# Three Level Hysteresis Current Controlled VSI for Power Injection and Conditioning in Grid Connected Solar PV Systems

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*Abstract*—**The penetration of solar PhotoVoltaic (PV) systems to the grid is gradually being increased as an alternative to conventional energy sources. The interfacing of solar PV systems to the grid requires efficient control strategies for the operation, control and Power Quality (PQ) improvement. This paper proposes a three-level Hysteresis Current Control (HCC) strategy for grid connected four leg Voltage Source Inverter (VSI). The main objective of three-level HCC for VSI is to perform solar power injection as well as power conditioning such as compensation of harmonics, reactive power, neutral current and current imbalance. Conventional HCC suffers from variation in switching frequency, whereas the three-level HCC exhibits a considerable reduction in switching frequency variation by considering offset hysteresis band, thus enhances the control performance. Here a three phase four wire supply system connected to both linear and nonlinear unbalanced loads are considered. The efficacy of the proposed control concept is demonstrated with different operating conditions using MATLAB/Simulink© simulation studies.**

***Keywords—solar photovoltaic systems; three-level hysteresis current control; voltage source inverter; power conditioning; power injection; power quality.***

## I. INTRODUCTION

The renewable energy sources have attracted a lot as a future energy solution because of growing global energy demand, increase in air pollution level and exhaustion of fossil fuels. Among non conventional energy sources, solar energy has been distinguished as the most emerging technology. In the current scenario, the growing penetration level of solar PV systems has made it compulsory to take them in account while determining the voltage regulations, stability and power quality of the grid. Hence, the solar PV systems are mandatory to act in accordance with technical and regulatory frameworks to make sure safe, reliable and efficient operation of overall system. The power electronics and digital control technology, plays a vital role in grid interfacing of solar PV systems to enhance the system operation with improved power quality at point of common coupling (PCC) [1]-[2].

On the other hand, enormous deployment of nonlinear loads such as power electronic converters, compact fluorescent lamps (CFLs), switch mode power supplies (SMPS), Xerox machines, computer printers, arc furnaces, welding machines, adjustable speed drives (ASDs) and uninterruptable power supply systems (UPSs) at PCC generates current harmonics, reactive power, neutral current and current imbalance which may deteriorate the supply system power quality.

The current controlled voltage source inverters (VSIs) are fundamental integrators to connect solar PV systems to the grid [3]. In recent times various control strategies for solar PV system, interfacing VSI with power conditioning functionality have been proposed [3]-[7]. A control strategy for renewable interfacing VSI based on instantaneous reactive power theory is presented in [3], where both load and inverter current sensing is essential to compensate the current harmonics injected by the nonlinear loads. A critical review of renewable interfaced grid connected inverter control strategies are demonstrated in [4], which gives a detailed discussion on hysteresis, SPWM, SVPWM modulation strategies using proportional integral (PI), proportional resonant (PR), repetitive, linear quadratic regulator. Among all of that hysteresis current control (HCC) is robust, provides fast dynamic response. Nevertheless, the switching frequency variation may burden the controller design. In [5] unit vector template generation based two level HCC is proposed, which is also suffers from switching frequency variation leads to switching losses in the VSI. To overcome this drawback an efficient control strategy is necessary for multifunctional grid connected VSI.

In this paper a three-level hysteresis current controlled VSI with solar PV interfacing is proposed to perform power injection and power conditioning. The three-level hysteresis current control (HCC) strategy overcomes the drawback of switching frequency variation by using offset hysteresis band (HB). Here the three-level hysteresis modulation is achieved by using two HB comparators displaced by small offset. The switching frequency of the VSI depends on the hysteresis band limit. Hence by adjusting the HB limit the VSI switching frequency can be minimized.

Apart from solar energy interfacing to the grid, the VSI is intended to operate as an active power filter (APF) for compensation of current harmonics, reactive power, neutral current and current imbalance. Therefore, the proposed system is capable to interface solar energy to the grid and simultaneously improve the power quality at the PCC in compliance with IEEE 1547.1 and IEEE 519 standards. The performance of the proposed system is examined by using MATLAB simulation studies.

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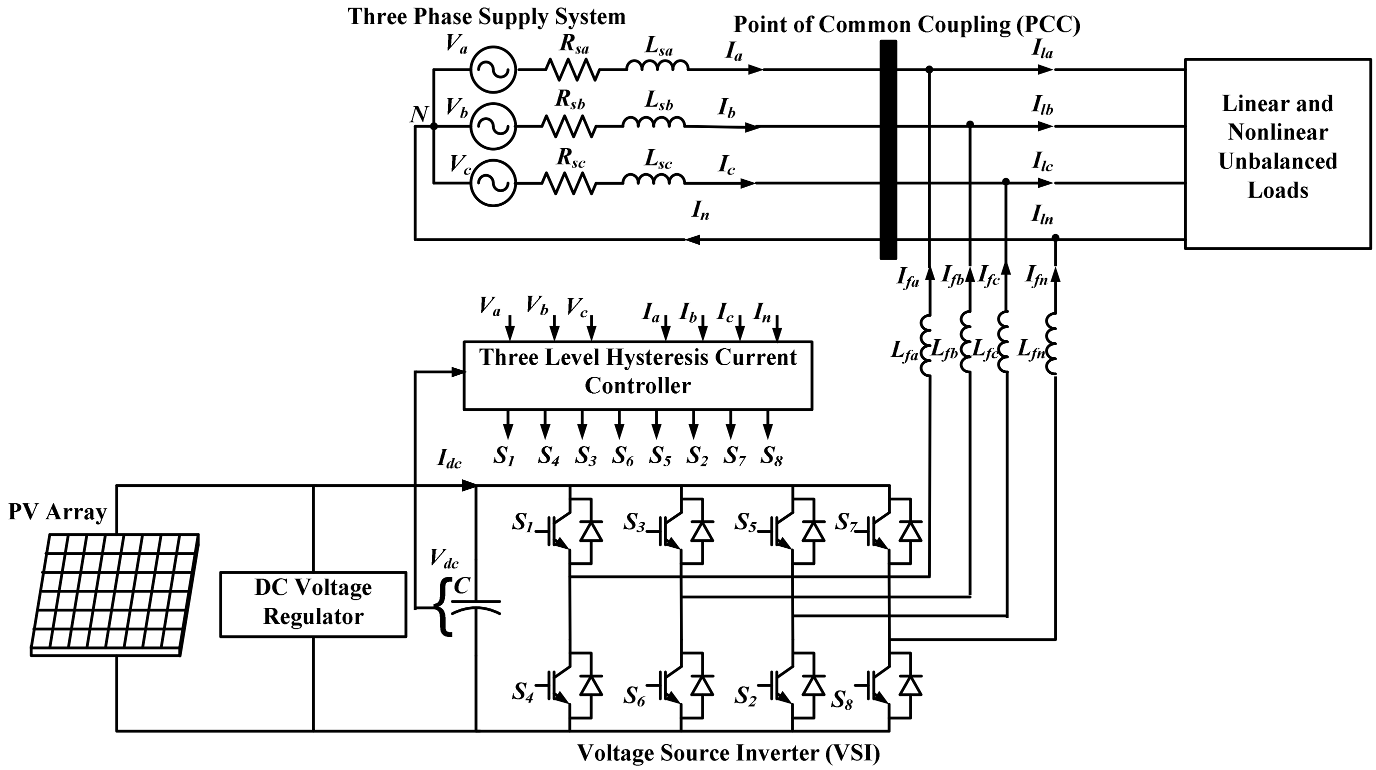


Fig.1. Structure of proposed solar PV based generation system

## II. Proposed System Configuration

The proposed system consists of solar PV array connected to the dc-link of a grid connected VSI as shown in Fig. 1. The three-level hysteresis current controlled VSI is a key element because it interfaces the solar energy to the grid in order to deliver the generated active power and also performs power conditioning. The irregular nature of solar energy may leads to variation in generated power.

The dc-link plays a crucial role in injecting this variable power from solar energy to the grid. The generated solar power is fed to the VSI by using a dc-dc boost voltage regulator thereby it produce a stabilized dc voltage ($V_{dc}$) to the dc link. The switching pulses for grid connected VSI is drawn from three-level HCC. Here a mixture of both linear and nonlinear loads is considered to evaluate the control performance.

The power injected to the grid is written as follows

$$P_g = V_{dc} * I_{dc} \quad (1)$$

Where

$V_{dc}$ = DC link voltage

$I_{dc}$ = Current injected by solar PV

The current controlled VSI is operated in such a way that it absorbs or injects active power from or to the grid.

If a nonlinear, unbalanced load is connected to the PCC, the proposed three-level HCC compensates the current harmonics, neutral current and current imbalance.

## III. Three-Level Hysteresis current control scheme

### *A. Reference Current Estimation*

In the proposed three-level HCC the dc link voltage ($V_{dc}$) regulation is done by using PID controller. The sensed dc-link voltage is passed through a low pass filter (LPF) to purge the switching ripples. The difference of this actual and reference dc-link voltage is given to a PID controller to retain a constant dc-link voltage under varying generation and load conditions.

The PID controller produces an active current ($I_k$) which is multiplied with grid voltage unit vector templates ($U_a$,$U_b$, and $U_c$) to generate the reference grid currents ($I_a^*$,$I_b^*$, and $I_c^*$). Here the reference neutral current is set to zero. The unit vector templates generated from grid synchronization angle ($\theta$) is as follows [5]:

$$\begin{aligned} U_a &= \sin(\theta) \\ U_b &= \sin(\theta - 2\pi/3) \\ U_c &= \sin(\theta + 2\pi/3) \end{aligned} \quad (2)$$

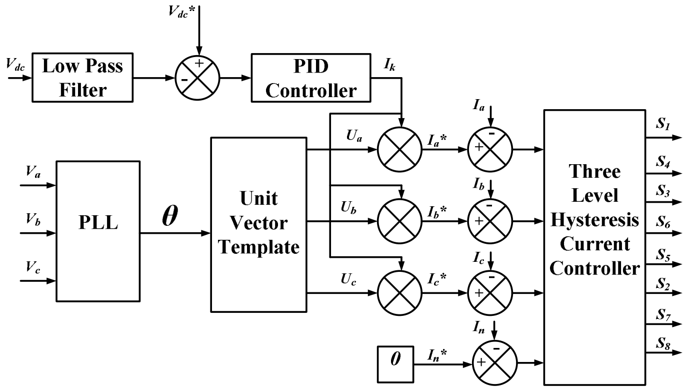


Fig.2. Block diagram of grid connected VSI control

The instantaneous reference currents $I_a^*$ $I_b^*$ *and* $I_c^*$ are written as:

$$\begin{aligned} I_a^* &= I_k.U_a \\ I_b^* &= I_k.U_b \\ I_c^* &= I_k.U_c \end{aligned} \tag{3}$$

The error signals ($I_{ae}$,$I_{be}$, $I_{ce}$ *and* $I_{ne}$) to the three-level HCC are written as:

$$\begin{aligned} I_{ae} &= I_a^* - I_a \\ I_{be} &= I_b^* - I_b \\ I_{ce} &= I_c^* - I_c \\ I_{ne} &= I_n^* - I_n \end{aligned} \tag{4}$$

The three-level HCC generates the switching pulses to the proposed grid connected VSI.

### B. Three-level HCC scheme

The switching logic for the proposed control algorithm for "a" phase is as follows. The same is adopted for all other phase. Here first read the values of actual phase current $I_a$ and reference current $I_a^*$

if ($I_a < (I_a^* + (0.05\text{x}I_a^*))$)
$S_1$=0 and $S_4$=0
end
if ($I_a < (I_a^* - (0.1\text{x}I_a^*))$)
$S_1$=0 and $S_4$=1;
end
if ($I_a > (I_a^* - (0.05\text{x}I_a^*))$)
$S_1$=0 and $S_4$=0;
end
if ($I_a > (I_a^* + (0.1\text{x}I_a^*))$)
$S_1$=1 and $S_4$=0;
end.

The conventional two level HCC operates by comparing a current error between the reference and the measured phase currents against fixed HBs. When the error exceeds the upper HB, the VSI output is switched low, and when the error falls below the lower HB, the inverter output switches high. Such a strategy does not use the inverter zero output condition which leads to huge switching variation thereby causes switching losses. The three-level HCC overcomes the above drawback by using an additional offset HB results significant reduction in magnitude, tracking error and switching frequency variation, while keeping all the benefits of two level HCC [8].

The maximum switching frequency of the conventional and three-level HCC based VSI is written as [8]:

Conventional HCC

$$f_{max}|_{conv\ HCC} = V_{dc}/BL \tag{5}$$

Three-level HCC

$$f_{max}|_{Three\text{-}level\ HCC} = \text{V}_{dc}/4BL \tag{6}$$

where

$B$ = Hysteresis band width

$L$ = interfacing inductance

From equations (5) and (6) it is observed that the maximum switching frequency of the three-level HCC is $1/4^{th}$ of the conventional HCC.

## IV. Simulation Results

The accuracy and validity of the proposed system is demonstrated by using MATLAB/Simulink© simulation studies with different test cases. The simulation parameters are given in Table I. The simulation response of source voltages ($V_{abc}$), source currents ($I_a$, $I_b$, and $I_c$), neutral current ($I_n$) and compensation currents ($I_{fa}$, $I_{fb}$, $I_{fc}$,and $I_{fn}$) are shown in below Fig.3 and Fig.4 respectively. The inverter is turned on at t=0.5s, thus the nonlinear load effect before t=0.5s are shown in Fig.3. After t=0.5s VSI is operated as APF for power conditioning and also power injection.

TABLE I. Simulation Parameters

| | |
|---|---|
| Source Voltage (phase to neutral) | 230V (RMS) , 50Hz |
| Source Impedance | R= 0.1Ω, L= 0.1 mH |
| Three phase Nonlinear load | Bridge rectifier with RL (R=100Ω,L= 10mH) load |
| Single phase Linear load between phase C & Neutral | R load (R=50Ω) |
| DC link Capacitance | 3500μf |
| DC link Voltage | 680 V |
| Ripple filter | 3 mH |
| PID controller gains | Kp=0.09, Ki=0.2 , Kd=0.2 |
| Maximum Switching Frequency | 12kHz |

### A. Power Conditioning Operation

Fig. 3 shows the simulated results for APF mode of operation when there is no power generation from solar PV. All the phase current waveforms along with neutral current are shown with respective to source side phase voltages. Fig. 3(a) shows the three phase supply voltage of the unbalanced linear and non-linear load currents. The grid current profile, when grid-interfacing inverter controlled as shunt APF, is shown in Fig. 3(b). It can be noticed from Fig.3(c) that the highly unbalanced load currents, after compensation, appear as pure sinusoidal balanced set of currents on grid side. The grid current THD's of each phase are reduced from 30.6% (a phase), 38% (b phase), 20% (c phase) to 3.96%, 3.68%, 4.25% respectively.

The load neutral current due to single-phase loads is effectively compensated by the 4th leg of inverter such that the current in grid side neutral conductor is reduced to zero.

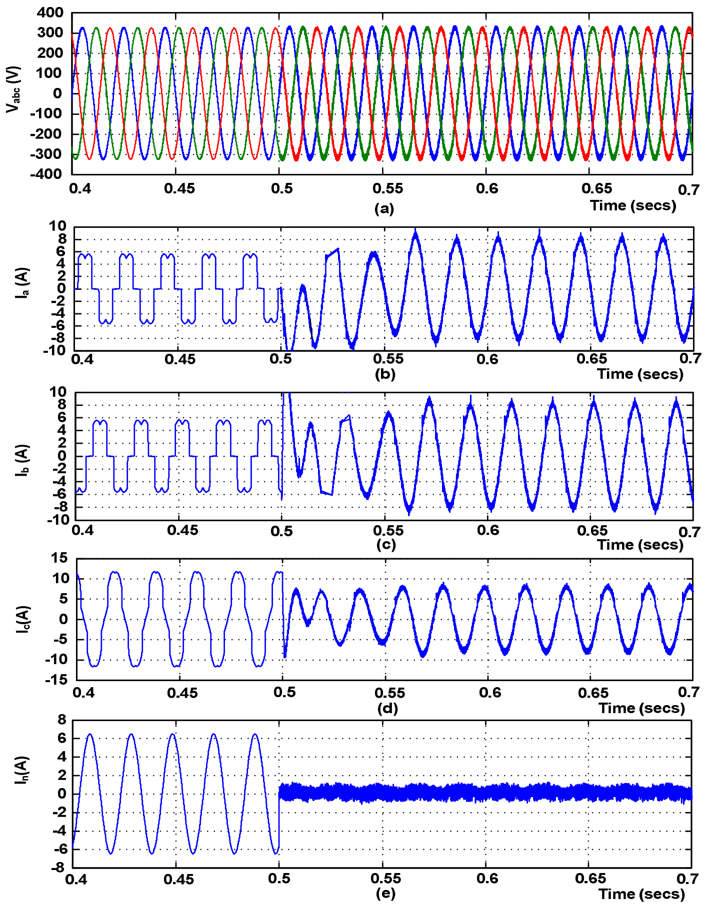


Fig.3. Simulation results (a) source voltages, (b) source current a phase, (c) source current b phase, (d) unbalance source current c phase, (e) neutral current

The Compensation currents injected by the VSI during APF operation on each phase are shown in Fig.4. Here the VSI operation is initiated at t=0.5 s.

### *B. Power Injection operation*

The active and reactive power exchange between source side and VSI are shown in Fig. 5 and Fig.6. Initially the load is driven by supply system, there is no power injection by solar PV. The VSI operation is initiated at t=0.5s, then the solar PV power is injected at PCC. From Fig.5. it is evident that after t=0.5s there is a drop in active power from 2kW to 1.5kW, Here remaining 500W power is injected by the solar PV system. The rating of the solar PV integrated to the VSI is 600W. In this case the grid interfacing VSI can concurrently be utilized to supply active power generated from solar PV to PCC and to improve the power quality at PCC.

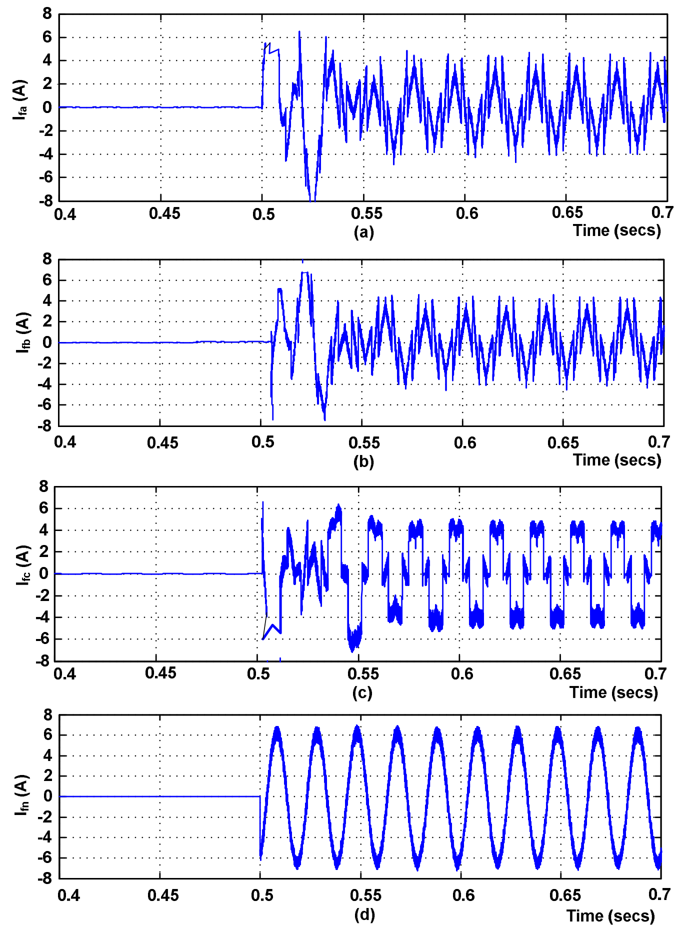


Fig.4. Simulation results (a) compensation current a phase, (b) compensation current b phase, (c) compensation current c phase, (d) neutral compensation current

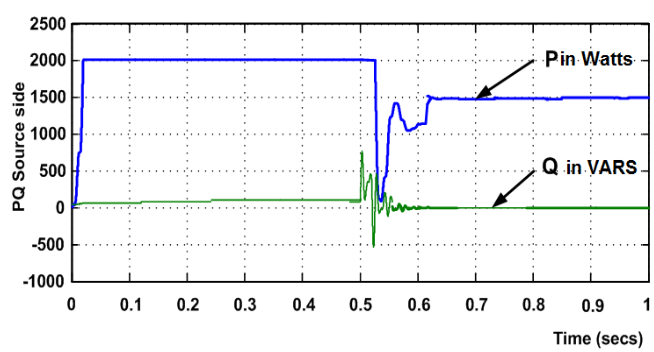


Fig.5. Active & reactive power at source side

The reactive power exchange also demonstrated in Fig.5. and Fig.6. Initially there is rise in VAR power in supply side up to 50W, at time t=0.5 s the VSI injected the compensating reactive power to make the VAR power approximately zero.

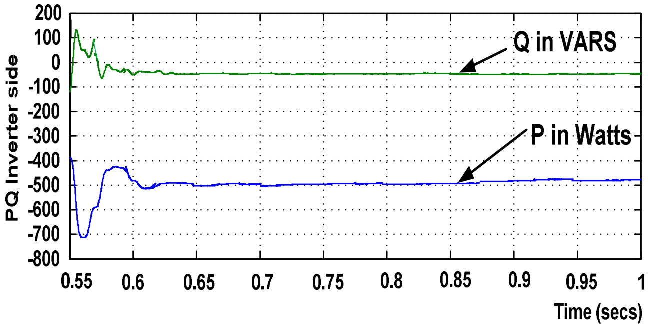


Fig.6. Active & reactive power at inverter side

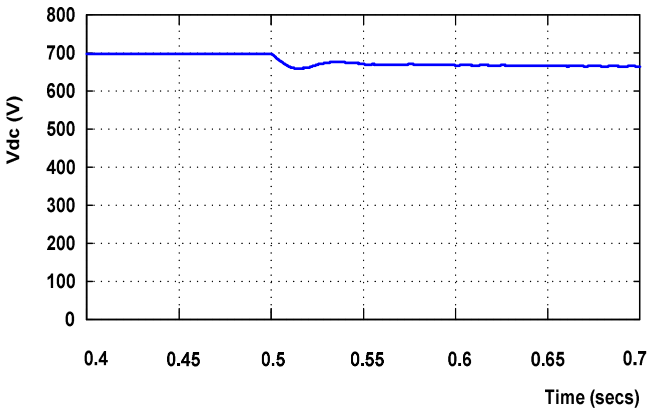


Fig.7. DC link Voltage

The DC link voltage across the VSI is maintained at 680 V, in order to assist the active and reactive power exchange. Hence from the simulation results, it is validated that the grid interfacing VSI can be effectively used to compensate the current harmonics, current imbalance, neutral current, load reactive power, and in addition to active power injection from solar PV.

## V. Conclusion

This paper enumerates the modeling and implementation of a three-level hysteresis current controlled grid connected VSI with solar PV interfacing. Proposed grid connected VSI configuration is modeled and simulated using MATLAB/Simulink. The simulation results justifies the performance of VSI as power injector as well as power conditioner for compensating current harmonics, reactive power, neutral current and current imbalance. The three-level HCC exhibits reduced switching frequency, dynamic control capability and easy implementation. The effectiveness of the control scheme has been confirmed by simulation results.

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