

Control Strategies of Grid Connected PWM Voltage Source Inverter

Mohamayee Mohapatra¹, B Chitti Babu² Member, IEEE, A.K.Panda³

^{1,2,3}Department of Electrical Engineering, National Institute of Technology, Rourkela (INDIA)

¹mohamayee@gmail.com, ²bcbabunitrkl@ieee.org, ³akpanda.ee@gmail.com

Abstract- This paper presents a comparative study between delta and delta-sigma modulator for mains connected inverter. Since the paper discusses the implementation of these controllers for grid-connected system, their evaluation is made in two operating conditions. First, in steady-state conditions, the contributions of controllers to the total harmonic distortion (THD) of the grid current, active and reactive power control and unity power factor operation is pursued. Further on, the transient behavior of controllers especially during sudden change in reactive loads and how they are able to provide reactive power demand in order to improve the voltage profile at PCC, control the active and reactive power independently and provides fast voltage regulation etc are studied. Their performances are also evaluated by various values of reference current and hysteresis bandwidth. The performances of these modulators are simulated in the MATLAB/SIMULINK environment and it is experimentally validated in the laboratory using TMS320F2812 DSP.

Key words – Current Controller; delta modulator; delta-sigma modulator; voltage source inverter (VSI); total harmonic distortion (THD); pulse width modulation (PWM); distributed power generation (DPGS); point of common coupling (PCC).

I INTRODUCTION

Now-a-days centralized power generating systems (coal, nuclear, hydro or gas powered plants) are facing problems due to shortage of fossil fuel, power loss due to long transmission lines, climate changes and pollution to environment [1]. Therefore emphasis has been increased on DG to meet rapidly increase in energy consumption, depleting of conventional sources and climate changes. The distributed generation is defined as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system. The DG penetration to the grid poses new challenges and problems to the network operators as these can have a significant impact on the system and equipment operations in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers [2],[3]. These are integrated to the grid in compliance with power quality standards. The technical

challenges associated with the DG can be divided into three categories [4]:

1. The system interface to the grid.
2. Operation and Control of DG.
3. Planning and Design.

The majority of electrical loads in distributed power generation system are non-unity power factor reactive loads which draws reactive power component of current as well as active power component [5]. There are many consumers and equipments which have rapid changes in the reactive power consumption. These changes can cause considerable variations of the load-side and PCC voltage. Draws of reactive component of current causes low power factor, low efficiency and poor utilization of distribution system and sometime it affect other consumers near by. Due to fast dynamic, accurate performance, inherent closed loop current control system; the current regulated VSI is chosen for compensating the power quality problems at the PCC. It is incorporated for the interfacing between DG and distribution networks. This inverter match the characteristics of DPGS and the requirements of the grid connections, improves the performance of DPGS, provides the DPGS with power system control capabilities, improves power quality and their effect on power system stability. With recent advances of semiconductor switching devices, operating frequency and lower capacity of switch mode power converters are much improved. In these converters pulse width modulation (PWM) technique is widely used for quick response and accurate control. The pulse width modulation (PWM) technique is widely used for DC/AC power inversion [6]. The fundamental aim of any PWM switching is to eliminate the lower order harmonics at relatively minimal commutation of inverter switches. Numerous current control techniques have been developed [7] as they offer substantial advantages in eliminating the dynamics in high-performance ac drive systems under field-orientation control, which may generally be classified as non-linear (hysteresis, delta and delta-sigma etc), linear (PI) and predictive current control. Conventional hysteresis control, gives excellent dynamic response, insensitive to load variations and relatively simple to implement [7]. Also a number of important disadvantages exist, including: (a) the current is not strictly limited within the hysteresis band, (b) the switching frequency is not fixed, increasing excessively for low filter inductance values and small hysteresis bands and (c) the harmonic spectrum contains sub harmonic and inter harmonic components[8].

This paper focuses on the comparative study between delta and delta-sigma modulator for mains connected inverter system. It discusses the power quality, reactive power compensation, unity power factor operation in both steady state and under transient i.e.

sudden change in reactive load. The performance of the proposed controllers are studied and analyzed in the computer simulation undertaken by MATLAB/SIMULINK environment. In this work, a DSP-based implementation of a limited switching frequency, Delta and Delta-Sigma modulated current control method is designed, simulated and implemented. Finally, experimental validation is presented through an industrial prototype implementation using TMS320F2812 DSP processor. The performance indices for comparison include RMS current error, average switching frequency, frequency spectrum, unity power factor operation and total harmonic distortion (THD) of grid current.

II. ANALYSIS OF PROPOSED CURRENT CONTROLLER

A. Analysis of Delta-Sigma Modulator applied to two-level inverter

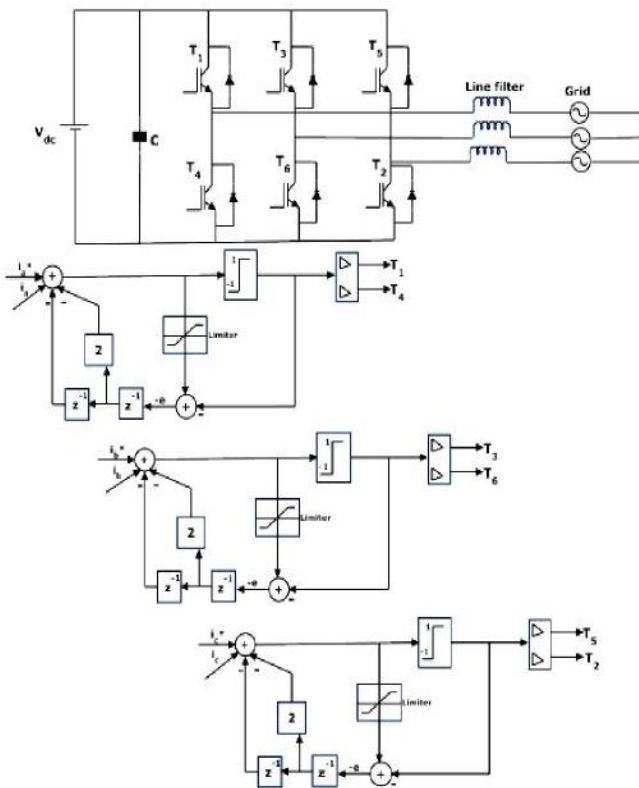


Figure 1: Schematic of the two-level inverter with the second order delta-sigma modulator

The second order delta-sigma modulator is realized by the error feedback structure [9] as shown in fig.3. In this scheme the load current is compared with the reference current and the error signal is fed to the quantizer. The input of the quantizer is again subtracted from the digital output of the quantizer. The difference between the input and output of the quantizer is a measure of the quantization error which is feedback and subtracted from the next input sample. z^{-1} represents 1 sample delay and 1 represents delay coefficients [10]. The delay is used to reflect the physical delay inherent in a quantizer. It forms the difference between the input and a digital approximation of the previous input that is feedback. When the quantizer input signal

is less than threshold level 0, output signal takes -1 and when the quantizer input signal is greater than threshold level 0, output signal takes +1. When the output signal of delta-sigma modulator does not change, it is unnecessary for switching operation. As a result, switching number of delta-sigma modulated converters is smaller than sampling frequency. On the other hand, minimum pulse width of delta-sigma modulated converter is determined only by the inverse of sampling frequency, it is not necessary to control minimum pulse width. In the circuit, quantization error signal e is added to the input signal. Input and output signal relations is represented as

$$y(z) = x(z) + (e_z - e_{z-1}) \tag{1}$$

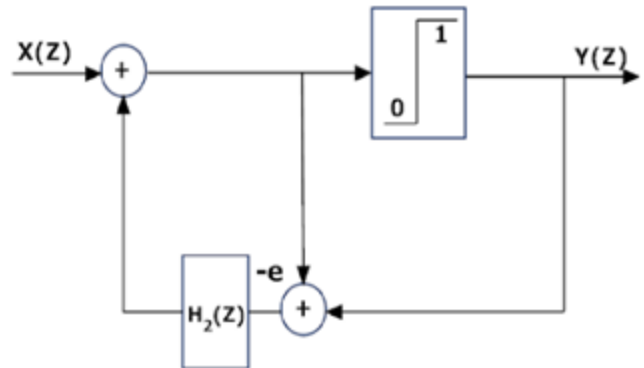


Figure 2: The delta-sigma modulator with error feedback structure

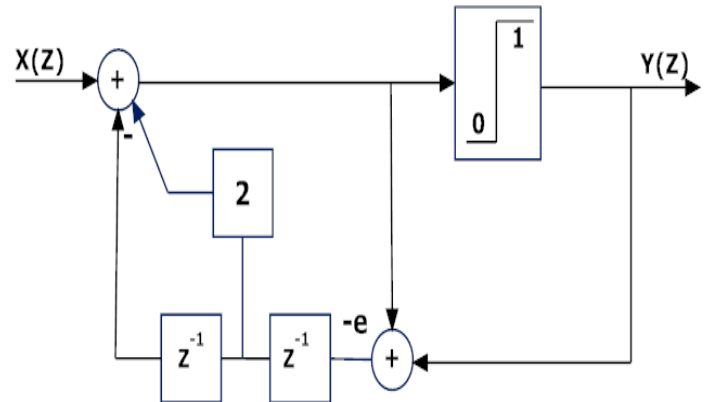


Figure 3: The second order delta-sigma modulator

In the simplest case $H(z)=z^{-1}$ chosen as transfer function of the feedback filter. So the overall transfer function becomes $H_1(z) = 1 - H(z) = 1 - z^{-1}$ (2)

A first order noise shaping is achieved. To obtain second order noise feedback filter transfer function can be selected as

$$H_2(z) = 1 - (1 - z^{-1})^2 = z^{-1}(2 - z^{-1}) \tag{3}$$

The system block diagram is shown in fig.3. The output is:

$$Y(z) = X(z) + (1 - z^{-1})^2 E(z) \tag{4}$$

This structure only needs delay, addition and shift operations. It can effectively reduce the Digital Signal Processing (DSP) run-time of the modulation algorithm. If the Quantizer is overloaded, that may cause - the delta-sigma modulator to be unstable. A limiter to prevent the quantizer from overloading is necessary as shown in fig.4.

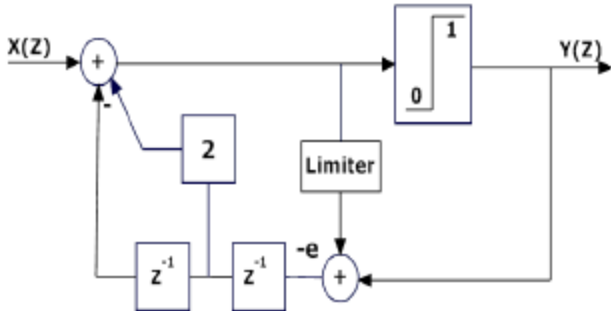


Figure 4: The second order delta-sigma modulator with a limiter to prevent overload

III. PROPOSED CONTROL ALGORITHM

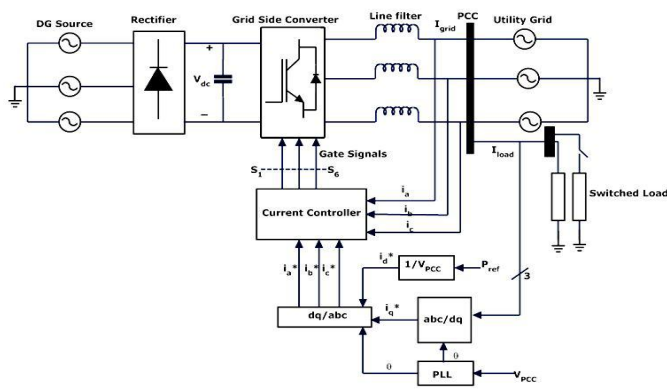


Figure 5: Overall block diagram of proposed current controller for grid connected VSI

The fundamental requirements of interfacing with the grid are as follows, the voltage magnitude and phase must equal to that required for the desired magnitude and direction of the power flow. The voltage is controlled by the transformer turn ratio and/or the rectifier inverter firing angle in a closed-loop control system. The frequency must be exactly equal to that of the grid, or else the system will not work. The frequency of the system is obtained by Phase Locked Loop(PLL). PLL provides angle (θ) which is used to generate unit vectors $\cos(\theta)$, $\sin(\theta)$ for transforming stationary two phase quantities in stationary reference frame into rotating two phase quantities in rotating frame. It tracks continuously the fundamental frequency of the measured system voltages. Fig. 6 shows the current control strategy with its control blocks connected to a typical power system. The Input is a three phase voltage supply as follows:

$$v_a = V \cos \omega t, \tag{5}$$

$$v_b = V \cos \left(\omega t - \frac{2\pi}{3} \right), \tag{6}$$

$$v_c = V \cos \left(\omega t + \frac{2\pi}{3} \right) \tag{7}$$

Where V and ω are the maximum phase voltage and angular frequency of the power source respectively. The load current i_{la} , i_{lb} and i_{lc} is converted from the three phase coordinates to the synchronously rotating frame by using park's Transformation which is given in equation(8), where θ is the instantaneous angle of the PCC voltage vector, obtained from Phase Locked Loop(PLL). The advantage of the rotating d-q coordinate is that the controlled quantity such as current becomes DC-value, which can eliminate current steady tracking error and realize the decoupling control for the d-axis current and q-axis current. In the d-q transformation, the zero sequence components are assumed zero and dq components are adjusted so that the voltage at the PCC has no q-axis component.

$$\begin{bmatrix} i_{dl} \\ i_{ql} \\ i_{0l} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} i_{al} \\ i_{bl} \\ i_{cl} \end{bmatrix} \tag{8}$$

The block diagram of the PLL system is shown in fig.6.

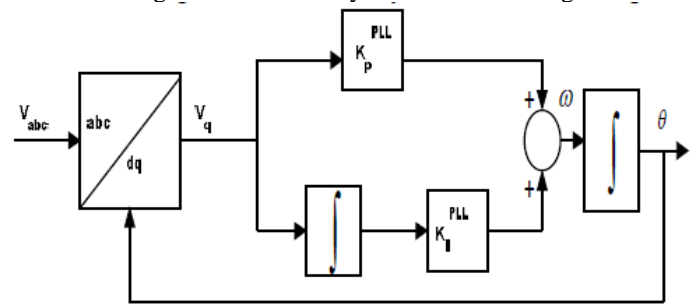


Figure 6: Block diagram of PLL

A PI regulator acts on the alignment error to set the rotation frequency ω and that frequency is integrated to give the transformation angle θ .

$$\omega = K_p^{PLL} v_q + K_I^{PLL} \int (v_q \times dt) \tag{9}$$

$$\theta = \int (\omega \times dt) \tag{10}$$

The resultant q -component is responsible for the reactive power flow through the utility network. From the relation between Reactive power and voltage amplitude, the reactive component of current is provided to regulate the PCC voltage is shown in fig.8. The power fed from DG is given by:

$$P = v_d \times i_d + v_q \times i_q \quad (11)$$

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. As mentioned earlier, we have

$$v_d = V_{PCC} \text{ and } v_q = 0 \quad (12)$$

Substituting equation (12) into (11) yields:

$$i_d = \frac{P}{V_{PCC}} \quad (13)$$

Selecting the reference active power of DG as the command signal given of the utility the equation (13) can be rewritten as follows:

$$i_d^* = \frac{P_{ref}}{V_{PCC}} \quad (14)$$

Where i_d^* is the direct component of the reference current of the voltage source inverter (VSI). This component is also responsible for the losses in both the converter and the capacitor. Applying inverse Park's transformation the dq reference components are transformed into three phase VSI reference currents.

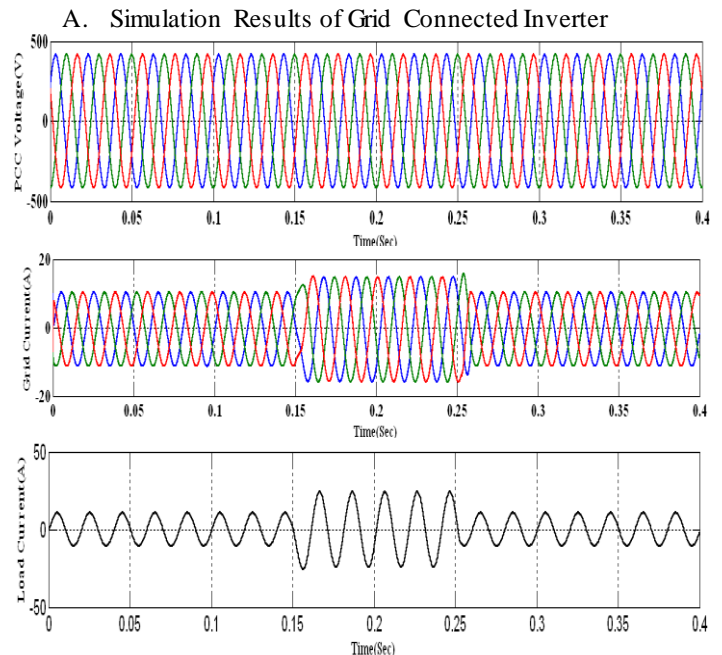
$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \sqrt{\frac{1}{2}} \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) & \sqrt{\frac{1}{2}} \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) & \sqrt{\frac{1}{2}} \end{bmatrix} \times \begin{bmatrix} i_d^* \\ i_q^* \\ i_0^* \end{bmatrix} \quad (15)$$

IV. RESULTS AND DISCUSSION

The control strategy of grid connected inverter is verified by the simulation study by Matlab 7.6, the elements such as diode rectifier, PWM inverter and inductors are from Simpower Systems, and the algorithm is realized by Simulink. The evaluation of the controllers is made in two situations, i.e., steady-state and transient operations. In steady-state operation, the quality of the controlled current is presented while in transient state, the controller response to a sudden reactive load change is studied. The simulation parameters are given table 1. The response of PCC voltage, grid current, Load current, dc-link voltage, active power, reactive power, power factor, RMS value of PCC voltage, RMS value of the load current, quadrature component of grid current are described and graphically illustrated in this section for the current controllers. The obtained results in the Simulink are verified experimentally in the laboratory by using TMS320F2812 DSP processor.

Table-1
Nominal Parameters for Simulation

Parameter	Values
V_{dc}	600V
R	0.02Ω
L	4mH
Grid voltage(L-L)	415V
Grid frequency	50Hz
P_{ref}	4kW
DC-link capacitor	900 μf
Hysteresis Bandwidth	0.5



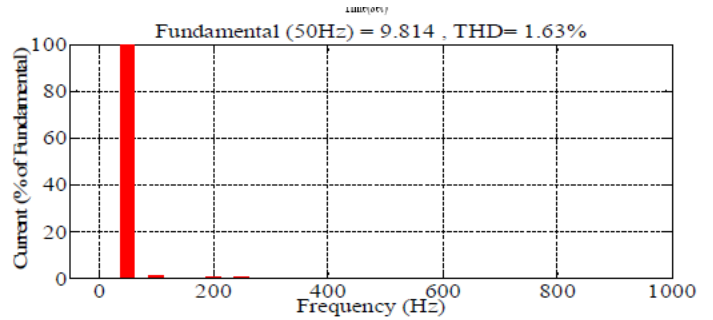
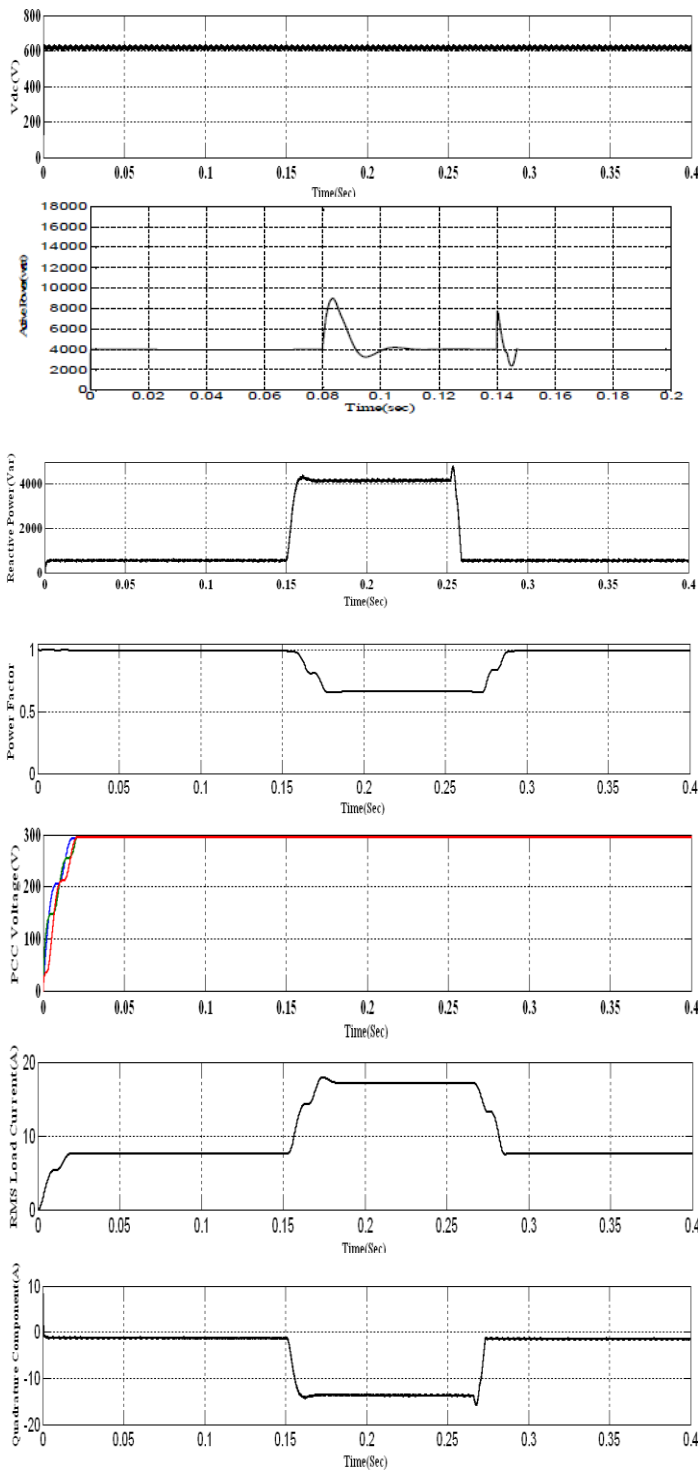


Figure 7: Response of Delta-Sigma Modulator under transient conditions (a)PCC voltage (b) Grid Current (c) Load Current (d) DC link voltage (e) Active power (f) Reactive Power (g) Power factor (h) RMS value of PCC voltage (i) RMS value of Load current (j) Quadrature component of Grid current(k)THD of Grid current.

In order to verify the dynamic performance, a step of 70% of the rated load is given and is shown in the Figure 7. First test simulates the situation of increase in current by instantly increasing the load demand from (4kW, 1kVar) to (4kW, 7kvar). As Figure 7(b) and Figure 7(c) illustrate, the controller have good dynamics, being able to track closely the current reference, without high overshoot and oscillations, during such transient condition. Consequently the reactive power, immediately follow the change on reactive power demand, as shown in the Figure 7 (f). The response occurs very fast and without any overshoot or oscillation. The estimated instantaneous reactive power reaches the demanded value within 30 μ Sec as can be observed in the Figure 7(f), which shows the dynamic performance with lower time scale. Additionally, one can note that the active power is almost insensitive to a change of the reactive power and remains fixed to its reference value as shown in Figure 7(g). It shows with initial load of (4kW, 1kvar) the load current is 6A and the grid current is 1.04A. When a high inductive load of is switched on at t=0.15 sec, the load current rises to 20A and the grid current change instantaneously at the load change and reaches to a value of 1.5A to compensate the reactive power at PCC. The grid current and load current settles to steady state values within less than a cycle. Reactive power draws from the grid is 4.2Kvar during transient. At t=0.25sec, load is removed, grid current and load current changes instantaneously to its previous values. But the voltage at PCC remains as usual as its original value. Figure 7. (a)-(f) shows the line voltage at PCC and its magnitude. Figure 7-d shows the DC link voltage which is constant (600Volt) that means the load change does not affect the DC link voltage. Figure 7-j shows the quadrature component (i_q^*) of the inverter current under dynamic changes of the load reactive power. Figure 7-e shows the active power which is almost constant and equal to its input command value (4kW). In this scheme the power command for the controller was set equal to the load power (4kW). Therefore, there is no current fed to the load from the utility, the load nearly takes its power from DG. When the load increases, the amount of increment in active power is drawn from the utility grid and mean while the reactive power is compensated by the VSI. This controller controls the active power and reactive power independently, maintains active power at its reference value while compensates reactive power.

Figure 7-i shows the magnitude of RMS value of load current which suddenly rises at $t=0.16$ sec from 1 A to 1.35A and reaches to its steady state at $t=0.185$ sec. Similarly grid current follows the track. As shown in Figure 7-k the THD of the controller is 1.63% whereas the THD of Delta modulator is

B. Experimental Results for Grid Connected Inverter

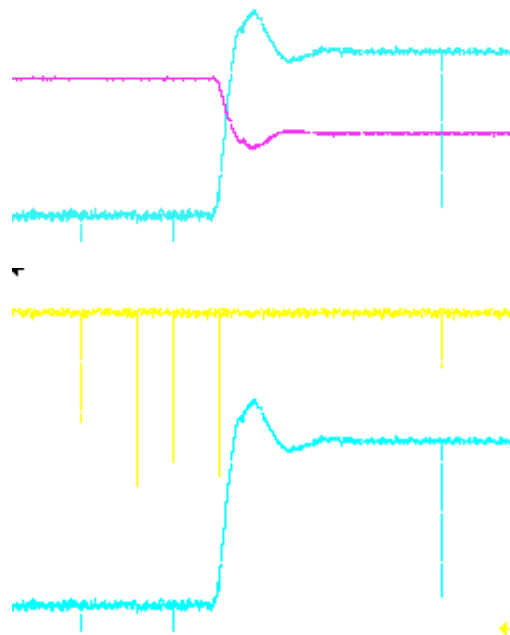
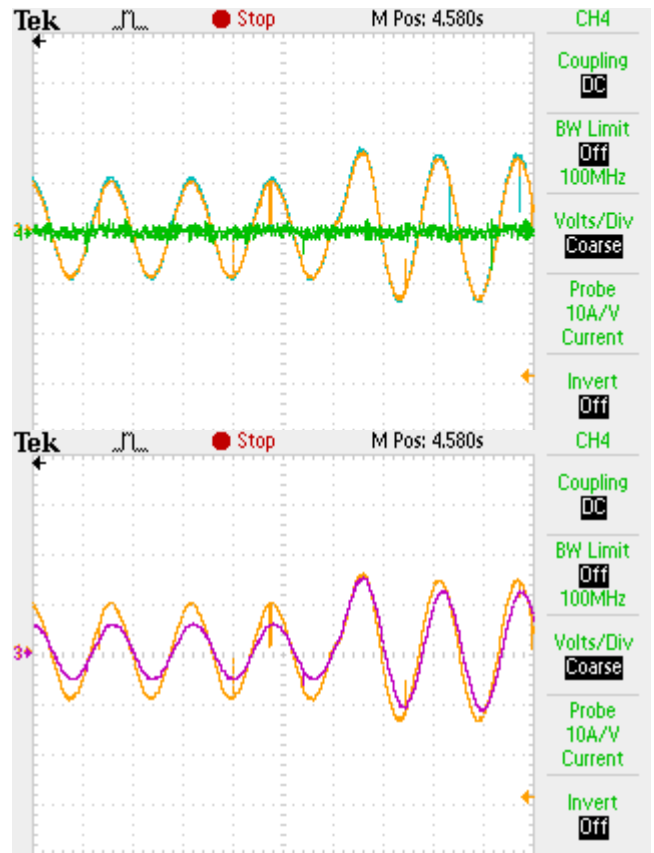
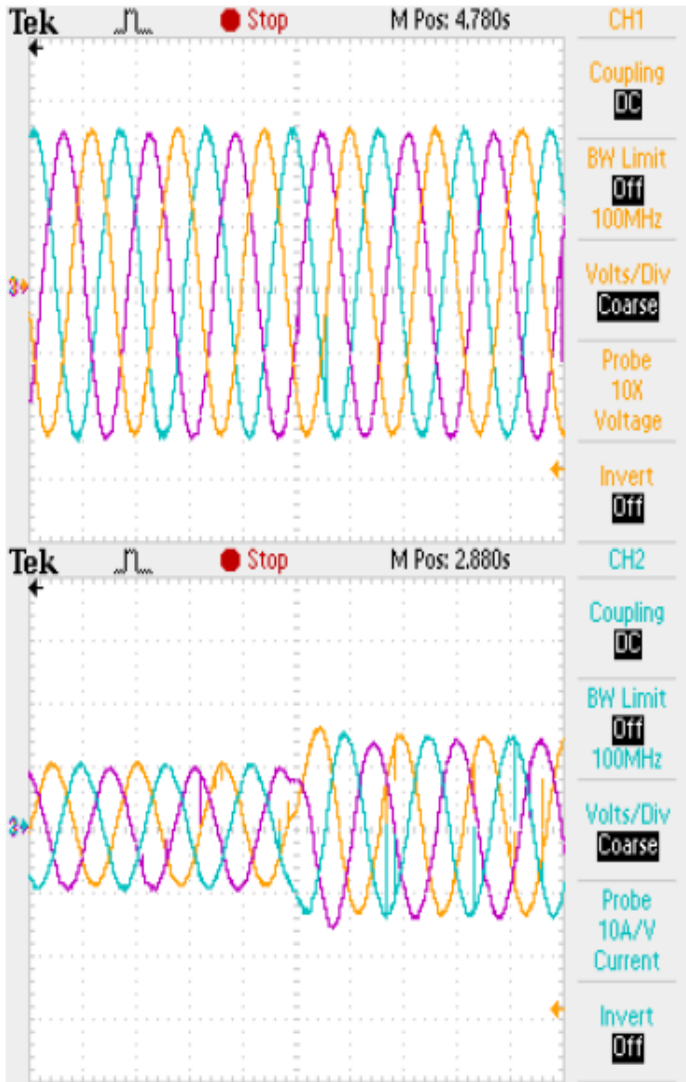


Figure 8: Experimental Results of Delta-Sigma Modulator (a) Grid voltage (b) grid Current (c) Current Vs Current error(d) grid current Vs

load current(d) quadrature component of current Vs Reactive power(e)
DC link voltage (f) Active and Reactive Power

The dynamic response has also been experimentally tested in the laboratory using TMS320F2812 DSP processor, in order to prove that the fast transient response is not affected in the experimental prototype. A step of the reactive load 70% of the rated value is shown in Figure 8. The grid current and consequently the estimated reactive power almost immediately follow the change on the demanded current and reactive power. A closer look at the rise time (Figure 8(f)) shows the instantaneous reactive power reaching the demanded value in approximately 30 μ s. Moreover, the active power is practically not affected by the change of the reactive power.

C. Comparative Analysis

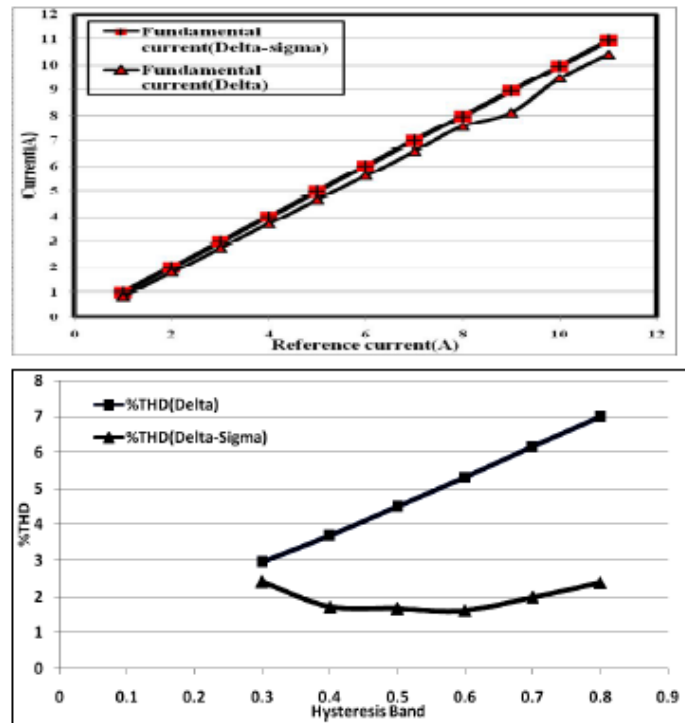
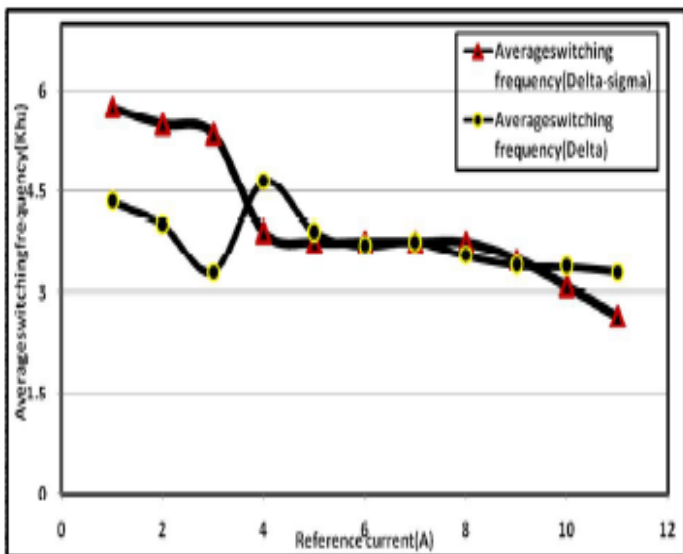
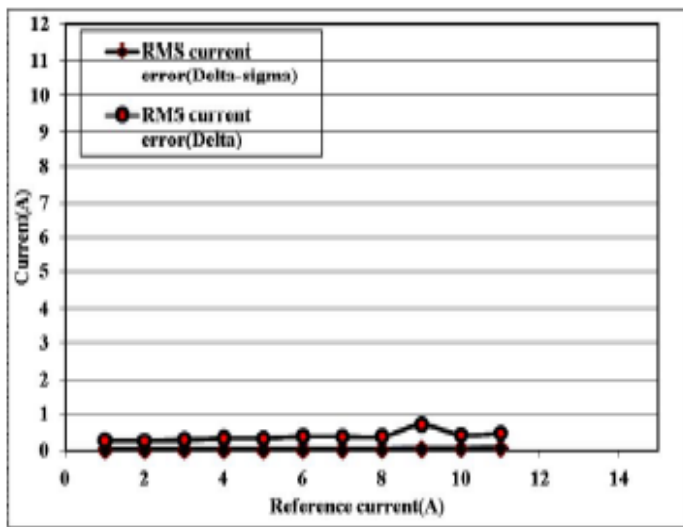


Figure 9: Plot for (a) RMS current error Vs Reference current (b) Average switching frequency Vs Reference current (c) Fundamental current Vs Reference current (d) % THD.

A key point in the comparative evaluation of different control strategies is to present suitable features to evaluate the performance level offered by each of the considered techniques. In the case this paper deals with delta and delta-sigma application. A important feature for the control's quality evaluation is the measurement of total harmonic distortion (THD) of the grid current waveforms as shown in Figure 9(d). It gives direct information about the control's capability of eliminating harmonic contents from the current drawn from the utility grid. But, the insight given by this measurement is rather poor, since all the various aspects of current regulation's quality are lumped in a single figure. Therefore, three additional features are taken into account here. One is the calculation of RMS value of the current error which is related to the energy of the error and, therefore to the dynamic performance of the current controller is shown in Figure 9 (a). Differently from current THD, this index includes the fundamental harmonic, namely, the error in the compensation of its reactive component. Second criterion considered here is average switching frequency is shown in Figure 9 (b). The average switching frequency is less and it minimizes the switching loss of the inverter. Third criterion considered here is the magnitude of the fundamental current which is shown in Figure 9(c). The delta-sigma modulator gives the magnitude of fundamental current which is closer to the reference current than the delta modulator.

V. CONCLUSION

This paper described the comparative study between delta and delta-sigmodulator for grid connected inverter system. The experimental results are similar to the theoretical analysis which is done in simulink. The comparative study has been based on the simulation. 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. The result shows that the delta-sigma modulator offers significant improvement in terms of waveform quality and current harmonic distortion over delta modulator. There are some advantages and disadvantages in every controller. This paper also discussed the comparative analysis between the two modulators by considering various values of Reference current and hysteresis band width. From that, we observed, delta-sigma modulator has less total harmonic distortion, unity Power factor, and lower RMS current error, less average switching frequency as compared to delta modulator. The average switching frequency is less which infers the reducing switching loss of the power switches and simultaneous increase in the efficiency of the inverter. As the output current distortion of delta-sigma modulator is less than delta modulator, noise level within unnecessary band is much reduced in the proposed scheme. For decreasing value of hysteresis bandwidth, the THD decreases. This implies that the proposed delta-sigma with lower THD can reduce the size of the filter and provides the active power requirement of load and simultaneously compensates the reactive power consumption by the load. The experimental results are validating the theoretical results.

REFERENCES

- [1] K. Purchala, R. Belmans, KULeuven L. Exarchakos, A.D. Hawkes, Distributed generation and the grid integration issues, Imperial College London.
- [2] F. Blaabjerg, R. Teodorescu, M. Liserre, and A.V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," IEEE Transaction on Industrial Electronics, vol.53, pp. 1398-1409, Oct. 2006.
- [3] Adrian Timbus, Marco Liserre, Remus Teodorescu, Pedro Rodriguez and Frede Blaabjerg, "Evaluation of Current Controllers for Distributed Power Generation Systems," IEEE Transactions On Power Electronics, Vol. 24, No. 3, pp.654-663, March 2009.
- [4] 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 International Spanish-Portuguese Conference on Electrical Engineering (1 ICHILIE), ZARAGOZA, Spain, 1-4 July, 2009.
- [5] Bhim Singh, Ambrish Chandra, Kamal AI-Haddad,

- Anuradha c and D.P. Kothari, Reactive power compensation and load balancing in electric power distribution systems, Electrical Power & Energy Systems, Vol. 20, No. 6, pp. 375-381, 1998.
- [6] F. Iov, M. Ciobotaru and F. Blaabjerg, "Power Electronics Control of Wind Energy in Distributed Power Systems," 11th International Conference on Optimization of Electrical and Electronic Equipment, vol., no., pp.XXIX-XLIV, 22-24 May 2008.
 - [7] M.P. Kazmierkowski, L.Malesani, PWM Current Control Techniques of voltage source converters-A Survey, Industrial Electronics, IEEE.Vol.45, no.5, oct.1998.
 - [8] T.Hornik and Q.C.Zhong, Control of grid-connected DC-AC Converters in Distributed Generation: Experimental comparison of different schemes, Power electronics controllers for Power systems, 2nd July 2009.
 - [9] Shaoan Dai, Annette von Jouanne, Alan Wallace, Gabor C. Temes, "Delta-Sigma Modulation Applications in Neutral-Point Clamped Inverters" IEEE 2003, pp.678-683.
 - [10] A.Hirota, S. Nagai and M. Nakaoka, "A novel delta-sigma modulated-DC power converter utilizing dither signal", Power Electronics Specialists Conference, 2000. PESC 00.2000 IEEE 31st Annual, Volume: 2, 2000, pp. 831 -836.
 - [11] A.Mertens, "Performance analysis of three-phase inverters controlled by synchronous delta-modulation systems", Industry Applications, IEEE Transactions on, Vol. 30, Issue 4, Jul/Aug 1994, pp.1016-1027.
 - [12] Steven R.Norsworthy, Richard Schreier and Garbor.C.Temes, "Delta Sigma Data Converters-Theory, Design and Simulation", IEEE press, 1996.