Modeling and Experimental Investigation on Vector Control of Grid-connected Inverter-Based Distributed Generation

Mohamayee Mohapatra, B. Chitti Babu, K.B. Mohanty

ABSTRACT

As the distributed generation (DG) systems based on small hydro, wind turbine and solar energy etc., are intermittent power sources, the grid-connected inverter is employed as an interfacing device to maintain voltage at the point of common coupling (PCC) and power quality. If these systems are not well controlled then their connection to the utility network can lead to grid instability or even failure. In order to solve this problem, current controller plays an important role on grid-connected inverter system. In this article vector control of grid connected-inverter system based on grid-flux oriented reference frame is presented. In addition, a modified delta-sigma modulator in the inner feedback loop is proposed to maintain voltage quality at the utility end with sinusoidal current injection. Moreover, the proposed control strategy ensures independent control of active and reactive power flowing into the grid. The overall performance of proposed control strategy is analyzed in MATLAB-Simulink environment and the obtained results are validated with experimental results in the laboratory prototype using a TMS320F2812 DSP platform.

Key Words: Current Controller, Delta modulator, Delta-sigma modulator, Distributed Generation (DG), Total Harmonic Distortion (THD), Vector Control, Voltage Source Inverter (VSI),

Nomenclature

v_a, v_b, v_c — phase voltages a, b, and c respectively
V_M — maximum phase voltage in volts
ω — angular frequency in radians
v_α, v_β — phase voltages in (α-β) stationary reference frame

i_α, i_β — phase currents in (α-β) stationary reference frame
v_d, v_q — phase voltages in (d-q) rotating reference frame
P_g, Q_g — *Active* and reactive power flows in the grid in *kW* and *kVAR*
e_{gd}, e_{gq} — grid phase voltage in (d-q) rotating reference frame
i_{gd}, i_{gq} — grid phase currents in (d-q) rotating reference frame
s_g — instantaneous power flowing into grid
P_{dc} — dc-link power in *kW*
U_{dc} — dc-link voltage in *V*
I_{dc} — dc-link current in A^{1*}
C — dc-link capacitance in *F*
P_s — supply power in *kW*
ω_c — gain cross-over frequency in *rad*
A — bandwidth in *Hz*
$i_{gq}{}^*, i_{gd}{}^*$ — grid reference d-q axis currents
U_{dc^*} — reference dc-link voltage in *V*
PI — proportional & integral controller
K_p, K_i — proportional & integral gain

INTRODUCTION

Due to dramatic increase of future energy demand and depletion of fossil fuels, renewable energy sources are playing a pivotal role in the today's energy scenario. Distributed generation (DG) based on renewable energy sources such as wind, solar, biomass etc., with energy storage are basically small scale power generation units (typically ranges from 20 kW to 20 MW) and they are located at the end user without having long transmission line. Among all, wind energy and photovoltaic solar are the more promising energy sources and their usage is rapidly growing. Moreover, it is feasible to implement interfaces having ability to operate in grid connected as well as in isolated mode without grid connection which is called micro grids [1]. However, due to intermittent nature of DG system non-sinusoidal currents are injected in to the network and it can cause serious power quality problems. For this reason, up-to-date technologies of power electronics converters are applied for DG integration. They must be capable of providing power flow control with high power factor and harmonic free sinusoidal current injection [2].

Three-phase Pulse Width Modulation (PWM) voltage source inverter (VSI) is used to interface DG system with utility network. In most cases control design for the PWM VSI involves two steps and these are choice of modulation strategy which corresponds to open loop control and design of dynamic close loop control [3]. The main functions of the controllers are to control the active and the reactive power of the grid independently with harmonic rejection. This approach is called Vector Control. Various control strategies have been proposed and are extensively studied in the available literature [3]-[8]. Proper power flow regulation using vector control was studied in [4]. Dual Vector Current control which was first proposed in [5] uses two VCCs for positive and negative sequence components along with DC link voltage control. In [6], the author has reported Synchronous PI current control which converts the three phase grid voltages to synchronously rotating (d-q) frame for proper decoupling. As a result, grid currents become DC variables and thus no steady state-state error adjustment is required. A method for active and reactive power control has also been reported in [7]. It controls the DC link voltage by designing a Voltage Control Loop. However, in case of three phase grid connected inverter voltages and currents are usually transferred to rotating d-q reference frame for making design of controller easier because the current space vector in the rotating d-q reference frame is fixed, the PI controllers operate on dc, rather than sinusoidal signals. A simple control technique is being employed in a grid connected inverter without applying the d-q transformation as reported in [8] which achieves zero steady state error in the stationary reference frame. However the transient response of PI controller is sluggish during sudden change in load or during fault conditions. B. Chitti Babu et all have proposed the decoupled control strategy with optimal LCL filter for grid-connected VSI. However, the control strategy is complicated as the multiple parameters are involving and it needs feedback linearization for decoupling.

In this article vector control of grid connected-inverter system based on grid-flux oriented reference frame is presented. In addition, a modified delta-sigma modulator in the inner feedback loop is proposed to maintain voltage quality at the utility end with sinusoidal current injection. Moreover, the proposed control strategy ensures independent control of active and reactive power flowing into the grid. The overall performance of proposed control strategy is analyzed in MATLAB-Simulink environment and the obtained results are validated with experimental results in the laboratory prototype using TMS320F2812 DSP platform.

MATHEMATICAL MODELING OF GRID CONNECTED INVERTER

The description of the system considered for modeling and implementation is shown in Figure 1. It consists of clean energy ac-source, ac-dc rectifier, dc-link, dc-ac PWM VSI and grid with interfacing inductance.

The modeling of PWM VSI is explained as follows:

The input is a three phase supply as follows:

$$V_a = V_m \cos \omega t \tag{1}$$

$$V_b = V_m \cos\left(\omega t - \tfrac{2\pi}{3}\right) \tag{2}$$

$$V_b = V_m \cos\left(\omega t + \tfrac{2\pi}{3}\right) \tag{3}$$

where V_m is the maximum phase voltage and ω is the angular frequency of the power source respectively.

The vector control is adopted for grid-connected converter where the grid currents are controlled in a synchronously rotating two axes reference frame i.e. transforming into dc equivalent. For the decoupling two co-ordinate transformations are adopted. The two transformations are Clark (α-β) and Park (d-q) transforms. Co-ordinate transformation is given by (4) from three phase (abc) to two phase stationary (α-β) (equal turn transformation):

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

The Transformation from the stationary reference frame to synchronously rotating frame is given by

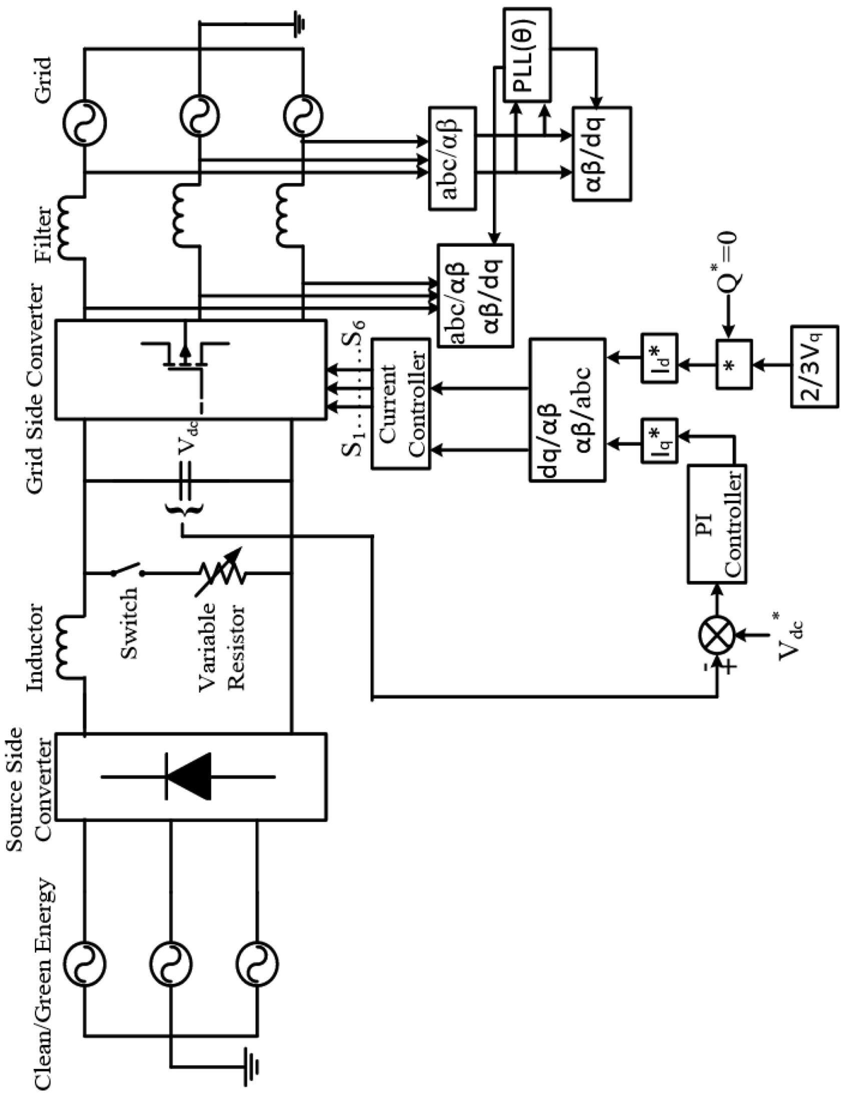


Figure 1. Control strategy of grid-connected VSI system

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (6)$$

In the *d-q* reference frame the active P and reactive Q powers are given by

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right) \quad (7)$$

$$Q = \frac{3}{2}\left(V_q I_d - V_d I_q\right) \quad (8)$$

CONTROL STRATEGY OF GRID- CONNECTED INVERTER

With reference to Figure 2, the grid flux vector is aligned with the *d*-axis and the grid voltage vector aligned with *q*-axis. Vector control regulates the length and position of the grid current vector in the grid flux orientated reference frame [10].

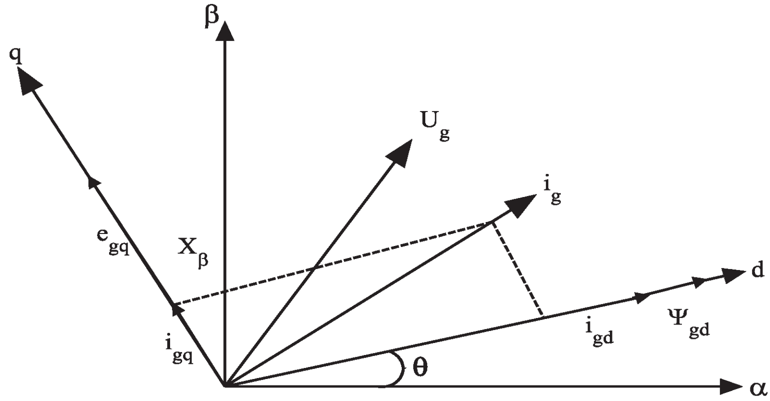


Figure 2. Rotating two axis grid-flux oriented reference frame

In this reference frame the real part of current corresponding to reactive power and imaginary part of current corresponding to active power. The reactive and active power can therefore be controlled independently since the current components are orthogonal. The active current component is generated by an outer direct voltage control loop and the reactive current reference can be set to zero for a unity power factor.

$$P_g = \frac{3}{2} e_{gq} i_{gq} \tag{9}$$

$$Q_g = \frac{3}{2} e_{gq} i_{gd} \tag{10}$$

As said earlier, the main aim of vector controlled grid-connected VSI is to independently control the instantaneous active and reactive grid currents with a high band width and It consists of f two control loops:

(1) Outer DC Control voltage loop
(2) Inner Current control loop

DC VOLTAGE CONTROLLER

The DC voltage controller is used to produce the reference current value for the current controller. Its aim is to keep the voltage constant on the DC side in normal condition or during grid faults or changes in input power. The instantaneous power flowing into grid can be written as

$$S_g = P_g + jQ_g = \frac{3}{2} e_g i_g^{\ *} = \frac{3}{2}(e_{gq} i_{gq} + j e_{gq} i_{gd}) \tag{11}$$

$$S_g = \frac{3}{2}(|e_g| i_{gq} + j |e_g| i_{gd}) \tag{12}$$

From the equation of instantaneous power, the active power is the real part of equation (11) is given by

$$P_g = \frac{3}{2}\left(|e_g| i_{gq}\right) \tag{13}$$

From Figure 3 [5], by neglecting the capacitor leakage, the direct voltage link power is given by

$$P_{dc} = U_{dc} I_{dc} = U_{dc} C \frac{dU_{dc}}{dt} \tag{14}$$

Assuming the converter losses can be neglected, the power balance in the direct voltage link system is given by

$$U_{dc} C \frac{dU_{dc}}{dt} = P_s - P_g = P_s - \frac{3}{2} \left| e_g \right| i_{gq} \tag{15}$$

Where P_s is the supply power which is independent of DC link voltage, Transfer function between direct voltage and grid current i_{gq} can be obtained as

$$U_{dc} = -\frac{3\left|e_g\right|}{2pCU_{dc}} i_{gq} \tag{16}$$

The transfer function is nonlinear. However it is reasonable to substitute the direct voltage with its reference value since the objective is to maintain constant DC link voltage. This assumption gives the following linear transfer function:

$$U_{dc} = -\frac{3\left|e_g\right|}{2pCU_{dc}^*} i_{gq} \tag{17}$$

$$U_{dc} = -Gi_{gq} \tag{18}$$

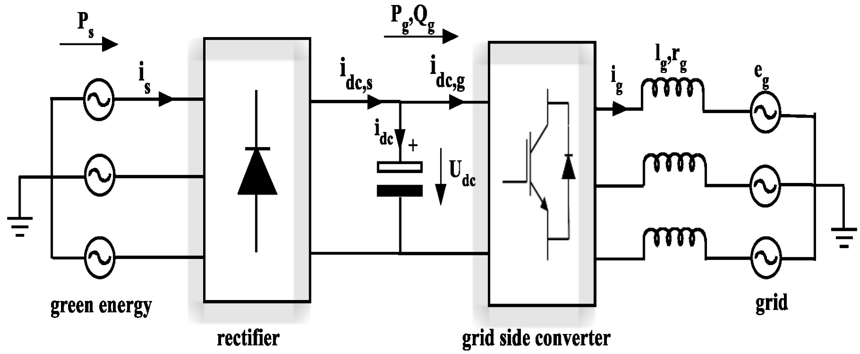


Figure 3. Power flow diagram of overall system

The approximation is valid for small variations in the DC voltage and also the grid voltage amplitude can be assumed constant during normal operation. Applying internal model control gives the direct voltage link controller as

$$F = \frac{\alpha}{p} G^{-1} = -\alpha \frac{2CU_{dc}^{\ *}}{3e_g} \tag{19}$$

From equation (9), a P-controller is obtained for regulating the direct voltage. Conventional PI controllers are used, that are standard structures which contain the basic proportional (P) component and the integrative (I) component. The P component makes a frequency characteristic with the same gain for all the frequencies and is related to the amount of the ripple. The I component minimizes errors at low frequencies. The complete closed loop dc-link voltage control structure is given in Figure 4.

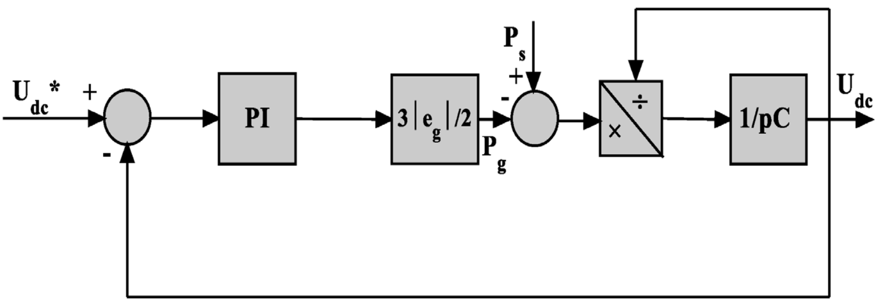


Figure 4. Block diagram of the closed-loop direct voltage control.

The following is often adapted for selecting the controller integration time in traditional PI-controller design.

$$T_i = \frac{10}{\omega_c} = \frac{10}{\alpha} \tag{20}$$

Where ω_c is the cross-over frequency and α is the desired bandwidth.

The active reference current of grid connected converter is given by

$$i_{gq}^{\ *} = k_p \left(1 + \frac{1}{T_i p}\right)\left(U_{dc}^{\ *} - U_{dc}\right) \tag{21}$$

OPEN LOOP REACTIVE POWER CONTROL

Reactive power exchange with the grid is controlled by the reactive current component. The simplest method of controlling reactive power is via open loop control. Taking the imaginary part of equation (11) gives the reactive reference current in equation (22). The complete Simulink model of proposed control strategy of grid-connected VSI is shown in Figure 5.

$$i_{gd}{}^{*} = \frac{2}{3e_{gq}} Q^{*} \tag{22}$$

Analysis of Proposed Current Controller

Analysis of Delta-Sigma Modulator applied to VSI –

The second order delta-sigma modulator is realized by the error feedback structure [11] as shown in Figure 6. 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 coefficients [12]. 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 [13].

In the circuit, quantization error signal e is added to the input signal. Input and output signal relations is represented as

$$y(z) = x(z) + \left(e_z - e_{z-1}\right) \tag{23}$$

In the simplest case $H(z) = z^{-1}$ chosen as transfer function of the

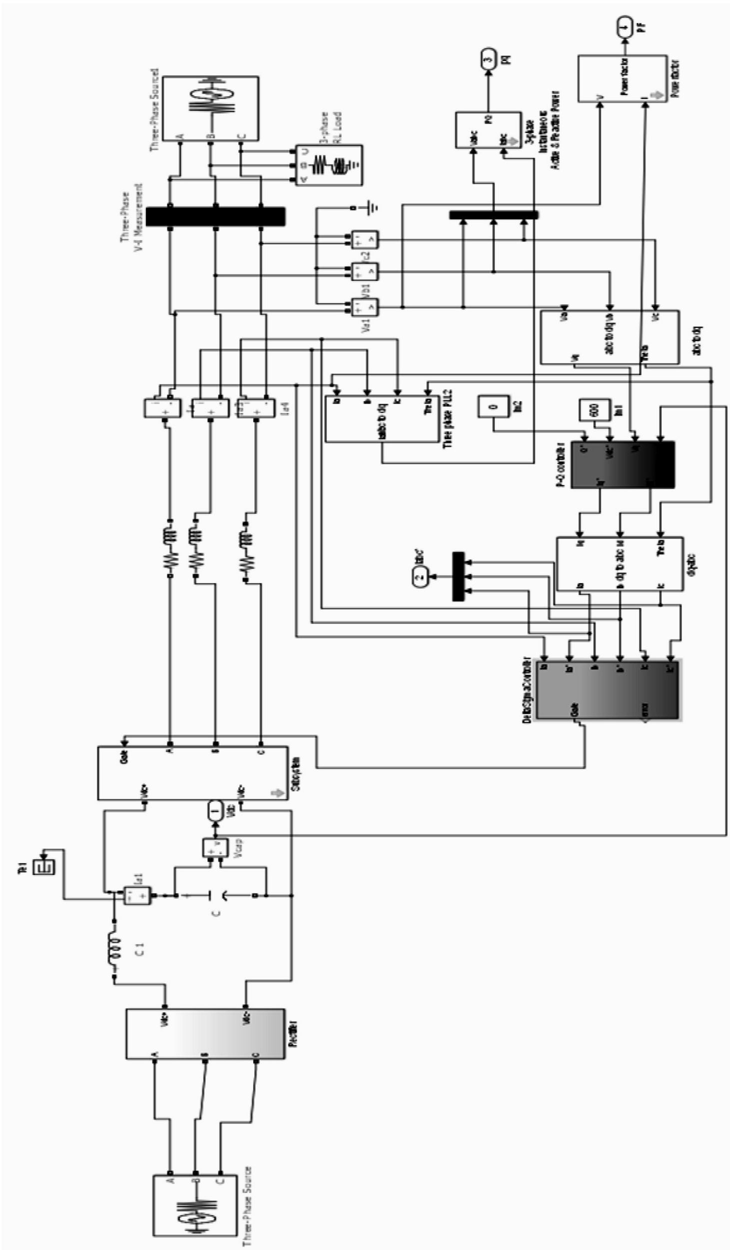


Figure 5. Complete Simulink model of proposed control strategy of grid-connected VSI system

feedback filter. So the overall transfer function becomes

$$H_1(z) = 1 - H(z) = 1 - z^{-1} \tag{24}$$

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

$$H_2(z) = 1 - (1 - z^{-1})^2 = z^{-1}(2 - z^{-1}) \tag{25}$$

The system block diagram is shown in Figure 7. The output is:

$$Y(z) = X(z) + (1 - z^{-1})^2 E(z) \tag{26}$$

This structure only needs delay, addition and shift operations. It can effectively reduce the Digital Signal Processing (DSP) run-time of the

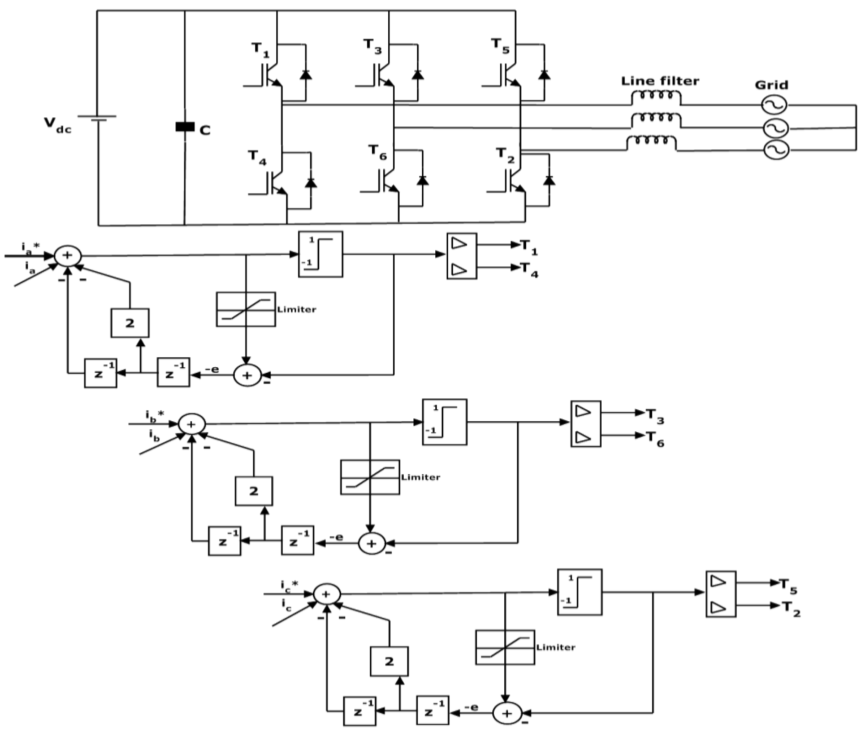


Figure 6: Schematic of the two- level inverter with the second order delta-sigma modulator

modulation algorithm [14]. 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 Figure 8. The corresponding Simulink model of delta-sigma modulator is illustrated in Figure 9.

RESULTS AND DISCUSSION

The proposed control strategy of grid-connected voltage source inverter is verified by the simulation study implemented in Matlab 7.6. Elements such as diode rectifier, PWM inverter and inductors are from Simpower Systems, and the algorithm are realized in Simulink. The obtained results have been experimentally verified in the laboratory, Figure

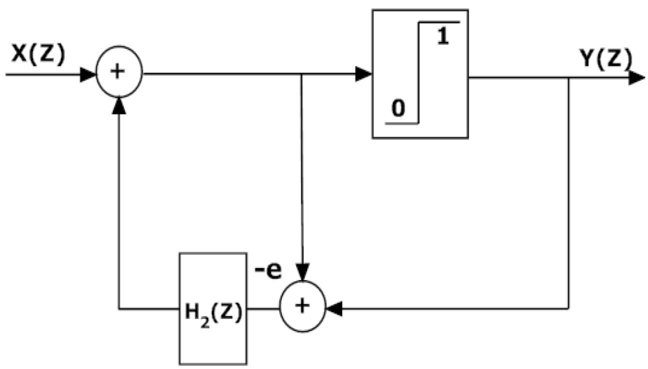


Figure 7. The delta-sigma modulator with error feedback structure

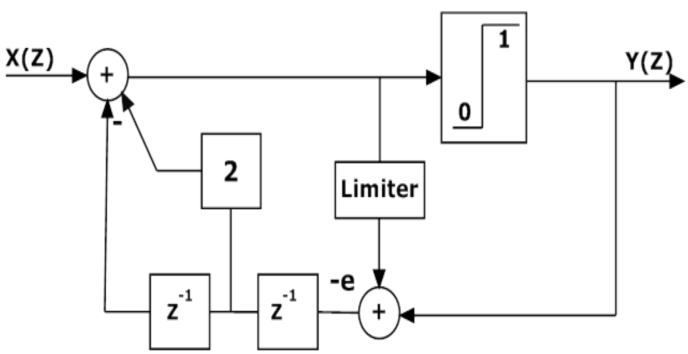


Figure 8. The second order delta-sigma modulator with a limiter to prevent overload

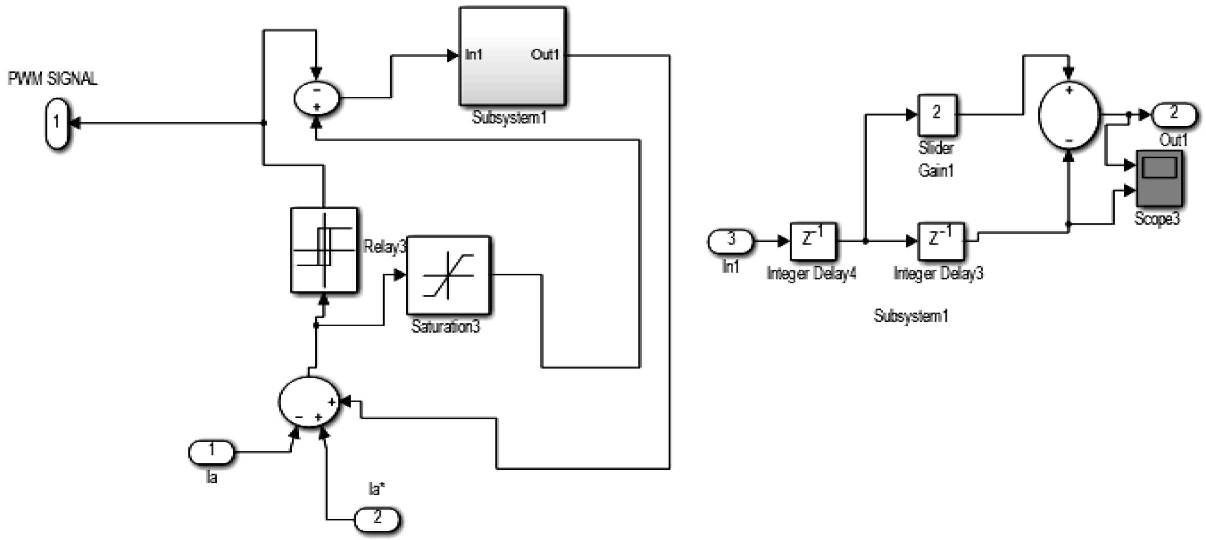


Figure 9. Simulink model of second order delta-sigma modulator for one phase

10, by using a TMS320F2812 DSP platform. The simulation parameters are as follows:

DC link reference voltage (U_{dc}*) = 600 V, Reference Reactive Power (Q^*) = 0 Var, Hysteresis Band Width (h) = 0.5, Proportional gain (K_p) =0.05, Integral gain (K_i) =20.

Simulation Results

The simulation results of the proposed control strategy to grid-connected VSI system and the results are presented in this section. Figure 11 shows the steady state performance concerning output phase currents, reference currents, superimposed current with current error, dc-link voltage, active and reactive power, and %THD, for the current regulated delta-sigma modulator. The magnitude of the grid currents and reference currents are same with no phase offset. As it might be observed, the controller has very good dynamic response, following closely the reference with zero steady-state error and zero overshoot. As illustrated in Figure 11 (a) and Figure 11(b), the currents takes 80 msec to reach the steady state. The high quality current at the utility end is the natural result of the controllers' ability to minimize distortions at the utility end and to maintain the power quality of the system. The current errors with the hysteresis band set at 5A. Like other PWM techniques the inverter output voltage is quasi-square wave whereas the grid output voltage is purely sinusoidal with no harmonics, as depicted in the Figure 11 (c). Under normal operating conditions, steady state dc-link voltage is a constant and the voltage regulator output, i.e., the q-axis current command, is also a constant, which yields a constant power drawn from the input ac stage and balanced three-phase input currents. The steady state value of dc-link voltage is equal to the reference value of the dc-link voltage which is set at 600V. As shown in Figure 11 (d), the settling time of the dc-link voltage is about 50msec i.e. less than three cycles. The active power of the grid connected VSI is measured as 3.5kW where as the reactive power reference is taken as zero to maintain unity power factor at the utility end is presented in Figure 11 (e). Moreover,THD measured are 1.64% which is shown in Figure 11 (f) which satisfies the limit specified in the IEEE 519-1992 standard.

Experimental Validation

The control of the grid side converter has been tested using the experimental test setup using TMS320F2812 DSP processor. The study case which is analyzed is similar with the simulation case from Figure 11 and it proves that the control system is well performed.

In order to validate the design of the control algorithm the shape of the voltage of the utility grid can be view in Figure 12 (a) where it can be seen that the grid current is almost sinusoidal with less ripples. Figure 12 (b) shows the reference and actual current and current error. It can be seen that the active and reactive current references are correctly estimated and the actual current follows its reference trajectory precisely with zero steady-state error and zero overshoot. The current error is confined within the hysteresis band. Figure 12 (c) shows the actual phase-*a* grid voltage and the control inverter output voltage. Figure 12 (d) is validating the dc-link voltage controller which provides a good tracking of the measured dc voltage to its reference. The dc voltage controller is reducing very fast the error and is keeping always the dc-link at the same constant value. Moreover, it can be notice that the grid current and voltage are in phase for the value of the reactive power fixed to 0. As a result, phase-a current is well synchronized with the fundamental grid voltage. In Figure 11(e) the active power is set to the rated value 3.5kW and the reactive power is set to 0 in order to obtain the grid current in phase with the grid voltage. In Figure 11 (f) the harmonic spectrum of the grid current is shown which satisfies IEEE-519-1992 standard. The proposed study showed an excellent agreement between simulated and experimental results.

CONCLUSIONS

We have presented the control strategy for grid-connected VSI systems based on delta-sigma modulators in the inner feed-forward control loop. 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. The proposed controller offers an excellent steady-state response featured by accurate control with zero steady-state error, low current ripple and highly sinusoidal waveform. Moreover, delta-sigma modulator has less total harmonic distortion with lesser average switching frequency which infers the reducing switching loss of the power switches and simultaneous increase in the efficiency of

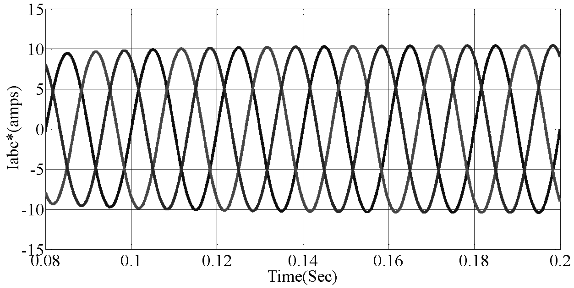
Figure 10. Photograph of Experimental Setup

the inverter. As the output current distortion of delta-sigma modulator is, 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 overall performance of delta-sigma modulator for grid-connected inverter has been verified by the presented results of MATLAB-simulations and experimental investigation of a laboratory model.

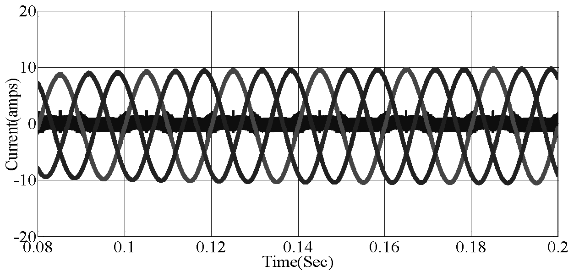
References

L. Chang and H.M. Kojabadi, "Review of interconnection standards for distributed power generation," Large Engineering Systems Conference on Power Engineering 2002 (LESCOPE' 02), pp.36 - 40, June 2002.

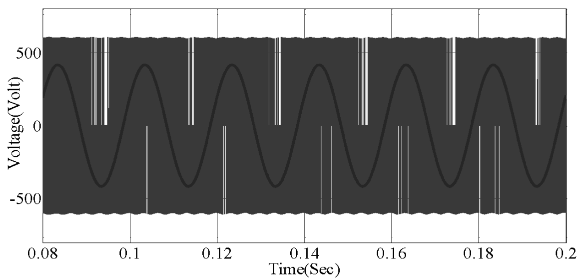
F. Iov, M. Ciobotaru and F. Blaabjerg, "Power Electronics Control of Wind Energy in Distributed Power Systems," 11th International Conference on Optimization of Elec-



(a)

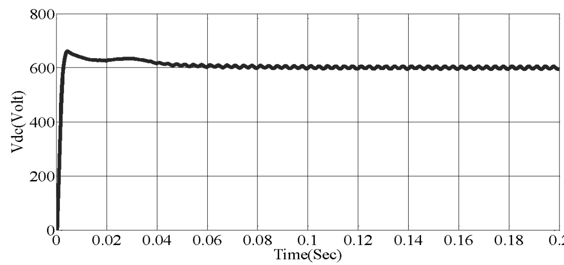


(b)

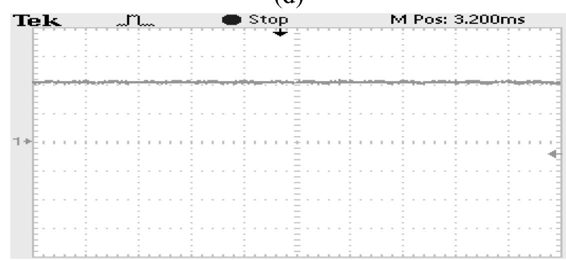


(c)

Figure 11. Simulation Results of delta-sigma Modulator (a) grid Current (b) Current Vs Current error(c) Inverter o/p voltage Vs Grid voltage (d) DC link voltage (e) Active and Reactive Power (f) % THD of grid current.



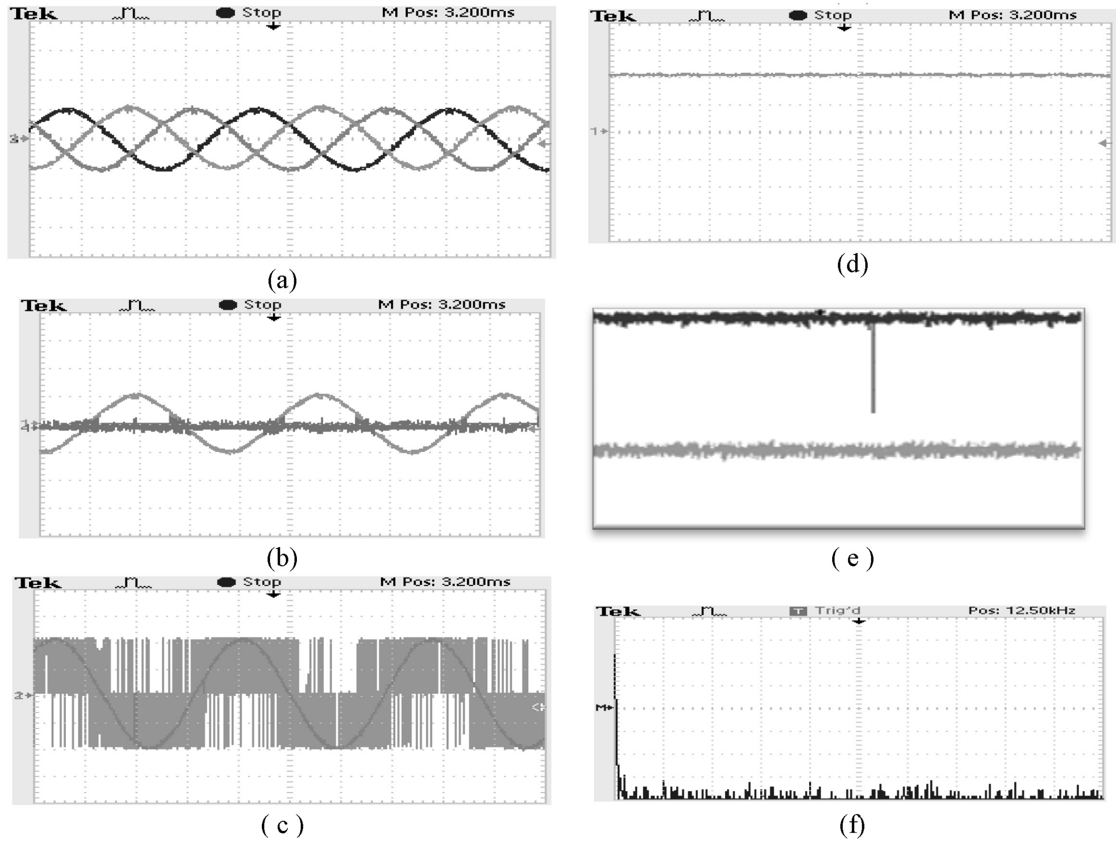
(d)



(X-axis-1 div=50ms, Y-axis-ch1, ch2 -1div=5V)

(e)

Figure 12. Experimental Results of delta-sigma Modulator (a) grid Current, (b) Current Vs Current error, (c) Inverter o/p voltage Vs Grid voltage, (d) DC link voltage, (e) Active and Reactive Power, (f) %THD of grid current.



trical and Electronic Equipment, pp.1109-1114, May 2008.
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.
Rolf Ottersten, “Vector Control of a Double-Sided PWM Converter and Induction Machine Drive,” PHD Thesis, Chalmers University of Technology, Goteborg, Sweden 2000.
Azaza, H., and Masmoudi, A., “Implementation of a dual vector control strategy in a doubly-fed machine drive,” *European Transactions on Elect. Power*, Vol. 15, No. 6, pp. 541–155, November 2005.
Schonardie, Mateus F. Martins, Denizar C., “Three-phase grid-connected photovoltaic system with active and reactive power control using *d-q-0* transformation,” IEEE 39th Annual Power Electronics Specialists Conference, pp. 1202-1207, 2008.
Zhou Dejia, Zhao Zhengming, Yuan Liqiang, Feng Bo, Zhao Zhiqiang, “Photovoltaic grid-connected system based on a synchronous current vector PI controller,” *Journal of Tsinghua Univ (Sci &Tech)*, Vol. 49, No.1, pp. 33-36, 2009.
Zmood, D.N.; Holmes, D.G., “Stationary frame current regulation of PWM inverters with zero steady-state error,” *Power Electronics, IEEE Transactions on*, vol.18, no.3,pp.814,822, May 2003
B. Chitti Babu1, Anup Anurag, Tontepu Sowmya, Debati Marandi, and Satarupa Bal, “Decoupled Control Strategy of Grid Interactive Inverter System with Optimal LCL
Filter Design,” *International Journal of Emerging Electric Power Systems*. Vol.14, Iss. 5, Pp. 477–486. Sep 2013.
Ahmed Ibrahim, “vector control of current regulated inverter connected to grid for wind energy applications.” *International Journal on Renewable Energy Technology,* vol.1, no.1, pp.145-151, 2009.
A. Mertens, “Performance analysis of three-phase inverters controlled by synchronous delta-modulation systems *IEEE Transactions on Industry Applications,* Vol. 30, Issue 4, pp.1016-1027, 1994.
Steven R. Norsworthy, Richard Schreirer and Garbor C. Temes, “Delta Sigma Data Converters-Theory, Design and Simulation,” *IEEE press*, 1996.
Shaoan Dai, Annette von Jouanne, Alan Wallace, Gabor C. Temes,” Delta-Sigma Modulation Applications in Neutral-Point Clamped Inverters,” Conference Record of the 38th IEEE IAS Annual Meeting., Vol.1, pp.678-683, Oct 2003.
A. Hirota, S. Nagai and M. Nakaoka, “A novel delta-sigma modulated-DC power converter utilizing dither signal,” Power Electronics Specialists Conference, 31st Annual IEEE PESC, conference, Vol. 2, pp. 831 -836, 2000.

ABOUT THE AUTHORS

Mohamayee Mohapatra received the B.E degree from Biju Patnaik University of Technology (BPUT), Rourkela, India, in 2003, and the M.Tech (By Res.,) degree from National Institute of Technology Rourkela, India, in 2012. She is currently working as a lecturer in IGIT Sarang, Odisha. India. Her interests include power electronics and drives, distributed power generation system, and power quality. E-mail: mohamayee@gmail.com

B. Chitti Babu (corresponding author) received the B.E degree in Electrical & Electronics Engineering from Madurai Kamaraj University, India and M.E degree in Power Electronics & Drives from Anna University Chennai, India and Ph.D. in Electrical Engineering from National Institute of Technology Rourkela, India in 2003, 2006 and 2012, respectively. He is currently a Postdoctoral Research Fellow with the Centrum ENET, VSB-Technical University of Ostrava, Czech Republic. He is a recipient of Post-Doctoral Research fellowship from STRONGTiES/European Union Project, U.K to carry out research work at Wroclaw University of Technology (WUT), Poland from 2013- 2014. His research interests include power electronics applications in distributed power generation systems and low-power electronics design, including photovoltaic energy systems. He is a senior member of IEEE, USA. E-mail: bcbabunitrkl@gmail.com

Kanungo Barada Mohanty has received B.E. degree from Sambalpur Univ., M.Tech. and Ph.D. degrees from Indian Institute of Technology, Kharagpur in the years 1989, 1991 and 2002 respectively, in Electrical Engineering. He is a faculty member of Electrical Engg. Dept, National Institute of Technology, Rourkela since 1991, and currently serving as an Associate Professor. He has published 17 journal papers and more than 40 conference papers. His research interests include control and estimation in induction machine specifically vector control, DTC and wind energy conversion systems. Dr. Mohanty is a Senior Member of the IEEE, Fellow of the IE (India), Fellow of IETE, and Life Member of Solar Energy Society of India. E-mail: kbmohanty@nitrkl.ac.in