Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN (O): 2320-5407
ISSN (P): 3107-4928

Article DOI: 10.21474/IJAR01/23355
DOI URL: http://dx.doi.org/10.21474/IJAR01/23355

CONFERENCE PAPER

REACTIVE POWER COMPENSATION OF MAINS CONNECTED INVERTER SYSTEM

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Manuscript Info

Manuscript History
Received: 8 February 2026
Final Accepted: 10 March 2026
Published: April 2026

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

Abstract

This paper presents the performance analysis of the delta-sigma modulator for mains connected inverter system. Since the paper discusses the implementation of this controller for grid-connected system, its evaluation is made in two operating conditions. First, in steady-state conditions, the contributions of controller 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 controller especially during sudden change in reactive loads is studied. It provides reactive power demand in order to improve the voltage profile at PCC, control the active and reactive power independently and fast voltage regulation etc. The performance of this modulator is simulated in the Matlab/Simulink environment.

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.

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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].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 [8]. 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[9] .This paper focuses on the 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 controller is studied and analyzed in the computer simulation undertaken by MATLAB/SIMULINK environment.

Analysis of Proposed Current Controller:-
Analysis of Delta-Sigma Modulator applied to two-level inverter:-

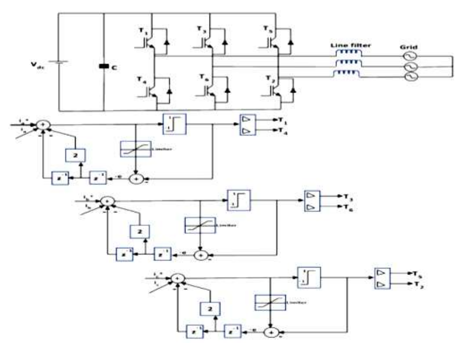

Figure 1: Schematic of the two- level inverter with the second order delta-sigma modulator

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

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

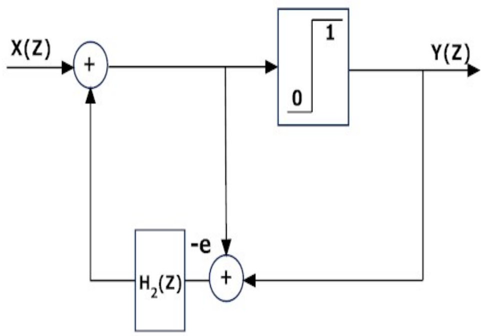

Figure 2: The delta-sigma modulator with error feedback structure

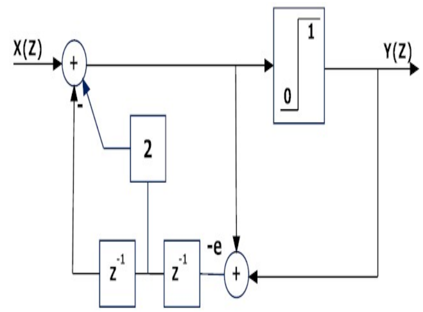

Figure 3: The second order delta-sigma modulator

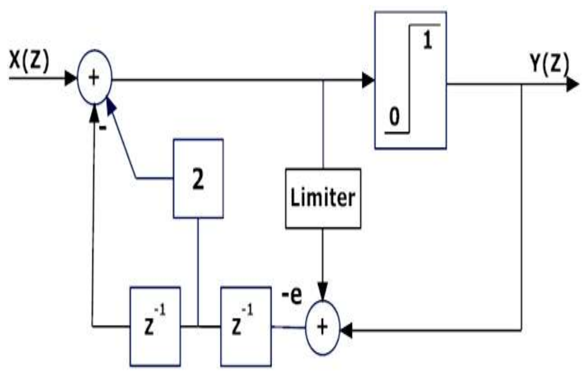

Figure 4: The second order delta-sigma modulator with a limiter to prevent overload

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

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

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

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

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.

Proposed Control Algorithm:-

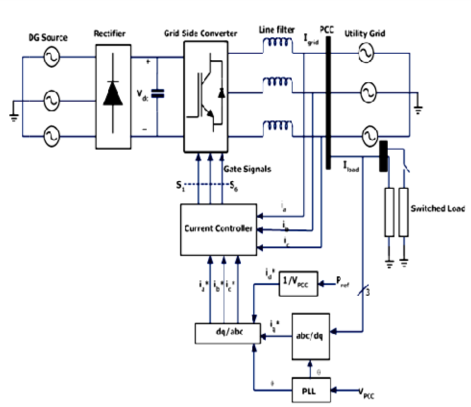

Figure 5: Over all block diagram of proposed current controller for grid connected VSI

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(θ), sin(θ) for transforming stationary two phase quantities in stationary reference frame into rotating two phase quantities in rotating frame. Fig. 5 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).

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

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

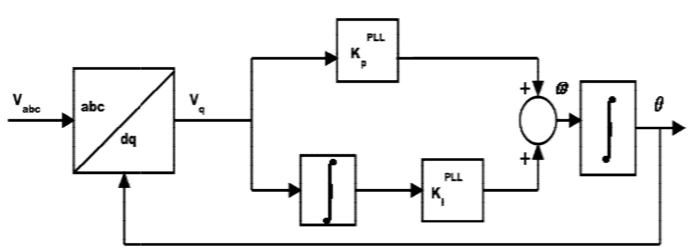

Figure 6: Block diagram of PLL

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.

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

$$\theta = \int (\omega \times dt) \quad (10)$$

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:

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

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

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

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.

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

Results and Discussion:-

The control strategy of grid connected inverter is verified by the simulation study by Matlab 7.6. 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.

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

Simulation Results of Grid Connected Inverter:-

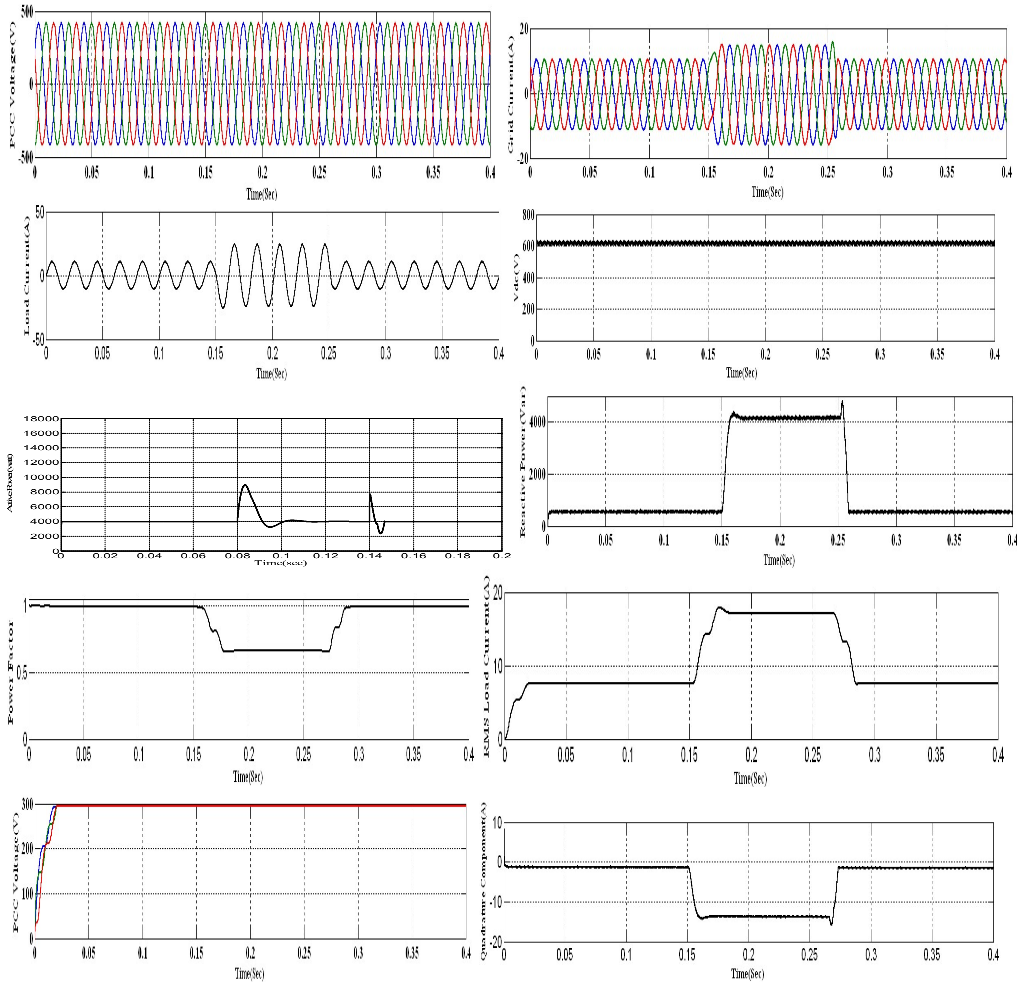

Figure 7: Response of Delta-Sigma Modulator under transient conditions (a)PCC voltage (b) Grid Current (c) Load Current (d) DC link voltage (e) Active power (f) Reactive Power (g) Power factor (h) RMS value of PCC voltage (i) RMS value of Load current (j) Quadrature component of Grid current.

In order to verify the dynamic performance, a step of 70% of the rated load is given and is shown in the Fig.7. First test simulates the situation of increase in current by instantly increasing the load demand from (4kW, 1kVar) to (4kW, 7kvar). As Fig. 7(b) and Fig. 7(c) illustrate, the controller have good dynamics, being able to track closely the current reference, without 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 30μSec as can be observed in the Figure 7(f), which shows the dynamic performance with lower time scale. The total harmonic distortion of the grid current is 1.64%.

Conclusion:-

This paper discusses the fast dynamic response, accurate performance, ease of implementation and inherent closed loop control of Delta-Sigma modulated current controlled grid connected PWM VSI for controlling the flow of energy and to overcome the power quality problems between the rectified DC sources and the utility network. The proposed Delta-Sigma modulator controls the active and reactive power independently with fast dynamic response. This modulator also reduced the harmonics amplitude variations of the unfiltered current and lowers the THD which can reduce the size of the filter. In addition, it 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.

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