ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Control Strategies for Harmonic Mitigation Using Two Voltage Source Inverters in a Three Phase Four Wire System

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Abstract

In electrical power systems, synchronization of power converters with grid is becoming a prime issue for proper operation. Voltage and frequency synchronization is necessary to integrate the different kinds of generation of electrical power with the grid system. Under uncertainity conditions the currents become unbalanced and also makes the the system unbalanced. Therefore injecting of proper amount of currents into the system is such a method to maximize the power delivery from the source. A dual power converter scheme is being used with a new control strategy to the three phase four wire system for more reliability. The test system results are obtained by using MATLAB/SIMULINK.

Keywords— ***power enhancement of three phase four wire distribution system, dual active power filter, symmetrical component theory (SCT), Park Transformation, Hysteresis controller, Zig-Zag Transformer.***

I. INTRODUCTION

The ever increasing integration of distributed generation systems, which should fulfil the tight requirements imposed by the grid operator regarding grid support under non-linear load conditions and other transient grid faults, has encouraged engineers and researchers to improve conventional control solutions for grid connected power converters. Here the electrical network is a dynamical system, whose behaviour depends upon many factors, like constraints set by power generation systems, the occurrence of grid faults and other contingences, the excitation of resonances or the existence of non-linear loads.A huge amount of appliances employed in domestics, commercials, and other industrial loads are prone to non-linear characteristics, and these are effecting entire power grid system of distribution. Day by day non-linear loads are increasing due to rapid technology development through out the world. In non-linear loads voltage and current relationships are not in phase. The Harmonic distortions leads to a distortion of three phase sinusoidal ac voltage by overlapping of positive sequence component due to grid voltage and negative sequence component due to loads and further deviation between current and voltage phases resulting poor power factor. Therefore, to protect from these different failure conditions such as permanent blackouts, hazards to humans, equipment damage employment of passive and active power filters with efficient controlling methods to keep continuity of the operation of the system and to make satisfy the consumer's demands, became a common practice. Land degradation because of the extraction of fuel from conventional means, limited resource availability, etc. This one made a foremost shift to new non-conventional resources. And also including other concerns like, clean energy, cutback in Electro Magnetic Interference EMI pollution, & economical reliability, etc. This led to practice of employing additional renewable energy sources to the existing distribution generation networks. The most efficient non-conventional alternative sources as (DER) Distribution Energy Resources for power generation sustain are wind energy, solar energy, wave, tidal energy, and geothermal energy.

Distribution power system i.e. three phase four wire system is implemented to which a parallel local

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generated network is interfaced such that efficient power can be exchanged to loads and main grid. This is called microgrid, (APF main) and the notion behind using a microgrid may facilitate as additional voltage source inverter with external DC source for power quality support. The additional Direct Current source voltage can be fed through various Distribution Energy Resources either individually or using combination. APF main or three phase three wire active power filter has two main functions such as, i) compensation of reactive power and several harmonic distortions ii) to facilitate injection of real power to grid iii) to improve overall power factor i.e. maximum power can be consumed to load without losses. While the three phase four wire active power filter (APF1) can compensate third order harmonics of zero sequence currents carried through neutral conductor of fourth wire, including other harmonic currents like positive sequence components. At point of common coupling, the positive sequence extraction of voltage is done using Parks Transformation (abc-dq0).

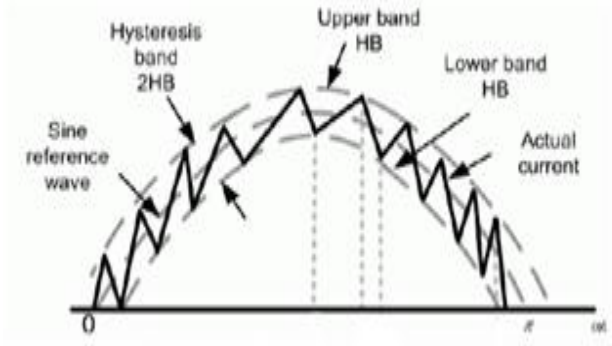
II. Controlling Strategies

Sine PWM

In three phase dc-ac converters, commonly used modulating techniques are like sinusoidal PWM, 60 degree PWM, 3rd harmonic PWM and space vector modulation. In the corresponding model the sinusoidal PWM technique is adopted. When carrier signal is compared with reference phases of vsa, vsb and vsc, the fallowing gate pulses, g1, g3, and g5 being produced [11].

Hysteresis Controller

In case of alternating current AC systems having devices like transformers, induction motors, etc, that have electromagnetic property produce hysteresis loop. Depending on material used for example, steel will have high magnetic strength H, iron may have less magnetic strength H comparatively, whereas air type may have very low magnetic strength H, compared to other two components. Less amount of H may have less hysteresis loop, hence more advantageous. The low coercive force is therefore preferable to prevent magnetic losses. Here the main objective is to generate a sinusoidal AC signal output. The current regulated PWM inverters are used almost in all applications like motor drives and continuous in AC supplies etc, where controlling of current plays the major role of operation in today's power electronic devices.



Filters

Filters basically do not add any new frequencies to input signals, nor change the component frequencies, but it will help to change phase relations and amplitudes of different frequencies. In other words, a filter helps to process a signal either by allowing or blocking the particular desired signal. It has a Gain dependent on frequency of a signal. Filters are further classified as per their properties like, analog/digital, continuous time/discrete time, linear/non-linear, time variant/time invariant, active/passive etc.

Passive Filters

The components that is inactive in nature, such as resistance, inductance and capacitance, to attenuate the corresponding harmonic frequencies by tuning it. At these particular frequencies low impedance path is provided by adjusting inductors and/or capacitors ratings. These filters may mitigate harmonics of two or three but not of multiple at different frequencies. The filters that can eliminate some of the harmonic components are such as, 5th and 7th.

1(a) Zig-Zag Transformer

Zig-Zag transformer, having winding connection of interconnected star type. Hence the vector sum of two

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
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phases is equalized by 120 degrees of each output. It helps to compensate more than 50% of 3rd order lower harmonic currents in neutral conductor. This can reduce maximum THD of the grid system. But it should be noted that the value of impedance of zero sequence should be small. And by proper adjustment of inductance and reactance values at neutral conductor within the filter, THD can be further brought down within the limits of IEEE 519 Standard Specifications without any compromise in power factor decrement. The only limit is due to its lower impedance, equipment may get little bulky using bunch of inductors, resistors, etc

Active Power Filters

If any fault occurs, the active power filter controller will get activated as a backup to mitigate various faults affecting the main grid. In many major industries, three phase four wire electrical distribution systems are implemented. Whenever these power systems connected to non-linear loads, may distort the grid sinusoidal source. Here neutral conductor will carry surplus neutral lower order harmonic currents. So it is recommended to filter out these excess neutral currents that may be possible using three phase four wire voltage source inverters VSI of PWM with APFs.

2 (a) Shunt Connected Active Power Filters (APFs)

Active power filters that are connected in parallel/shunt at PCC of transmission line of power distribution systems, for proper mitigation of harmonic currents by injecting equal amount but opposite of compensating harmonic currents. The harmonic components injected through current source, generated by load with 〖180〗^0 phase shift. Such that the load carrying harmonic current will get cancelled out. Load power factor can also be compensated using appropriate control techniques. Hence these shunt connected APFs are often used in several applications to mitigate harmonic components of currents, reactive power and unbalanced load currents.

III. PROPOSED MODEL

The function of grid connected mode Dual Active Power Filter (DAPF) is developed with the help of symmetrical component theory (SCT) [10] using controlling algorithms. At point of common coupling PCC the positive sequence extraction of voltage is done using Park Transformation (abc-dq0) of both active power filters independently. As shown in fig.1, a three phase four wire distribution system with dual parallel-connected active power filters of three phase four wire(APF1) and three phase three wire (APF main or microgrid) is implemented. The symmetrical component theory SCT is such that three phase distorted ac source expressed by the “sum of components in the positive, negative and zero sequence.” The concept is simpler for analysis of unbalanced faults and/or non-linear conditions. It converts linear transformation of three phase components to a new set of components, called symmetrical components [6].

[Note: In three phase three wire (APF main) have external DC voltage Vdc; in three phase four wire (APF1) DC-link capacitor (C = C1 + C2); iaf = (iam + iax), ibf = (ibm + ibx), & icf = (icm + icx), L3 = (Lm + Lx), R3 = (Rm + Rx) and N as neutral line, as shown in fig.1.]

In APF main or also called as microgrid with connected DC source voltage externally. This power can be obtained from various distributed energy resources or DER, is adjusted and tuned by trial and error method in simulation, adapted from [6].

Hence the distorted three-phase ac source voltage represented in generalized for compensation as [3]:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = V^{+}\begin{bmatrix} \sin(\omega t + \Phi^{+}) \\ \sin(\omega t - 120^{\circ} + \Phi^{+}) \\ \sin(\omega t + 120^{\circ} + \Phi^{+}) \end{bmatrix}$$

$$+V^{-}\begin{bmatrix} \sin(\omega t + \Phi^{-}) \\ \sin(\omega t - 120^{\circ} + \Phi^{-}) \\ \sin(\omega t + 120^{\circ} + \Phi^{-}) \end{bmatrix} + V^{0}\begin{bmatrix} \sin(\omega t + \Phi^{0}) \\ \sin(\omega t + \Phi^{0}) \\ \sin(\omega t + \Phi^{0}) \end{bmatrix} \quad (1)$$

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

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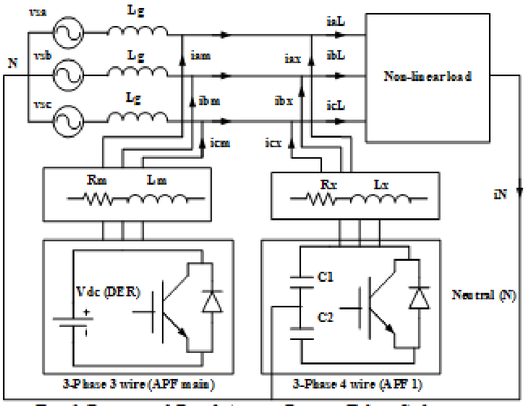

Fig.1 Proposed Dual Active Power Filter Scheme

A Dual APF is considered as shown in fig.1 [6]. Neglecting Lg reactors, the three phase circuit equations connecting APF1 and APF main independently as [1],

$$L3\ d/dt\ iaf = vsa - R3\ iaf - Vaf \qquad (2)$$
$$L3\ d/dt\ ibf = vsb - R3\ ibf - Vbf \qquad (3)$$
$$L3\ d/dt\ icf = vsc - R3\ icf - Vcf \qquad (4)$$

Park Transformation (abc-dq0) or Synchronous Reference Frame SRF for dual APFs individually, given as:

$$\begin{bmatrix} Vd \\ Vq \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} vsa \\ vsb \\ vsc \end{bmatrix} \qquad (5)$$

Here factor 2/3 is by power invariance method also known for time invariant. It is added as a factor of correction such that scaling errors can be eliminated, occurred because of multiplication.

State model analysis of APF1 and APF main:

$$L3\ d/dt\ idf = vd - R3\ idf - Vdf + \omega eL3iqf \qquad (6)$$
$$L3\ d/dt\ iqf = vq - R3\ iqf - Vqf - \omega eL3idf \qquad (7)$$

Where vd and vq for d-q axes of SRF, ωe as power system frequency. And DC-link voltage feedback of APF1:

$$C3\ d/dt\ Vdc = fa\ (iaf) + fb\ (ibf) + fc\ (icf) \qquad (8)$$

Where fb, fc are switching functions, C3 as capacitance of DC-link APF1.
Whereas from equation (8) in d-q axes frame of APF1

$$C3\ d/dt\ Vdc3 = 3/2\ (fd\ idf+fq\ iqf) \qquad (9)$$

Assuming three phase voltages as balanced, hence

$$vd = Vm \qquad (10)$$
$$vq = 0 \qquad (11)$$

where Vm is input peak value of phase voltage.

The instantaneous real and imaginary power symbolized as pL and qL on the load side at three phase balanced load condition can be expressed as [1],

$$pL = 3/2\ Vm\ idL \qquad (12)$$
$$qL = -\,3/2\ Vm\ iqL \qquad (13)$$

The above equations (12) and (13) are applicable for both unbalanced and balanced loading conditions, in which pL and qL are dependent on only idL and iqL respectively. If we assume that, both active power filters having harmonic current as fully compensated then equations (12) and (13) can be further expressed as [1],

$$ps = 3/2\ Vm\ i1 \qquad (14)$$
$$qs = 0 \qquad (15)$$

ps and qs are instantaneous real and imaginary power respectively. Here "i1" in equation (14) is described through d- axis current idL.

And idf * and iqf * as reference currents obtained using feedback of load idL and low pass filter, [1] i.e.,

$$Idf^* = i1 - idL \qquad (16)$$
$$Iqf^* = -\,iqL \qquad (17)$$

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 resulted [1],

$$Idf^* = Idc + I1 - IdL \qquad (18)$$
$$Idc = Gdc(s)\ (Vdc^* - Vdc) \qquad (19)$$

Where, Idc is DC-link voltage regulator, current command. While Vdc* is DC-link voltage command and Vdc is feedback of DC-link voltage. Therefore,

$$Vdf^* = Vm - R3\ Idf - Udf + \omega eL3Iqf \qquad (20)$$
$$Vqf^* = -\,R3\ Iqf - Uqf - \omega eL3Idf \qquad (21)$$

Where, active power filter's current regulators as voltage commands are Udf and Uqf.

From equations (20) and (21), the terms 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 only positive sequence. And 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 Gdf(s)

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
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and Gqf(s) controller's gain of dq-axes respectively. Therefore, [1]

$$Udf = Gdf(s)\,(Idf^* - Idf) \tag{22}$$
$$Uqf = Gqf(s)\,(Iqf^* - Iqf) \tag{23}$$

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

$$\begin{bmatrix} Vaf^* \\ Vbf^* \\ Vcf^* \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\omega t & \cos\omega t & 1 \\ \sin\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \sin\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix}\begin{bmatrix} Vdf^* \\ Vqf^* \\ 0 \end{bmatrix} \tag{24}$$

From equations (22) and (23),

$$Gdf(s) = (\,Kpdf + Kidf/s\,) \tag{25}$$
$$Gqf(s) = (\,Kpqf + Kiqf/s\,) \tag{26}$$

Here PI controllers [1], [13] Gdf(s) and Gqf(s) are for control response time delay, and reduce overshoot problems. & DC-link voltage feedback time delay as:

$$Gdc(s) = (Kpdc + Kidc\,/\,s) \tag{27}$$

Low pass filter transfer function (current controller) as,

$$1\,/\,(1+sT) \tag{28}$$

Here T = 1/ω, delay time between load current and reference current of APF. ω, as cut-off frequency help to eliminate harmonic current and keep the system stable.

Hence the low pass filter attenuates higher than cut-off frequency signals and passes that are lower than cut-off frequency signals. And first order delay improves tracking capability of current regulators with analytical model simplification.

The neutral current of source (grid) should be zero and can be expressed as [6]:

$$ias + ibs + ics = 0 \tag{29}$$

Considering Φ as angle of phase between the source current ias and as positive sequence voltage at fundamental as

$$\angle vfa^+ = \angle ias + \Phi \tag{30}$$

Therefore the average active power to load (PL) has to be deliver by the grid source side and is illustrated as

$$PL = vfa^+\, ias + vfb^+\, ibs + vfc^+\, ics \tag{31}$$

Specifications

Input:
Vsa = vsb = vsc = 98 volts; Frequency (fundamental) = 60 hz
Grid inductance Lg = 0.0004 Henry; Resistance R = 0.03 Ω
Non-Linear Load (Rectfier):
Load resistance RL = 8.67 Ω; Inductance L = 0.0031 Henry;
Capacitor C = 0.0033 Farad
Active Power Filter (APF 1):
Resistance R3 = 0.03 Ω; Inductance L3 = 0.0002 Henry;
Capacitor C1 = C2 = 2.35 milli Farad
Active Power Filter (APF main or microgrid):
Resistance R3 = 0.03 Ω; Inductance L3 = 0.0002 Henry;
DC inverter voltage Vdc = 100 volts
Control structure (dq0-abc) for APF 1 & APF main:
kp = 62.5; ki = 375; R3 = 0.03 Ω; ωeL3 = 0.885;
Idf* (d-axis low pas filter transfer function), T = 0.01;
Iqf* (q-axis), gain = -1
DC-link voltage regulation:
PI controller (Gdc(s)), kp = 0.381; ki = 1.2;
Reference voltage Vdc* = 240 volts
Zig-Zag Transformer, SI units in (pu) per unit:
Zero-sequence Resistance (R0) = 0.01 Ω; zero-sequence reactance (X0) = 0.0002 Ω
Sine PWM function: f (u) = - (asin(u)*2/pi*100)

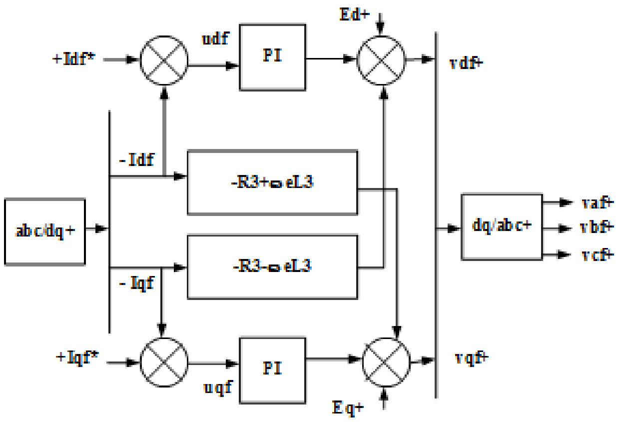

Fig.6 Control Structure using Park Transformation

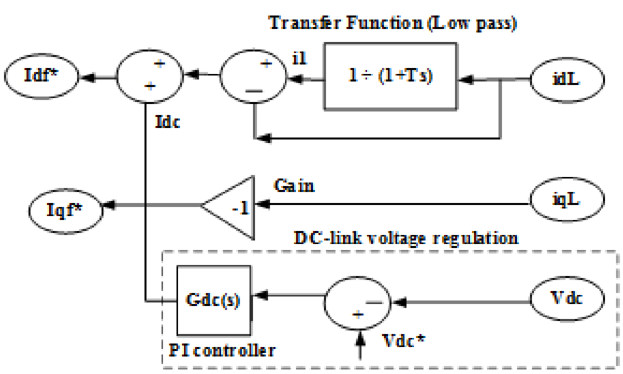

Fig.7 DC-link voltage regulator & low pass filter block

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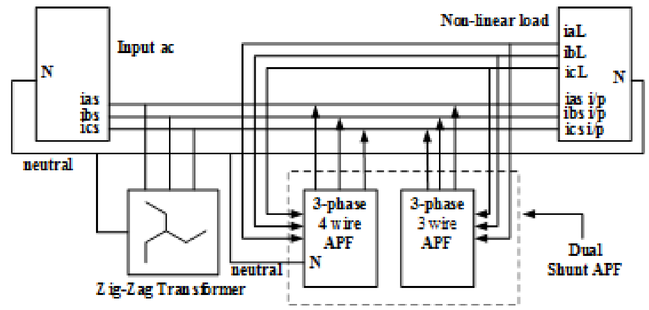

Fig.8 Modified block model with Zig-Zag Transformer

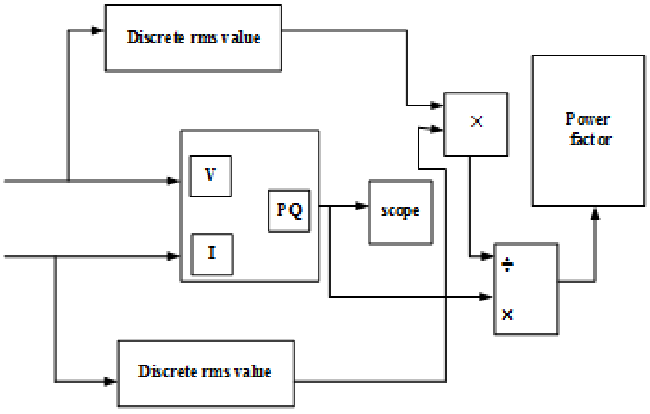

Fig.9 Power Factor Block

TABLE.1 FINAL RESULTS

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 (cos Φ)*
Without DAPF	16.08 %	0.8773
With DAPF (Sine PWM)	10.61 %	0.7414
With DAPF (Hysteresis Controller)	1.07 %	0.1676
With DAPF (Sine PWM) & Zig-Zag Transformer	3.77%	0.7839

IV. SIMULATION RESULTS

1. Without Dual APF

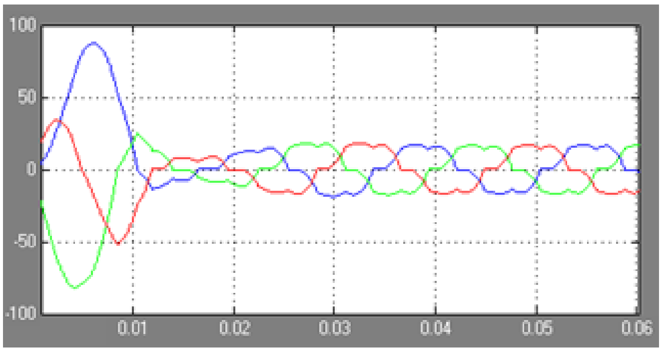

Fig.8 Three Phase AC Source Current under Non-Linear Load

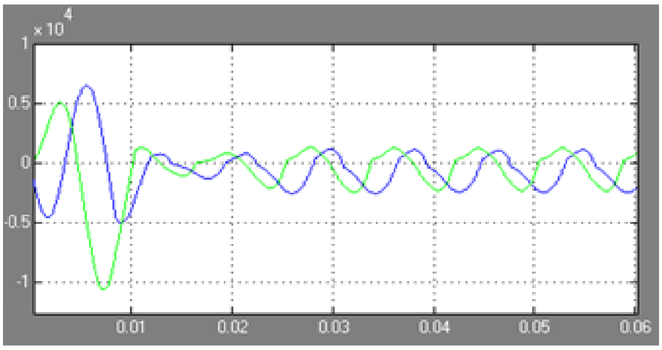

Fig.9 Three Phase Power Oscillations

2. With Dual APF (Sine PWM)

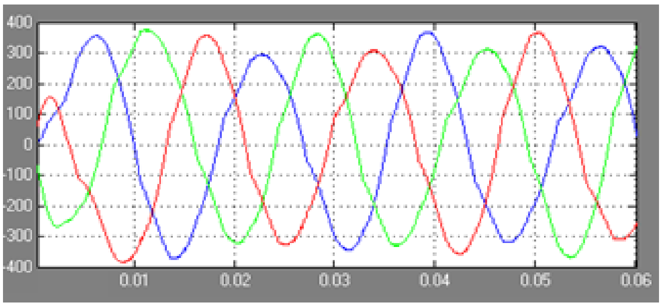

Fig.10 Three Phase AC Source Current under Non-Linear Load

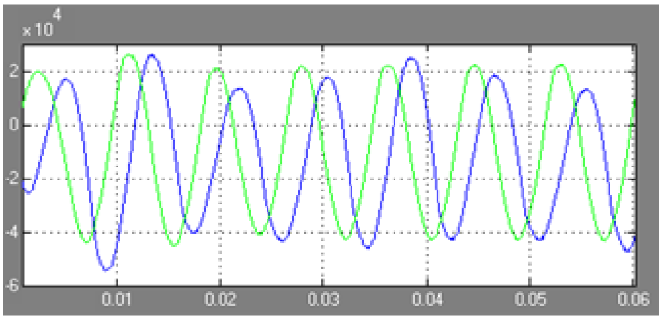

Fig.10 Three Phase Power Oscillations

3. With Dual APF (Hysteresis Controller)

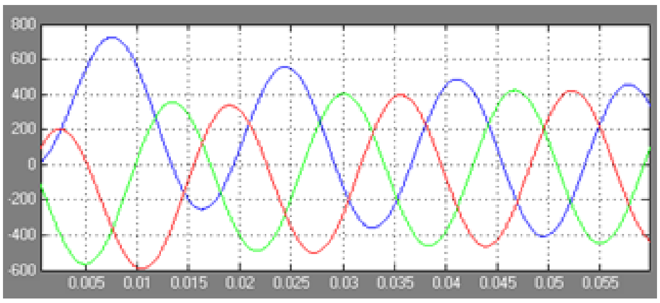

Fig.11 Three Phase AC Source Current under Non-Linear Load

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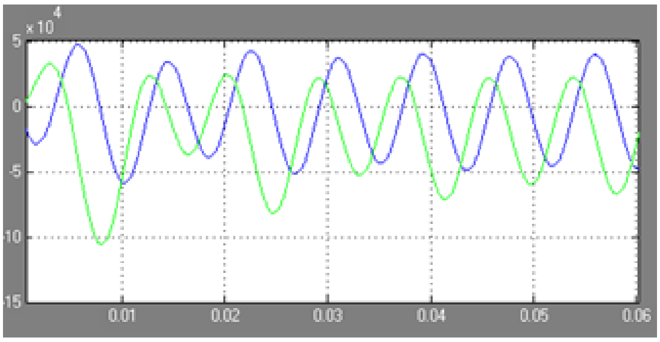

Fig.12 Three Phase Power Oscillations

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

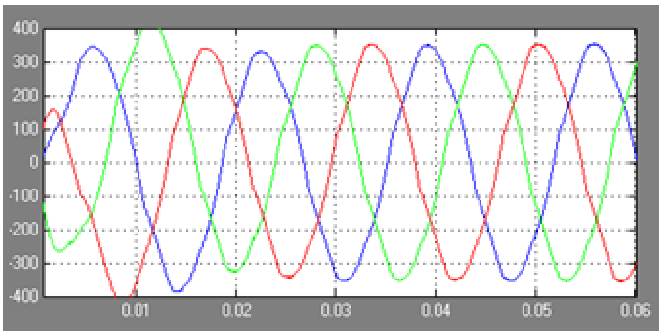

Fig.13 Three Phase AC Source Current under Non-Linear Load

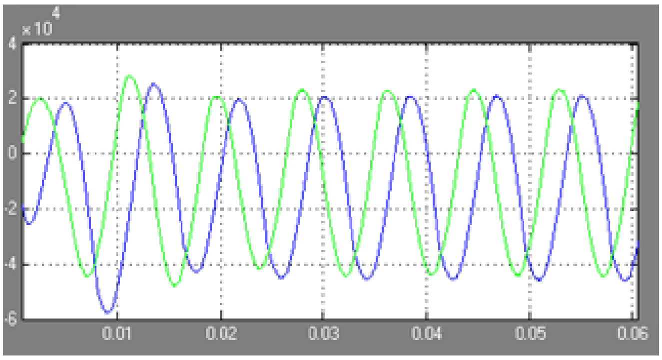

Fig.14 Three Phase Power Oscillations

V. CONCLUSION

Harmonics and oscillations are viable to cancel out in any system. By using SCT control algorithms and Proportional-Intigral controllers, the reference and measured currents can be simplified to a delay time of first order, including better regulation in DC-link voltage of Active Power Filterss. In DAPF scheme, an additional three phase three wire APFmain topology as micro grid is used. Therefore the need of dc-link voltage is eliminated. And keep maintained system continuity even if it fails to operate. The hysteresis controller used t to reduce the total harmonic distortion effectively but it results a poor power factor. Therefore the system model is replaced by sinusoidal Pulse Width Modulation technique and an effective passive filter zig-zag transformer is connected to neutral line of three phase four wire power distribution system to cancel out lower third order odd harmonics of zero sequence. Although total harmonic distortion reduced not as effective with hysteresis controller but is brought down within the limits of IEEE standards specifications. And further near to unity power factor is attained, i.e., maximum power of desired is being consumed to the loads successfully and system stability is accomplished.

References

[1] H.H.Kuo, S.N.Yeh and J.C.Hwang, "Novel analytical model for design and implementation of three-phase active power filter controller," IEE Proceedings, Vol.148, No. 4, July 2001.

[2] J.Alekha, K.Kusal kumar," power enhancement by adopting dual active power filter scheme with control strategies under grid distortions". International Journal & Magazine of Engineering, Technology, Management and Research. ISSN NO:2348-4845.

[3] Yantao Song and Bingsen Wang, "Survey on Reliability of Power Electronic Systems," IEEE Transaction on Power electronics, vol.28, No.1, January 2013.

[4] A Joun Wiley and Sons, Ltd, "Grid converters for photovoltaic and wind power systems," IEEE, Publication 2011.

[5] Maur´ıcio Aredes, "Three-Phase Four-Wire Shunt Active Filter Control Strategies," IEEE Transactions On Power Electronics, Vol. 12, No. 2, March 1997.

[6] Pedro Rodriguez, Adrian V. Timbus, Remus Teodorescu, Marco Liserre, and Frede Blaabjerg, "Flexible Active Power Control of Distributed Power

Generation Systems During Grid Faults," IEEE Transactions On Industrial Electronics, Vol. 54, No. 5, October 2007.

[7] M. V. Manoj Kumar, Mahesh K. Mishra, and Chandan Kumar, "A Grid-Connected Dual Voltage Source Inverter With Power Quality Improvement Features," IEEE Transactions On Sustainable Energy, Vol. 6, No. 2, April 2015.

[8] Mukhtiar Singh, Vinod Khadkikar, Ambrish Chandra, and Rajiv K. Varma, "Grid Interconnection of Renewable Energy Sources at the Distribution Level With Power-Quality Improvement Features," IEEE Transactions On Power Delivery, Vol. 26, No. 1, January 2011.

[9] Poh Chiang Loh, Lei Zhang, and Feng Gao, "Compact Integrated Energy Systems for Distributed Generation" IEEE Transactions On Industrial Electronics, Vol. 60, No. 4, April 2013.

[10] E.ON Netz GmbH, Bayreuth, "Grid Code: High and Extra high voltage" April 2006.

[11] Dhanpat Rai Publications (P) Ltd, "Electrical Circuit's Analysis".

[12] Muhammad H. Rashid, "Power Electronics Handbook", Editor-In-Chief.

[13] Muhammad H. Rashid, "Power Electronics Circuits, Devices, And Applications", Pearson, Third Edition.

[14] A. Nagoor Kani, "Control Systems", RBA Publications, First Edition.

[15] J. W. Kolar, and T. Friedli, "The Essence of Three-Phase PFC Rectifier Systems - Part I," IEEE Transactions on Power Electronics, Vol. 28, No. 1, pp. 176-198, January 2013.

[16] Dr. P. S. Bimbhra, "Electrical Machinery".