method, by which all the harmonics of interest are suppressed. A method is devised to allow setting transportation delay compensation, individually for each harmonics, which is important for Shunt Hybrid Active Power Filter. A three phase shunt hybrid active filter is simulated using PSIM simulation package to validate the selective harmonic detection method. Simulation results verifying the performance of the method and operation of shunt hybrid active filter are also given.

Key Words-- Digital Signal Processor (DSP), Power Quality (PQ), Pulse Width Modulation (PWM), Shunt Hybrid Active Filter, Unit vector, Voltage Source Converter (VSC), Synchronous reference frame, Adaptive Notch Filter (ANF).

I. INTRODUCTION

THE continuously growing use of non-linear loads such as adjustable speed drives, switched mode power supply driven electronics equipments, energy efficient lighting introduces huge Power Quality (PQ) issues[1]. The traditional solutions to such PQ issues were based on tuned filters. Tuned filters cannot adapt to the varying harmonics spectrum, which is often the reality. They are also susceptible to sink the harmonics injected by neighbouring loads. Such passive power filters (PPF) may also cause parallel or series resonance with the other elements of the grid, giving rise to amplification of certain harmonics. Various Active Filter configurations have been reported [2] as alternative solutions which can overcome these shortcomings of the passive filters. The shunt Active Power Filter (APF) was proposed [3] and the same is recognized as a cost effective solution for harmonic compensation in low and medium power applications. Shunt APFs pose many practical limitations in high power applications due to their large volt ampere rating, high Electro-Magnetic Interference (EMI) and high power losses [4]. Hybrid Active Power Filters (HAPF) has been proposed [5] as a PQ solution in high power applications which can overcome the limitations of APFs. HAPFs are combinations of both passive and active power filters. Series Hybrid Active Power Filter [6] proposed in 1988 is less popular in the industrial applications due to its inherent drawbacks such as its full load current rating, lack of isolation and difficulty in maintenance, since it is connected in series to the circuit. Whereas, Shunt Hybrid Active Power Filter [7]-[8] can overcome these shortcomings, which is realized by connecting three-phase PWM voltage-source converter in series to the passive filter branch as shown in Fig. 1. This topology also allows connecting of converter in series with already installed passive power filter which will in turn improve its compensation characteristics significantly. Hence, shunt HAPF offer a practically viable and cost effective topology in high power applications.

The method used to obtain the harmonic current references has a high impact on the performances of all active filters [9]. The harmonic detection method can be broadly classified either as time-domain or frequency-domain. The time-domain method offers increased speed and calls for less calculation compared to frequency-domain methods. Many approaches have been reported to determine the harmonic current reference for APF. Common methods used for harmonic detection in time-domain are Notch Filtering [10], Instantaneous Reactive Power Theory (IRPT) [11], Modified IRPT [12], Synchronous Reference Frame Theory (SRF) [13], Modified SRF Theory [14], Synchronous individual harmonic d-q frame [15] and flux based controllers [16]. Frequency domain techniques are based on the Fourier analysis of the load current signals. Different methods reported are, Discrete Fourier Transform (DFT) [17], Fast Fourier Transforms [18] and Recurring Discrete Fourier Transform (RDFT) [19]. Few other methods are also reported which includes Synthetic Sinusoid [20] Sinusoidal subtraction [21] and Enslin’s Correlation Techniques [22]. For time-varying harmonics applications, methods such as Wavelet filtering [23], Kalman filters [24] are used. In last several years, the interest on investigating various techniques for compensation of selected current harmonics has significantly increased [25]-[28]. Complex Notch Filter (CNF) concepts are employed for extraction of current and control of distributed generators connected to the grid[29]. In [30] a technique for adaptive estimation of the frequency of unbalanced three-phase power systems using complex coefficient first-order notch filters is presented.

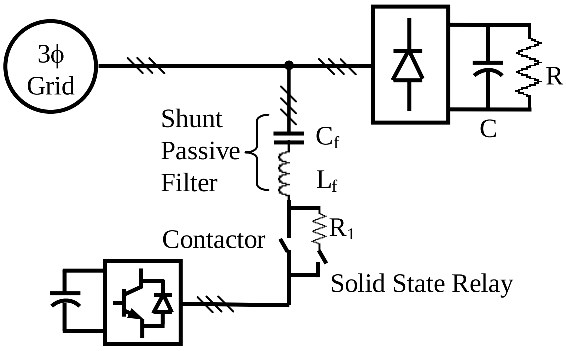


Fig. 1. Shunt Hybrid Active Power Filter.

In selective harmonics method the active filter is not forced to eliminate all the distorting components, but only the more significant ones. This feature ensures good harmonic compensation performance with reduced power converter rating, reduced bandwidth and lower switching frequency.

This paper presents Shunt Hybrid Active Power Filter with a control scheme using a simple selective harmonic detection method, which can be implemented in digital platform. The simulation results of the scheme are presented. This scheme uses Adaptive Notch Filters to extract the dominant harmonics present in the load current, in conjunction with synchronous reference technique. The transportation delay due to Sensors, ADC sampling and DSP program cycle can be mitigated using appropriate multiplication factors which are calculated by trigonometric equations, for each harmonics separately. This is very important for the Shunt Hybrid Active Power Filter, because effect of the transportation delay will be different when the frequency of interest is above, below or equal to the resonant frequency of the passive filter.

A transformer-less, 415V, 50Hz, 50kVA shunt HAPF is designed and the same is used to compensate the harmonics current of a three-phase diode rectifier non-linear load.

This paper is organized as follows. Section II explains Shunt Hybrid Active Filter configuration. Section III details the selective harmonic detection method used. Section IV explains control scheme used to control Shunt HAPF and section V details the circuit configuration used for simulation. Section VI gives simulation results.

II. Shunt Hybrid Active Power Filter

The shunt HAPF topology used in this paper, shown in Fig. 1, is implemented with a three-phase PWM voltage-source converter connected in series to the passive filter built using inductor, L_f, and capacitor, C_f. The filter capacitor, C_f, is designed to offer high impedance to the line frequency and drops most of the grid voltage across it. Hence effectively no or negligible fundamental voltage appears across the a.c. terminals of the

APF used in the shunt HAPF. This reduces the d.c. voltage requirement to a much lower level and allows it to connect to grid directly without transformer. This in turn reduces the VA rating of APF and makes shunt HAPF topology suitable for high power applications. It may be noted that since grid voltage appears across the LC filter, it will force a fundamental reactive current to flow into it.

To compensate the harmonics present in the grid current the scheme will force all the harmonic currents present in the load current to flow into shunt HAPF, whereas it restricts the sinking of other harmonic currents present in the grid. This improves the filtering performance of the passive filter, and prevent from overloading. Moreover, compensation characteristics of already installed PPF can also be significantly improved by connecting an APF in series with PPF, giving more flexibility and adding insensitivity to grid parameter variations.

Following are the practical operational sequence of the Shunt HAPF (SHAPF):

Fig.1 shows the one line diagram of the SHAPF connected to a distribution feeder. The non-linear load is represented by a diode bridge connected to a d.c. capacitor C and load resistor R. SHAPF consists of an L-C series filter L_f, C_f tuned for a dominant lower harmonics frequency, connected to the 3 phase IGBT based PWM converter through a combination of contactor, Resistor R_1 and solid state relay SSR.

Before starting the SHAPF, a.c. capacitor, C_f, should be pre-charged to prevent over-currents during startup. After powering the control supply the start action is initiated. Now, the three upper IGBTs of the converter are turned on while the bottom three IGBTs are turned off. Then the SSR will be made on bringing the resistance, R_1 of value 50Ω, into the power circuit, forming wye-connected LCR filter. The resistor R_1 prevents over-currents from flowing into the shunt HAPF at startup. After a time of 400ms, the contactor will be turned on, bypassing the resistor. After this, the PWM signal will be provided to IGBTs based on the modulating signals generated by controller.

III. CONTROLLER FOR HARMONIC SUPPRESSION

In the proposed selective harmonic detection method the unit vector in (1) rotates at grid fundamental frequency in positive sequence and is derived from grid voltage using the method given in reference [31].

$$\cos\theta = \sin\omega_1 t \qquad \text{and} \qquad \sin\theta = -\cos\omega_1 t \tag{1}$$

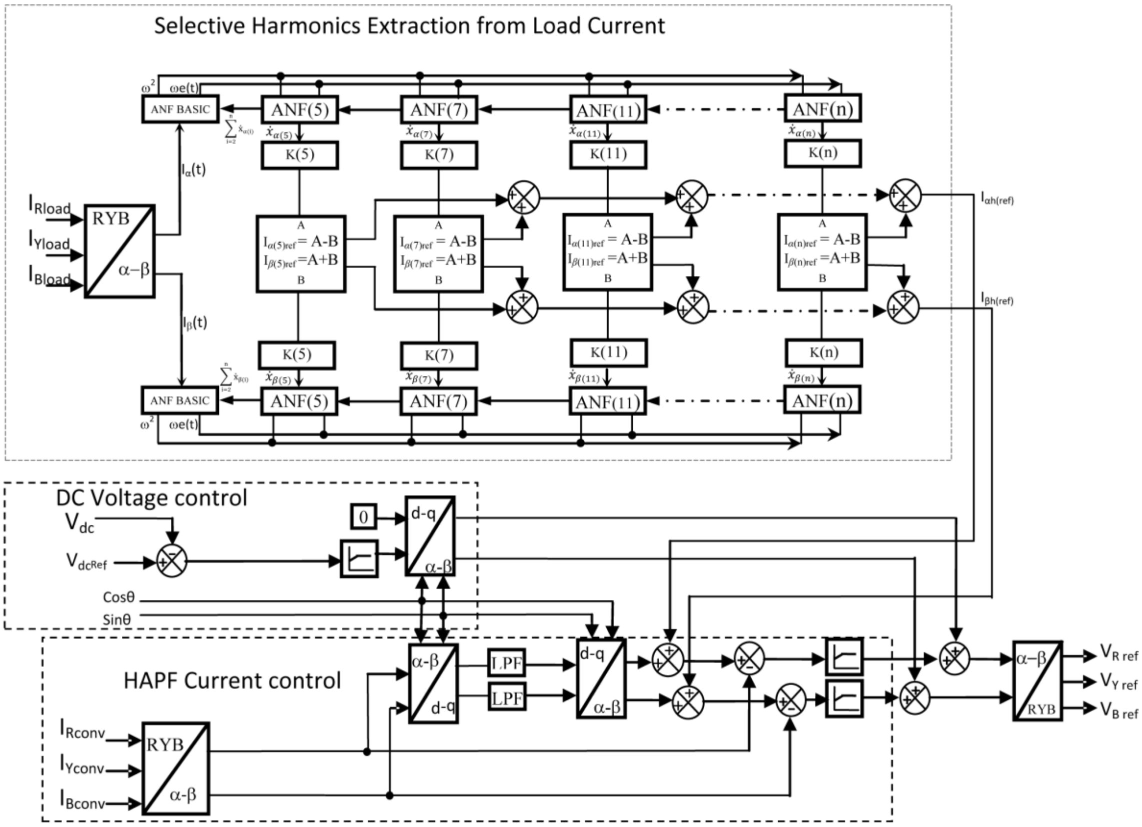
Let R-phase, Y-phase and B-phase load current of a three-phase balanced non-linear load be,

$$\begin{aligned} I_{Rload}(t) = {} & I_1 \sin(\omega_1 t - \phi_1) + \\ & \sum_{k=1}^{n} I_{6k-1} \sin\left([6k-1]\omega_1 t - \phi_{(6k-1)}\right) + \\ & \sum_{k=1}^{n} I_{6k+1} \sin\left([6k+1]\omega_1 t - \phi_{(6k+1)}\right) \end{aligned} \tag{2}$$

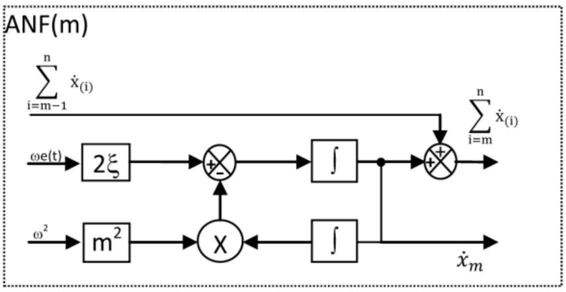
$$I_{Yload}(t) = I_1 \sin(\omega_1 t - \phi_1 - 120) + \sum_{k=1}^{n} I_{6k-1} \sin\left([6k-1]\omega_1 t - \phi_{(6k-1)} - ((6k-1)\times 120)\right) + \sum_{k=1}^{n} I_{6k+1} \sin\left([6k+1]\omega_1 t - \phi_{(6k+1)} - ((6k+1)\times 120)\right) \quad (3)$$

$$I_{Bload}(t) = I_1 \sin(\omega_1 t - \phi_1 - 240) + \sum_{k=1}^{n} I_{6k-1} \sin\left([6k-1]\omega_1 t - \phi_{(6k-1)} - ((6k-1)\times 240)\right) + \sum_{k=1}^{n} I_{6k+1} \sin\left([6k+1]\omega_1 t - \phi_{(6k+1)} - ((6k+1)\times 240)\right) \quad (4)$$

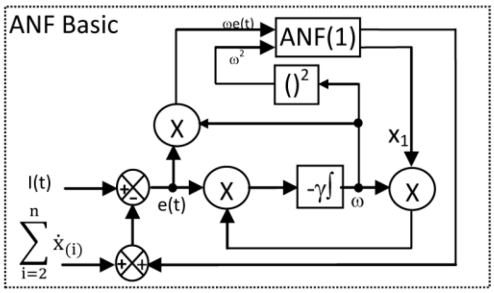
where, 1_{1-n}, ϕ_{1-n} and ω_{1-n} are the current peak of fundamental and harmonics current (1 to n), phase angle of the current components with respective voltages and respective frequency. The suffix to the above parameters represents the order of harmonics. Transformation of (2), (3) and (4) into α-β coordinate is given by,



(a)



(b)



(c)

Fig2. (a) Block diagram of Controller with ANF based Selective Harmonics Extractor (b) Block diagram of ANF (c) Block diagram of ANF Basic

$$I_{\alpha}(t) = \frac{3}{2} I_1 \sin\left(\omega_1 t - \phi_1\right) + \sum_{k=1}^{n} \frac{3}{2} I_{6k-1} \sin\left((6k-1)\omega_1 t - \phi_{(6k-1)}\right) + \sum_{k=1}^{n} \frac{3}{2} I_{6k+1} \sin\left((6k+1)\omega_1 t - \phi_{(6k+1)}\right) \quad (5)$$

$$I_{\beta}(t) = -\frac{3}{2} I_1 \cos\left(\omega_1 t - \phi_1\right) + \sum_{k=1}^{n} \frac{3}{2} I_{6k-1} \cos\left[(6k-1)\omega_1 t - \phi_{(6k-1)}\right] - \sum_{k=1}^{n} \frac{3}{2} I_{6k+1} \cos\left[(6k+1)\omega_1 t - \phi_{(6k+1)}\right] \quad (6)$$

The equation for the transformation from α-β coordinate to *d-q* coordinate is given as,

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \quad (7)$$

where, $\cos\theta$ and $\sin\theta$ are given in (1).

By filtering out the harmonics in the frequencies, in steps (for, 1 to n), with the help of Adaptive Notch Filters (ANF), of each dominant frequency, as proposed and demonstrated by M. Karimi-Ghartemani et.al [32], and further explored in [33] one can separate each harmonics of interest. This can be limited to say upto 5^{th} harmonics, 7^{th} harmonics, 11^{th} harmonics or upto 13^{th} so on, depending on the dominance of the harmonics, as shown in Fig. 2. After separating out each harmonics, limiting each values to the desired level and introducing desired phase angle compensation (using trigonometric method) for each one of the harmonics of interest, all of the current harmonics values are added together to form the reference values for the total harmonics in the α-β frame ($X_{\alpha h(ref)}$ and $X_{\beta h(ref)}$).

The block diagram of harmonic extraction method using ANF method and the control scheme is shown in Fig. 2. In this method ξ represents the depth of the notch and hence the noise sensitivity and γ represents the adaptation speed or settling time in the event of a transient.

The resonant frequency of the series passive filter, of the shunt HAPF is chosen as 7^{th} order. Hence for frequency below 7^{th} order, the nature of passive filter is capacitive and above 7^{th} order, nature will be inductive. Hence the effect of transportation delay on the harmonics below 7^{th} order will be different from the one above 7^{th} order. In this method, desired 'transportation delay compensation' and 'harmonic compensation limit' can be set individually for each harmonic, using trigonometric operations of α and β quantities, which are "sine" and "cosine" functions of same quantity. The constants $K_{\alpha(n)}$ and $K_{\beta(n)}$ are derived as follows:

$$K_{\alpha(n)} = k_{(n)} \sin\theta_{d(n)} \quad (8)$$

$$K_{\beta(n)} = k_{(n)} \cos\theta_{d(n)} \quad (9)$$

Where, $K_{\alpha(n)}$ is the multiplication factor for α quantities and $K_{\beta(n)}$ is the multiplication factor for β quantities of n^{th} harmonics; $k_{(n)}$ is the limiting factor and $\theta_{d(n)}$ is the transportation delay for n^{th} harmonics.

The general equation for transformation from *d-q* coordinate to α-β coordinate is given by (10).

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X_d \\ X_q \end{bmatrix} \tag{10}$$

Advantages of this new proposed scheme are:

- Selected harmonics in the grid can be attenuated and the limit for each harmonic can be set independently as decided by the capability of APF or as required by the value stipulated by IEEE 519-1992 standard.
- It can be easily implemented in digital platforms.
- The transportation delay compensation can be set individually for each harmonics, which is important for Shunt Hybrid Active Power Filter.
- Any order of harmonics can be extracted by appropriate notch filter.

IV. CONTROL ALGORITHM

For the extraction of individual harmonics a selective harmonics extraction technique is employed. In this method, the transportation delay due to Sensors, ADC sampling and DSP program cycle can be mitigated using multiplication factors which are calculated by trigonometric equations, because they can be seen separately. Here, we will use the selected harmonic achieved in α-β plane shown inside dotted line block in Fig. 2(a). Converter current is oriented along the grid voltage using the unit vectors in (1), using equation (7). After orientation, the fundamental components of *d*-axis and *q*-axis converter currents are extracted using low pass filters. During the startup procedure when all the three upper IGBTs are turned ON, the *d*-axis and *q*-axis converter current represent the capacitive reactive current drawn by the passive filter, because the grid voltage is dropped across it. Since grid voltage needs to drop across the passive filter, this capacitive reactive current should be untouched by the current controller. To achieve this, fundamental *d*-axis and *q*-axis components extracted from the converter current are converted to α-β quantities and added with α-β components of load current (harmonics part only), which are extracted by the Adaptive Notch Filter method. This results into the total α-axis and β-axis current references. The current controller is implemented in α-β plane. The estimated current references are compared with α-β component of converter current. The angle between grid voltage and capacitive reactive current flowing through the passive filter are always less than 90^0, because of the presence of stray resistances of filter inductor and capacitor in addition to their inductance and capacitance. The small active power resulting from the shortfall of phase angle from 90^0 is responsible for charging the d.c. bus of active filter to the required voltage level, which can be controlled by modulating the PWM converter to generate a voltage in phase with capacitive reactive current. Hence d.c. bus controller output will be a *q*-axis quantity while keeping *d*-axis quantity to zero. A PI-controller is used to regulate the d.c. bus voltage at constant level. The output of this controller is a voltage reference, in α-β plane, to the active filter to keep the d.c. bus voltage to the set value. This voltage reference is added with the output from the current controller, implemented by using PI-controller, to get the modulating signal. Space vector modulation technique is used for switching the IGBT. The block diagram of the control strategy is shown in Fig. 2.

V. CIRCUIT CONFIGURATION AND SIMULATION

A shunt HAPF of 50-kVA, 415-V input, 50Hz, rating with the topology shown in Fig. 1 is simulated using PSIM 9.0.6. Three-phase diode bridge rectifier connected to the grid of 415V line to line rms, 50Hz, with d.c. side capacitor and loaded with resistance, is used as the load for the shunt HAPF. The source inductance of the grid is chosen as 58.4µH. In the scheme, a three-phase PWM voltage-source converter is connected in series with a passive filter branch, consisting of inductor and capacitor. The series capacitor, C_f, is designed in such a way that it offers high impedance to the line frequency and most of the supply voltage is dropped across the filter capacitor. In simulation, C_f is chosen as 140µF. The resonant frequency of the passive filter is fixed to 7^{th} harmonic order and hence passive filter inductor value, L_f , is chosen as 1.5mH. The d.c. bus of the active power filter is set to 300V with a d.c. bus capacitance of 8200µF. Time constant for the voltage controller is set to be 100ms and that for current controller is set as 125µs.

In this simulation work the parameters ξ is chosen as 1.0 and γ is chosen as 0.5.

VI. RESULTS

The simulation of a shunt HAPF with selective harmonic detection method was carried out using PSIM. The unit vector constructed from the grid voltage is shown in Fig. 3. This unit vector is used from transformation between α-β plane and *d-q* plane in either direction, which are shown in Fig. 2. To analyze the transient response of the selective harmonic extraction method, the resistive load connected to the three-phase diode bridge rectifier is suddenly integrated to the circuit using a switch. The total load current and the extracted α-axis and β-axis harmonics current reference are shown in Fig. 4. It is evident from Fig. 4 that the maximum transient response time of the selective harmonic extraction method is better than 80msec.

Table I gives the percentage reduction in individual harmonic when shunt HAPF is incorporated in the simulation model. It was observed that the source current T.H.D. is brought down to 8.4% from 59.4%. The major harmonics like, 5^{th} and 7^{th} are brought down from 53.1% to 4.2% and 23.4% to 2.6% respectively. Fig. 5 shows the source current waveform before and after compensation along with the converter current.

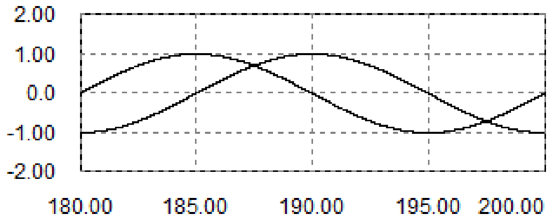


Fig. 3. Unit vector

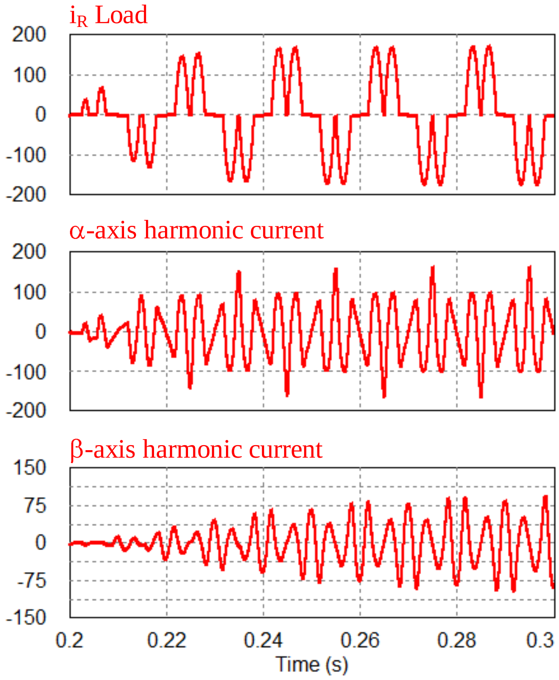


Fig. 4. Transient response of α-β axis harmonics current in Selective harmonic extractor

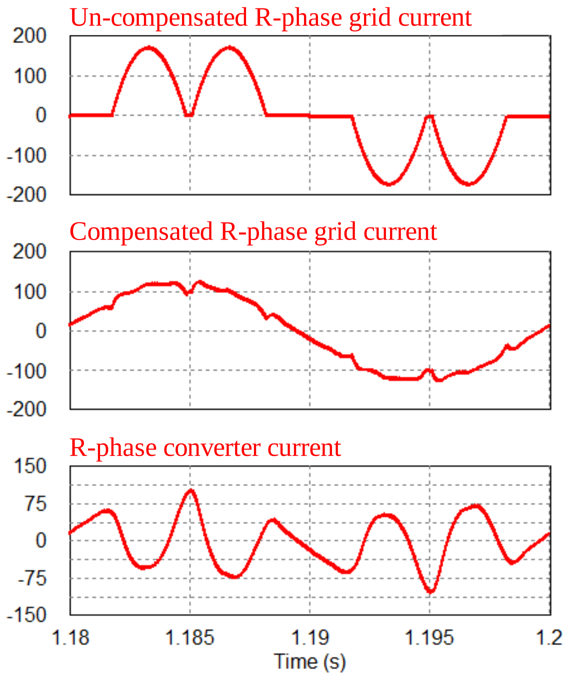


Fig.5. Un-compensated (a) and Compensated (b) grid current, Converter current (c)

TABLE I CURRENT HARMONICS AS % OF F.L FUNDAMENTAL

	Shunt HAPF OFF	Shunt HAPF ON
Fundamental	100.00	100.00
Harmonic 5	53.1	4.2
Harmonic 7	23.4	2.6
Harmonic 11	7.9	1.6
Harmonic 13	7.5	1.9
Total (I THD)	59.4	8.4

VII. CONCLUSION

This paper presented Shunt Hybrid Active Power Filter with a digital controller using a simple selective harmonic detection method based on Adaptive Notch Filter which can be easily implemented in digital platform. By using this control technique, selected harmonics in the grid can be attenuated and it is shown that limit for each harmonic can be set independently. This selective harmonic method also shows that any order of harmonics can be extracted. The method also facilitates compensation of the transportation delay for each harmonics separately. The scheme is validated by simulation and the results confirmed the theoretical expectations.

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