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Design and implementation of nonlinear integral backstepping control strategy for single-phase grid-connected VSI

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ABSTRACT

This paper presents the design and the implementation of a nonlinear integral backstepping control strategy for a single-phase grid-connected voltage source inverter (VSI). The proposed control strategy aims to resolve the problem of the sinusoidal reference current tracking, to have a rapid transient response needed to deal with the transient incident such as grid voltage drops and to generate into the grid a current with fewer harmonics. These properties are verified by seeking the direction, the amplitude and the transient response of the injected grid current. An experimental VSI prototype is used to validate the effectiveness of the proposed controller, basing on a digital signal processor DSP microcontroller. The achieved results show that the well- obtained properties satisfy the grid current injection conditions.

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1. INTRODUCTION

Grid-connected VSI are mostly used as a part of conversion systems interfaces in distributed power generation, which is based on renewable energies like wind and PV energy systems. Generally, these interfaces have been introduced between the renewable energy sources and the grid in order to convert a DC voltage to an AC form [1]-[5]. To ensure a sinusoidal output current, usually, a filter is used. So, the performances of these devices can be typically evaluated by checking the energy efficiency, the total harmonic distortion (THD), and the transient response.

For this kind of inverters, different linear and nonlinear control strategies have been proposed to allow a great tracking of a sinusoidal reference. Among them, the linear PI control system has been used to regulate the injected grid current. This controller doesn't increase computation in the system algorithm, which makes its implementation easier for the whole control system. Nevertheless, In spite of these advantages, the PI control system has many limitations, especially against nonlinear systems [6]. This controller can't deal perfectly with sinusoidal references without using grid voltage feed-forward, which can be considering as a weakness in grid-connected inverters. So, to alleviate the drawbacks of the PI control system, PR controller is used as an alternative solution to track sinusoidal references, and with an additional resonant term, this controller can suppress some specific harmonic component [7]-[9]. To get more performances, other approaches like nonlinear control strategies, considered as non-selective techniques, for grid-connected inverters have been reported in the literature. In [10], a comparative study between sliding mode control (SMC) strategy with the PI controller for current inverter have been addressing. This study shows the effectiveness of the SMC that gives good tracking and fast transient response contrary to the PI controller. This rapid dynamic response is needed to overcome some transient incidents such as a transient low voltage. Also, in [11], [12], the predictive control strategy is proposed to regulate the grid current of a grid-connected inverter.

The synchronization of the current output of the inverter with the utility grid is considered as an important challenge. In order to achieve this operation, digital and analog PLL are investigated in many studies. With analog PLL, some electronic devices are added to the circuit, which increases the complexity of the system and the control part. But with digital PLL, easy implementation, more performance, and low cost will be noted to the system [13], [14].

Recently, the backstepping control strategy has obtained a tremendous attention as a solution for control of nonlinear systems [15], [16]. The idea behind this procedure is to devise the system to subsystems of the first order, and by adopting the Lyapunov function to ensure the stability of the whole system, the control law is derived from different stages that give a virtual control law for the subsystem. So, by going step by step, the global control law for the last subsystem is obtained.

In order to get a fast dynamic response of the injected grid current and to track a sinusoidal reference pricisely, this paper proposes a nonlinear backstepping control strategy with an integral action for a grid-connected VSI prototype. The experimental prototype consists of: a full bridge inverter, an L-filter that is adopted to allow a reasonable harmonic current attenuation. The proposed control strategy is verified experimentally under consideration of grid current conditions.

2. SYSTEM DESCRIPTION AND MODELING

2.1. System description

Figure 1 shows the circuit of the used PWM VSI which is formed by: four power switches (S1, S2, S3, and S4) selected from fast IGBT devices, a low pass filter composed by L-filter (Lf) placed between the inverter and the grid (vg). The input voltage is obtained from a dc power supply (V_{dc}) to ensure a constant voltage level.

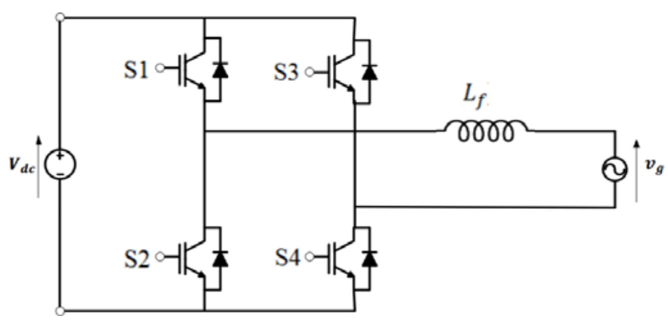


Figure 1. Description of the VSI system

The power switches of the VSI are controlled using comparative blocs of two sinusoidal references signals (v_c and v_{csh}) shifted by 180° with a high-frequency triangular carrier signal (v_{tri}), as shown in Figure 2. The possible switching is established by taking into account the logic operation in Table 1.

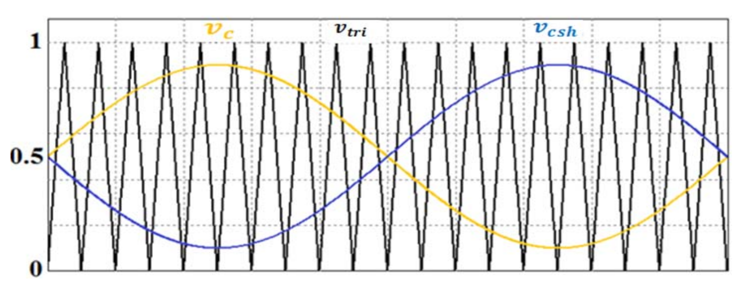


Figure 2. Description of the VSI system

Table 1. Switching logic for power switches

Logic operation	On switch
$v_c \geq v_{tri}$	S1
Not S1	S2
$v_{csh} \leq v_{tri}$	S3
Not S3	S4

2.2. VSI system modelling

According to Kirchhoff's laws applied to the above circuit shows in Figure 1, and owing to the symmetry property of the positive-half and negative-half period in the unipolar PWM switching (three-level), the dynamic equation relating between the injected current and grid voltage and that define system model is given as:

$$L_f \frac{di_g}{dt} = D_c V_{dc} - v_g \tag{1}$$

Where D_c represent the duty cycle of the switches S1 and S4 during one switching period.

By considering the definition of this duty cycle (modulation index) $D_c = {v_c}/{V_{tri}}$ and the inverter dynamic $K_{PWM} = {V_{dc}}/{V_{tri}}$, the grid current dynamic can be derived as:

$$\dot{i_g} = \frac{1}{L_f}(K_{PWM} v_c - v_g) \tag{2}$$

Where, v_c is the sinusoidal control signal, and V_{tri} is the amplitude of the triangular carrier signal.

3. GRID CURRENT CONTROL UNDER BACKSTEPPING WITH INTEGRAL ACTION

3.1. The objectif of the control strategy

The purposes behind of integral backstepping control of the This PWM VSI connected to the grid include three main objectives: The first one is to inject a sinusoidal current (ig) into the grid with respecting of the power factor correction (PFC), in other words, the injected grid current and the grid voltage should be in phase ($0.9 \leq \cos\varphi \leq 1$). The second purpose is to have a rapid dynamic of the injected grid current with a THD less than 5%. The third purpose is the control stability of the grid-connected VSI which increases the robustness of the whole system.

As shown in Figure 3, the control strategy of the integral backstepping of the grid- connected is achieved by using the PLL bloc that gives the reference current, the control block, and the unipolar PWM switching method.

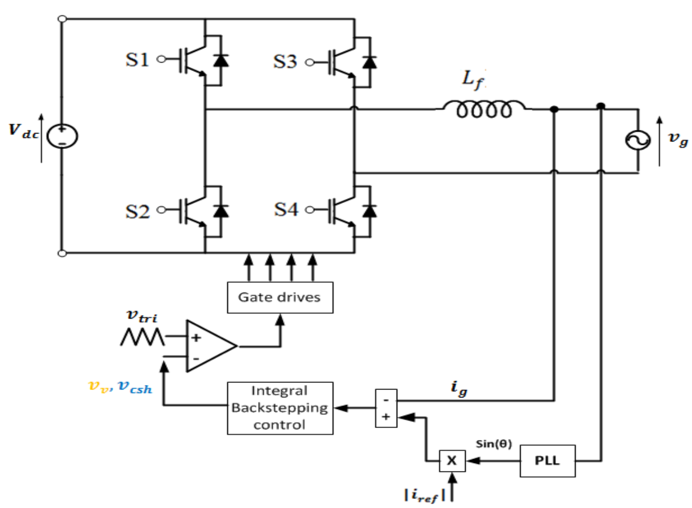


Figure 3. Control strategy description

3.2. PLL block

All Phase locked loops (PLL) have the main structure in spite of their diversities. This structure is composed of a phase detector, a loop filter, and a voltage controlled oscillator. The difference between PLLs is located at their phase detector. In this paper, the used PLL, that is based on power calculation, is investigated in [13], and its structure is depicted in Figure 4. Where v_g is the grid voltage that is assumed by a pure sinusoidal input, ω_ff is the nominal value of the frequency, and θ^ reflects the estimated voltage angle.

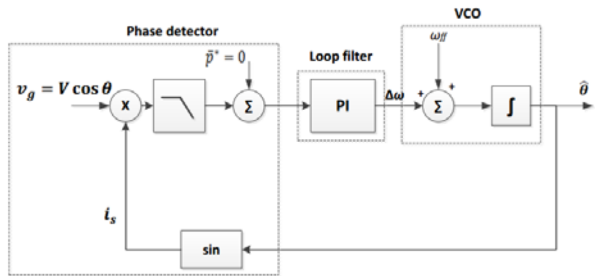


Figure 4. Grid angle estimation by using PLL block

For the sake of the simplicity, before the loop filter, a sinusoidal multiplier block is used in this PLL to fulfill the phase angle detector role. Therefore, this block makes the particularity of the proposed PLL. According to Figure 3, The fictitious power is mathematically given as:

$$p = v_g * is \tag{3}$$

By substituting the terms V_g and is, this power will be:

$$p = V\cos\theta\sin\hat{\theta} \tag{4}$$

$$p = \frac{V}{2}\sin(\theta - \hat{\theta}) + \frac{V}{2}\sin(\theta + \hat{\theta}) \tag{5}$$

By taking into account the output of the phase detector equal to zero, the multiplication of grid voltage, which serves as the input, with the fictitious current i_s gives two terms: the first one is a small dc term, and the second one contains a double frequency. To keep up the dc part, a low pass filter is used. In this case, by passing through the VCO block, the estimated grid voltage angle will be equal to the monitored angle.

3.3. Grid current control under integral backstepping control

Regarding the stability of V_{dc} getting from a constant power supply, the backstepping procedure will be designed in one step (one subsystem of the grid current dynamic is considered).

The grid current error with the integral action can be defined as:

$$z_e = i_{ref} - i_g + K_i \int i_{ref} - i_g \tag{6}$$

Where K_i is a constant parameter and i_{ref} is the current reference.

The integral action is added to have more robustness of the controller, especially to have a good tracking with zero error. The derivative of the above expression is given by the following equation:

$$\dot{z_e} = \dot{i}_{ref} - \dot{i}_g + K_i(i_{ref} - i_g) \tag{7}$$

Substituting the dynamic equation of i_g current in 2, the error dynamic $\dot{z_e}$ can be given as:

$$\dot{z_e} = \frac{K_{pwm}}{L_f} v_c - \frac{1}{L_f} v_g - \dot{i}_{cmd} + K_i(i_{ref} - i_g) \tag{8}$$

To ensure the system stability and to define the control law, a Lyapunov function can be defined as:

$$V_e = \frac{1}{2} z_e^2 \tag{9}$$

Its dynamic is given as:

$$\dot{V}_e = z_e \dot{z}_e \tag{10}$$

So, this derivative can be negative by imposing:

$$\dot{z}_e = -K_e z_e \tag{11}$$

Where K_e is a constant parameter.
And the control law can be concluded as:

$$v_c = \frac{L_f}{K_{pwm}} \dot{i}_{cmd} + \frac{1}{K_{pwm}} v_g - K_i \left(i_{ref} - i_g\right) + K_e{}' z_e \tag{12}$$

In this case, the Lyapunov function derivative is:

$$\dot{V}_e = -K_e z_e^2 \tag{13}$$

4. EXPERIMENTAL VALIDATION

4.1. Experimental tests with integral backstepping control strategy

To validate the proposed nonlinear integral backstepping controller, an experimental prototype of a grid-connected VSI system is used, and its description is depicted in Figure 5. The voltage V_{dc} is obtained from a variable DC power supply of 63V/3A. The full bridge PWM inverter is driven by 2.5 kHz signals that are generated by a digital signal processor DSP. This latter is a DSP TMS20F28379D Launchpad with a clock of 200 MHz, manufactured by Texas Instrument. The program of the control system that is uploaded on the DSP is carried out by using the embedded coder tool of Matlab/Simulink, on which is a PWM bloc is implemented. To be adapted with A/D conversion block, the measured grid voltage and the injected current by Hall Effect sensors are implemented on circuit board. The value of the L-filter is 30mH and it is selected for harmonic attenuation. An autotransformer is added between the grid and the L-filter so that the RMS value of grid voltage is 36V.

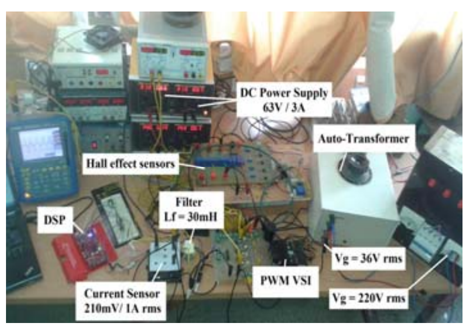
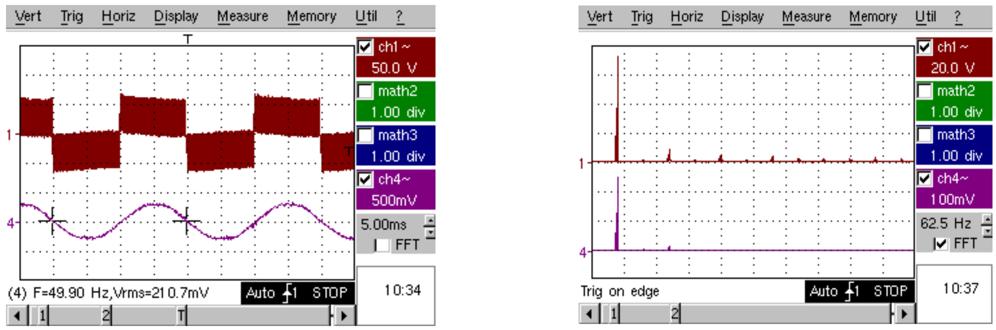


Figure 5. The used experimental test bench

In this section, the main objective of the whole system is to inject into the grid a current with RMS value of 1A. The unfiltered output voltage of the inverter and the injected current responses are depicted in Figure 6a, by using the reference current that is generated by the PLL block. According to this figure, it should be noted that the sensor current delivers 210 mV for each 1A RMS and the integral backstepping controller track perfectly the sinusoidal reference in phase and amplitude. Figure 6b shows the FFT spectrum of the unfiltered output voltage of the inverter and the grid injected current; it can be observed that the obtained THD is acceptable, which confirm that under integral backstepping control of the grid-connected VSI with L-filter, fewer harmonics are present.



(a) (b)

Figure 6. (a) The unfiltered voltage output of the inverter (ch1) and the injected current ig (ch4), (b) FFT spectrum under integral backstepping control

Figure 7 illustrates the responses of the injected current and the grid voltage, which its RMS value is 1A. According to this figure, the synchronization mode is reached under integral backstepping control, which confirms the effectiveness of the control strategy and the PLL block. This achieved performance that reflects the condition of PFC is helpful to fulfill the grid-connected condition of VSI. Controller gains are: K_e=12 and K_i=0.2.

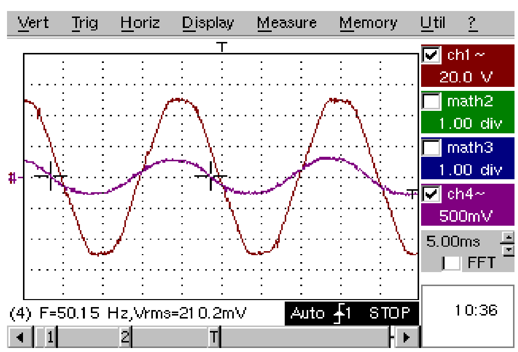
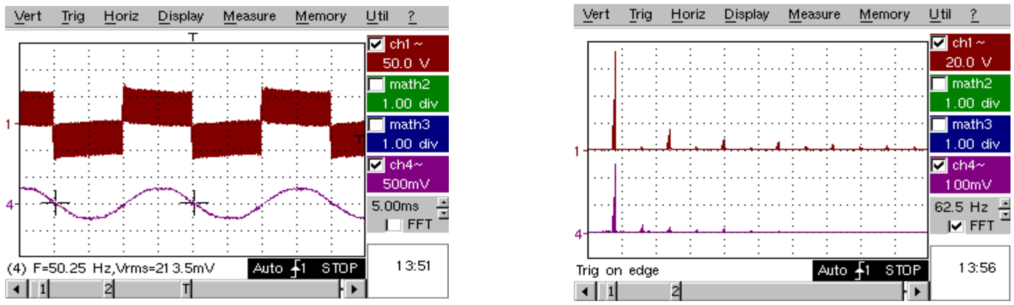


Figure 7. Grid voltage (ch1) and the injected current ig (ch4) under integral backstepping control

4.2. Comparative Experimental Results

To show the importance of the proposed integral backstepping control, a comparative experimental tests between this latter and a PI control system are exposed in this section. For this purpose, the backstepping controller block is substituted by a PI control system block.

Firstly, the block of PI controller is inapt to regulate the grid current under the sinusoidal reference, it need the grid voltage feed forward, which can be considered as drawback for the grid-connected application and which lead to doubt concerning the linearity of the controller in this case. On the other hand, to access the transient response of the PI block controller against the backstepping controller, the current reference is varied as a step. Using PI control system bloc, and under the same conditions, the injected grid current and the unfiltered voltage output of the VSI with their FFT spectrums are illustrated in Figure 8. It can be noted that, comparatively with the integral backstepping control, the THD is increased, and the desired injected current value is less precise, which is considered as a weakness of the control system robustness for the grid-connected VSI.



(a) (b)

Figure 8. (a) The unfiltered voltage output of the inverter (ch1) and injected grid current (ch4); (b) FFT spectrum, under PI control

Figure 9 gives the grid voltage and the injected current; it can be seen that the PFC condition is respected, the injected grid current is not perfectly precise (213.1mV) against integral backstepping control (210.2mV).

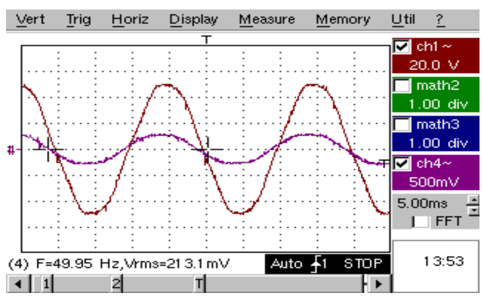
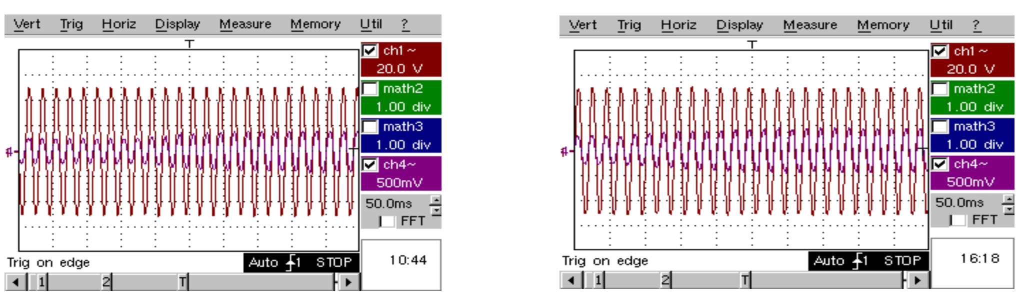


Figure 9. The grid voltage (ch1) and the injected current (ch4) under PI control

Also, according to Figure 10 that gives the grid current responses of PI control system and integral backstepping controller, it can be seen that under the latter in Figure 10(a), the transient response of the injected current is more rapid comparatively with the PI block in Figure 10(b), and the grid injected current in the case of integral backstepping control reaches the magnitude step reference within some milliseconds.

Regarding the experimental results, and in terms of comparison, it can be concluded that the proposed integral backstepping control designed for the grid-connected VSI owns excellent properties including robust control performance, acceptable THD ratio that and the main feature is the rapid dynamic of the current injected into the grid.



(a) (b)

Figure 10. Grid voltage (ch1) and grid current responses with variation of the grid current reference (ch4): (a) under integral backstepping control (b) under PI control

5. CONCLUSION

In this paper, a nonlinear control strategy based on integral backstepping technique for grid-connected VSI is designed and implemented on DSP board. This configuration circuit with the proposed controller is designated for distributed power generation of a renewable energy source, and to overcome the sinusoidal reference tracking. The stability of the control system is verified by Lyapunov theory procedure, and the dynamic model of the VSI is well descripted and verified also under the control system.

Based on the experimental results, the proposed integral backstepping control can improve the performance and robustness of VSI system, with a good sinusoidal reference tracking. Moreover, the rapid dynamic transient response of the injected current is needed for the clean distributed power energy, which is considered as a feature of the applied control strategy. Also, the current harmonic distortion ratio is well ameliorated and the process of grid current injection is strictly respected under the condition of PFC.

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