Fryze Power Theory with Adaptive-HCC based Active Power Line Conditioners

Karuppanan P, Kamala Kanta Mahapatra, Jeyaraman.K and Jeraldine Viji

***Abstract*-- This paper presents a Fryze power theory based three-phase, three-wire Active Power Line Conditioner (APLC) for power quality enhancement. The shunt APLC system is used for harmonics and reactive power compensation due to non-linear loads. The compensation control strategy is proposed on active and non-active power in the time domain based generalized Fryze currents minimization theory. PWM-voltage source inverter based active power filter gate control switching signals are brought out from adaptive-Hysteresis Current Controller (HCC). This Fryze power theory method maintains the capacitance voltage of the inverter constant without any additional controller circuit. The shunt APLC system is investigated using extensive simulation studies and the performance parameters are obtained under different steady state and transient conditions. A comparative assessment of fixed-HCC and adaptive-HCC are carried out.**

Index Terms-- Fryze power theory, active power line conditioner, Power quality, Harmonics, adaptive-hysteresis current controller

I. INTRODUCTION

Active power line conditioners (APLC) or active power filters (APF) have grown substantially for solving power quality problems [1-2]. In recent years power quality effect in industrial as well as home utilities has become a matter of serious concern due to the intensive use of power electronic equipment. Continuing proliferation of nonlinear loads are creating disturbances like harmonic pollution and reactive power problems in the power distribution networks [3]. Traditionally these problems are solved by passive LC filters. But these passive filters introduce tuning problems, resonance, large in size and limited to few harmonics. So the active power-line conditioners has become popular than passive filters [4]. It compensates the current harmonics and reactive power simultaneously. The APLC has the ability to keep the mains current balanced and sinusoidal after compensation regardless of whether the load is linear/non-linear and balanced or unbalanced [3-5].

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In 1932, S. Fryze developed new control method that facilitates extracting the fundamental component of load current, commonly known as Fryze power theory. In 1979 M. Depenbrock promoted the power analysis method based on the Fryze power theory and it was further modified by F. Buchholz [6-7]. This improved method is now known as FBD (Fryze-Buchholz-Dpenbrock) method and it is used in time domain analysis [8-9]. In 1984, H.Akagi introduced instantaneous reactive power theory [10]. In 1995, S.Bhattacharya proposed synchronous reference frame method for active filter [11]. But these approaches are rather complicated because this includes Park transformation and p-q or d-q transforms. The time domain FBD approach is an alternative that is used to analyze the relationship of voltage, current and reactive power calculation is adopted [12]. The VSI switching signals are derived from adaptive-hysteresis current controller [13-16].

This paper presents generalized Fryze power theory (or Fryze current minimization) based active filter for power line conditioning. The shunt APLC is implemented with three-phase PWM-voltage source inverter and is connected at PCC for compensating the current harmonics by injecting equal but opposite harmonic compensating current. The reference currents are extracted using Fryze power theory method. The inverter gate drivel signals are derived from adaptive-hysteresis current controller. This Fryze power method maintains the dc-side capacitance voltage of the inverter constant without any external controller circuit. The shunt APLC system is investigated under diode and thyristor rectifier load conditions. A comparative assessment of fixed-HCC and adaptive-HCC are done.

II. DESIGN OF SHUNT APLC SYSTEM

Active filter for power line conditioning system is connected in the distribution network at the PCC through filter inductor and operates in a closed loop. The shunt APLC system consists of 3-phase inverter, RL-filters, a compensation controller (Fryze power theory controller) and switching signals generator (adaptive-hysteresis current controller) as shown in Fig. 1. The filter inductor provides smoothing and isolation for high frequency components. The filter suppresses the harmonics caused by the switching operation of the power transistors. Control of the current wave shape is limited by switching frequency of inverter and by the available driving voltage across the interfacing inductance. The three phase supply source connected to the non-linear load (such as diode or thyristor rectifier R-L load).

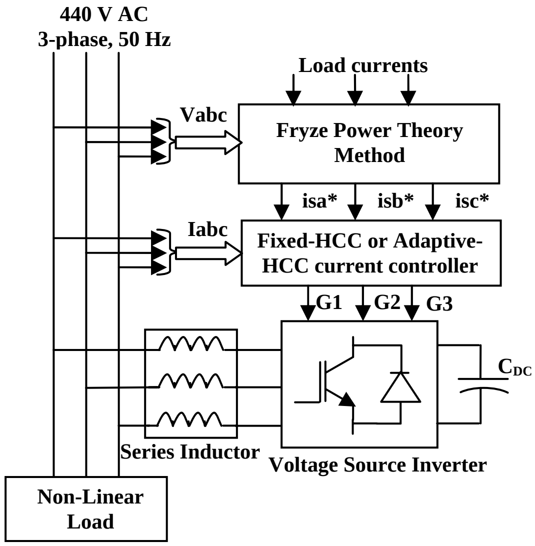

Fig. 1 shunt active power line conditioners system

This nonlinear load current will have fundamental and harmonic current components, which can be represented as [5]

$$\begin{aligned} i_L(t) &= \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n) \\ &= I_1 \sin(\omega t + \Phi_1) + \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \end{aligned} \quad (1)$$

The instantaneous load power can be obtained from the source voltage and current, the calculation is given as

$$\begin{aligned} p_L(t) &= i_s(t) * v_s(t) \\ &= V_m \sin^2 \omega t * \cos\varphi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\varphi_1 \\ &\quad + V_m \sin\omega t * \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \quad (2)$$

This load power contains fundamental or real power $p_f(t)$, reactive power $p_r(t)$ and harmonics power $p_h(t)$. The active (fundamental) power drawn by the load can be written as

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\varphi_1 = v_s(t) * i_s(t) \quad (3)$$

From this equation, the source current drawn from the mains after compensation should be sinusoidal; this is represented as

$$i_s(t) = p_f(t) / v_s(t) = I_1 \cos\varphi_1 \sin\omega t = I_{\max} \sin\omega t \quad (4)$$

If the active power filter provides the total reactive and harmonic power, source current $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. At this time, the active filter must provide the compensation current:

$$i_c(t) = i_L(t) - i_s(t) \quad (5)$$

Therefore, the Fryze theory based controller of the APLC extracts the fundamental component of the load current that can be used for compensating the harmonics and reactive power simultaneously.

III. Control Strategies

The control strategies consist of fryze power theory and adaptive-hysteresis current controller.

A) Fryze Power Theory algorithm

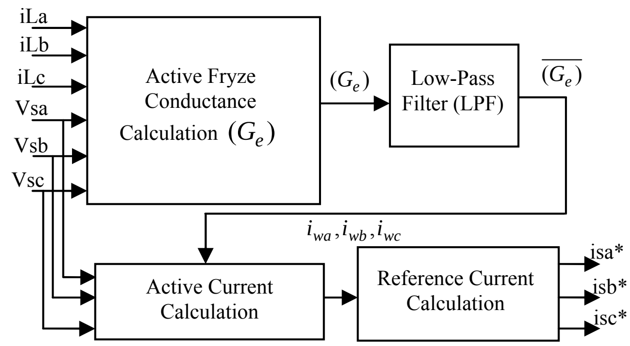

Fig. 2 Block diagram of generalized Fryze Power Theory method

The generalized Fryze power theory method presents a minimum rms value so that the same three phase average active power is drawn from the source as the original load current shown in Fig. 2. This reduces the ohmic losses in the transmission line and guarantees linearity between the supply voltage and compensated current. The instantaneous equivalent conductance (G_e) is calculated from the three phase instantaneous active power $(p_{3\phi})$ [6-9]

$$\begin{aligned} p_{3\varphi}(t) &= v_{sa}(t) i_{sa}(t) + v_{sb}(t) i_{sb}(t) + v_{sc}(t) i_{sc}(t) \\ &= p_{sa}(t) + p_{sb}(t) + p_{sc}(t) \end{aligned} \quad (6)$$

Moreover the root mean square (rms) aggregate voltage is derived from the instantaneous value of phase voltages, it's given as

$$V_{\Sigma} = \sqrt{\left(v_{sa}{}^2(t) + v_{sb}{}^2(t) + v_{sc}{}^2(t) \right)} \quad (7)$$

The conductance or admittance (G_e) is represented by an average value instead of a varying instantaneous value. The instantaneous conductance is calculated from the three phase instantaneous phase voltages v_{a1}, v_{b1} *and* v_{c1} calculated from the positive sequence voltage detector V_{+1} and load currents i_{La}, i_{Lb} *and* i_{Lc}. It's derived as [12]

$$Ge = \frac{v_{a1} i_{La} + v_{b1} i_{Lb} + v_{c1} i_{Lc}}{v_{a1}{}^2 + v_{b1}{}^2 + v_{c1}{}^2} \quad (8)$$

The average conductance (G_e) pass through Butterworth design based Low Pass Filter (LPF). The LPF cutoff or sampling frequency is assigned 50 Hz fundamental frequency that allows only the fundamental signals to the active current section. The instantaneous active currents i_{wa}, i_{wb} *and* i_{wc} of the load current are directly calculated by multiplying (G_e) by phase voltages v_a, v_b *and* v_c respectively and are defined as

$$\begin{aligned} i_{wa} &= \overline{G_e} v_a \\ i_{wb} &= \overline{G_e} v_b \\ i_{wc} &= \overline{G_e} v_c \end{aligned} \tag{9}$$

The desired reference source currents calculated from the active current, after compensation, can be written as

$$i_{sa}* = i_{wa} = I_{rms} \sin \omega t \tag{10}$$

$$i_{sb}* = i_{wb} = I_{rms} \sin(\omega t - 120^0) \tag{11}$$

$$i_{sc}* = i_{wc} = I_{rms} \sin(\omega t + 120^0) \tag{12}$$

Here i_{rms} is root mean square line current and the magnitude is unity. The control strategy indicates that shunt APLC should draw the inverse of the non active current of the load and the results shown compensates that currents are proportional to the corresponding phase voltage.

B) Hysteresis Current Controller

The hysteresis current controller is utilized independently for each phase and directly generates the switching patterns for the PWM-voltage source inverter. It imposes a bang-bang instantaneous control method that draws the APF compensation current to follow its reference signal within a certain band limit.

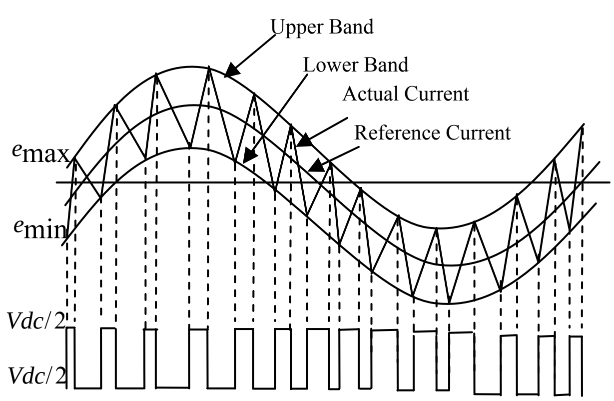

Fig. 3 Hysteresis current controllers

This control scheme inflicts on reference current $i_{ref}(t)$ to form the upper and lower limits of a hysteresis band. The actual current $i_{actual}(t)$ is compared with $i_{ref}(t)$ and the resulting error is subjected to a hysteresis controller to determine the gating signals of the inverter as shown in Fig. 3. The switching performance is defined as [13]

$$S = \begin{cases} OFF & if \;\; i_{actual}(t) > i_{ref}(t) + H \\ ON & if \;\; i_{actual}(t) < i_{ref}(t) - H \end{cases} \tag{13}$$

The advantages of fixed-HCC are simple design and unconditioned stability. However, this control scheme exhibits several unsatisfactory features such as uneven switching frequency, possible generation of resonances. It is also difficult to design passive high pass filter system. This unpredictable switching function affects the APF efficiency and reliability. Adaptive-hysteresis current controller overcomes the fixed-HCC demerits. This adaptive-HCC changes the bandwidth according to instantaneous compensation current variation.

C) Adaptive-HCC

The adaptive-hysteresis current controller is used to generate the voltage source inverter switching signals. The adaptive-HCC changes the hysteresis bandwidth based on instantaneous compensation current variation to optimize the required switching frequency. Fig. 4 shows the inverter current and voltage waves for phase a . The current i_a tends to cross the lower hysteresis band at point 1, where the inverter switch S1is switched ON. The linearly rising current $(i_a +)$ then touches the upper band at point 2, where the inverter switch S4 is switched ON. The linearly falling current $(i_a -)$ then touches the lower band at point 3.

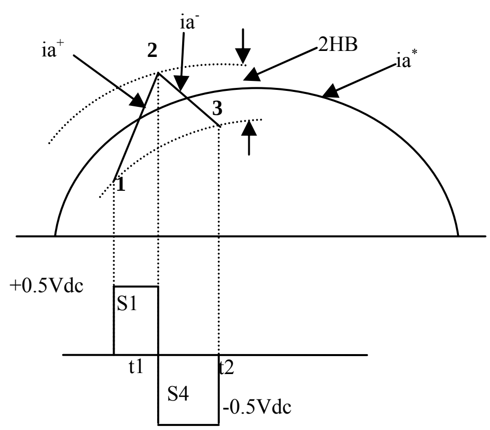

Fig. 4 current and voltage waves with adaptive-HCC

The following equations can be written in the switching intervals t_1 and t_2 [14-15]

$$\frac{di_a^+}{dt} = \frac{1}{L}(0.5V_{dc} - V_{sa}) \tag{14}$$

$$\frac{di_a^-}{dt} = -\frac{1}{L}(0.5V_{dc} + V_{sa}) \tag{15}$$

where $L =$ phase inductance; $(i_a +)$ and $(i_a -)$ are the respective rising and falling current segments. From the geometry of Fig. 4, we can write

$$\frac{di_a^+}{dt}t_1 - \frac{di_a*}{dt}t_1 = 2HB \qquad (16)$$

$$\frac{di_a^-}{dt}t_2 - \frac{di_a*}{dt}t_1 = -2HB \qquad (17)$$

$$t_1 + t_2 = T_c = 1/f_c \qquad (18)$$

Where t_1 and t_2 are the respective switching intervals, and f_c is the modulation frequency. Adding $(16)\,and\,(17)$ and substituting (18) we can write

$$\frac{di_a^+}{dt}t_1 - \frac{di_a^-}{dt}t_2 - \frac{1}{f_c}\frac{di_a^*}{dt} = 0 \qquad (19)$$

Subtracting $(17)\,from\,(16)$, we get

$$\frac{di_a^+}{dt}t_1 - \frac{di_a^-}{dt}t_2 - (t_1 - t_2)\frac{di_a^*}{dt} = 4HB \qquad (20)$$

Substituting $(15)\,in\,(20)$, we get

$$\frac{di_a^+}{dt}(t_1 + t_2) - (t_1 - t_2)\frac{di_a^*}{dt} = 4HB \qquad (21)$$

Substituting $(17)\,in\,(21)$, and simplifying,

$$(t_1 - t_2) = \frac{di_a^* / dt}{f_c(di_a^+ / dt)} \qquad (22)$$

Substituting $(22)\,in\,(21)$, we compute

$$HB = \left\{\frac{0.125V_{dc}}{f_c\,L}\left[1 - \frac{4L^2}{V_{dc}^{\,2}}\left(\frac{V_{sa}}{L} + m\right)^2\right]\right\} \qquad (23)$$

Here, $m = di_a^*/dt$ is the slope of reference current signals. The hysteresis band HB can be modulated at different points of the fundamental frequency cycle to control the switching pattern of the inverter. The calculated hysteresis bandwidth HB is applied to the variable HCC. The variable hysteresis current control is created by S-functions in Matlab to produce gate control signals, which operates the voltage source inverter for harmonics and reactive power compensation.

IV. Simulation Result and Analysis

The performance of the fryze power theory based active power filter is evaluated through Matlab using Simulink tools. This system is tested under both steady state and transient condition with diode- rectifier and thyristor-rectifier loads. The system parameters values are; Line to line source voltage is 440 V; System frequency (f) is 50 Hz; Source impedance of R_S, L_S is 1 Ω and 0.5 mH respectively. Filter impedance of R_c, L_c are 1 Ω and1.3 mH respectively; Diode and thyristor rectifier R_L L_L load are 20 Ω; 100 mH; DC side capacitance (C_{DC}) is 1100 µF; Power devices used are IGBTs with anti parallel diodes.

Case 1 Steady state

This shunt active filter system is simulated and several important parameters are verified. The waveforms presented are results obtained through hysteresis current controller based active filter system with thyristor-rectifier R-L load. This load generates six-pulse rectifier waveform. The rectifier load current or source current before compensation is shown in Fig. 5 (a). This non-linear load contains fundamental and harmonic components. The shunt active filter is connected in the power distribution grid at the PCC for compensating the current harmonics by injecting equal but opposite harmonic compensating current. This active filter must provide the harmonic current or compensation current as shown in Fig. 5 (b). It is cancelling the original distortion and improving the power quality. The source current after compensation is presented in Fig. 5 (c) that indicates that current is sinusoidal. The load current and source current are plotted together for comparison purpose in Fig. 5 (d). The results are shown for a-phase only; other phases are just phase shifted by 120^0

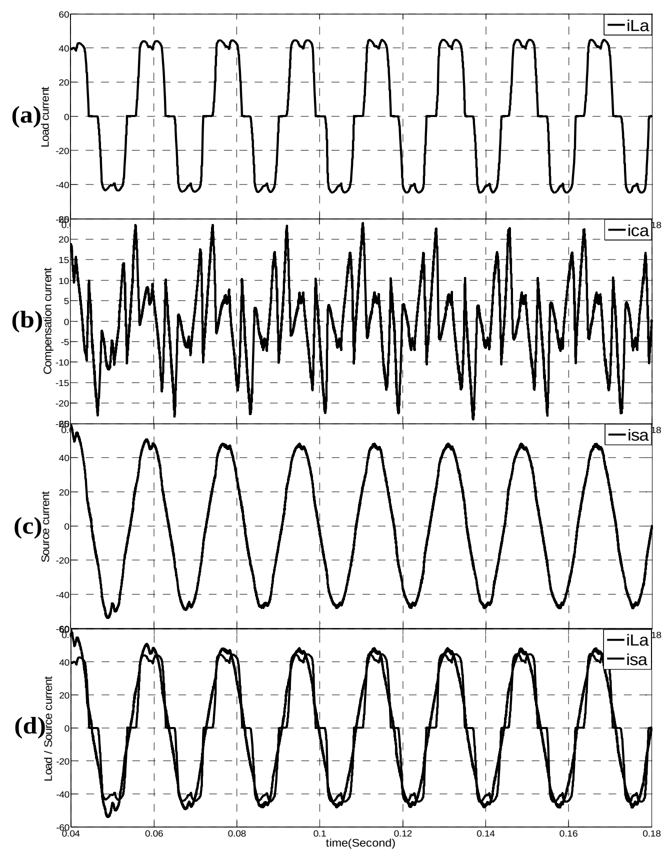

Fig. 5 (a) Load current, (b) compensation currents and (c) source current after compensation and (d) Load current compare with source current.

Case 2 Transient state

For investigating transient behavior, the operating conditions are suddenly changed during the time period T=0.06 to 0.12s. In transient, the active filter system is simulated for both diode and thyristor-rectifier loads. However, the waveforms presented are results obtained through adaptive –HCC based active filter system with diode-rectifier R-L load. The simulation waveform of the three-phase ac supply voltages are shown in Fig. 6 (a). It indicates that voltages are balanced. The diode-rectifier load current is shown in Fig. 6 (b) that contains fundamental and harmonic components. The APF supplies the compensating current that is shown in Fig. 6 (c). The source current after compensation is presented in Fig. 6 (d) indicates that currents become sinusoidal after compensation.

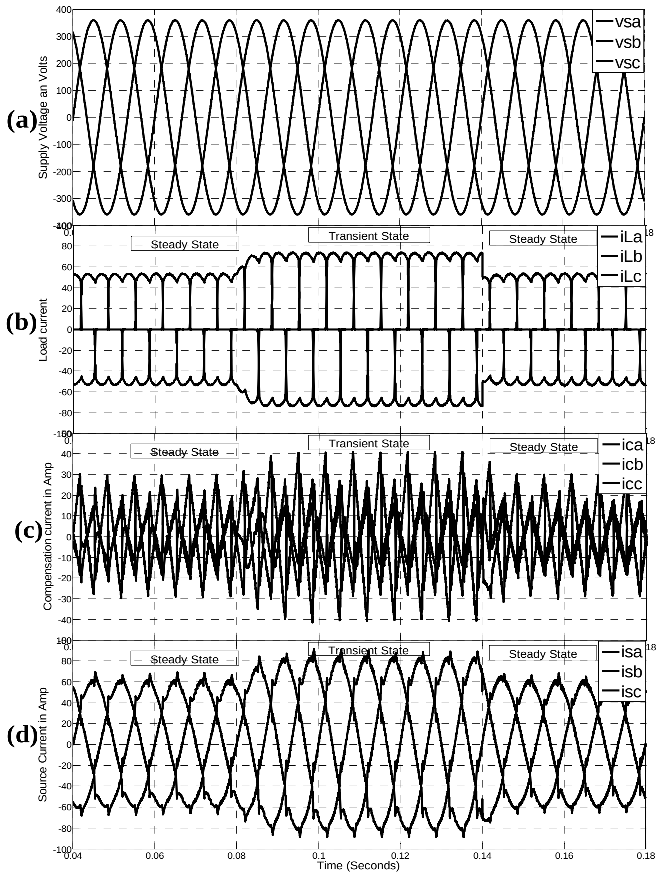

Fig. 6 (a) supply voltage, (b) Load current, (c) compensation currents and (d) source current after compensation current.

The fryze power theory controller maintains the DC-side capacitor voltage constant without any additional circuit that shown in Fig. 6 (e). It serves as an energy storage element to supply real power to operate active power inverter. This waveform is for the case with adaptive-HCC based active filter system with diode-rectifier R-L load under transient conditions.

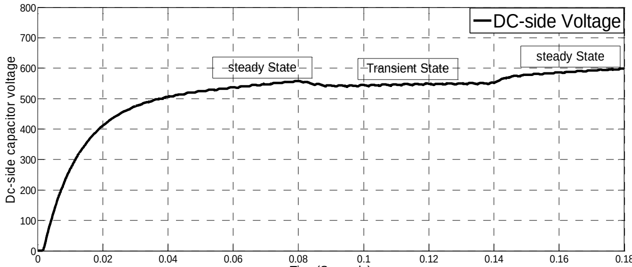

Fig. 6 (e) DC side capacitor voltages

The Fast Fourier Transform (FFT) is used to extract the presence of different harmonics along with the fundamental frequency 50 Hz. The orders of the harmonics are plotted without and with active power filter. Fig. 7 (a) shows the spectrum of all frequency components with thyristor-rectifier load condition in steady state. Fig. 7 (b) shows the spectra of all frequency components with diode-rectifier load in transient-state condition.

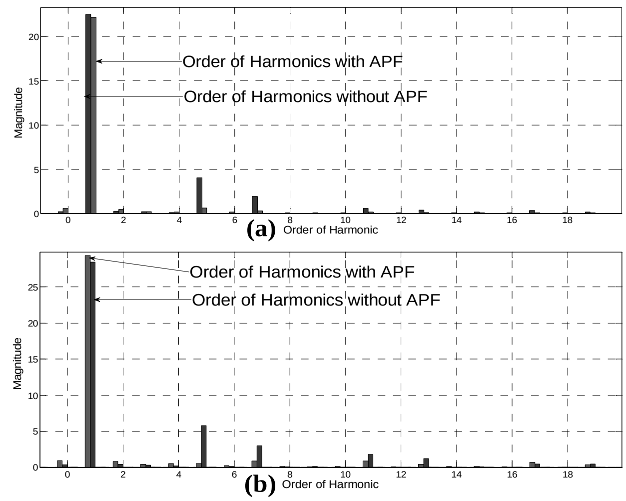

Fig. 7 Order of harmonics (a) under thyristor-rectifier with steady state and (b) under diode-rectifier with transient state

The active power and reactive power are calculated by averaging the voltage and current product at the fundamental frequency. The Fig. 8 is plotted under thyristor-rectifier load in the steady state condition. The active and reactive power (P=8.83 kW, Q=1.2 kVAR) measured without active filter and with active filter (P=8.53 kW, Q=45.1 VAR).

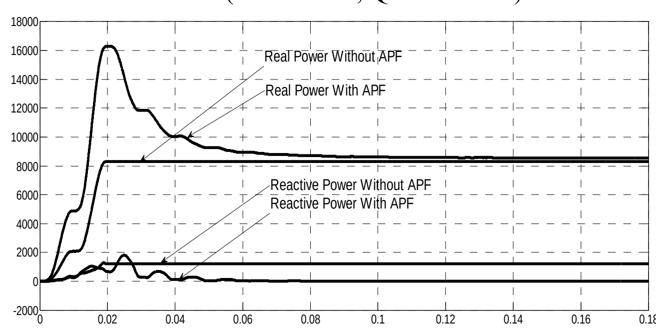

Fig. 8 Active and Reactive power with or without active filter.

The Total Harmonic Distortion (THD) is computed for source current on the ac main network. The fryze power theory based compensator filter makes the source current in the supply line sinusoidal after compensation. The total harmonic distortion measured with or without active power filter that are presented in Table 1. The Real (P) and Reactive (Q) power is calculated and given in the Table 2. This result is measured under diode-rectifier and thyristor-rectifier load condition. This result indicates that fryze power theory based shunt active filter is suppressing reactive power and hence improves the power quality. The FFT analysis of the APLC system indicates that the THD of the source current less than 5 % that is in compliance with IEEE-519 harmonic standards.

Table 1 Total harmonic distortion (THD) measurements

Rectifier Load	Conditions	Without APF	With HCC based APF	With Adaptive-HCC based APF
Diode	Steady state	26.18 %	4.86 %	4.71 %
	Transient state		4.79 %	4.63 %
	Power factor	0.9794	0.9976	0.9998
Thyristor	Steady state	22.11 %	3.74 %	1.77 %
	Transient state		3.86 %	2.21 %
	Power factor	0.9669	0.9977	0.9998

Table 2 Real and Reactive-power measurements

Rectifier Load	Conditions	Without APF	With HCC based APF	With Adaptive-HCC based APF
Diode	Steady state	P=10.11 kW Q=504.7 VAR	P=10.54 kW Q=122.6 VAR	P=10.83 kW Q=48.6 VAR
	Transient state		P=10.58 kW Q=127.2 VAR	P=10.79 kW Q=60.9 VAR
Thyristor	Steady state	P=8.83 kW Q=1.2 kVAR	P=8.53 kW Q=45.1 VAR	P=8.88 kW Q=36.7 VAR
	Transient state		P=8.58 kW Q=95.6 VAR	P=8.89 kW Q=32.8 VAR

V. CONCLUSION

This investigation demonstrates that voltage source inverter based shunt active power filter facilitates improving the power quality. The fryze power theory extracts the fundamental or reference components from the distorted line currents. The inverter switching signals are derived from adaptive-hysteresis current controller. The fryze power theory approach maintains the DC-side capacitor voltage of the inverter nearly constant without any external control circuit. The shunt active power filter in conjunction with the proposed controller performs perfectly under steady state and transient conditions. The important performance parameters are computed under both diode and thyristor rectifier loads. This fryze power theory approach brings the THD of the source current to be less than 5% that is in compliance with IEEE-519 and IEC 61000-3 standards.

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