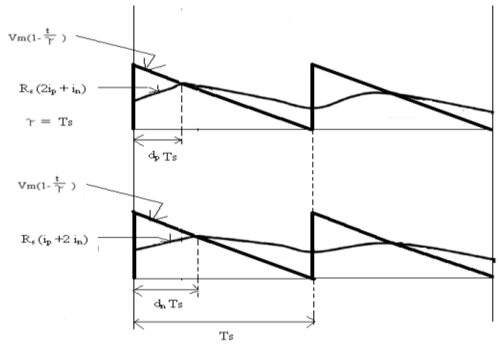

Figure 2: Operation waveforms of one-cycle controlled APF controller

PROPOSED MODEL SCHEME

With the help of instantaneous symmetrical component theory (ISCT), the function of grid connected Dual Active Power Filter (DAPF) is analyzed and developed[10], with control algorithms. At PCC the positive sequence extraction of voltage is done byabc-dq0 transformation as shown in fig(2) of active power filters independently. As in *fig.1*, a three phase four wire power system with dual active power filters in shunt of three phase four wire(APF1)and micro grid (APF main) is implemented. Instantaneous symmetrical component theory ISCT is as, three phase distorted ac source will be "sum of components in the positive, negative and zero sequence." It is therefore simple in the analysis under non-linear load conditions. Moreover, converts the linear transformation to a new set of components of three phase, called symmetrical components [6].

[**Note:** Micro grid(APF main) have external DC voltageV_{dc}; in three phase four wire (APF1) DC-link capacitor (C $=C_1 + C_2$); $i_{af} = (i_{am} + i_{ax})$,$i_{bf} = (i_{bm} + i_{bx})$, &$i_{cf} = (i_{cm} + i_{cx})$, $L_3 = (L_m + L_x)$, $R_3 = (R_m + R_x)$ and N as neutral line, as shown in *fig.1*.]

The power of micro grid can be obtained from several distributed energy resources (DER), is adjusted and tuned by trial and error method in simulation, adapted from [6].

Therefore distorted three-phase ac source voltage for compensation as [3]:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = V^{+} \begin{bmatrix} \sin(\omega t + \Phi^{+}) \\ \sin(\omega t - 120° + \Phi^{+}) \\ \sin(\omega t + 120° + \Phi^{+}) \end{bmatrix} + V^{-} \begin{bmatrix} \sin(\omega t + \Phi^{-}) \\ \sin(\omega t - 120° + \Phi^{-}) \\ \sin(\omega t + 120° + \Phi^{-}) \end{bmatrix} + V^{0} \begin{bmatrix} \sin(\omega t + \Phi^{0}) \\ \sin(\omega t + \Phi^{0}) \\ \sin(\omega t + \Phi^{0}) \end{bmatrix} \quad \ldots\ldots\ldots..(6)$$

Where V^{+}, V^{-} and V^{0} are the amplitude of the voltage, Φ^{+},Φ^{-} and Φ^{0} as initial phase angles.

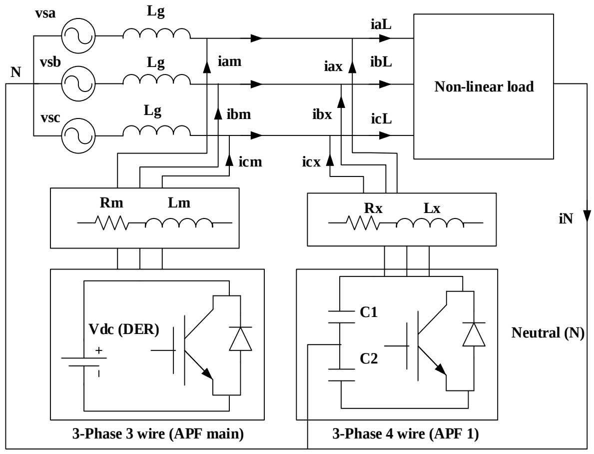

Figure 3: Proposed Dual Active Power Filter Scheme

A Dual APF is reflected as shown in *fig.1* [6]. Neglecting Lg reactors, 3-phase circuit equations connecting APF1 and APF main independently as [1],

$$\frac{L_3\, d}{dt} i_{af} = V_{sa} - R_3 i_{af} - V_{af} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

$$\frac{L_3 d}{dt} i_{bf} = V_{sb} - R_3 i_{bf} - V_{bf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

$$\frac{L_3 d}{dt} i_{cf} = V_{sc} - R_3 i_{cf} - V_{cf} \quad \ldots\ldots\ldots\ldots\ldots\ldots..(9)$$

The abc-dq0Transformation or Synchronous Reference Frame SRF for each APFs separately, given as:

$$\begin{bmatrix} Vd \\ Vq \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} vsa \\ vsb \\ vsc \end{bmatrix} \quad .(10)$$

Factor 2/3 by power invariance method also called time invariant. And added as a factor of correction such that scaling errors can be eliminated occurred due to multiplication.

State model analysis of APF1 and APF main (micro grid):

$$\frac{L_3 d}{dt} i_{df} = V_d - R_{3 i_{df}} - V_{df} + \omega_e L_3 i_{qf} \ldots\ldots\ldots.. (11)$$

$$\frac{L_3 d}{dt} i_{qf} = V_q - R_3 i_{qf} - V_{qf} - \omega_e L_3 i_{df} \ldots\ldots\ldots(12)$$

Where v_d and v_q for d-q axes of SRF, ωe as power system frequency. Moreover, DC-link voltage feedback of APF1:

$$\frac{C_3 d}{dt} V_{dc} = f_a(i_{af}) + f_b(i_{bf}) + f_c(i_{cf}) \ldots\ldots\ldots..(13)$$

Where f_b, fc are switching functions, C3 as the capacitance of DC-link APF1.

Whereas from equation (8) in d-q axes frame of APF

$\frac{C_3 d}{dt} V_{dc3} = \frac{3}{2}\,(f_d\, i_{df} + f_q\, i_{qf})$……………………..(14)

Assuming three phase voltages as balanced, hence

$V_d = V_m$ ……………………..(15)

$V_q = 0$ ………………………(16)

Where V_m is input peak value of phase voltage.

The instantaneous real and reactive power given as P_L and q_L on the load side at three phase balanced load condition can be expressed as [1],

$P_L = \frac{3}{2} V_m i_{dl}$ ……………………..(17)

$q_L = -\frac{3}{2} V_m\, i_{ql}$ ………………..(18)

The above equations (17) and (18) are valid for both unbalanced and balanced loading conditions, in which P_L and q_L are dependent on i_{dl} and i_{ql} only. If assuming, both active power filters having harmonic current as fully compensated then equations (17) and (18) can be further expressed as [1],

$P_s = \frac{3}{2} V_m\, i_1$ ……………………..(19)

q_s =0……………………..(20)

P_s and q_s are instantaneous real and reactive power respectively. Here "i1" in equation (19) is labeled through d- axis current i_{dl}.

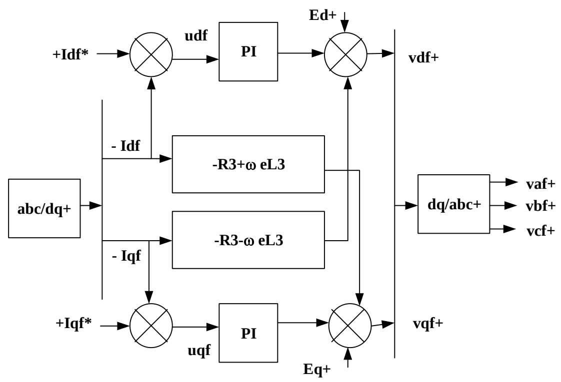

Figure 4: Control Structure using Park Transformation

And i_{df} * and i_{qf} * as reference currents obtained using feedback of load and low pass filter, [1] i.e.,

$I_{df} *= i_1 - i_{dl}$ ………………………(21)

$I_{qf} *= -i_{ql}$ ……………………………………(22)

Control of an Active Power Filter can be obtained by compensating voltage fluctuation across DC-link of APF1 & APF main. Final d-axis reference current of both may result [1],

$I_{df} *= I_{dc} + I_1 - I_{dl}$………………………..(23)

$I_{dc} = G_{dc}(s)(V_{dc} * - V_{dc})$……………..(24)

Where, I_{dc} is the DC-link voltage regulator, current command. While V_{dc}* is DC-link voltage command and V_{dc} is feedback of DC-link voltage. Therefore,

$V_{df} *= V_m - R_3 I_{df} - U_{df} + \omega_e L_3 I_{qf}$………………(25)

$V_{qf} *= -R_3 I_{qf} - U_{qf} - \omega_e L_3 I_{df}$…………………..(26)

Where active power filter's current regulators as voltage commands are U_{df} and U_{qf}.

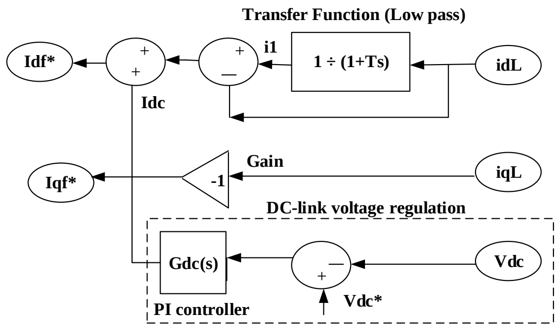

Figure 5: DC-link voltage regulator & low pass filter block

From equations (25) and (26), the terms ω_e ωeL3Iqf & –ωeL3Idf is due to cross-coupling in d-q current control loops [1], [3]. This is generally possible when the main source voltage sinusoidal balanced waveform consists of the only positive sequence. Moreover, non-linear loads with negative sequence currents flowing in three phase power system may result overlapping of both sequences. Hence there is a need for decoupling of these effects that may possible using PI controllers as $G_{df}(s)$ and $G_{qf}(s)$ controller's gain of dq-axes respectively. Therefore, [1]

$U_{df} = G_{df}(s)\left(I_{df} * - I_{df}\right)$……………………(27)

$U_{qf} = G_{qf}(s)(I_{qf} * - I_{qf})$…………………(28)

The Inverse Park Transformation or (dq0 to abc) is represented as,

$$\begin{bmatrix} Vaf^* \\ Vbf^* \\ Vcf^* \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\omega t & \cos\omega t & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} Vdf^* \\ Vqf^* \\ 0 \end{bmatrix} \quad \ldots(29)$$

From equations (22) and (23),

$$G_{dc}(s) = (K_p d_f + \frac{K_i d_f}{s}) \ldots\ldots(30)$$

$$G_{qf}(s) = (K_q q_f + \frac{K_i q_f}{s}) \ldots\ldots(31)$$

Here [1], [13] G_{df}(s) and G_{qf}(s) are for control response time delay as PI controllers, to reduce overshoot complications. & feedback DC-link voltage time delay as:

$$G_{dc}(s) = (K_p d_c + \frac{K_i d_c}{s}) \ldots\ldots(32)$$

Low pass filter transfer function (current controller) as,

1 / (1+sT) ………………..(33)

Here T = 1/ω, the delay time between the load current and reference current of APF. ω, as cut-off frequency will compensate harmonic current and keep the stability of the system.

While low pass filter attenuates signals of higher than cut-off frequency. Moreover, first order delay improves current regulators tracking capability with simplified model analysis.

SIMULATION RESULTS

Without APF :

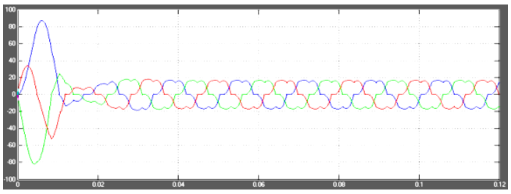

Figure 6: Three Phase AC Source Current under Non-Linear Load

The fig 3 and fig 4 shows the basic 3-phase 4-wire system is considered without using any shunt connected APFs and is having 16.2% of THD when connected to a non-linear load

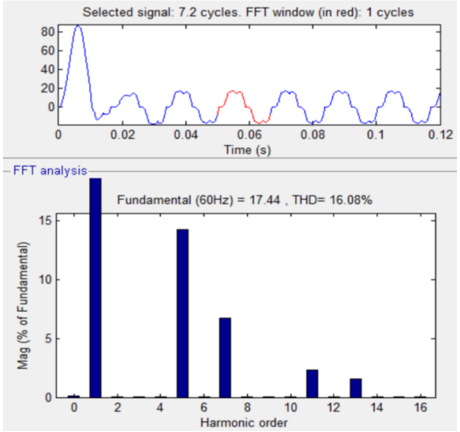

Figure 7: THD Analysis

With Single APF (Sine PWM):

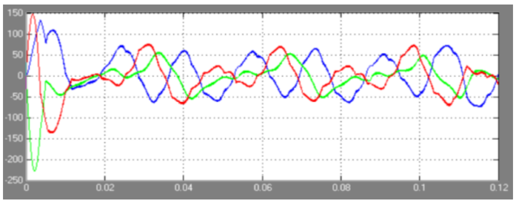

Figure 8: Three Phase AC Source Current under Non-Linear Load

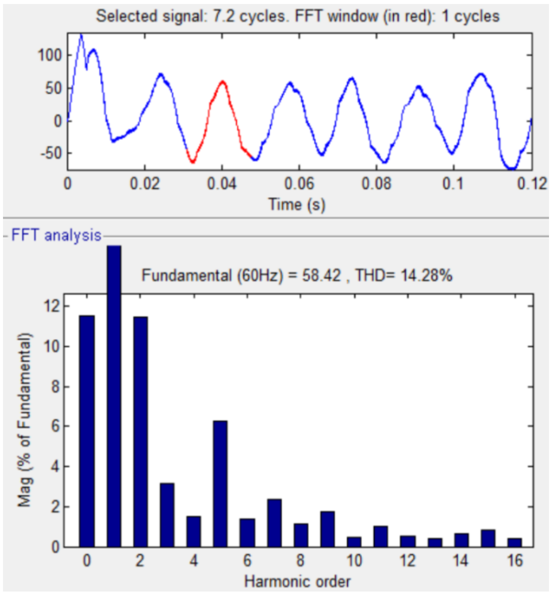

Figure 9: THD Analysis

THD after connecting a 3-phase 4-wire APF is parallel to the main system, is reduced to 14.28% using sine PWM technique to which park's transformation is used for network simplification with in the APF system as shown in Fig 5 and Fig 6. However, as per the IEEE standards, harmonic currents still has to be reduced.

With Dual APF (Sine PWM):

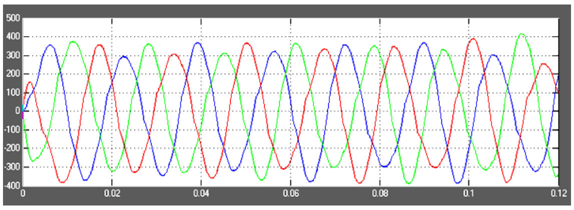

Figure 10: Three Phase AC Source Current under Non-Linear Load

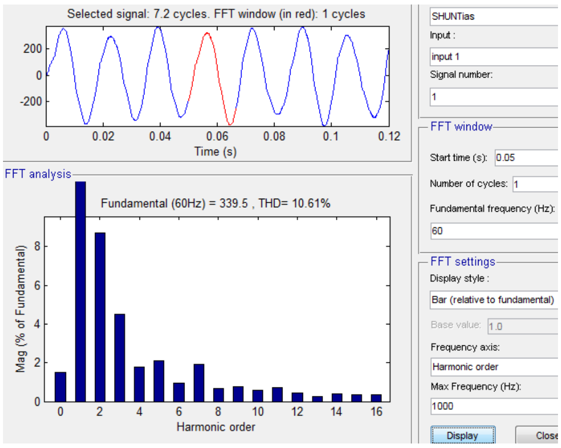

Figure 11: THD Analysis

Here a 3-phase 3-wire APF also called micro grid is placed in addition with 3-phase 4-wire APF , such that proper injection of real power can be done and mitigation of THD has brought down the percentage to 10, provided with external DC source for power quality support.

With Dual APF (Sine PWM) &Zig-Zag Transformer :

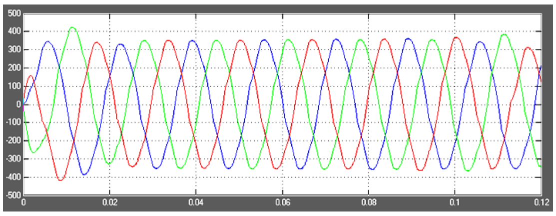

Figure 12: Three Phase AC Source Current under Non-Linear Load

Since,neutral wire carries odd lower order harmonics,hence passive filter (or) zig-zag transformer also called Grounding transformer further eliminated harmonic currents , bringing down THD to 4.28% nearly 50% of harmonic distortion is mitigated

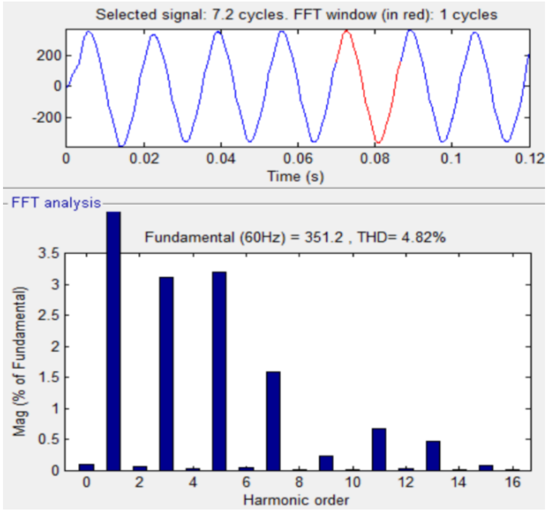

Figure 13: THD Analysis

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With Dual APF (Hysteresis Current Controller) :

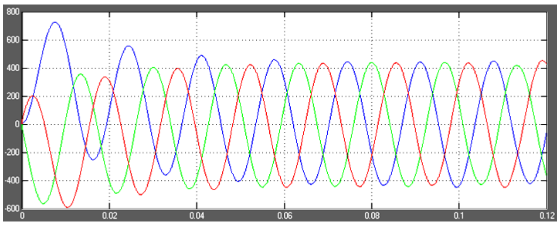

Figure 14: Three Phase AC Source Current under Non-Linear Load

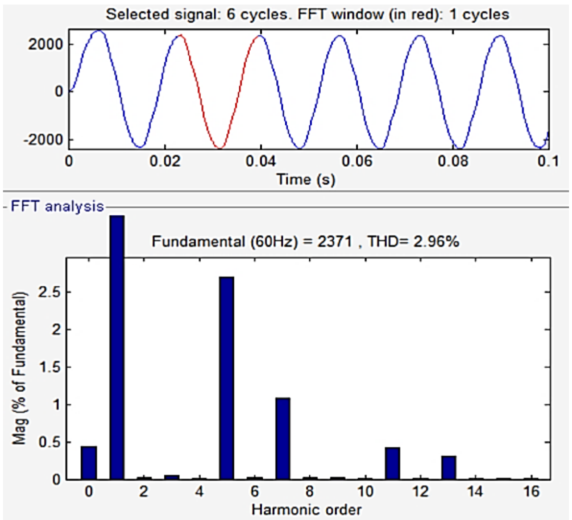

Figure 15: THD Analysis

In the final design, hysteresis current controller is designed for its simplicity and reliability; the APFs gate signal control is replaced by relays.THD is brought down to 2.97%, and power factor is maintained near to unity by adding capacitor bank for power factor correction. Hence successful maximum power consumption of loads is attained.

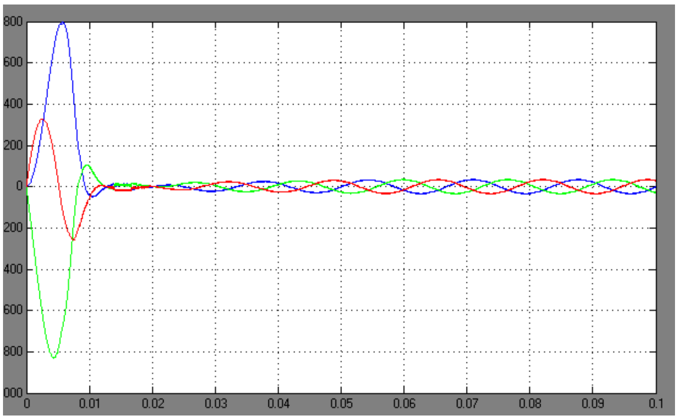

Figure 16: Source current with pi one cycle control

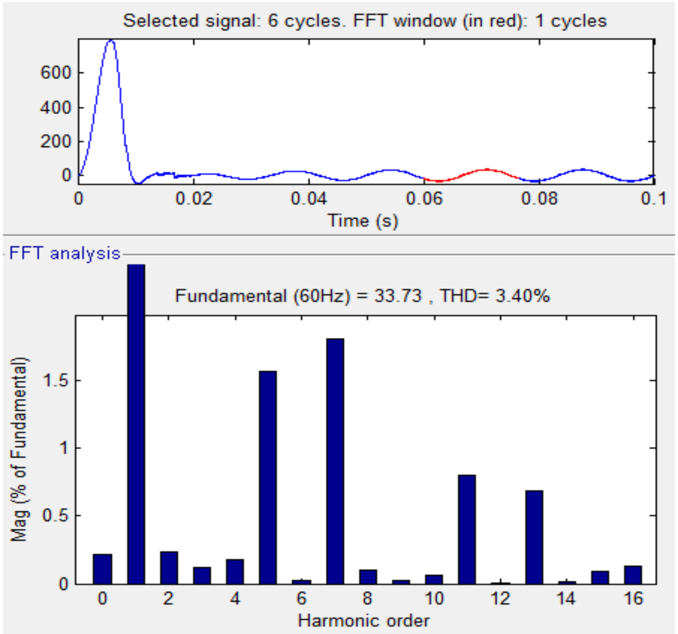

Figure 17: Total Harmonic Distortion with pi one cycle controller

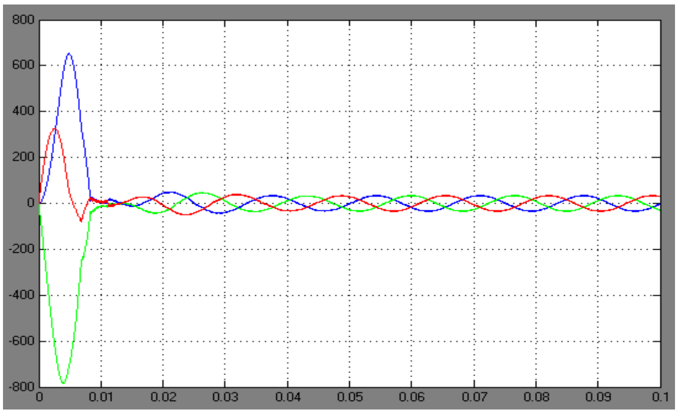

Figure 18: Source current with fuzzy one cycle control

TABLE.1

FINAL RESULTS& COMPARISONS

Three Phase Four Wire Distribution System with & without Dual Shunt (DAPF) Active Power Filter		
	Total Harmonic Distortion (THD) at phase-A source current (ias)	***Power factor (cosΦ)***
Without DAPF	16.08 %	0.8773
With Single Shunt Active Power Filter (Sine PWM)	14.28%	0.5251
With DAPF (Sine PWM)	10.61 %	0.7414
WithDAPF (Sine PWM) &Zig-Zag Transformer	4.82%	0.7839
One cycle controlled DAPF	3.40%	0.8336
WithDAPF (Hysteresis Controller)	2.96 %	0.6758
Fuzzy logic controlled DAPF	2.84%	0.8564

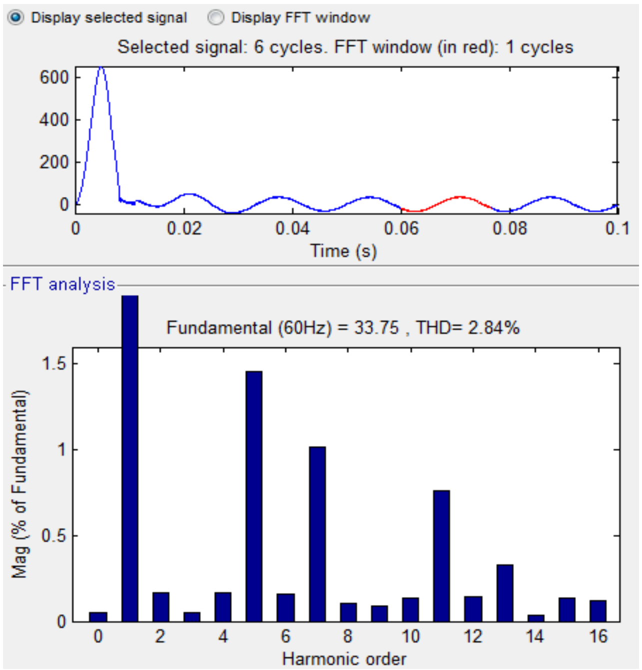

Figure 19: THD with fuzzy one cycle controller

CONCLUSION

After the thorough analysis of the proposed scheme, harmonic currents and the power oscillations are seem feasible to cancel out. With the help of Instantaneous Symmetrical Component Theory (ISCT) control algorithms including PI- controllers, the feedback currents, and the reference currents can be simplified to a first order delay time. Further, the Active Power Filters are rectified by regulating DC-link voltage. In this DAPF model scheme, an additional micro grid is implemented for real power injection. By introducing this model, the necessity of additional dc-link voltage is excluded. If micro grid system fails or stopped working will not be get affected to the main system continuity operation, since APF1 of three phase four wire inverter will be in operating condition as alternate. The system model using sinusoidal Pulse Width Modulation technique with additional an effective passive filter is connected such that to cancel out third order odd harmonics. Although total harmonic distortion got reduced but by using modified scheme i.e., hysteresis current controller, total harmonic distortion got reduced to the maximum extent as per IEEE standard limits. It includes fast and dynamic response with much simpler circuitry design. In order to maintain power factor constant near to unity, capacitors bank as power factor correction is added. Hence the desired maximum power is successfully delivered to the required loads and stabilization of system is achieved.

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