Robust Output voltage regulation and unity power factor with Sliding Mode Control

Abdelhalim KESSAL, Lazhar RAHMANI

Abstract— **The regulation by sliding modes is especially recognized for its qualities of robustness and dynamic response. This paper will briefly point out the principles of the regulation by sliding mode as well as the extension of those to the continuous adjustment of the output voltage of a rectifier in cascade with a chopper and the improvement of the power-factor at the entry. Based on the choice of the sliding surface, various fashions of control are studied. Accordingly, a proposed sliding surface utilizing all the variables of state will be used, thus improving the performances of the system in terms of robustness and dynamic response. Real-time implementation is performed on an experimental test bench using a rapid prototyping tool. Results show that the proposed controller gives better performances under large load disturbance and plant uncertainties.**

Key words: **Power factor correction, boost converter, sliding mode control**

I. INTRODUCTION

Conventionally, traditional controllers by PID are used in order to control the energy converters. Techniques of linearization are applied to converter of energy, which makes it possible to deduce from it a model simplified which will be thereafter used to make the design of the controller [1], [2].

In addition, being given a controller who bases on a model "small variation", the family of controllers PID does not manage to function in a satisfactory way for large variations around point of operation [3]. In order to take into account the nonlinear structure of system and owing to the fact that the controlled entry is in all or nothing, it is particularly interesting to apply the principle of sliding modes for the control of the systems to variable structure like the converters of energy. The control by sliding modes makes it possible to control the instantaneous value of the output signal of the chopper (voltage or current), which involves a better management of the transitory modes. This kind of control also proved its interest with respect to standard controllers of converters, in particular when the robustness and the dynamic response are concerned [4 -6].

Accordingly, we are interested in this paper in the application of the principle of sliding modes for control of the bench of the power factor corrector (PFC). We briefly initially point out the principle of control by sliding modes. Thereafter, we will evoke the application of this principle for the control of the bench of PFC. Based on the choice of the sliding surface; various modes of control will be studied. We then study a mode of control based on a sliding surface utilizing all the variables of state, this in order to improve the performances of the closed loop. The essential concepts related to this kind of control such as the conditions of convergence, existence, or stability of the sliding mode, are studied in detail.

II. THE MATHEMATICAL MODEL OF PFC BOOST

The mathematical model of the boost power factor corrector in state space form is obtained by application of basic laws governing the operation of the system. A basic converter topology is shown in Fig. 1.

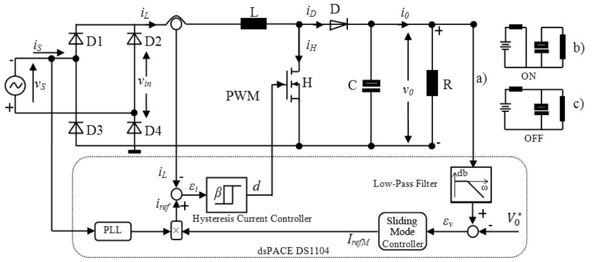

Figure 1: Boost Dc-Dc converter

The dynamics of this converter operating in the continuous conduction mode can be easily obtained by:

$$\begin{cases} C\frac{dv_O}{dt} = (1-d)i_L - \frac{v_O}{R} \\ L\frac{di_L}{dt} = v_{in} - (1-d)v_O \end{cases} \quad (1)$$

Variables of state are: inductance current i_L and capacitance voltage v_o. The control input d, representing the switch position function, is a discrete signal taking values in the set $\{0; 1\}$. The system parameters are constituted by L, which is the inductance of the input circuit; C the capacitor of the output filter; and R, the output load resistance. The rectified voltage source is v_{in}. It is assumed that the circuit is in continuous conduction mode, i.e. the average value of the inductor current never drops to zero, due to load variations.

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III. SLIDING MODE CONTROL

The sliding mode control theory provides a method to design a system in such a way that the controlled system is to be insensitive to parameter variations and external load disturbances [7]. The approach is realized by the use of a high speed switching control law which forces the trajectory of the system to move to a predetermined path in the state variable space (called Sliding or Switching Surface and it is a line in case of two dimensions) and to stay in that surface thereafter. Before the system reaches the switching surface, there is a control directed towards the switching surface which is called reaching mode. The regime of a control system in the sliding surface is called Sliding Mode. In sliding mode a system's response remains insensitive to certain parameters variations and unknown disturbances.

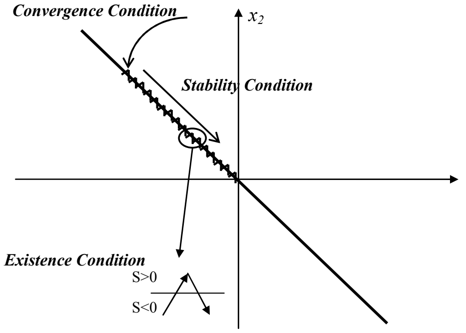

Figure 2 Sliding mode control

The Variable Structure System (VSS) theory has been applied to nonlinear systems. One of the main features of this method is that one only needs to drive the error to a switching surface, after which the system is in sliding mode and robust against modeling uncertainties and disturbances [6]. A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that map plant state to a control surface and the switching among different functions is determined by plant state that is represented by a switching function.

The state equation can be rewritten as:

$$x(t) = f(x, t, u) \tag{2}$$

Where, x is the state vector of the system, u is the control input and f is a function vector. If the function vector f is discontinuous on a surface $S(x)=0$ called sliding surface in the sliding mode theory then:

The system is in sliding mode if its representative point moves on the sliding surface $S(x)=0$. The sliding surface is also called as switching function because the control action switches depending on its sign on the two sides of the sliding surface.

In sliding mode theory, the control problem is to find a control input u such that the state vector x tracks a desired trajectory x^* in the presence of model uncertainties and external disturbance. The sliding surface may then be:

$$S(x) = x - x^* \tag{3}$$

If the initial condition $S(0)=0$ is not satisfied then the tracking can only be achieved after a transient phase called reaching mode.

Since the aim is to force the system states to the sliding surface, the adopted control strategy must guarantee the system trajectory move toward and stay on the sliding surface from any initial condition if the following condition meets [8-10],

$$S\dot{S} \leq -\eta\, |S| \tag{4}$$

Where, η is a positive constant that guarantees the system trajectories hit the sliding surface in finite time [1]

IV. SLIDING MODE CONTROLLER DESIGN

Taking $x_1=i_L$ and $x_2=v_o$ as the states of the systems and using the state equations given in equations (1), now the aim is to achieve a desired constant output voltage V_o^*. That is, in steady state the output voltage should be the desired voltage V^*. Thus,

$$x_2 = V_o^* \tag{5}$$
$$\dot{x}_2 = \dot{V}_o^* = 0 \tag{6}$$

From the general sliding mode control theory, the state variable error, defined by difference to the reference value, forms the sliding function:

$$S(x) = ({x_2}^* - x_2) = (V_o^* - v_o) \tag{7}$$

As mentioned earlier, that the trajectory of the voltage v_o rest on its sliding surface $S(v_o)=0$, we must apply an equivalent current i_{eq} which can be calculated by taking into account the following invariance conditions:

$$\begin{cases} S(v_o) = (V_o^* - v_o) = 0 \\ \dot{S}(v_o) = -\frac{dv_o(t)}{dt} = 0 \end{cases} \tag{8}$$

The equivalent current vector i_{eq}, can be determined as follows:

$$\begin{cases} V_o^* = v_o \\ \frac{dS(v_o)}{dt} = -\frac{dv_o(t)}{dt} = -\frac{1}{C}\left(i_L - \frac{v_o}{R}\right) = 0 \end{cases} \Rightarrow \begin{cases} i_{eq} = \frac{V_o^*}{R} \\ i_{eq} = \frac{v_o}{R} \end{cases} \tag{9}$$

Equation (9) defines the equivalent vector control which guarantees continuous voltage v_o to stay on the sliding surface. However, the operation of the chopper has discrete operation. Therefore the derivative of the function $\dot{S}(v_o)$ is not zero. In addition, the equivalent current vector given by the equation (9) does not control v_o outside the sliding surface. For these reasons, we must consider the derivative of the switching function $\dot{S}(v_o)$ in the control law. Given that the use of hysteresis can impose on a chopping of each period a mean value i_L, equal to the current vector control reference i_{ref}, the amplitude of input current reference can be deduced from equation (9) by:

$$I_{ref} = \frac{v_o}{R} - C\frac{dS(v_o)}{dt} = i_{eq} - C\frac{dS(v_o)}{dt} = i_{eq} + i_{att} \qquad (10)$$

The amplitude of the vector control I_{ref} is composed of two terms: The first is the equivalent control vector i_{eq}, while the second term $i_{att} = C\frac{dS(v_o)}{dt}$ involves the derivative of the switching function to bring the controlled path to the sliding surface.

The choice of the derivative expression of the switching function so that the conditions of attractiveness are met will eventually determine the attractive current vector i_{att}. By choosing an attractive structure for constant reference voltage and proportional action, attractive current vector i_{att} is expressed as follows [11]:

$$i_{att} = -C(-q\,Sign\,(S(v_o)) - k\,S(v_o)) \qquad (11)$$

Where: q and k are positive real.

Expression of the vector control current amplitude I_{ref} to be applied is given by the following relationship:

$$I_{ref} = i_{eq} + i_{att} = \frac{V_o^*}{R} + C\left(q\,Sign\,(S(v_o)) + k\,S(v_o)\right) \qquad (12)$$

To ensure that v_o tends to its sliding surface, requires that the condition of attractiveness $S(v_o).\dot{S}(v_o) < 0$ is verified

$$S(v_o).\dot{S}(v_o) = \\ -\frac{S^2(v_o)}{RC} - k.S^2(v_o) - q.S(v_o)\,Sign\,(S(v_o)) \qquad (13)$$

It consists of the sum of three negative terms each.

The role of factor q is to reduce the oscillations and ensure the stability, while k is applied to have a fast response. Figure 3 presents a synoptic of the designed sliding mode controller, inserted in output voltage loop.

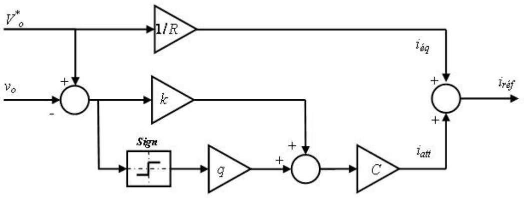

Figure 3 Sliding mode controller for voltage loop.

The desired current reference is obtained by multiplying Iref and a sin wave produced by the PLL to get a synchronized signal with input voltage.

V. SIMULATION AND EXPERIMENTAL RESULTS

The closed-loop control is necessary to maintain the output voltage when the input voltage has some variation. The analysis of converter shows that the system dynamics can be divided into fast (current) and slow (voltage) motion. In this study two-loop control, an inner current control loop and an outer voltage control loop are used. The voltage loop controller is a sliding mode type controller; since the motion rate of the current is much faster than that of the output voltage, a hysteresis controller is used in the inner current loop. The block diagram of the overall system is shown in Figure 1.

Simulations were performed on a typical `boost' converter circuit with the following parameter values:

The magnitude of supply voltage	V_{SM}=150V
Input Inductance L	22.5mH
Output Capacity C	940 µF
Load Resistance R	220Ω, 100Ω
DC bus output voltage reference	V^*_o=160V

The experimental prototype was built around the dSPACE1104 controller board with the same values of simulations.

Figures 4 and 5 present output voltage and input current for steady state, obtained via simulation and experimental respectively, with THD=3.05% and power factor near to unity (0.996).

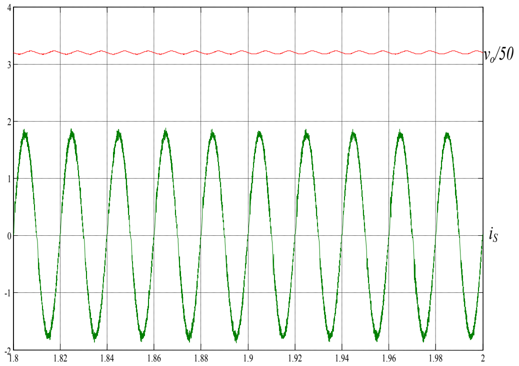

Figure 4 Simulated Output voltage and input current.

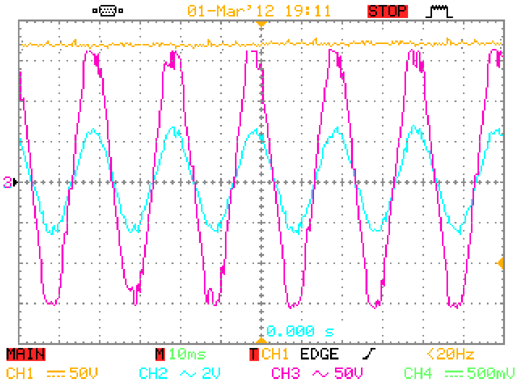

Figure 5 Experimental output voltage and input current.

Figure 6 shows output voltage transient response during a change in the reference voltage from 160 to 192V, then from 192V to 160V.

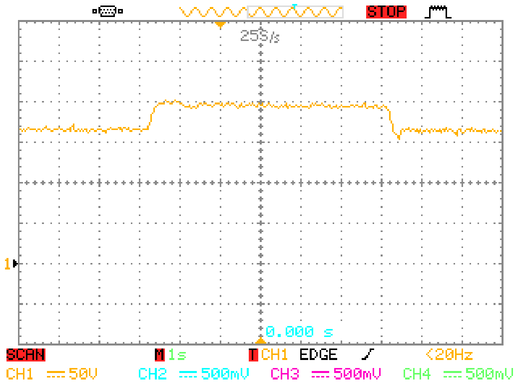

Figure 6 Transient waveform of output voltage with reference variations.

It is known that the sliding mode control is regarded as a robust feedback control technique with respect to matched unmodelled external perturbation signals and plant parameter variations. In order to test the robustness of sliding mode control scheme, the load resistor has been let to change with 50% of its nominal value (approximately 100Ω). Figure 7 shows the recovering features of the proposed controller to the imposed load variations. As expected, the output voltage is robust when the load was subject to a sudden un-modeled variation from 212Ω to 312Ω then to 212Ω.

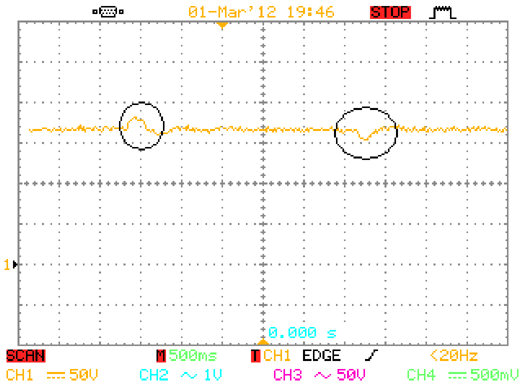

Figure 7 Transient waveform of output voltage with load variations.

Table 1: Transient values corresponding to Figure 6.

Control	*V^*_0*	*Δv_o (V)*	*Δt (S)*	*THD*
SMC	↑	0.1	0.15	2.3%
	↓		0.20	
PI	↑	*1--2*	*0.75*	*2.5%*
	↓		*0.8*	
Fuzzy	↑	*0.2*	*0.4*	*3%*
	↓		*0.4*	

Table 2: Transient values corresponding to Figure 7.

Control	*Load*	*Δv_0 (V)*	*Δt*
SMC	↑	*12.8*	*0.25*
	↓	*12.8*	*0.25*
PI	↑	*16*	*0.5*
	↓	*16*	*0.7*
Fuzzy	↑	*13*	*0.4*
	↓	*13*	*0.3*

Table 1 and Table 2 present a comparative study between different regulators applied in the voltage loop[12], it's clear that sliding mode controller offer best responses compared to PI or fuzzy regulators, the response takes 0.15s and 0.2s to maintain the reference value, 0.35s and 0.25s for the correction of the voltage level. The input current THD is better than other cases, which confirms the robustness and performance or SMC regulator.

VI. CONCLUSION

In this paper, the practical design constraints of power-factor-correction power supplies that use a sliding mode control to achieve high power factor and fast regulation have been study. In addition, a small-signal model of the proposed converter was developed from which an optimal sliding mode compensator is designed for the converter system with peak-current mode control. However, the input current harmonic content is very close to the limit specified in IEEE 519 Standard. The static and dynamic of sliding mode controller for the voltage loop and hysteresis controller for the current loop are excellent. Experimental results have shown that fast dynamic response, good output regulation, low harmonic distortion, and high power factor can be achieved with the proposed single-stage converter and control scheme.

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