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Design of practical sliding-mode controllers with constant switching frequency for power converters

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ABSTRACT

A novel experimentally motivated method in order to design a family of easy-to-implement sliding-mode controllers for power converters is proposed. Two main results are presented. First, the relation between sliding-mode control and average control is reinterpreted so that the limitation of the switching frequency for the closed-loop system is achieved in a more direct way than other methods so far reported in the literature. For this purpose, a class of sliding surfaces which makes the associated equivalent control be the system average control is proposed. Second, the achievement of a constant switching frequency in the controlled system is assured without requiring the sliding-mode-based controller to be modified, unlike most previous works. As a result, the proposed sliding surfaces-type can be directly implemented via a pulse-width modulator. The control methodology is implemented for the voltage control in a boost converter prototype in which the load is considered unknown. Experimental results confirm high performance and robustness under parameters variation. Furthermore, the solution proposed is easy to implement and well-suited for other power converters.

1. Introduction

The main goal of this paper is to design a class of easy-to-implement sliding-mode controllers for power converters in which the control switches with a fixed known frequency established by the designer. For this purpose, a new type of switching surfaces is proposed. These surfaces make the equivalent control be the average control and consequently, they can be directly implemented by means of a pulse-width modulator (PWM).

Sliding-mode control (SMC) has been proven to be effective in a wide range of practical control problems with nonlinear complex dynamics [1]. Such a success is mainly due to the relatively simple design procedure, the good controlled system performance, in addition to the robustness under input perturbations and variations of system dynamic properties.

The main characteristic of systems exhibiting sliding modes is their discontinuous nature. The sliding motion can be either intrinsic to the system or be induced in it by means of a discontinuous control. SMC is particularly appropriate for power electronics systems because these are intrinsically discontinuous. This fact has attracted the interest of many power electronics engineers, who have applied SMC to power converters.

The SMC-design process gives an expression for the switch position in power converters. In the ideal case, the switching frequency is infinity, which obviously cannot be achieved. Nevertheless, the higher the switching frequency is, the better the approximation to an ideal sliding mode is. However, due to the characteristics of the actual switch, an upper limit for this switching frequency must be imposed. In many applications, having a constant switching frequency is desirable, but sometimes is mandatory. Due to this fact, methods to limit the switching frequency have been proposed. In

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Section 2, where the SMC-design process is revisited, these methods are discussed.

The implementation of SMC for power converters usually involves two steps. First, to design an ideal SMC by means of an ideal sliding surface. Second, to modify the sliding surface in order to implement the control with a constant switching frequency, or at least with an upper limit for the switching frequency. Ideal SMC algorithms are usually simple, however, its implementation becomes difficult due to the necessity of the second design step. This drawback is overcome in this paper. If a controller has the form specified in this paper then it can be straightforwardly implemented assuring a constant switching frequency, without requiring the control law to be modified.

The problem of achieving a constant switching frequency has been addressed in several works [2–11]. Most of these solutions are based on a relation between the SMC and the average control. Such a relation arises from the physical meaning of the equivalent control associated with a SMC. A different interpretation of the SMC-average-control relation is given in Section 2, which will be the basis for proposing a new class of controllers in Section 3.

The SMC proposed in this paper is based on a class of sliding surfaces which can be directly implemented by using a PWM, and, hence, with a constant switching frequency. The main idea followed is that one surface in which the system has desired dynamics is akin to be embedded into a sliding surface. In [12], following the work in [13], a preliminary sketch of this proposal was presented. Nevertheless, in the present paper, the validity of the sliding-mode-based control methodology is analytically proven.

The idea of using a surface in order to build the sliding surface for the closed-loop system has been successfully implemented in a boost-converter prototype. The simulations and experimental results for the example show that the controller is easy to implement and yet is robust under load and input voltage variations.

2. Relation between sliding-mode controllers and average controllers in power electronics

Power converters can be modelled by

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})u, \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^n$ is the system state vector, usually consisting of inductor currents and capacitor voltages. f and g are continuous vector fields and $u \in \{0, 1\}$ is the switch position which makes the system discontinuous. The dot stands for the derivative with respect to time.

The SMC-design process aims at determining the switch position u, which generally has the form,

$$u = \begin{cases} 0 & \text{if}\, \sigma(\mathbf{x}, t) < 0, \\ 1 & \text{if}\, \sigma(\mathbf{x}, t) > 0, \end{cases} \tag{2}$$

where σ is a smooth scalar function. Since sliding-mode controllers are intrinsically discontinuous, it is natural to use a discontinuous system model for designing these controllers.

If a sliding-mode controller works then, at some time, the system trajectory will evolve on the surface $\sigma = 0$. When this happens, the system trajectory is described by means of the equivalent dynamics [14,15],

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})u_{\text{eq}}, \tag{3}$$

where u_{eq}, referred to as the equivalent control, is the solution for u of the equation $\dot{\sigma} = 0$. Dynamics described by (3) are valid just in the ideal case of infinity switching frequency. In a more practical case of having a high but limited switching frequency, the system trajectory does not evolve on the surface $\sigma = 0$ but in a boundary layer [15]. In this case, (3) can be written as

$$\dot{\tilde{\mathbf{x}}} = \mathbf{f}(\tilde{\mathbf{x}}) + \mathbf{g}(\tilde{\mathbf{x}})\mathbf{u}_{\mathbf{eq}}, \tag{4}$$

where $\tilde{\mathbf{x}}$ is the average of $\mathbf{x}$.

Controller (2) cannot be directly implemented because, in this case, the frequency would operate in free run, just limited by physical constraints of the switch element. To have a good efficiency and to protect the switch element, among other practical considerations, the switching frequency must be assured to have an upper limit. To this end, a hysteresis band could be used in (2) instead of the sign of σ. Alternatively, the switch could be assured to be in on (off)-mode for a constant time and modulate the on (off)-time. In some applications, it is highly convenient, and even mandatory, to have a constant switching frequency. The hysteresis band and constant on-time can only lead to a constant switching frequency in the stationary state.

On the other hand, average control is based on the model

$$\dot{\tilde{\mathbf{x}}} = \mathbf{f}(\tilde{\mathbf{x}}) + \mathbf{g}(\tilde{\mathbf{x}})\mathbf{d}. \tag{5}$$

Vector $\tilde{\mathbf{x}}$ consists of the average of inductor currents and capacitors voltages; f and g are the same continuous vector fields than those appearing in (1); $d \in [0, 1]$ is the duty cycle.

The average-controller design process yields to an expression for the duty cycle,

$$d = \frac{\text{Num}(\tilde{\mathbf{x}})}{\text{Den}(\tilde{\mathbf{x}})}. \tag{6}$$

This signal must be passed through a PWM to carry out the actual switching.

In [15], it is proven that u_{eq} is the average of u. Hence, the performance of a sliding-mode controller u should be like the performance of an average controller d provided that $u_{\text{eq}} = d$. This idea is proven in [16]. Consequently, it is posible to design a sliding-mode controller as that defined in Eq. (2) and implement it with a PWM by making $d = u_{\text{eq}}$. Thus, a constant switching frequency is achieved (Fig. 1). This idea is the basis of several works [3,4,7,9,11]. The problem is that the implementation of u_{eq} is usually far more difficult than σ. By using the equivalence between u_{eq} and d, an alternative method to simplify the sliding-mode controller implementation is proposed in [9]. Instead of using a PWM in order to achieve (6), it could be assured that $\text{Den}(\tilde{\mathbf{x}})u_{\text{eq}} = \text{Num}(\tilde{\mathbf{x}})$, and therefore, there is no need to use a divisor. However, for this purpose, it is necessary that the PWM has a sawtooth with variable amplitude. All

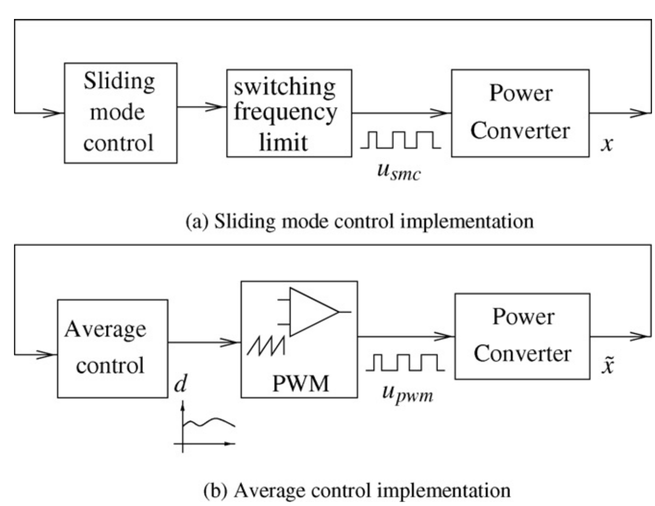

Fig. 1. Relation between SMC and average controls: if $d = u_{\text{eq}}$ then u_{smc} and u_{pwm} are similar.