Three Level Hysteresis Current Controller based Active Power Filter for Harmonic Compensation

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Abstract— **This paper present three-phase four-wire active filter for power line conditioning (PLC) to improve power quality in the distribution network. The active power filter (APF) is implemented with PWM based current controlled voltage source inverter (VSI). This VSI switching signals are generated through proposed three-level hysteresis current controller (HCC) that achieves significant reduction in the magnitude and variation of the switching frequency; it is indicating improved performance compared to 2-level HCC. The shunt APLC system is modeled and investigated under different unbalanced non-linear load conditions using Matlab programs. The simulation results reveal that the active power filter is effectively compensating the current harmonics and reactive power at point of common coupling. The active power line conditioner system is in compliance with IEEE 519 and IEC 61000-3 recommended harmonic standards.**

Keywords— **Active Power Line Conditioners (APLC), PI-Controller, 3-level Hysteresis Current Controller (HCC), Harmonics, Power quality**

I.INTRODUCTION

Active power line conditioners (APLC) or active power filters (APF) are being investigated and developed as a feasible solution for solving power quality problems [1]. In recent years power quality issue in industrial as well as manufacturing utilities has become a subject of serious concern due to the intensive use of power electronic equipment [2]. Continuing proliferation of nonlinear loads such as power converters, SMPS, photo copiers, printer, UPS, ASDs are creating disturbances like harmonic pollution and reactive power problems in the power distribution lines [3]. Conventionally these problems are solved by passive L-C filters. But these L-C filters introduce tuning and aging problems, resonance, are large in size and are suited for fixed harmonic compensation [4]. So active power-line conditioners have become popular than passive filters; it compensates the harmonics and reactive power simultaneously [5]. The active power filter topology can be connected in series or shunt and combinations of both (unified power quality conditioners). Passive filters combined with active shunt and series are some typical (hybrid) configurations that can be used for the same purpose. Shunt active filter is more popular than series filter, because most of the industrial applications require current harmonics compensation [1] [4-5].

The shunt active power converter can be executed with current source inverter (CSI) or voltage source inverter (VSI) [6]. The voltage source inverter has three coupling inductors in series in the ac-side and an energy storage capacitor on the dc-side. Similarly, the current source inverter has three coupling capacitors in parallel in the ac-side and an energy storage inductor in series with the dc-side [7]. In general the voltage source inverter type is preferred for the shunt active power circuit due to the lower losses in the dc-side and it is possible to create multilevel inverter topologies for higher power level applications. The current control techniques of the voltage source inverters can be broadly classified into linear and non-linear controller [4-7].

The linear current controllers generate required variable voltage which is then fed into sine-triangle pulse width modulation (PWM) to generate the gate drives switching pulses for the VSI. The non-linear current controllers are based on hysteresis bands, in which actual currents are compared to reference currents instantaneously [8-9]. The current error is either exceeding the upper limit or lower limit of the hysteresis band; according to band limit, the upper or lower switch becomes ON or OFF. The range of the current error directly controls the voltage source inverter switching transistor (MOSFET or IGBT switches) [10].

The linear current controllers are characterized by constant switching frequency. On the other hand the non-linear current controllers are characterized by varying switching frequencies [9]. It provides fast response to transient conditions and hence the non-linear hysteresis current control is the most sought after method of current control. It provides advantages like automatic peak current limitation, simple hardware implementation, load parameter independence and unconditional stability. Conventionally two level hysteresis controllers are used, because the circuit is very simple [11]; however it does not use zero voltage from the inverter dc-side; only positive and negative dc supply voltages are used [12-13]. It is known that the harmonic performance of 2-level modulation is inferior to 3-level modulation [9]. The 2-level modulation generates significant sideband harmonics around the switching frequency. Therefore, the 3-level hysteresis modulation implemented with 3-level switching process is adopted in this paper. This approach provides superior performance on harmonic perspective.

This paper describes three-phase four-wire shunt active power line conditioners for current harmonic compensation under non-linear load conditions. . The three phase active power filter is implemented with current controlled voltage source inverter (VSI). The VSI switching signals are derived from 3-level hysteresis current controller; it is indicating improved performance compared to 2-level HCC. The shunt APLC system is investigated under unbalanced non-linear load conditions.

II. HYSTERESIS CURRENT CONTROLLER

The hysteresis band current control for active power filter line currents can be carried out to generate the switching pattern of the inverter. There are various current control methods proposed for such active power filter configurations; but the hysteresis current control method has the highest rate among other current control methods, because of quick current controllability, easy implementation and unconditioned stability [10-11]. The hysteresis band current control is robust, provides excellent dynamics and fastest control with minimum hardware. This paper presents two-level and three-level hysteresis current controller for proposed active power filter systems and a comparison between those.

A) Two-level hysteresis current controller:

Conventional hysteresis current control operates the PWM voltage source inverter by comparing the current error $e(t)$ against fixed hysteresis bands. This current error is difference between the desired current $i_{ref}(t)$ and the current being injected by the inverter $i_{actual}(t)$ as shown in Fig 1.

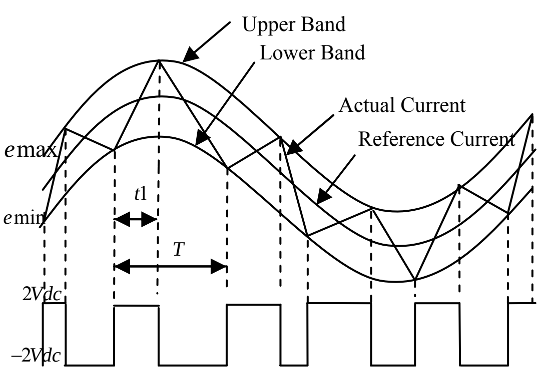

Fig 1 Diagram of two-level hysteresis current control

If the error current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned OFF and the lower switch is turned ON. If the error current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned OFF and the upper switch is turned ON. These two level switching strategies does not use the inverter zero output condition, but the 3-level switching is possible by incorporating zero level [9].

This control strategy of the switching frequency can be determined that follows. The rate of change of phase current at any point in time is written as

$$\frac{dI}{dt} = \frac{\Delta I}{\Delta t} = \frac{\pm 2V_{dc}}{L} \Rightarrow \Delta t = \frac{\Delta I\, L}{\pm 2V_{dc}} \tag{1}$$

Where $\pm 2V_{dc}$ is depending on inverter switching state, ΔI is rate of changing inverter current, Δt is rate of changing in time period and L is series inductance of the filter. A complete switching cycle goes from $0 \to t_1 \to T$.

For the period $0 \to t_1,\ \Delta t = t_1$ and therefore:

$$t_1 = \frac{+\Delta I\, L}{2V_{dc}} \tag{2}$$

For the period $t_1 \to T/2,\ \Delta t = T - t_1$ and therefore:

$$T - t_1 = \frac{-\Delta I\, L}{-2V_{dc}} \tag{3}$$

The total switching time is obtained by combining these two equations and it give as:

$$f_s = \frac{1}{T} = \frac{V_{dc}^{\ 2}}{\Delta I\, L V_{dc}} \ \rightarrow\ f_{\max} = \frac{V_{dc}}{\Delta I\, L} \tag{4}$$

Here $f_{\max}$ is maximum switching frequency of the inverter. The variation in the switching frequency influences the performance of the current controller both in terms of harmonics and the maximum switching frequency.

B) Three-level hysteresis current controller:

The implementation of three level modulations hysteresis controller are set as upper and lower band overlap boundaries and displacement by a small offset current. Whenever the current error $e(t)$ crosses an outer hysteresis boundary, that time the inverter output is set to an active positive or negative output to force a reversal of the current error. Similarly whenever the current error reaches an inner hysteresis boundary, that time the inverter output is set to a zero condition and the current error will be forced to reverse direction without reaching the next outer boundary. If the selection of a zero output does not reverse the current error, it will continue through the inner boundary to the next outer hysteresis boundary, at which point an opposite polarity inverter output will be commanded and the current will reverse anyway.

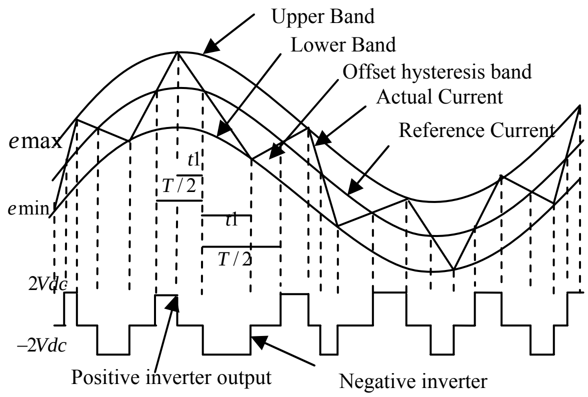

Fig 2 Diagram of three-level hysteresis current control

This switching process is shown in Fig 2, where the current error is bounded between the upper-inner and lower-outer hysteresis boundaries for a positive inverter output, similarly the lower-inner and upper-outer hysteresis boundaries for a negative inverter output. This new switching process introduces a positive or negative dc offset error into the average output current that is depending on the active output voltage. However, this error can be corrected by adding a compensation factor of hysteresis band offset magnitude to the reference current; it is positive when a positive inverter output is in utilize and negative when a negative inverter output is in utilize. The MATLAB program for a-phase switching operation of the inverter is given as

```
if errora>0
      if errora>=(h)
      swa=0;
      end
    if errora<=del
      swa=1;
 end

if errora<0
      if errora<=(-h)
      swa=2;
      end
    if errora>=(-del)
      swa=1;
     end
```

If swa=0 implies the switch state is +Vdc; elseif swa=1 is implies the switch state is 0; elseif swa=2 is implies the switch state is +Vdc; Similarly the b-phase and c-phase switching function can be performed to the three phase voltage source inverter.

The switching frequency for the three level controllers can be derived as follows; a three level switching cycle goes from $0 \rightarrow t_1 \rightarrow T/2$.

For the period $0 \rightarrow t_1, \Delta t = t_1$ and therefore:

$t_1 = -\Delta I\, L$

For the period $t_1 \rightarrow T/2,\ \Delta t = T/2 - t_1$ and therefore:

$$T/2 - t_1 = \frac{+\Delta I\, L}{+2V_{dc}} \qquad (5)$$

The total switching time is obtained by combining these two equations and it give as:

$$f_s = \frac{2V_{dc}}{8\Delta I\, L V_{dc}} \rightarrow f_{\max} = \frac{V_{dc}}{4\Delta I\, L} \qquad (6)$$

Here $f_{\max}$ is maximum switching frequency of the inverter. Comparing equation (4) with (6), it can be seen that the maximum switching frequency has been reduced by a factor of 4 for the three level controllers. Therefore, it will have a significantly reduced harmonic bandwidth compared to a two level hysteresis controller at the same average switching frequency and an expected corresponding improvement in harmonic performance.

III.SIMULATION RESULT AND ANALYSIS

The performance of the three-phase four-wire shunt APLC system is evaluated through Matlab programs in order to program and test the system under unbalanced non-linear load conditions. The system parameters values are; Line to line source voltage is 440 V; System frequency (f) is 50 Hz; DC-link capacitor C1=1100 µF and C2=1100 µF ; Reference dc voltage 600 V; Interface inductor is 2 mH and 1 Ω full bridge rectifier load 168 + j 16 Ω.

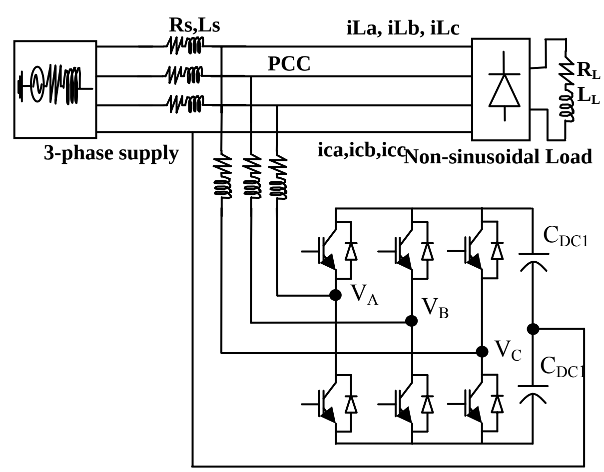

Fig 3 APLC system implemented with voltage source inverter

The conventional power circuit of the voltage source inverter based active power filter connected at the point of common coupling, as shown in Fig 3. The voltage source inverter has six power transistors with freewheeling diodes and two energy storages capacitor on DC-side that is implemented as a four-wire active power filter.

The three-phase four-wire AC power supply connected to the unbalanced non-linear load as shown in Fig 3. The supply voltage is balanced and that is defined as $v_s(t) = V_m \sin \omega t$. The measurement of the 3-phase instantaneous supply voltage is shown in Fig 4.

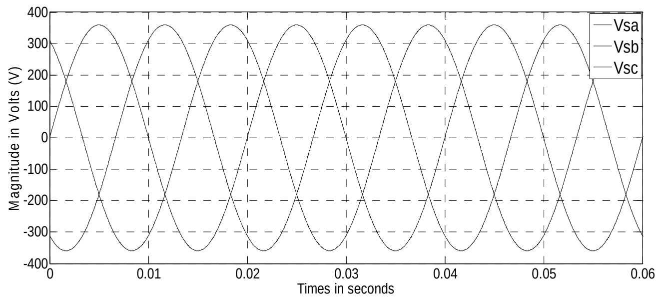

Fig 4 balanced three-phase supply voltages

The source draws non-sinusoidal or harmonic current due to the non-linear load. This nonlinear load current contains the fundamental signals and harmonic current components. Fig 5 shows the unbalanced non-linear load current or source current before compensation. It is indicate that the source current is having harmonic components due to the non-linear load.

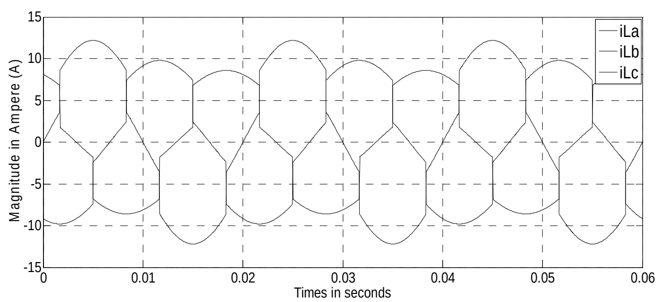

Fig 5 Source current before compensation

The 3-phase source voltages are converted to the 3-phase unit current(s) while corresponding phase angles are maintained. The unit current is defined as

$$
\begin{aligned}
i_a &= \sin \omega t, \\
i_b &= \sin(\omega t - 120^0) \ and \qquad (7) \\
i_c &= \sin(\omega t + 120^0)
\end{aligned}
$$

These unit currents multiplied with peak reference current for generating the reference currents. The proposed PI-control scheme estimates the peak reference current of an APF system. The two storage DC-side capacitor voltage is sensed and compared with a reference voltage. The error $e = V_{dc,ref} - (V_{dc1} + V_{dc2})$ at the n^{th} sampling instant is used as input for PI-controller. Its transfer function can be represented as

$$H(s) = K_P + K_I / s \qquad (8)$$

where, K_P [K_P =0.3] is determines the dynamic response of the DC-side voltage and K_I [K_I =15] is determines the settling time. The PI- controller controls the DC-side capacitor voltage and estimates the magnitude of peak reference current. The peak current multiplied with output of unit current vector for determines the reference current, that shown in Fig 6.

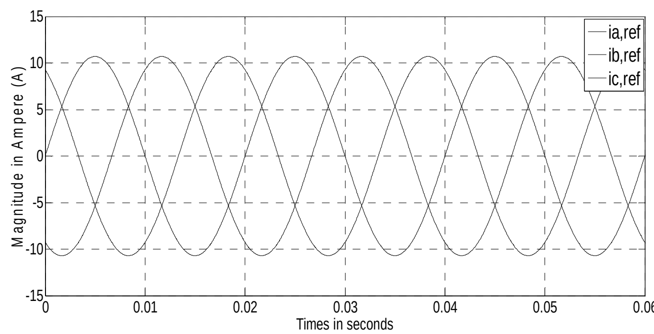

Fig 6 three-phase reference current

The reference current is compared with inverter current. Thus switching pulses using two-level hysteresis controllers for VSI are generated. These two level switching strategies does not use the inverter zero output condition. It has $+Vdc$ *and* $-Vdc$ inverter output of two-level hysteresis modulation controller, as shown in Fig 7.

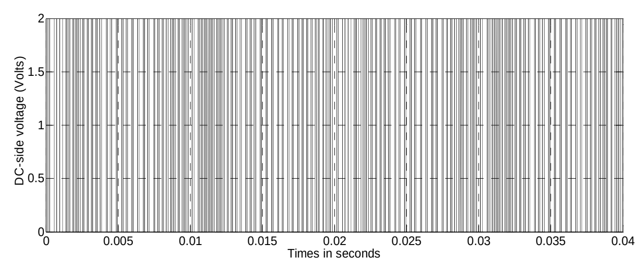

Fig 7 switching pattern of 2-level hysteresis current controller

The three level modulations hysteresis controller are set as upper and lower band overlap boundaries and their displacement by a small offset current. The reference current is compared with inverter current that gives the current error. If the current error crosses an outer hysteresis boundary, that times the inverter output is set to a positive or negative. If the current error reaches an inner hysteresis boundary, that time the inverter output is set to a zero condition, shown in Fig 8. It has $+Vdc$, 0 *and* $-Vdc$ inverter output, because of three-level hysteresis modulation controller. Therefore, three-level modulation have a significantly reduced harmonic bandwidth compared to a two level hysteresis controller at the same average switching frequency and an expected corresponding improvement in harmonic performance.

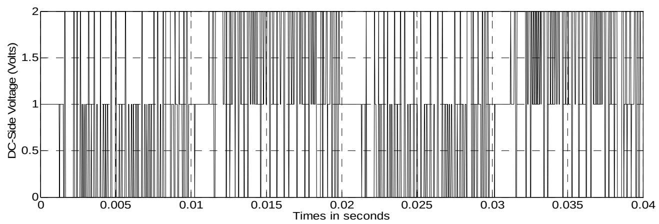

Fig 8 switching pattern of 3-level hysteresis current controller

The power circuit of the voltage source inverter based active power filter connected at the point of common coupling for compensates the current harmonics. The active filter must provide the harmonic filter current or compensation current as $i_c(t) = i_L(t) - i_s(t)$. Fig 9 shows the required compensation current for eliminating the harmonics.

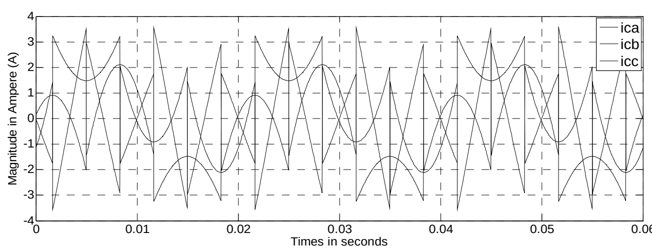

Fig 9 compensation or filter current

The active filter must provide the harmonic filter current or compensation current. The current harmonics are compensated by injecting equal but opposite current distortion components at the PCC, there by canceling the original harmonic and improving the power quality. The simulation result of source current after compensation is presented in Fig 10 that indicates the current is sinusoidal.

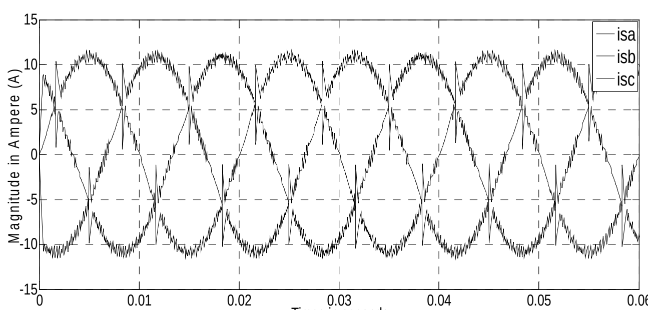

Fig 10 Source currents after active power filter compensation.

The two DC-side capacitors voltage is controlled by proportional integral (PI) controller. The PI-controller maintains the capacitors voltage with small ripple in steady and transient state, shown in Fig 11. It serves as an energy storage element to supply a real power to operate three-phase voltage source inverter.

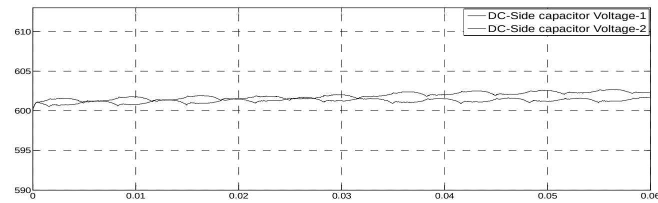

Fig 11 Dc-side capacitor voltage

The Fast Fourier Transform (FFT) is used to measures the order of harmonics with the fundamental frequency 50 Hz at the source current. These harmonics are plotted for source current before active filter compensation that is shown in Fig 12 (a). The Total harmonic Distortion (THD) of the distorted line current is 25.41%. From the harmonic spectrum, it is observed that the supply current is distorted due to the dominancy of fifth and seventh harmonic components. The orders of the harmonics are also plotted for source current after active filter compensation that is shown in Fig 12 (b). THD comes down to 3.74 %.

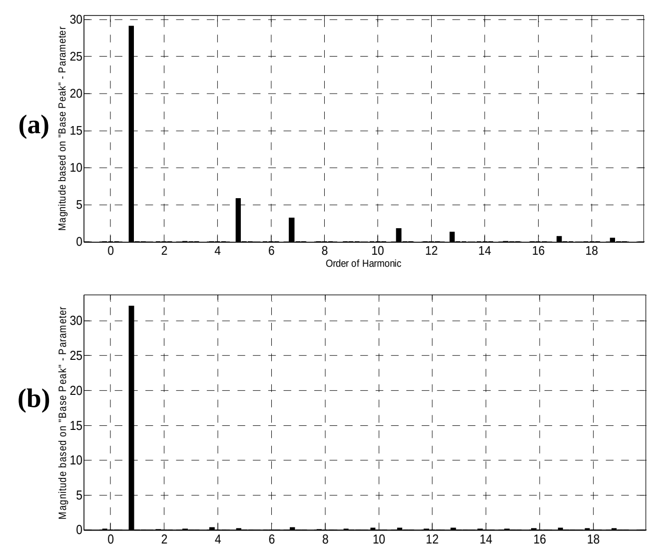

Fig 12 Order of harmonics (a) the source current without active filter (THD=25.41%), (b) with active power filter(THD=3.74%)

The active filter is effectively compensating the current harmonics and making the source current is sinusoidal in the distribution system. FFT analysis confirms that the active filter brings the THD of the source current to be less than 5% in compliance with IEEE 519-1992 and IEC 61000-3 standards of harmonics.

V. CONCLUSIONS

This paper presents design and implementation of a three level hysteresis current control scheme for three-phase four-wire active power line conditioners. The three-level hysteresis controller reduces the variation of the switching frequency and it indicates improved performance compared to 2-level HCC. This active power filter system is tested and verified using MATLAB program. These results demonstrate that the active filter is effective in compensating current harmonics that facilitates improves power quality in the distribution network.

REFERENCES

[1] Fermin Barrero, Salvador Martinez, Fernando Yeves and Pedro M. Martinez "Active Power Filters for Line Conditioning: A Critical Evaluation" IEEE Trans on Power Delivery, Vol.15, No.1, pp.319-325, 2000.

[2] Christopher K. Duffey and Ray.P. Stratford "Update of Harmonic Standard IEEE-519: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems" IEEE Trans on Industry Appl, Vol.25, No.6, pp.1025-1034, 1989.

[3] Joseph S. Subjak, JR and John S. Mcquilkin "Harmonics- Causes, Effects, Measurements, and Analysis: An Update" IEEE Trans on Industry Appl,Vol.26, No.6,pp.1034-1042, 1990.

[4] Bhim Singh, Kamal Al-Haddad and Ambrish Chandrs "A Review of Active Filters foe Power Quality Improvements" IEEE Trans on Industrial Electronics, Vol.46, No.5, pp. 960-970, Oct-1999.

[5] Prasad N. Enjeti, Wajiha Shireen, Paul Packebush and Ira J. Pitel "Analysis and Design of a New Active Power Filter to Cancel Neutral Current Harmonics in Three-phase Four-Wire Electric Distribution Systems" IEEE Trans on Industry appl,Vol.30, No.6, Nov/Dec-1994

[6] W.M.Grady, M.J.Samotyj, A.H.Noyola "Survey of Active Power Line Conditioning Methodologies" IEEE Trans on Power Delivery, Vol.5, No.3, pp.1536-1542, 1990

[7] Maria Isabel Milanes Montero, Enrique Romero Cadaval, and Fermin Barrero Gonzalez "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems" IEEE Trans on Power Elects, Vol. 22,No.1,2007.

[8] O.Vodyakho T.Kim "Shunt active filter based on three-level inverter for 3-phase four-wire systems" IET Power Electron,Vol.2,No.3, pp. 216–226, 2006

[9] G.H. Bode and D.G. Holmes "Implementation of Three Level Hysteresis Current Control for a Single Phase Voltage Source Inverter" IEEE-Conference, pp.7803-5692, 2000.

[10] Brod D.M, Novotny D.M "Current control of VSI-PWM Inverter"- IEEE Trans on Industry Appl, Vol.21, pp.562-570, 1985

[11] Jiang Zeng, Chang Yu, Qingru Qi, Zheng Yan, Yixin Ni, B.L. Zhang, Shousun Chen and Felix F. Wu (2004) "A novel hysteresis current control for active power filter with constant frequency" Electric Power Systems Research 68, pp.75-82

[12] Marian P. Kaunierkowski, Maciej A. Dzieniakowslu (1994) "Review of Current Regulation Techniques For Three-phase PWM Inverters" Conference on IECON'94, Vol.1, pp.567 – 575,1994

[13] N.Belhaouchet and L. Rahmani Development of Adaptive Hysteresis-band Current Control of PWM Three-Phase AC Chopper with Constant Switching Frequency, Electric Power Components and Systems, Vol.33, No.10, pp.583-598, 2009