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3-Phase Inverter with Sliding Mode Control

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Abstract: A sliding-mode control using a new sliding surface just depending on the output voltage is proposed for the boost inverter. It overcomes some disadvantages that the traditional sliding-mode control has. The surface is derived from the current- mode control idea of indirectly controlling the output voltage through the inductor current. The controller has a fast response, is robust under load and input voltage variations, and yet is remarkable simple to implement. Although it is strongly nonlinear, it can be implemented using standard electronics circuitry and only needs voltage measurements. Unlike the common approach of generating a sinusoidal voltage in both capacitors of the inverter, the strategy here proposed, focuses on generating a sinusoidal voltage on the load despite the capacitors voltage form. As a consequence, the desired output voltage is just necessary as a reference to implement the controller.

Index Terms: Single Stage Inverter, Boost Inverter, Sliding Mode Control.

I. INTRODUCTION

It has been pointed out that the traditional inverter can be seen as two buck converters connected differentially through the load. This observation has lead to propose an inverter topology formed by two boost converters [1], [2]. The boost inverter, as this topology has been called, is able to generate, in a single stage, a sinusoidal voltage with larger or smaller amplitude than its input dc voltage. Due to its boosting capability, the boost inverter has drawn the attention of several researchers. Among other applications, it has been applied in UPS systems [3], [4]. Nevertheless, control difficulty is still a matter of concern in the design process of a boost inverter. It is well known that the average model of the boost converter is a bounded-input, nonlinear, non-minimum-phase with a highly-varying parameter system [5], [6]. On the other hand, a fast response and robustness under load and input voltage variations is usually required on applications. Together, these characteristics and requirements make the control of a boost converter a difficult problem. A great effort has been dedicated and a variety of solutions have been proposed to cope with this problem [6]–[15]. Since the boost inverter is formed by two boost converters, it inherits the control difficulty. Furthermore, in the case of the boost inverter the control goal is tracking (ac generation) instead of the easier regulation problem (dc-dc conversion). This work was partially supported by CONACYT Mexico under grant 44969 Control of the boost inverter have been achieved by controlling each boost converter separately. In this approach each boost is controlled to generate a sinusoidal voltage which are 180 degrees out of phase each other. In this way the load voltage is a sinusoid with twice the amplitude of the sinusoid generated by each converter. Since a boost converter cannot generate a voltage lower than its input dc voltage, the sinusoid generated by each boost converter, must be mounted on a dc voltage. Control of the boost inverter by controlling each boost converter separately has been successfully achieved in [3], [16], [17]. However, such controllers have some disadvantages. In [3], [16] a sliding-mode control with a sliding surface consisting in a linear combination of the inductor current and output voltage errors is employed. This controller requires an inductor current reference which is not formally specified. In practice, the implementation of such a reference is obtained from the actual current output, hence, it is not a real (exogenous) reference. The two loop control strategy for each boost converter proposed in [17] achieves a good performance, both in steady state and in the transient. Nevertheless, it is difficult to implement it using analog circuitry. Both loops have a PI controller, which means four parameter to adjust for each boost. Furthermore the complete controller requires four current sensors and four divisions (two for each converter). Instead of controlling each boost separately, in this paper a single controller focused on generating a sinusoidal voltage on the load despite the capacitor voltage form, is proposed for the first time. The idea behind the current-mode control is taken to propose a sliding-mode control with a dynamical sliding surface. The resulting controller is very easy to implement, does not need current sensors and only the desired output voltage is used as reference. Furthermore, it has a fast response and is robust under input voltage and load variations. In Section II the boost inverter and its control problem are described. Current-mode control is briefly discussed in Section III, its underlying idea is then used to propose the controller in Section IV. Simulations results and comparison of the proposed controller with that proposed in [17] are presented in Section V. Experimental results are shown in Section VI. These results confirm the predicted performance and robustness of the controller. Final conclusions are given in the last Section.

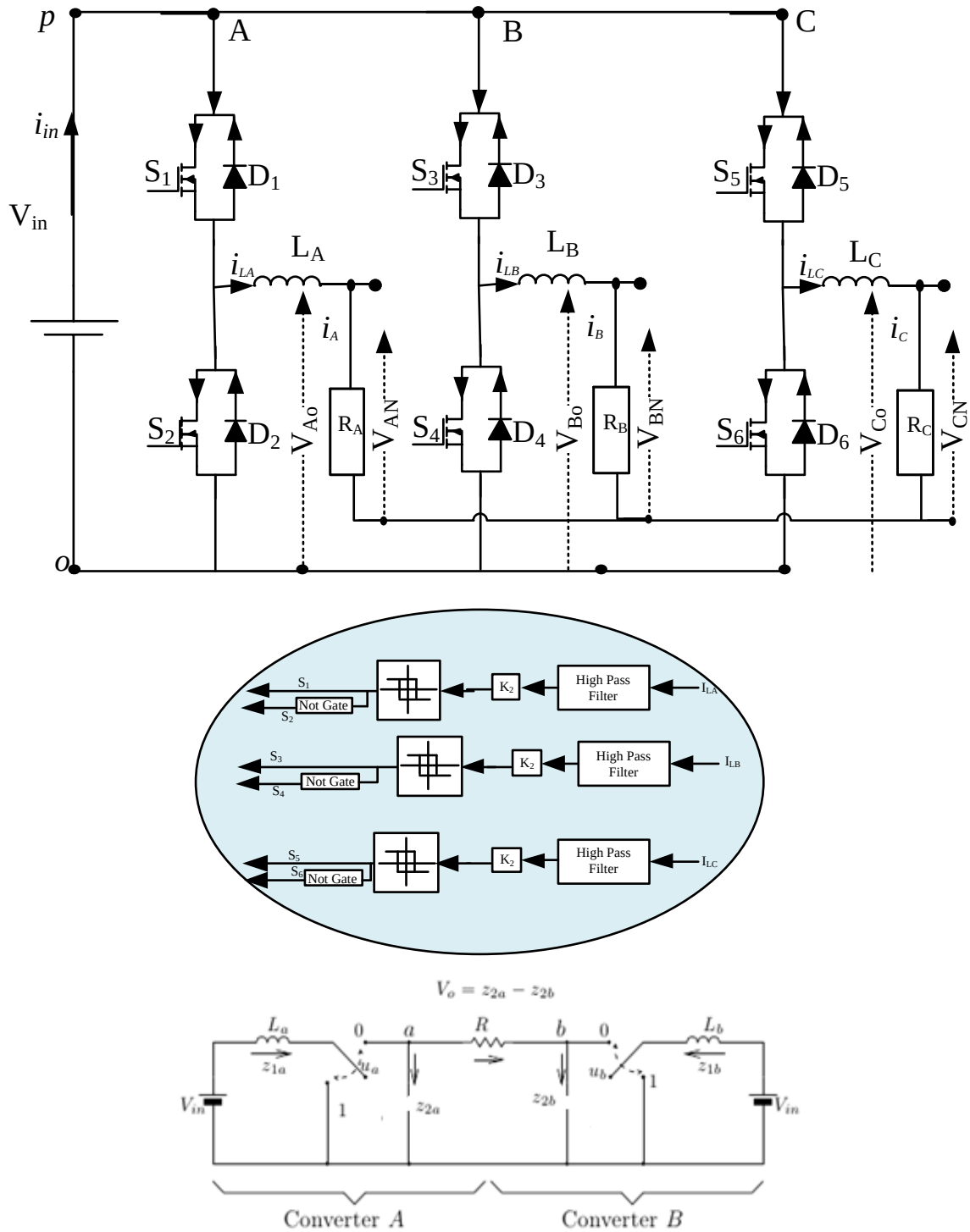


Fig. 2. The boost inverter: representation to emphasize that it is formed by two boost converters

II. THE BOOST INVERTER CONTROL PROBLEM

Figure 1 shows a diagram of the boost inverter. The circuit is redrawn in Fig. 2 to emphasize that it is composed of two boost converters with the load connected differentially. Note that the two power supplies appearing in Fig. 2 are indeed the same. Applying the Kirchhoff's laws, a model for each switch position can be obtained which results:

- For $u_a = 1, u_b = 1$

$$\dot{Z}_{1a} = \frac{V_{in}}{L} \quad (1a)$$

$$\dot{Z}_{2a} = -\frac{Z_{2a} - Z_{2b}}{RC} \quad (1b)$$

$$\dot{Z}_{1b} = \frac{V_{in}}{L} \quad (1c)$$

$$\dot{Z}_{2b} = -\frac{Z_{2b} - Z_{2a}}{RC} \quad (1d)$$

For $u_a = 0, u_b = 0$

$$\dot{Z}_{1a} = \frac{V_{in} - Z_{2a}}{L} \quad (2a)$$

$$\dot{Z}_{2a} = -\frac{Z_{2a} - Z_{2b}}{RC} + \frac{Z_{1a}}{C} \quad (2b)$$

$$\dot{Z}_{1b} = \frac{V_{in} - Z_{2b}}{L} \quad (2c)$$

$$\dot{Z}_{2b} = -\frac{Z_{2b} - Z_{2a}}{RC} + \frac{Z_{1b}}{C} \quad (2d)$$

where Z_{1a} & Z_{1b} are the current through the inductor of converter A and B respectively. $Z_{2a} = V_a$ and $Z_{2b} = V_b$ are the capacitors voltage (see Fig. 2). Combining both models results

$$\dot{Z}_{1a} = \frac{V_{in} - (1 - u_a)Z_{2a}}{L} \quad (3a)$$

$$\dot{Z}_{2a} = -\frac{Z_{2a} - Z_{2b}}{RC} + \frac{(1 - u_a)Z_{1a}}{C} \quad (3b)$$

$$\dot{Z}_{1b} = \frac{V_{in} - (1 - u_b)Z_{2b}}{L} \quad (3c)$$

$$\dot{Z}_{2b} = -\frac{Z_{2b} - Z_{2a}}{RC} + \frac{(1 - u_b)Z_{1b}}{C} \quad (3d)$$

System (3) is a discontinuous model for the boost inverter. From this model it is possible to obtain an average model which is commonly used to control the boost inverter [18]. In this paper the discontinuous model is used, nevertheless the control objective and other relationships must be expressed in its average form. For that reason the following notation is introduced. The average of a function $f(t)$ is given by

$$\bar{f}(t) = \frac{1}{T} \int_{t-T}^t f(s) ds$$

where T is the switching period. Unlike previous approaches, where each boost is controlled separately and the switches of the circuit are independent, in this work, it is considered that the switches are complementary, that is $u_b = 1 - u_a$. The objective of the boost inverter can be expressed as: To design a switching policy for $u = u_a$ such that

$\tilde{V}_o = \tilde{Z}_{2a} - \tilde{Z}_{2b} \rightarrow V_{ref}$ with a suitable speed of convergence and robustness under load and input voltage variations.

Our equations(given equations)

$$\dot{I}_L = \frac{V_{in}}{L}$$

$$\dot{I}_L = \frac{-V_0}{L}$$

$$\dot{I}_L = \frac{1}{L} [U_1 V_{in} - V_0 + U_1 V_0]$$

$$L \dot{I}_L = U_1 V_{in} - V_0 + U_1 V_0$$

$$L \dot{I}_{Lref} = U_1 (V_{in} + V_0) - V_0$$

$$\frac{(L \dot{I}_{Lref} + V_0)}{(V_{in} + V_0)} = U_1$$

$$\sigma = Lk_p (V_c - V_{cref})$$

III. CURRENT MODE CONTROL

The current mode control (CMC), also regarded as current programming control, is a robust DC-DC power converter control scheme that has been successfully tested and is widely used in the literature [24]. A simplified implementation diagram of the current mode control taken from [25] is shown in Fig. 5, where S_n is a signal proportional to the inductor current and V_{CTRL} is called the control voltage. In fact, the control voltage is the output of a sub-circuit which has the converter output voltage error as an input according to the following equation

$$V_{CTRL} = G_{CMC} (V_{oref} - V_o) \quad (4)$$

This means that the modulator in Fig. 5 makes the inductor current to be controlled by the control voltage V_{CTRL} which is a function of the voltage error. Usually, the block V_{CTRL} is a proportional integral (PI) controller. In this case, the circuit strives to make:

$$I_L = K_p (V_{oref} - V_o) + \int K_p (V_{oref} - V_o) dt \quad (5)$$

The current mode control idea has been shown to be related with the back-stepping design procedure [24]. Fig.5 Current mode control modulator. Current signal S_n is compared with control voltage V_{CTRL} to control the duty cycle.

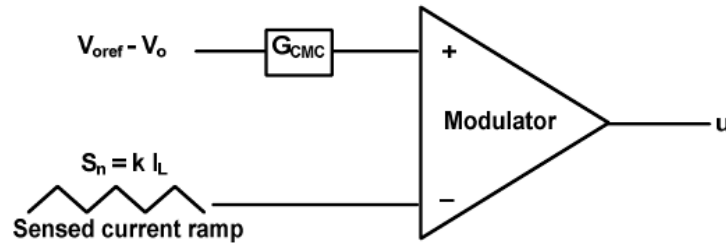


Fig.5 Current mode control modulator

IV. THE PROPOSED CONTROL STRATEGY

Based on the CMC, the proposed control strategy is obtained by considering the inductor current I_L in (3) as a virtual variable to control the capacitor voltage V_c . In this way, a desirable form of I_L is obtained. Then, the control u_1 is designed to drive I_L to its desired form.

Let I_{Lref} to be the desired form of I_L and assume for a moment that $I_L = I_{Lref}$. From (3a):

$$L I_{Lref} = U_1 (V_{in} + V_c) - V_c \quad (6)$$

If I_{Lref} is known, then u_1 can be designed from (6) to make $I_L = I_{Lref}$ as follow:

$$\frac{(L I_{Lref} + V_c)}{(V_{in} + V_c)} = U_1 \quad (7)$$

The controller could be implemented according to (7), however, to eliminate the derivative appearing in it we can consider the control u_1 in (7) as the equivalent control of a certain sliding surface σ . Then, u_1 must be the solution for $\sigma(u) = 0$. From (6) we can write:

$$\sigma = U_1(V_{in} + V_c) - V_c - LI_{Lref} = 0 \quad (8)$$

If the right hand side of (8) is multiplied by a constant, the sliding surface remains the same and consequently the performance does not change. Multiplying the right hand side by K and integrating both sides yielding:

$$\sigma = \left[\int (U_1(V_{in} + V_c) - V_c) dt - LI_{Lref} \right] \quad (9)$$

Substituting equation (5) in (9) gives the following non-linear equation of the sliding surface which is represented in cascaded block diagram as shown in Fig. 6.

$$\sigma = Lk_p(V_c - V_{cref}) \quad (10)$$

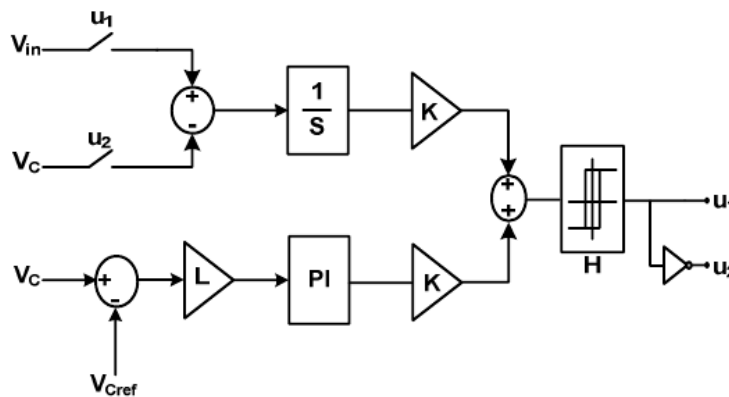


Fig. 6 Non-linear sliding mode controller scheme

Modified Modulation Scheme For Three-Phase Inverter

One third of period	Reference voltage
$0 \leq \omega t \leq 2\frac{\pi}{3}$	$V_{a \text{ ref}} = V_{ab}$ $V_{b \text{ ref}} = 0$ $V_{c \text{ ref}} = -V_{bc}$
$2\frac{\pi}{3} \leq \omega t \leq 4\frac{\pi}{3}$	$V_{a \text{ ref}} = -V_{ca}$ $V_{b \text{ ref}} = V_{bc}$ $V_{c \text{ ref}} = 0$
$2\frac{\pi}{3} \leq \omega t \leq 2\pi$	$V_{a \text{ ref}} = 0$ $V_{b \text{ ref}} = -V_{ab}$ $V_{c \text{ ref}} = V_{ca}$

- where V_{ab} , V_{bc} , and V_{ca} are the desired line voltages
- This modified modulation is inspired from the dead band PWM inverters
- In a three-phase circuit, keeping one leg of the inverter inactive will not result in loss of controllability

V. Simulations results

The proposed controller has been designed and simulated to evaluate its performance. Also, performance assessment for the proposed controller and the previously introduced controllers is compared this three phase sliding mode control perform a better response and robust controller the results of this controller given below Parameters of the proposed system

DC input voltage	400 V
AC output phase voltage	230 V RMS, 50 Hz
Switching frequency	20 KHz
Inverter inductance	1 mH
Load	10 Ω

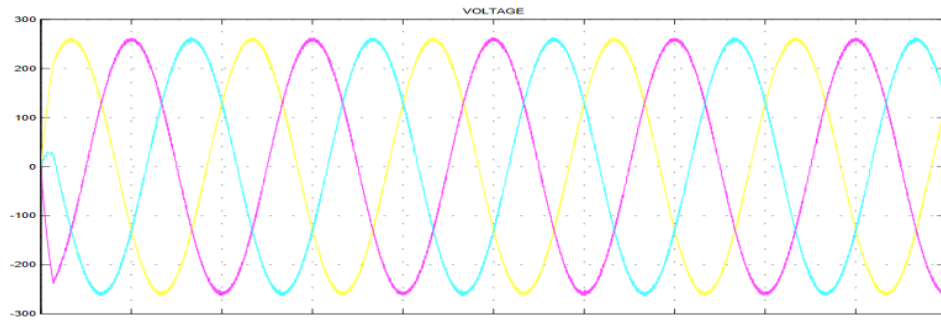


Fig. 7. Phase Voltages of 3-Phase inverter

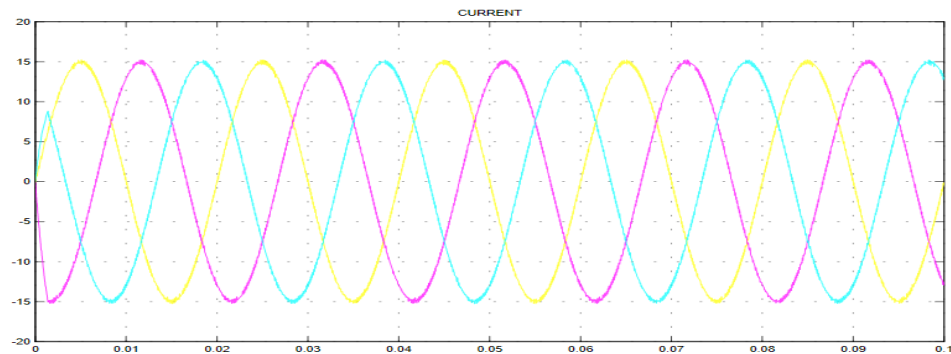


Fig. 8. Load Currents of 3-Phase inverter

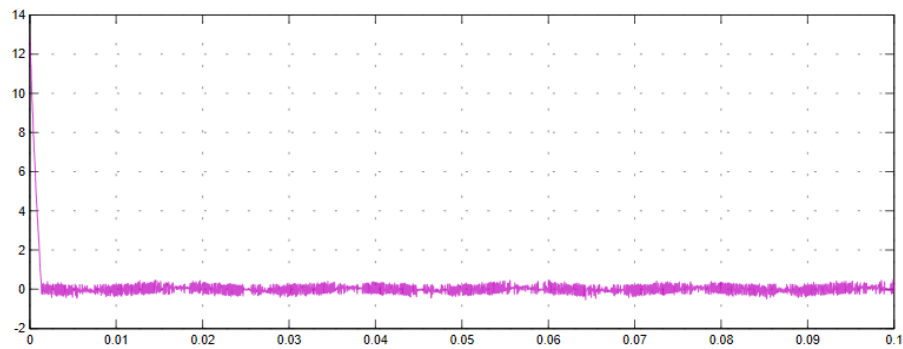


Fig. 9. Sliding Surface error

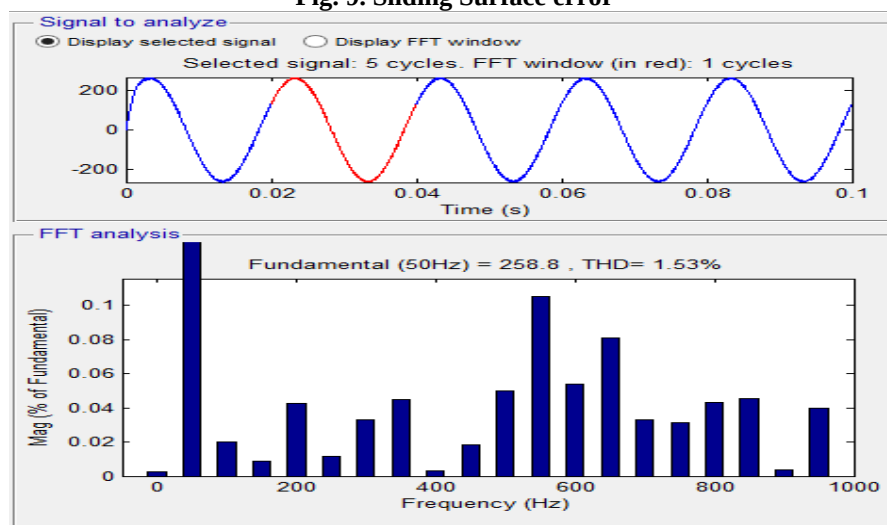


Fig. 10. THD of Phase Voltage of 3-Phase inverter

VI. Conclusion

Inverter place a vital role in many industries like renewable energy sources based power extraction and etc. And it is found that inverter with high quality and low harmonics are need full. The results shown in the paper

reveals that three phase inverter with a R-load has produced low content of harmonics and highly reliability is attained and hence it is suitable for various renewable energy based power sources and their grid interaction.

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