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Comparative Study Between Adaptive Hysteresis and SVPWM Current Control for Grid-connected Inverter System

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Abstract—**Now a day's distributed generation (DG) system uses current regulated PWM voltage source inverters (VSI) for connecting the utility grid with DG source in order to meet the following objectives: 1) To ensure the grid stability 2) active and reactive power control through voltage and frequency control 3) Improvement of power quality (i.e. harmonic mitigation) etc. In this paper the comparative study between adaptive hysteresis and SVPWM current controller is presented in order to ensure the sinusoidal current injected in to the grid. The performance indices include THD of the grid current, fast current tracking during steady state and transient conditions. SVPWM current controller ensures less THD of the grid current at PCC, better dc-link voltage utilization over adaptive hysteresis current controller. The studied system is modeled and simulated in the MATLAB Simulink environment.**

Keywords- adaptive hysteresis control; voltage source inverter (VSI); total harmonic distortion (THD); utility grid; current control; distributed generation (DG).

I. NOMENCLATURE

i_{La}, i_{Lb}, i_{Lc}	Three-phase load currents
i_{Ld}, i_{Lq}	d and q axis current components
ω	Angular frequency
θ	Transformation angle
V_d, V_q	d-q component of PCC voltage
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

II. INTRODUCTION

Distributed generation (DG) systems becomes more prominent in the world electricity market due to the increased demand for electric power generation, the deregulation of the electric power industry and the requirements to reduce the greenhouse gas emissions etc. DG sources and their interconnection should satisfy certain requirements and specifications when interconnecting with existing electric power systems (EPS). For an inverter-interfaced DG system, the power quality of the utility grid largely depends on the inverter's controller performance. For the past couple of decades, current regulated VSI is widely used for grid-connected inverter system in order to meet the following objectives. 1) To ensure the grid stability 2) active and reactive power control through voltage and frequency control 3) Improvement of power quality (i.e. harmonic mitigation) etc [1]. As compared with the open loop voltage PWM converters, the current-controlled PWM has several advantages such as fast dynamic response, inherent peak-current protection, good dc-link utilization, instantaneous current control etc [2].

Basically current control schemes have similar structures that include an inner current feedback loop, and it performs dual tasks: the current error compensation and the PWM modulation. The current control strategies, based on the space vector PWM (SVPWM) is widely employed for three-phase VSI essentially, the SVWPM-based current controller is a kind of linear control strategies and has clearly separated current error compensation and PWM parts, which makes it possible to exploit the advantages of SVWPM as well as to independently design the overall control structure. SVPWM has many advantages such as constant switching frequency, well-defined harmonic spectrum, optimum switching patterns, and excellent DC-link utilization, etc. However, as a voltage-type modulator, SVPWM has certain drawbacks compared to current-type modulators. Since SVPWM is an open-loop voltage-type modulator, the current controller may be sensitive to the disturbance of the back-EMF and the nonlinearity of the system such as the switching dead time and control delay due to computation and sampling. For grid-connected applications, this will result in the compromised output current due to grid harmonic disturbances. Moreover, SVPWM lacks an inherent over-current protection, which is especially problematic for a grid-connected inverter system.

On the other hand, for fast current tracking, unconditional stability and easy implementation, hysteresis band current control (HBCC) technique has the highest rate over sinusoidal PWM. However, 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 compensating current waveform. However, there are device limitations and increasing the switching frequency causes 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 [3].Here studied system is modeled and simulated in the MATLAB Simulink environment.

III. CUREENT CONTROL STRATEGIES FOR GRID CONNECTED INVERTER SYSTEM

A current controlled VSI is generally used to interface utility grid with the DG system which is shown in fig.1.Since the voltage at the point of common coupling should not be regulated by DGs, the current control strategy of grid connected inverters plays a dominant role in providing high quality power to electric grids. In this section, different modern current control structure for three-phase grid–connected VSI for distributed generation is highlighted.

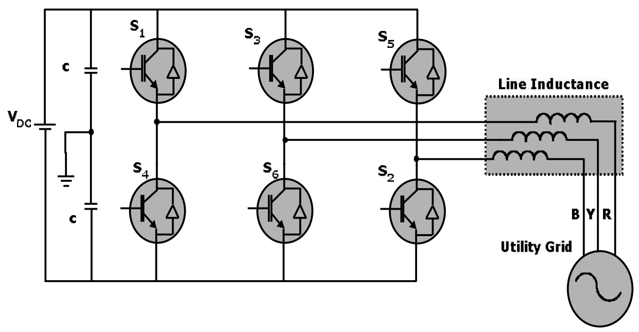

Figure 1. Three phase inverter connected to utility grid

The strategies of current controllers can be classified as: ramp comparison controllers, hysteresis controllers, and predictive controllers. The ramp comparison controller compares the current errors to triangle wave to generate the inverter firing signals. The hysteresis controllers utilize some type of hysteresis in the comparison of the currents to the current reference. The predictive controllers calculate the inverter voltages required to force the measured currents to follow the current reference.

In this context the hysteresis current controller (HCC) is insensitive to system parameters and is extremely simple for implementation but in the other hand high current ripple and variable switching frequency are the drawbacks of HCC [4].The predictive controllers are the most complex and require knowledge of the load and extensive hardware which may limit the dynamic response of the controller [5].

Proportional Resonant (PR) controller with harmonic compensators used to reduce the harmonic distortions in the alternative voltage or current waves. However, the harmonic compensators of the PR controller are limited to several low-order current harmonics [6].Recently, intelligent controllers like neural network and fuzzy logic controller are also been proposed in the literature [7].

IV. ANALYSIS OF ADAPTIVE HYSTERESIS BAND CURRENT CONTROLLER

A. Reference Supply Current Computation

Before analyzing the adaptive hysteresis band current controller, first step is to calculate the reference current from there phase load current by parks' transformation method. The three phase load currents shown in fig.2 have already been transformed to the synchronous reference frame (a-b-c to d-q-0 transformation). A high pass filter is used to extract the dc component representing the fundamental frequency of the currents. The coordinate transformation from three-phase load currents (i_{La}, i_{Lb}, i_{Lc}) to the synchronous reference frame based load currents (i_{Ld}, i_{Lq}, i_{L0}) is obtained as follows:

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

A low pass filter is used to extract the dc component of i_{Lq}. This dc value is used as i_{qref} for inverter q axis reference current in synchronous reference frame. In synchronous reference frame, i_{dref} (d axis reference current) controls active power injection. This d axis reference current could be generated from other controllers with notification of DG source.

Three phase reference currents have been made from i_{dref} and i_{qref} by using the synchronous reference frame to a-b-c transformation that is shown in equation (2).

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

A three phase PLL (Phase Locked Loop) is used to detect the angle of grid voltage which is used in transformation

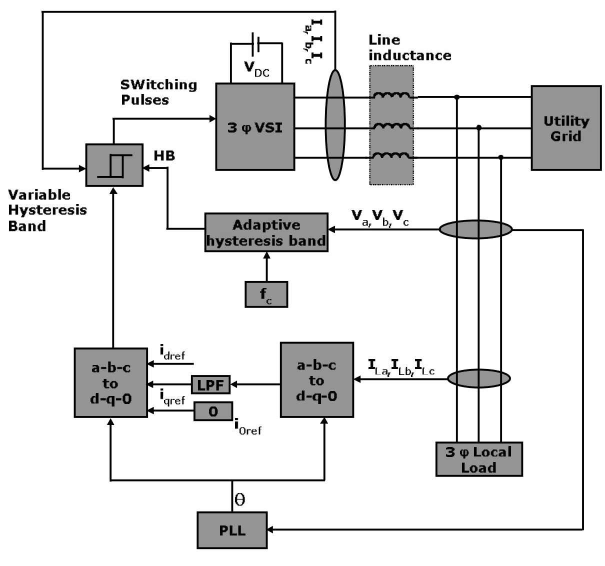

Figure 2. Block diagram for adaptive hysteresis current control of three-phase grid-connected VSI

B. Adaptive Hysteresis-band Calculation

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(3) 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.

$$\delta = i - i_{ref} \tag{3}$$

The switching logic is formulated as follows:

If δ >HB upper switch is OFF and lower switch is ON

(S_4=1, S_1=0).

If δ <-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 calculated.

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.Fig.3 shows the PWM current and voltage waveforms for phase a.

When the currents i_a tends to cross the lower hysteresis band at point 1, where S_1 is switched on. The linearly rising current (i_a^+) then touches the upper band at point P, where is S_4 switched on. The following equations can be written in the respective switching intervals t_1 and t_2 from fig.3.

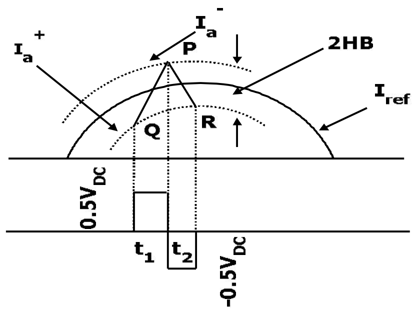

Figure 3. Current and voltage wave with hysteresis band current control

$$di_a^+ = \frac{1}{L}\left(0.5V_{DC} - V_a\right) \tag{4}$$

$$di_a^- = -\frac{1}{L}\left(0.5V_{DC} + V_a\right) \tag{5}$$

From fig.3,

$$\frac{di_a^+}{dt}t_1 - \frac{di_{aref}}{dt}t_1 = 2HB \tag{6}$$

$$\frac{di_a^-}{dt}t_2 - \frac{di_{aref}}{dt}t_2 = -2HB \tag{7}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{8}$$

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

Adding equation (6) and (7) and substituting in equation (8) we can write

$$\frac{di_a^+}{dt}t_1 + \frac{di_a^-}{dt}t_2 - \frac{1}{f_c}\frac{di_{aref}}{dt} = 0 \tag{9}$$

Subtracting equation (7) from (6)

$$\frac{di_a^+}{dt}t_1 - \frac{di_a^-}{dt}t_2 - \left(t_1 - t_2\right)\frac{di_{aref}}{dt} = 4HB \tag{10}$$

Substituting equation (5) in (10)

$$\left(t_1 + t_2\right)\frac{di_a^+}{dt} - \left(t_1 - t_2\right)\frac{di_{aref}}{dt} = 4HB \tag{11}$$

Substituting equation (5) in equation (9) and solving

$$\left(t_1 - t_2\right) = \frac{di_{aref}/dt}{f_c\left(di_a^+/dt\right)} \tag{12}$$

Substituting equation (12) in (11)

$$HB = \frac{0.125V_{DC}}{f_c L}\left[1 - \frac{4L^2}{V_{DC}^2}\left(\frac{V_a}{L} + m\right)^2\right] \tag{13}$$

Where f_c is modulation frequency, $m = di_{a\,ref}/dt$ 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.

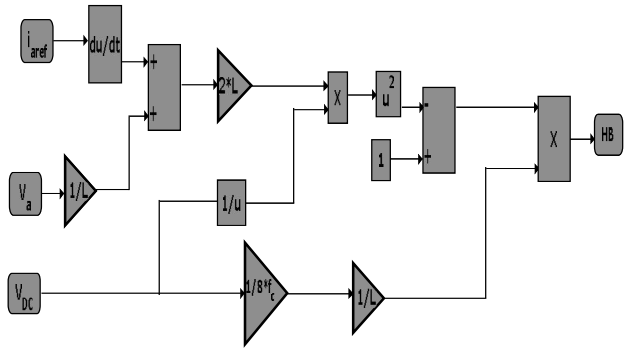

Figure 4. The adaptive hysteresis band width calculation block diagram

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 [8][9].

V. ANALYSIS OF SVPWM CURRENT CONTROLLER

SVPWM is employed to generate the desired output voltage vector V* in d-q reference frame. For a three-phase VSI, there are totally eight possible switching patterns and each of them determines a voltage space vector.

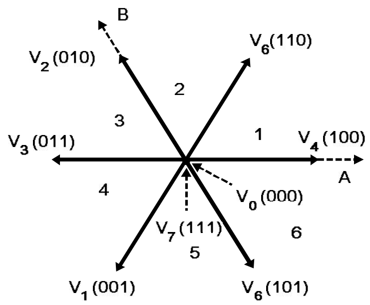

Figure 5. Voltage space vector of three phase VSI

As shown in fig.5 eight voltage space vectors divide the entire vector space into six sectors, namely 1 ~ 6. Except two zero vectors, V_0 and V_7, all other active space vectors have the same magnitude of (2/3) V_{DC}.

According to the phase angle of the reference voltage vector in the d-q coordinates and the grid angle indicating the relative position of the d-axis to the A-axis, the sector in which the reference voltage vector is located can be easily found out. In SVPWM, the reference voltage vector should be synthesized by the adjacent vectors of the located sector in order to minimize the switching times and to minimize the current harmonics.

An example of the synthesizing procedure in Sector 1 is described by fig. 6. Where T is the PWM period, T_1 and T_2 are time durations of two active vectors in each PWM cycle, T_0 is the time duration of zero active vectors in each PWM cycle and equals to (T_0-T_1-T_2).

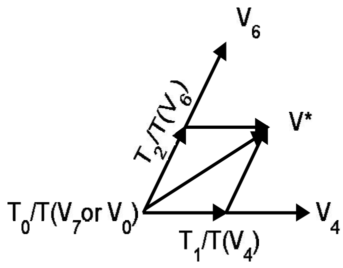

Figure 6. Synthesizing of voltage vector using adjacent vector

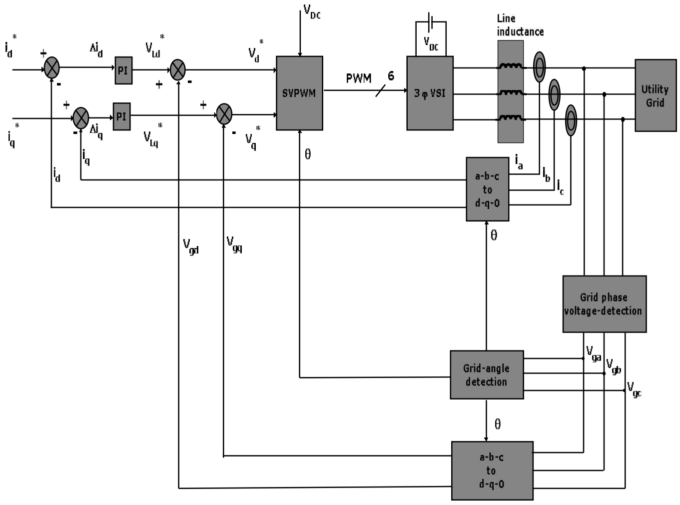

Figure 7. Block diagram of the SVPWM-based current control system for three phase VSl

After T_1, T_2 and T_0 are found out; the three-phase PWM pulses are generated by one of symmetrical methods. This method makes each switching component switch once in one carrier period, bringing all of them to a fixed switching frequency, and with the appropriate placement of zero vectors, the entire voltage vector is split into ripple frequency to the double of switching frequency [10] [11].

VI. SIMULATION RESULTS AND DISCUSSION

Computer simulation has been carried out using MATLAB/Simulink environment in order to validate the performance of the adaptive hysteresis and SVPWM current control strategies for three phase grid connected inverter system. For that 230 V is considered as phase voltage of the grid system with the frequency of 50 Hz. 600 V and 420 V has been considered as dc-link voltage for adaptive and SVPWM current controllers respectively. The line inductance is 5mH and dc-link capacitance value is 2200μF.

A. Steady State Analysis

Fig.8 shows the steady state response of adaptive hysteresis current controller.

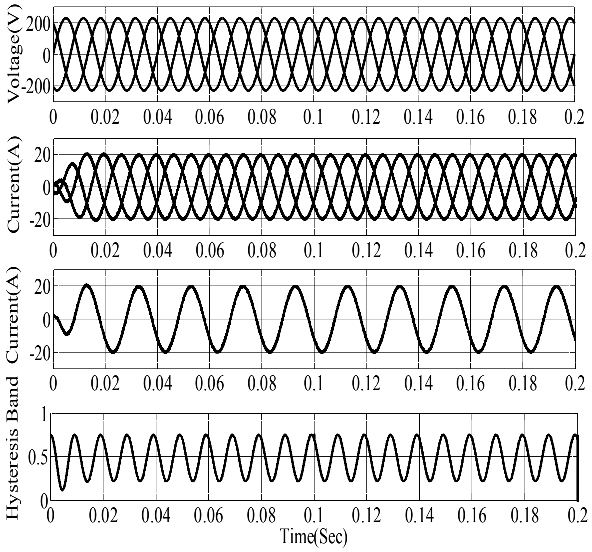

Figure 8. Simulation results for the steady-state response of adaptive hysteresis current controller(a) grid voltage at PCC (b)grid current (c) Inverter output phase current (d) hysteresis band

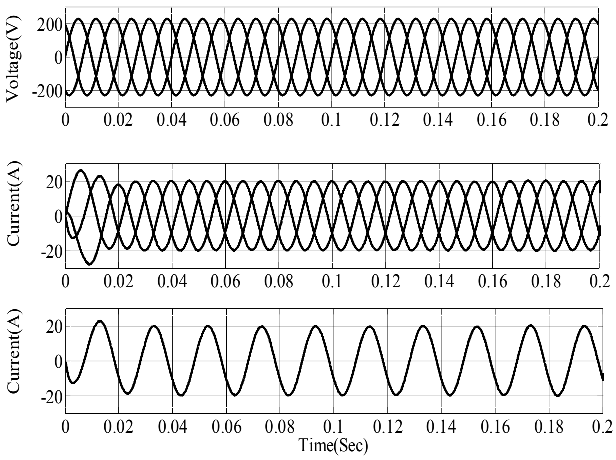

Figure 9. Simulation result of the steady-state response of SVPWM current controller (a) grid voltage at PCC (b) grid current (c) Inverter output phase current

Fig.8 (a) and fig.8 (b) shows the three-phase grid voltage and grid current waveforms under steady state conditions. These are almost close to sinusoidal waveforms. Fig.8(c) shows the inverter output phase-current with adaptive hysteresis current controller .The corresponding hysteresis band is shown in fig. 8 (d) which is almost constant over the fundamental period. The corresponding steady state response of SVPWM current controller is shown in fig. 9.

B. Transient Analysis

In order to analyze the dynamic response of both the current controllers, the load is applied with step changes at 0.1 sec and the related simulation results are shown fig.10 and fig.11. Fig.10 (a) and fig.10 (b) shows the three-phase grid voltage and grid current waveforms under transient conditions for adaptive hysteresis controller. At 0.1 sec grid current reduced to 10 amps from 20 amps. During these conditions usually the grid current waveforms are distorted and it leads to more THD at PCC. But due to action of adaptive hysteresis controller, the load current tracks the reference current command at a faster rate and the grid current approaches the sinusoidal response. The corresponding adaptive band for adaptive hysteresis current controller is shown in fig.10 (d) which varies according to the load variations in order to maintain the constant switching frequency of operation. Fig.10 (e) shows the response of dc-link voltage which maintains constant at 600 V.

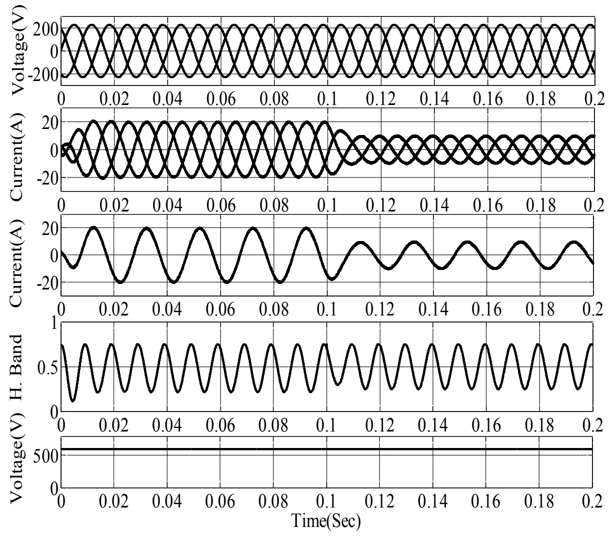

Figure 10. Simulation results for the transient response of adaptive hysteresis current controller (a) grid voltage at PCC (b) grid current (c) Inverter output phase current (d) hysteresis band (e) Dc-link voltage

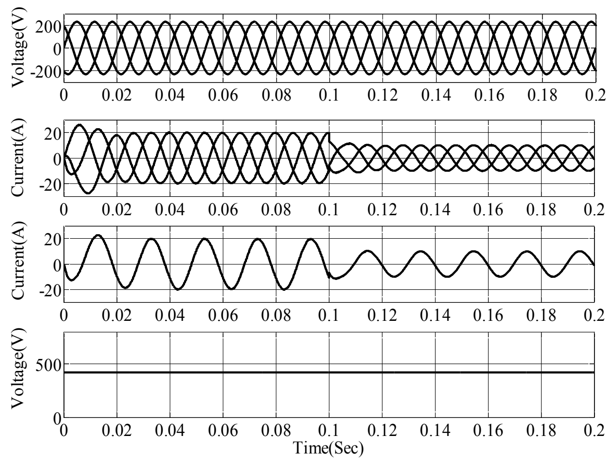

Figure 11. Simulation results for the transient response of SVPWM current controller (a) grid voltage at PCC (b) grid current (c) Inverter output phase current (d) Dc-link voltage.

The related simulation results for SVPWM current controller is shown in fig.11 under transient conditions. From the simulation results we found that, Grid current distortion and corresponding THD of grid currents are less as compared to adaptive hysteresis current controller. The Utilization of dc-link voltage is better as in the case of SVPWM current controller over adaptive hysteresis current controller. But the dynamic response of adaptive hysteresis current controller is relatively better than SVPWM current controller.

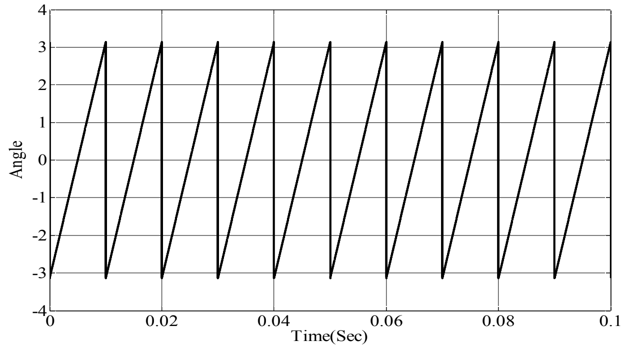

Figure 12. Response of PLL

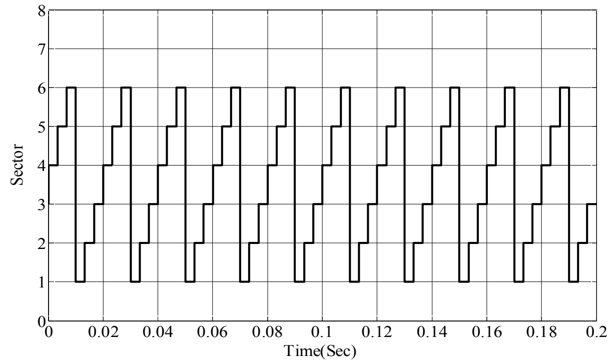

Figure 13. Angle sector of SVPWM controller

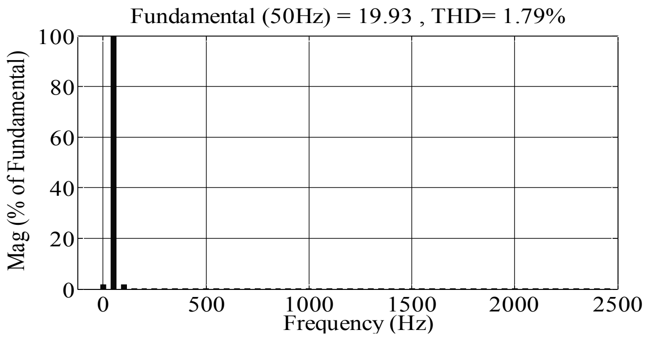

Figure 14. THD of grid current for adaptive hysteresis current controller

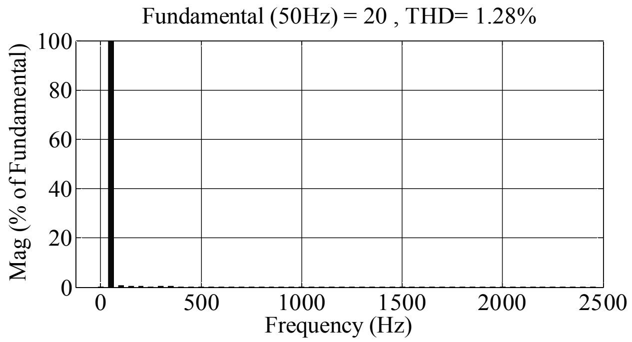

Figure 15. THD of grid current for SVPWM current controller

The response of PLL for detecting the phase angle of grid component is shown in fig.12.The corresponding angle sector of SVPWM current controller is shown in fig.13.Fig.14 & 15 depicts the THD value of grid current waveform at PCC for both adaptive hysteresis and SVPWM current controller respectively. It reveals that, SVPWM current controller gives less THD (1.28%) of grid current at PCC over adaptive hysteresis current controller (1.79%).

VII. CONCLUSION

The paper describes the comparative study between adaptive hysteresis and SVPWM current controllers for grid connected inverter system. From the study we observed that, adaptive hysteresis current controller provides good dynamic response over SVPWM current controller during transient conditions. But the SVPWM current controller provides better utilization of Dc-link voltage along with lesser THD of grid current at PCC under steady state and transient conditions.

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