Abstract—This paper presents a new control algorithm for 3-phase shunt active power filter to compensate harmonics and reactive power requirements of nonlinear loads under non-ideal mains. The control algorithm compensates only customer-generated harmonics and allows similar level of harmonic distortion as present in the distorted voltage. Therefore, the resultant source current will have the same waveform as that of the supply voltage. Due to similar shape of source voltage and current, reactive power is compensated completely. It works effectively under ideal mains condition. The proposed scheme provides an additional feature of compensation of either harmonics only, or the compensation of both harmonics and reactive power simultaneously, based on the desired capacity of the APF. Various simulation results are presented with distorted as well as ideal mains.

Index Terms—Active power filter, harmonic and reactive power compensation, non-ideal mains voltage, power quality.

I. INTRODUCTION

In recent years, power electronic converters utilizing switching devices are widely used in various industrial as well as domestic applications for the control of power flow to almost all types of electrical loads. These converters take the advantages of all the recent advances and improvements of power electronics, suffer from the problem of drawing non-sinusoidal current and reactive power from the source and pollute the supply. These controllers are being used in increasing numbers and their contribution to the waveform distortion is of growing interest to the power utilities. Various standards are set the limit these harmonics.

Active Power Filters (APF) are researched and developed as a viable alternative over the passive filters to solve these problems. The APF can compensate the harmonics and reactive power requirement of the non-linear load effectively. Presently APFs are designed to absorb all the harmonics generated and/or reactive power required by the load and make the source current sinusoidal. Most of the APF developed are based on the instantaneous reactive power theory for the calculation of the desired compensation current [1]-[4]. In this theory the mains voltages are assumed as an ideal source. However, in most industrial power system mains voltages are often unbalanced and/or distorted and affect the calculation accuracy of the compensation current. When the mains voltage are distorted, the performance of the instantaneous reactive power theory is significantly affected [6]. Although several improved algorithms are proposed [3], most control circuits are complicated and are not easy to implement.

Another approach is proposed which does not require sensing the harmonic or VAR requirement of the load [5]-[7]. This scheme is aimed the mains current to be balanced and undistorted in spite of distorted and/or unbalanced mains. Although, this method is simple and easy to implement, it compensates both harmonics and reactive power simultaneously and does not provide the compensation of harmonics only. Usually compensation of both harmonics and reactive power simultaneously is not preferred due to limited rating of the APF. Also, in this case the reactive volt-ampere requirement is not completely compensated due to the waveform difference between the mains voltage and current.

Although, the generated voltage waveform is always sinusoidal but there are many devices that distort the mains voltage and these distortions are propagated all over the network. If such distorted supply is being used by a customer which is true in general, the harmonic generated may be much more than the harmonics generated in case of harmonic free supply. To make the mains current sinusoidal, customers have to put active filter even if load is resistive or some times they have to put large size active filter even though they are not responsible for certain harmonics present due to non-sinusoidal supply.

This paper presents a new control algorithm for 3-phase shunt active power filter to compensate only those harmonics, which are generated by the customer using harmonic generated loads. Therefore, the resultant source
current will have the same waveform as that of the supply voltage. Due to similar shape of source voltage and current, unity power factor is achieved, which provide more effective reduction of voltage THD at network buses and lower loss on the line resistance than the other classical methods [11,12]. The proposed scheme provides an additional feature of compensation of either harmonics only, or the compensation of both harmonics and reactive power simultaneously, based on the desired capacity of the APF. Also, unlike [4], it is applicable to both 1-phase as well as 3-phase systems.

II. PROPOSED ALGORITHM

K. Srinivasan [8],[9] have proposed a method to separate out the customer and supply side harmonic contributions. Based on this principle it is possible to estimate the reference current, which customer should draw from the utility. Each frequency component of the total source current in a distorted supply system is having two components, one conforming current and other non-conforming current. The sum of all frequencies of conforming current is defined as total conforming current and it is the current, which customer should be allowed to draw from a non-sinusoidal supply voltage network. On the other hand sum of all frequencies of non-conforming current is the total non-conforming current and it is the current, which APF should compensate. This concept is used here for the estimation of reference current for harmonic compensation. A modified algorithm is proposed for the compensation of both harmonic and reactive power simultaneously.

A non-sinusoidal voltage and load current as a general case can be expressed as -

\[ V_\text{s}(t) = 100\sin(\omega t + 30) + 10\sin(3\omega t + 60) + 10\sin(9\omega t + 100) \]
\[ i_\text{s}(t) = 80\sin(\omega t + 5) + 20\sin(3\omega t + 80) + 10\sin(7\omega t - 100) \]

Fig. 1(a) shows the voltage \( V_\text{s} \) and extracted current \( i_\text{s} \) waveform distorted to the same level but not in phase. Fig. 1(b) shows the voltage \( V_\text{s} \) and extracted current \( i_\text{s} \) waveform distorted to the same level and in phase with each other i.e. load draw only active power from the source and the reactive power demand is zero. While the distortion present in current waveform is of the same level as present in the voltage waveform. Frequency component of such voltage and currents are presented in fig 2.

On examining the corresponding frequency components of any voltage and current distorted to the same extent, following relationships are deduces—

(i) Current to voltage amplitude ratio is constant for all frequencies.
(ii) Current to voltage phase difference of the \( n^{th} \) harmonic is \( n \) times the current to voltage phase difference of the fundamental, for only harmonic compensation.
(iii) Phase angle of \( n^{th} \) harmonic current is same of the \( n^{th} \) harmonic voltage, for harmonic and reactive power compensation simultaneously.

A. Mathematical Expressions

Any non-sinusoidal signal can be expressed as a sum of sinusoidal signal of various frequencies. Based on this the utility voltage \( V_\text{s} \) and load current \( i_\text{s} \) can be expressed as –

\[ V_\text{s}(t) = \sum_{n=1}^{k} V_n \sin(n\omega t + \theta_n) \]
\[ i_\text{s}(t) = \sum_{n=1}^{k} I_n \sin(n\omega t + \phi_n) \]

Where, \( \theta_n \) and \( \phi_n \) are the phase difference of \( n^{th} \) order voltage and current waveform. The reference current drawn from the source is the portion of the current, which retains the same level of distortion as the voltage, while at the same time accounts for the entire fundamental frequency component. The reference current has the same graphical pattern of variation as the voltage. It might have a time leg or
lead or may be in phase with the voltage, depending on the harmonic or harmonic and reactive power compensation capability. Thus the fundamental frequency component of the reference current will equal to the fundamental frequency component of load current \(I_1\) (plus loss component) for harmonic compensation, and \(I_1\cos\phi_1\) (plus loss component) for both harmonic and reactive power compensation respectively [11]. All other frequency components will be in the same proportion as their counterparts in the voltage, which can be mathematically expressed as –

\[
\text{For both Harmonic and Reactive Power Compensation}
\]

\[
i_{\text{ref}}(t) = \frac{1}{V_1} \sum_{n=1}^{N} \left( I_n \right) \sin(\omega t + \theta_n) \tag{3}
\]

\[
\text{For Harmonic Compensation}
\]

\[
i_{\text{ref}}(t) = \frac{1}{V_1} \sum_{n=1}^{N} \left( I_n \right) \sin(\omega t + \theta_n + n(\alpha - \theta_1)) \tag{4}
\]

The balance of reference and load current will flow from the APF and should be attributable to the customer. It contains only loss component as the fundamental frequency component.

\[
i_c(t) = i_l(t) - i_{\text{ref}}(t) \tag{5}
\]

III. ESTIMATION OF REFERENCE CURRENT

The reference current component are estimated by measuring the supply voltage harmonics, fundamental load current and their respective angles, as per equation (3) and (4). The complete schematic diagram of the proposed 3-phase shunt active power filter is shown in fig. 3.

A. For harmonic and reactive power compensation

For the compensation of both harmonic and reactive power simultaneously, both voltage and current should be in phase. Fundamental voltage and fundamental current gives the scaling required (\(I_1/V_1\)) for all the current harmonics. All the voltage frequency components are scaled by this factor and rotated by the angle of the harmonic voltage (i.e. \(\theta_1\) for the 3rd harmonic, \(\theta_3\) for the 5th harmonic etc.) to obtain the harmonic components of the reference current. The sum of fundamental and harmonic component obtained as per equations (3) gives the estimated reference current, which is having same shape as the source voltage and in phase of it. Since the shape of source current is same as the source voltage and are in phase with each other reactive power is compensated completely.

B. For harmonic compensation

For the compensation of harmonics, the fundamental frequency current is 100% conforming and it is responsible for the power transfer to load and no portion of fundamental frequency can be considered as non-conforming. Therefore, fundamental voltage and fundamental current gives the rotation angle and the scaling required (\(I_1/V_1\)) for all the conforming current harmonics. If all the voltage frequency component are properly scaled and rotated by appropriate angles (3\(^{rd}\) harmonics by 3 times fundamental current-voltage angle, 5\(^{th}\) harmonic by 5 times fundamental current-voltage angle etc.), the harmonic components of reference current can be obtained as described in eq. (4). The sum of the fundamental load current and harmonic components obtained gives the resultant reference current, which has the same shape of the voltage waveform but may not be in phase.

Current that should be drawn from the utility, whose shape is similar to that of the voltage remains the responsibility of the utility. The rest of the current is attributed to the customer. The advantage of splitting in this manner is that:

- Utility have the responsibility of maintaining the distortion free voltage, while
- Customer have the responsibility of maintaining the distortion free current.

i.e., if distortion presents in the utility voltage, similar level of distortion are allowed in the current, so that customer have to install a lower capacity APF.

IV. SIMULATION RESULTS

Various simulation results are obtained using MATLAB and its tools Power System Blockset and Simulink. A 3-phase thyristor converter with firing angle \(\alpha=30^\circ\) is used as a nonlinear load. A voltage source PWM converter with a dc bus capacitor is used as an APF. The source voltages and load currents of two phase are measured and their harmonic components are computed. Using fundamental load current and voltage harmonics reference currents are obtained. DC bus capacitor voltage is regulated to obtain the loss component and added with the fundamental component of load current. For simulation study following 3-phase mains voltages are used –

\[
v_a = 325 \sin(\alpha + 30^\circ) + 30 \sin(5\alpha + 120^\circ) + 30 \sin(5\alpha + 120^\circ) \tag{6}
\]

Various simulation results are obtained by the proposed algorithm, under distorted mains, which can be used for the compensation of either harmonics only, or for the compensation of both harmonic and reactive simultaneously. The important aspect of this algorithm is that, it allows the similar level of harmonics in compensated current as present in the utility voltage. However, if the mains voltage is distortion free, compensated source current will also be free from distortion.

A. Harmonic & Reactive Power Compensation

Fig. 4 shows the simulation results of the proposed algorithm under distorted mains voltages, for harmonic and reactive power compensation simultaneously. Fig. 4(a) shows the source voltage, load current, source current, APF current and DC capacitor voltage for phase ‘A’. Fig. 4(b)
shows the frequency spectrum of load and compensated source currents, while fig. 4(c) shows the three source currents with their respective source voltages. It is observed that, the shape of the source voltages and currents are same, and they are in phase with each other, so that reactive power is fully compensated.

After compensation the harmonic level of the compensated current is same as present in the source voltage. In order to study the performance of the APF under transient condition, load is changed from 50+j31.4 to 25+j31.4. Figure 4(d) shows various waveforms during load change condition. The change in source current is found smooth. Steady state is reached within 3-4 cycles.
Fig. 4(d) Various waveforms during load change for harmonic & reactive power compensation simultaneously

Proposed algorithm works satisfactorily with ideal mains. Fig. 5 shows the three-phase compensated current with their respective sinusoidal source voltages. Compensated source current becomes sinusoidal and in phase with the source voltage. For only harmonic compensation case compensated current will be sinusoidal but displaced with the source voltage by an angle $\phi_1$.

![Fig. 5 Simulation results for harmonic and reactive power compensation simultaneously with ideal mains.](image)

B. Only Harmonic Compensation

Various simulation results are obtained with the proposed algorithm for only harmonic compensation. Fig. 6 shows the three-phase source current with their respective phase voltages. It is observed that, the harmonic level of the compensated source current is same as present in the source voltage. The shape of the source voltages and currents are same, but they are not in phase, hence no reactive power is compensated.

V. Conclusions

A new control algorithm is proposed which estimate the reference compensating current in frequency domain. It is capable to maintain similar distortion level in the compensated source current as present in the mains voltage thereby attributes the responsibility of utility and customer at PCC. The voltage is the responsibility of the utility, while the customer is responsible for current. Due to similar shape of compensated source current and source voltage, unity power factor operation can be achieved even under distorted mains conditions. Unity power factor operation provides harmonics at the same frequencies of the source voltage, as a consequence lowers the voltage THD at the user busbar. It is also capable to achieve only harmonic compensation. Proposed algorithm works effectively under ideal mains condition as compared to other methods. By maintaining the similar distortion level in source current as present in the distorted mains, some times customer has to put a small size active filter, as compared to maintaining the source current sinusoidal. Work in this direction is in progress and will be reported later.

Fig. 6 Compensated source currents of all the three phases with their respective source voltage for only harmonic compensation

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VII. References