

Dynamic Performance of Adaptive Hysteresis Current Controller for Mains-connected Inverter System

B.Chitti Babu, *Member, IEEE*, Mohamayee Mohapatra, *Student Member, IEEE*,
Satyaranjan Jena, *Student Member, IEEE*, Amiya Naik

Department of Electrical Engineering, National Institute of Technology, Rourkela (INDIA)

E-mail: bcbabunitrkl@gmail.com, mohamayee@gmail.com, srj.nitrkl@gmail.com, naikamiya@gmail.com

Abstract- In most of the situations, power electronics converters are mainly used as an interfacing device between distributed generation (DG) system and utility grid in order to meet the following objectives: 1) grid synchronization 2) active and reactive power control through voltage and frequency control 3) improvement of power quality (i.e. harmonic elimination) etc. But due to wide variation of the reactive power in the consumers-end, the voltage at the point of common coupling (PCC) is usually affected. In this paper adaptive hysteresis current controller is proposed for inverter-interfaced grid connected system in order to meet the active and reactive power demand during load variations and both can be controlled independently. The proposed controller reduces the current harmonic at PCC considerably. It observes that the adaptive hysteresis current controller can provide the low switching frequency of operation of inverter switches irrespective of load variations and it ensures lower total harmonic distortion (THD). The studied system is modeled and simulated in the MATLAB Simulink environment.

Keywords—Adaptive hysteresis current controller, Point of common coupling (PCC), distributed generation (DG), Reactive power control.

NOMENCLATURE

i_{la}, i_{lb}, i_{lc}	three phase grid current
i_d, i_q	d and q axis current
ω	angular frequency
θ	transformation angle
V_d, V_q	d-q component of PCC voltage
P_{ref}	reference value of active power
V_{dc}	dc-link voltage
V_a, V_b, V_c	grid voltage per phase
f_c	modulation frequency
L	line inductance
V_{pcc}	voltage at PCC

I. INTRODUCTION

In recent years, the increase of energy demand and the problems of fossil-fuel sources due to their environmental pollution and future shortages, have led to the development of technologies needed to use non pollution alternative energy

sources such as photovoltaic and wind sources (consuming renewable energy) and fuel cells etc.

For past couple of decades high development of the power electronics has made the energy produced by the above alternative sources can easily accessible at the consumer premises and available at affordable cost. Moreover, it allows the spreading of the distributed generation (DG) system consisting in the use of a great number of small and medium generation systems connected to the distribution grid to feed a dedicated consumer or to be support of the grid itself [1].

In the most of literatures three-phase pwm voltage source inverters have been used in high performance ac motor drives, active filters, high power factor ac/dc converters, uninterruptible power supply (UPS) systems etc [2]-[5]. In all the above applications the control structures comprising an internal current control loop and it decides the performance of the converter system. In the current scenario, current regulated pwm voltage source inverters are greatly employed in grid connected DG systems in order to control the active and reactive power independently, power quality improvement and to improve the load dynamics etc [6]. They serve as an interfacing media between DG source and utility end.

As the PWM VSI is used as an interfacing device between DG and distribution networks, the command signal for the VSI, which is basically a current signal, will include the information of the active power, which is produced by DG system and reactive power, which will be injected in to the system through VSI in order to control the voltage at the PCC or the load reactive power [7].

Basically grid-connected VSI uses hysteresis current controller in the inner feedback loop for improving the dynamic performance of the system along with easy of implementation. But in the HCC based PWM VSI the interval between two consecutive switching actions varies constantly within a power frequency cycle. It means that the switching frequency is not constant but varies in time with operation point and conditions. In principle increasing inverter operation frequency helps to get a better compensating waveform. However there are device limitations and increasing the switching frequency cause increasing switching losses, audible noise and EMF related problems. The range of frequencies used is based on a compromise between these two different

factors. In this paper, the control of switching frequency is realized by introducing an adaptive hysteresis band current control algorithm. Adaptive hysteresis current controller changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and THD at PCC [8]. In addition, independent control of active and reactive power has been realized during load variations by the proposed controller with good dynamic response.

The paper is organized as follows – current control strategies in grid connected system are given in section II. Analysis of adaptive hysteresis band current control in section III. Section IV dedicated to results and discussion, followed by conclusion in section V.

II. CURRENT CONTROL STRATEGIES IN GRID CONNECTED VSI SYSTEM

A current controlled VSI is generally used to synchronize the utility grid with the distributed generation as shown in Fig.1. With advances in modern power semiconductor technology fast switching devices such as IGBT's and IGCT's are widely used as switches in inverter circuits. The control loop comprises adaptive Hysteresis current controller in the inner loop followed by variable Hysteresis band. The band can be adjusted according to the load current variation in order to maintain the switching frequency of the inverter switch constant. The converter manages the amount of I_{Inverter} injected to the PCC bus. The load current, I_L is converted from the three phase coordinates to the synchronously rotating frame by using equation (1), where θ is the instantaneous angle of the PCC voltage vector, obtained from phase locked loop (PLL) circuit.

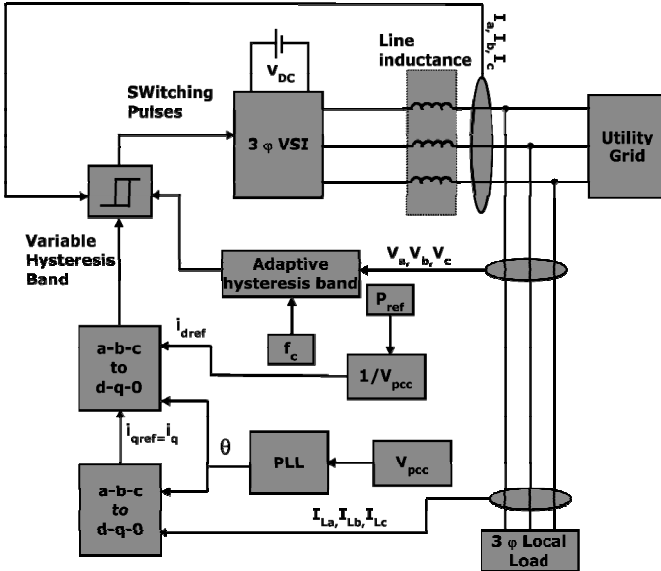


Fig.1. Block diagram for proposed current control of three-phase grid-connected VSI

A. Reference supply currents computation

Before analyzing the adaptive hysteresis band current controller we have to calculate the reference current from there

phase load current by parks' transformation method. The three phase load currents shown in Fig.1 have already been transformed to the synchronous reference frame (a-b-c to d-q-0 transformation).

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - (2\pi/3)) & \cos(\omega t + (2\pi/3)) \\ \sin(\omega t) & -\sin(\omega t - (2\pi/3)) & -\sin(\omega t + (2\pi/3)) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

The adjustment of the dq-transformation is so that the voltage at the PCC has no q-axis component. A PI regulator controls the angular frequency by (2). Then the transformation angle can be determined by (2).

$$\omega = k_p^{PLL} v_q + k_I^{PLL} \int (v_q \times dt) \quad (2)$$

$$\theta = \int (\omega \times dt) \quad (3)$$

It is assumed that there is no path for the zero sequence components, therefore i_0 in (1) and v_0 in Fig.2 can be ignored. However, these variables have been considered in the formulation to present the general case.

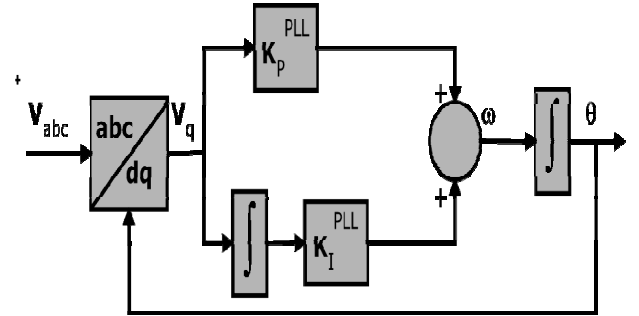


Fig.2. Block diagram of PLL

The resultant q-component is responsible for the reactive power flow through the utility network. To compensate the reactive component the quadrature component (i.e., i_{qref}) of the reference current of VSI, I_{Inverter} , equal to the quadrature component (i.e., i_q) of the load current (I_{Load}).

The generated active power of DG is expressed by the

$$P = v_d \times i_d + v_q \times i_q \quad (4)$$

Where v_d and v_q are the dq components of the PCC voltage (V_{PCC}) in the synchronously rotating frame, respectively and i_d and i_q are the dq component of the three phase DG current, I_{Inverter} . As mentioned before, we have:

$$v_d = v_{PCC} \text{ \& } v_q = 0 \quad (5)$$

Hence

$$I_d = \frac{P}{V_{PCC}} \quad (6)$$

Selecting the reference active power of DG as the command signal given of the utility the equation (6) can be rewritten, as follows:

$$I_{dref} = \frac{P_{ref}}{V_{PCC}} \quad (7)$$

Where i_{dref} is the direct component of the reference current of the VSI, $I_{inverter*}$. This component is also responsible for the losses in both the converter and the capacitor. Finally, applying inverse dq transformation rotating at the supply frequency ω by the equation (8), the three-phase VSI reference currents are determined from the d-q reference components [9].

$$\begin{bmatrix} i_{aref} \\ i_{bref} \\ i_{cref} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - (2\pi/3)) & \cos(\omega t - (2\pi/3)) & 1 \\ \sin(\omega t + (2\pi/3)) & \cos(\omega t + (2\pi/3)) & 1 \end{bmatrix} X \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (8)$$

III. ANALYSIS OF ADAPTIVE HYSTERESIS CURRENT CONTROLLER

The hysteresis band current control technique has proven to be most suitable for all the applications of current controlled voltage source inverters. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy. On the other hand, the basic hysteresis technique exhibits also several undesirable features; such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters. The conventional hysteresis band current control scheme used for the control of grid connected line current is already discussed. This is composed of a hysteresis around the reference line current. By notice equation (9) the reference line current of the grid connected inverter is referred to as i_{ref} , measured line current of the grid connected inverter is referred to as i and difference between i and i_{ref} is referred to as δ . The hysteresis band current controller assigns the switching pattern of grid connected inverter.

$$\delta = i - i_{ref} \quad (9)$$

The switching logic is formulated as follows:

If $\delta > HB$ upper switch is OFF and lower switch is ON ($S_4=1$, $S_1=0$).

If $\delta < -HB$ upper switch is ON and lower switch is OFF ($S_4=0$, $S_1=1$).

The switching logic for phases B and C is similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

In case of hysteresis band current control the rate of change of the line current vary the switching frequency,

therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform. Furthermore, the line inductance value of the grid connected inverter and the dc link voltage are the main parameters determining the rate of change of grid connected inverter line currents.

The bandwidth of the hysteresis current controller determines the allowable current shaping error. By changing the bandwidth the user can control the average switching frequency of the grid connected inverter and evaluate the performance for different values of hysteresis bandwidth. In principle, increasing the inverter operating frequency helps to get a better current waveform. However, there are device limitations and increasing the switching frequency causes increased switching losses, and EMI related problems. The range of switching frequencies used is based on a compromise between these factors. However, the current control with a fixed hysteresis band has its own disadvantage as discussed above [10]-[11].

Fig.3. shows the PWM current and voltage waveforms for phase a. The currents i_a tends to cross the lower hysteresis band at point Q, where S_1 is switched on. The linearly rising current (i_a^+) then touches the upper band at point P, where S_4 is switched on. The following equations can be written in the respective switching intervals t_1 and t_2 from Fig.3.

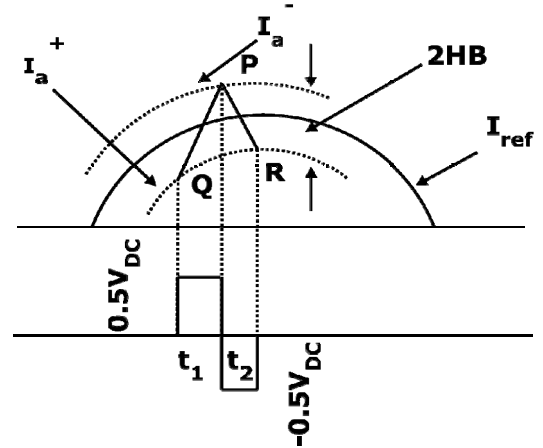


Fig.3. Current and voltage wave with hysteresis band current control

$$di_a^+ = \frac{1}{L}(0.5V_{DC} - V_a) \quad (10)$$

$$di_a^- = -\frac{1}{L}(0.5V_{DC} + V_a) \quad (11)$$

From fig.3

$$\frac{di_a^+}{dt}t_1 - \frac{di_{aref}}{dt}t_1 = 2HB \quad (12)$$

$$\frac{di_a^-}{dt}t_2 - \frac{di_{aref}}{dt}t_2 = -2HB \quad (13)$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \quad (14)$$

where t_1 and t_2 are the respective switching intervals and f_c is the switching frequency.

Adding equation (12) and (13) and substituting in equation (14) we can write

$$\frac{di_a^+}{dt} t_1 + \frac{di_a^-}{dt} t_2 - \frac{1}{f_c} \frac{di_{aref}}{dt} = 0 \quad (15)$$

Subtracting equation (13) from (14)

$$\frac{di_a^+}{dt} t_1 - \frac{di_a^-}{dt} t_2 - (t_1 - t_2) \frac{di_{aref}}{dt} = 4HB \quad (16)$$

Substituting equation (11) in (16)

$$(t_1 + t_2) \frac{di_a^+}{dt} - (t_1 - t_2) \frac{di_{aref}}{dt} = 4HB \quad (17)$$

Substituting equation (11) in equation (15) and solving

$$(t_1 - t_2) = \frac{di_{aref}/dt}{f_c (di_a^+/dt)} \quad (18)$$

Substituting equation (18) in (17)

$$HB = \frac{0.125V_{DC}}{f_c L} \left[1 - \frac{4L^2}{V_{DC}^2} \left(\frac{V_a}{L} + m \right)^2 \right] \quad (19)$$

where f_c is modulation frequency, $m = di_{aref}/dt$ is the slope of command current wave. Hysteresis band (HB) can be modulated at different points of fundamental frequency cycle to control the switching pattern of the inverter. For symmetrical operation of all three phases, it is expected that the hysteresis bandwidth (HB) profiles HB_a , HB_b and HB_c will be same, but have phase difference.

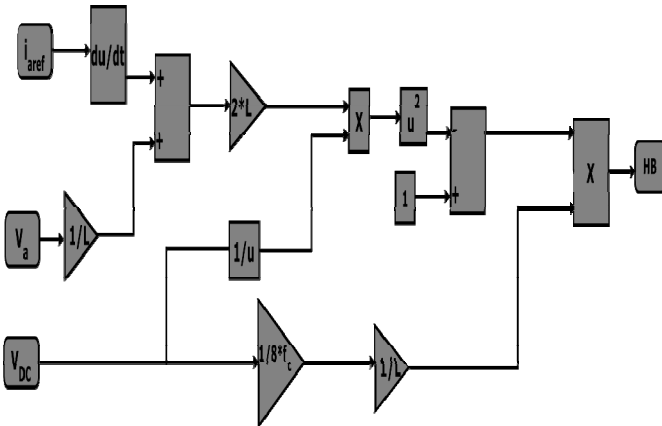


Fig.4.The adaptive hysteresis band width calculation block diagram

The adaptive hysteresis band current controller changes the hysteresis bandwidth according to instantaneous current variation (di_{aref}/dt) and V_{dc} voltage to minimize the influence of current distortion on modulated waveform.

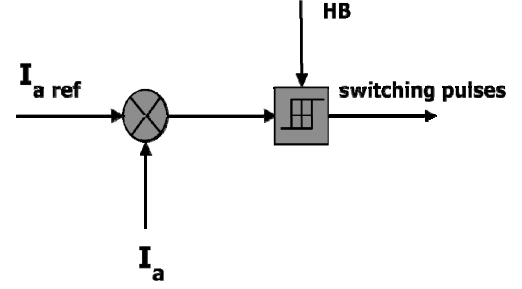


Fig. 5.Variable Hysteresis band current controller

IV. RESULTS & DISCUSSION

The section reveals the simulation results for proposed current control algorithm applied to three-phase mains connected inverter system. The studied model has been developed and simulated in the MATLAB/simulink environment. For simulation, following parameters has been considered and are given in the table.1.

Table-I: Parameters for Simulation

Parameter	Value
V_{dc}	600V
Switching frequency	12KHz
P_{ref}	4000W
Grid voltage(L-L)	400V
Grid Frequency	50 Hz

The waveforms of three-phase load currents and grid currents are shown in fig.6 & fig.7 respectively. During steady state conditions load current maintains at 5.5 amps and grid current maintains at 11 amps till 0.08 sec. At 0.08 seconds load current increases to 12 amps till 0.14 sec. In the mean while grid currents also increases to 15 amps. During this condition the voltage at the PCC would be affected. But the action has been taken by the adaptive hysteresis current controller and it regulates the voltage by providing reactive power demand through VSI. The corresponding grid voltage waveform is shown in fig.8. The combined three-phase grid currents and load currents are shown in fig. 9. The fig 10 shows that the VSI succeeded in tracking and compensating the reactive power of the load with fast dynamic response from 0.08 sec to 0.146 sec. The amount of reactive power supplied by VSI is nearly 4 kVAR and it tracks the steady state with in 0.1 sec. The corresponding response of three-phase active power is shown in fig.11 which maintains at almost 4 kW. But there is a transient at $t=0.08$ sec and $t=0.14$ sec due to switching action of the breaker as the reactive power increases between these

periods. So proposed controller controls the active and reactive power independently and it regulates the voltage at PCC during variable load conditions.

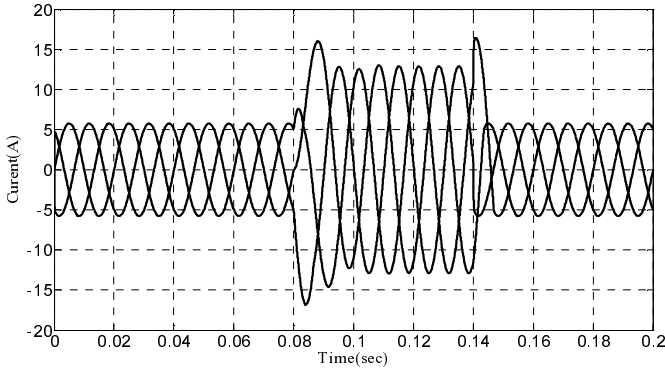


Fig. 6. Three-phase load-current waveforms during load variations

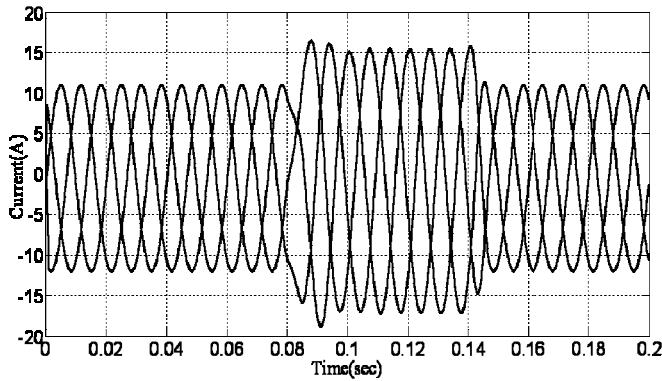


Fig. 7. Three-phase grid-current waveforms during load variations

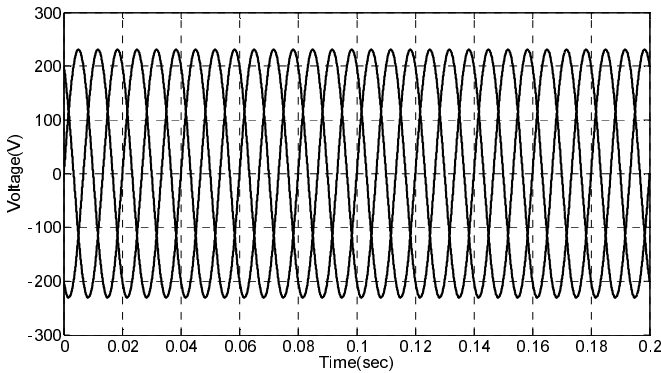


Fig. 8. Three-phase grid-voltage waveforms

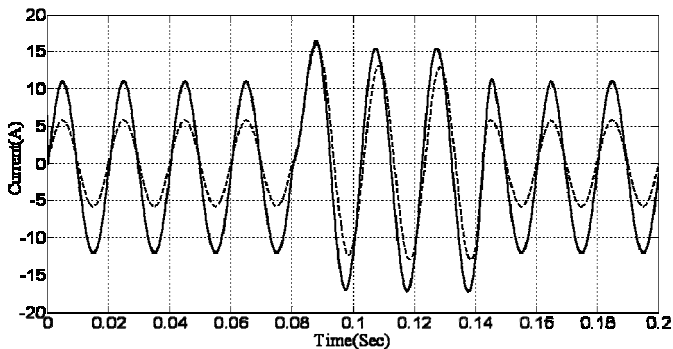


Fig. 9. Three-phase load-current and grid current waveforms during load variations

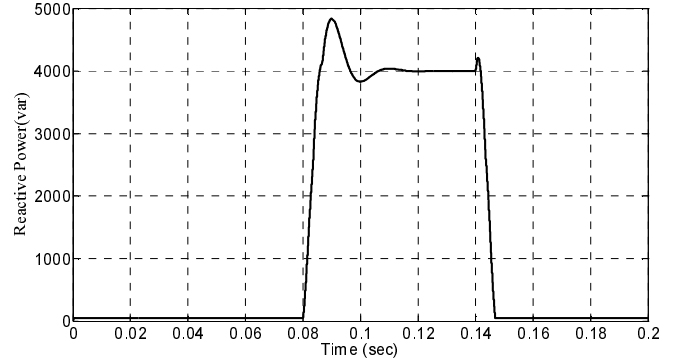


Fig. 10. Response of reactive power demand during load variations

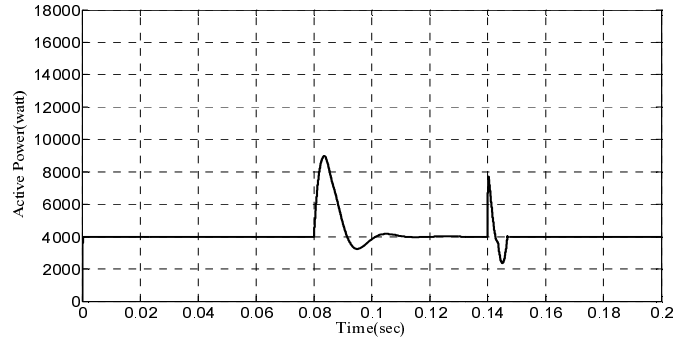


Fig. 11. Response of active power demand during load variations

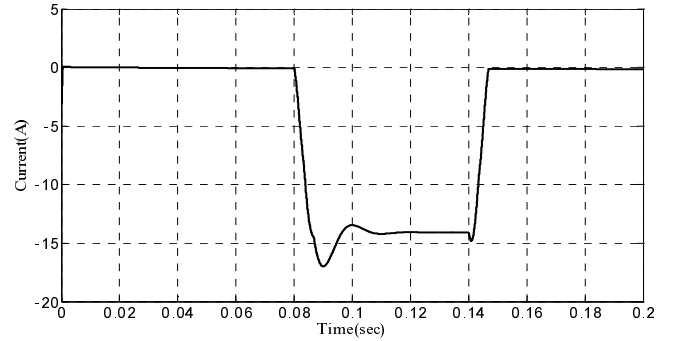


Fig. 12. Response of quadrature current component of grid current current

Fig.12 shows the quadrature component of the reference current under variable load conditions with changes of the load reactive power.

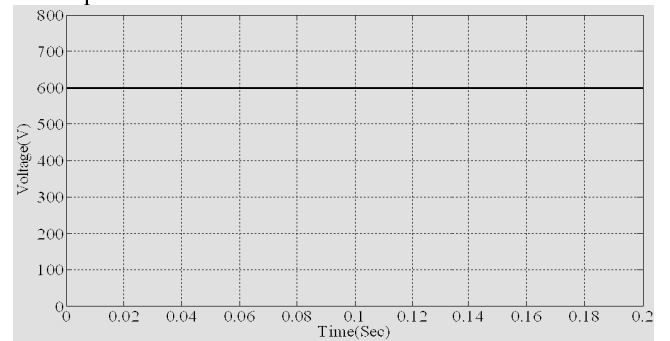


Fig. 13. Response of DC-link voltage

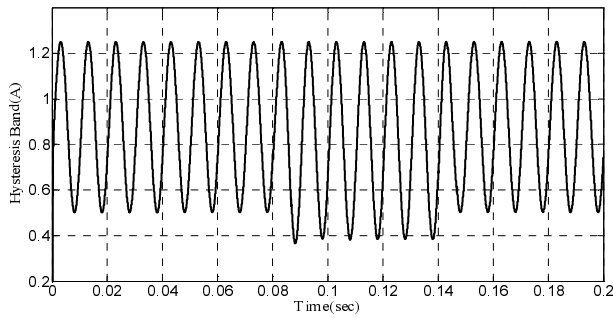


Fig. 14. Adaptive hysteresis-band

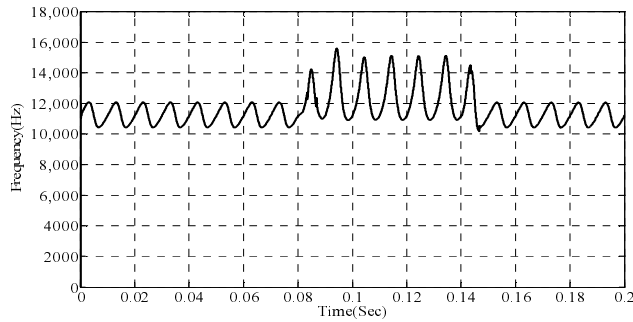


Fig. 15. Switching frequency variations

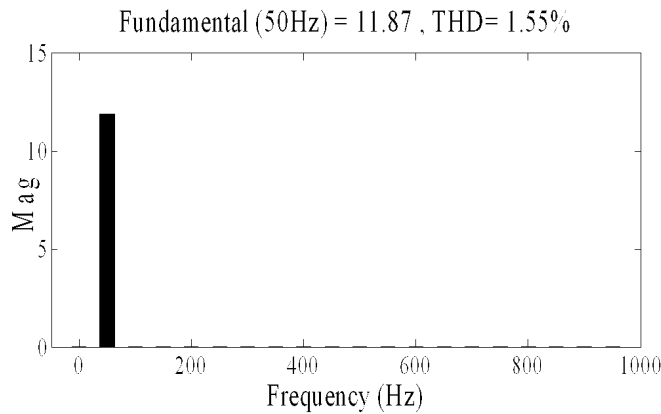


Fig. 16. THD of three-phase grid current

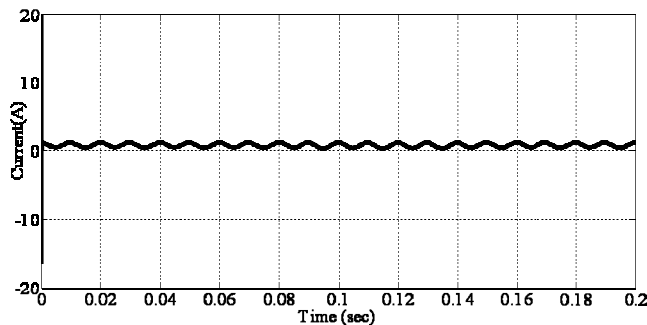


Fig. 17. Current error by adaptive Hysteresis controller

Fig.14 shows the variation of hysteresis band & in fig.15 the variation of switching frequency is shown. The change in switching frequency occur during the period when load changes. The THD of grid current is depicted by fig.16 and it maintains at par with IEEE standard. The corresponding current error is shown in fig.17 and it almost zero, in that way

adaptive current controllers improves the dynamic response of system during load variations.

V.CONCLUSIONS

This paper described the dynamic performance of adaptive hysteresis current controller for grid connected inverter system during load variations. The study includes independent control of active and reactive power of the utility end, harmonic current reduction via current error minimization and lesser THD at the PCC. From the study we observed that, adaptive hysteresis current controller can enable to reduce the current error at load terminal, thus in turn it reduces the THD of load current and it provides nearly constant switching frequency of operation by adjusting its hysteresis-band. In addition, we also observed that the voltage profile at PCC can be maintained constant irrespective of the variation of the reactive power consumption and it reduces the EMI effects, which are the important requirements of the distribution system to satisfy the sensitive loads like medical equipments etc.

ACKNOWLEDGMENT

Authors would like to acknowledge Dr.S.R.Samantaray for his valuable guidance against the study on reactive power management during grid abnormalities.

REFERENCES

- [1] F.Blaabjerg, Zhe Chen, and S.B. Kjaer. "Power Electronics as Efficient Interface in Dispersed Power Generation Systems", IEEE Transactions on Power Electronics, 19(5):1184–1194, Sept. 2004.
- [2] M.Azizur Rahman, Ali M. Osheiba. "Analysis of current controllers for voltage-source inverter" IEEE Transaction on Industrial Electronics, vol.44, no.4, August 1997.
- [3] D.Wuest, E.Jenni: "Space Vector Based Current Control schemes for voltage source inverter", IEEE PESC'93 conference, Seattle, 1993, pp. 986-992.
- [4] D.M. Brod and D.W. Novotny: "Current control of VSI-PWM inverter", IEEE Trans. Industrial Applications, Vol. IA, My/June 1985. pp.562-570
- [5] M.P.Kazmierkowaski, L.Malesani: "PWM Current Control Techniques of voltage source converters-A Survey", IEEE Trans. on Industrial Electronics, Vol.45, no.5, oct.1998.
- [6] T.L. grant and T.H.Barton, "Control Strategies for PWM drives", Proc. of IEEE Industrial Application. Society. Annual Meeting . PP.785-792.
- [7] T.Hornik and Q.C.Zhong, "Control of grid-connected DC-AC Converters in Distributed Generation: Experimental comparison of different schemes", Proc. of IEEE 6th International Conference-Workshop on Compatibility and Power Electronics CPE 2009.Spain.pp.271-278.
- [8] Ghani, P.; Chiane, A.A.; Kojabadi, H.M.; "An adaptive hysteresis band current controller for inverter base DG with reactive power compensate" Proc. of IEEE PEDSTC 2010. Pp. 429–434.
- [9] M.Davari, I.Salabeigi, G.B.Gharehpetian, S.H.Fathi, J.Milimonfared, Application of Sigma-Delta Modulation in Multifunction Current Controller for Inverter-Based Distributed Generation, In Proceeding of 11th Inter.Spanish-Portuguese Conf on Elect.Engg (11CHILIE), ZARAGOZA, Spain, 1-4 July, 2009.
- [10] B.K. Bose, "An adaptive hysteresis band current control technique of a voltage feed PWM inverter for machine drive system", IEEE Trans. Ind. Electron. 37 (5) (1990) 402–406.
- [11] N.Belhaouchet, L. Rahmani, S. Begag "A novel adaptive HBCC technique for three-phase shunt APF" Elsevier Journal on Electric Power Systems Research, Volume 79, Issue 7, July 2009, Pages 1097-1104.