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Analysis and design of sliding mode controller gains for boost power factor corrector

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A B S T R A C T

This paper presents a systematic procedure to compute the gains of sliding mode controller based on an optimization scheme. This controller is oriented to drive an AC–DC converter operating in continuous mode with power factor near unity, and in order to improve static and dynamic performances with large variations of reference voltage and load. This study shows the great influence of the controller gains on the global performances of the system. Hence, a methodology for choosing the gains is detailed. The sliding surface used in this study contains two state variables, input current and output voltage; the advantage of this surface is getting reactions against various disturbances—at the power source, the reference of the output, or the value of the load. The controller is experimentally confirmed for steady-state performance and transient response.

1. Introduction

Usually, traditional PID controllers are used for the control of power converters [1–3]. Simple models of converters are generally obtained from signals averaging and linearization techniques; these models may then be used for control design [4,5]. On the other hand, PID controllers failed to satisfactorily perform constrained specifications under large parameter variations and load disturbances [2]. Another choice for controlling power converter is to use the sliding control techniques. Sliding mode control (SMC) of variable structure systems such as power converters is particularly interesting because of its natural robustness, its capability of system order reduction, and suitability for the nonlinearity aspect of power converters [5–7]. However, despite being a popular research subject, SMC is still rarely applied in practical AC–DC converters. It is mainly due to the fact that no systematic procedure is available for the design of SMC in practical applications [8]. For example, the influence of the controller gains on the closed loop system performances for a given application is not properly clarified, and most of the previous works are limited to the study of the influence of these parameters only on the existence and stability of sliding mode [9,10]. In other cases an empirical approach is adopted for selecting these gains of SMC; computer simulation and experiments were performed to study the effect of the various control gains on the response of the output voltage [10]. Therefore in this paper, analysis and design of SMC for power factor corrector (PFC) are studied. After studying and analyzing different existing solutions for sliding mode control of PFC, a control mode that allows a direct control of the voltage of boost converter is proposed. The performances of the controller in terms of robustness and dynamic response will be improved. Most literature works are concerned with the study of hitting, existence and stability conditions of the SMC. The contribution of this paper goes beyond this direction by involving the study of the influence of control parameters on system performances. In this context, an optimization algorithm is developed in order to choose the controller parameters based on a predefined specification for a given real application.

Accordingly, this paper is oriented in the application of the sliding modes for control of the bench of the power factor corrector (PFC). Principle of control by sliding modes is described briefly. Thereafter, the application of this principle for the control of the bench of PFC will be evoked. Based on the choice of the sliding surface, various modes of control will be studied. Then a mode of control based on a sliding surface utilizing all the variables of state are studied; this is in order to improve the performances of the closed loop. The important concepts associated to this type of control such as the convergence conditions, existence, or stability of the sliding mode, are considered carefully.

This paper proposes a systematic analysis, design and digital implementation of the proposed controller, composed by linear controller in the DC voltage loop and sliding mode controller in the current loop. This controller is verified by detailed MATLAB/Simulink based on simulations through the use of a continuous time plant model and a discrete time controller. Design is comprehensive in the sense that it accounts for sampling effects,

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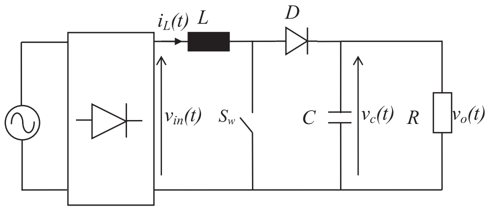

Fig. 1. Boost converter circuit.

computation delays, hardware filtering for antialiasing, and software filtering for measurement noise reduction, where necessary. Real-time implementation is done on an experimental prototype using the dSPACE DS1104 controller board. This controller is experimentally compared for steady-state performance and transient response over the entire range of input and load conditions for which the system is designed. The paper is organized as follows. In Sections 2 and 3, a description of converter, and a design and analysis of controllers are given. The experimental setup is detailed in Section 4. Section 5 presents the obtained results with discussions.

2. Mathematical model of boost converter

The basic circuit diagram of the DC–DC converter with front end solid state input power factor conditioner used in the proposed scheme is shown in Fig. 1.

The power circuit is that of an elementary step-up converter. When the boost switch S_w is turned on ($u=1$), the inductor current builds up, and energy is stored in the magnetic field of the inductor, whereas the boost diode D is reverse biased, and the capacitor supplies power to the load. This is the first mode operation. As soon as the boost switch is turned off ($u=0$), the power circuit changes mode, and the stored energy in the inductor, together with the energy coming from the input AC source, is pumped to the output circuitry (capacitor–load combination). This is mode 2 of the circuit. Then the state space model for the boost PFC in continuous current mode can be found by the circuit analysis. The output voltage and inductor current dynamics are governed by the variable structure real switched system.

$$\begin{cases} C\frac{dv_o}{dt}=(1-u)i_L-i_o \\ L\frac{di_L}{dt}=v_{in}-(1-u)v_o \end{cases} \tag{1}$$

In order to obtain a sinusoidal input current in phase with the input voltage, the control unit should act in such a way that v_{in} sees a resistive load equal to the ratio of v_{in} and i_L. This has been done by comparing the actual current passing through the inductor with a current reference, which is derived from v_{in} and has an amplitude determined by the output voltage controller.

3. Design of sliding mode controller

The control objectives of the PFC are twofold: regulate the output voltage v_o to a reference voltage V_{ref} and give the input current i_L a rectified sine waveform in phase with the rectified voltage v_{in}. The design of sliding mode controller for PFC starts with the choice of sliding surface. As it is shown in [11], it is clear that direct surface v_o-V_{ref} can tend to zero only if the current increases continuously. Usually, a cascade control structure is used, which leads to solve the control problem using two control loops [12]: an outer voltage loop which generates the reference current from voltage error and an inner current loop which controls the inductor current via sliding mode that replace classical hysteresis current control (Fig. 2).

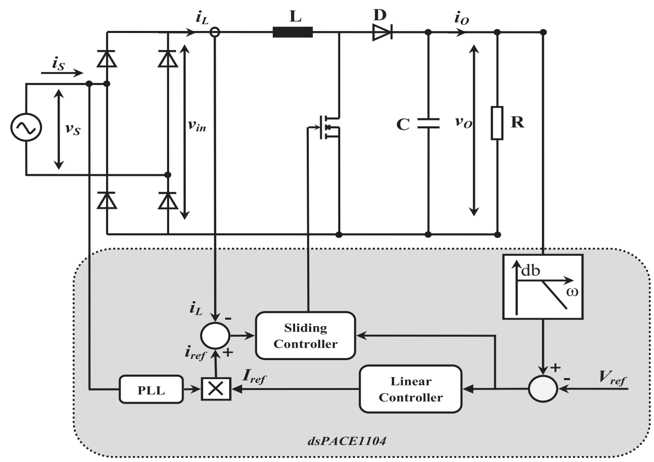

Fig. 2. Boost converter circuit governed by sliding mode controller.

This control of the output voltage of AC–DC converter meets the criteria of stability and existence of sliding mode. However, it is difficult to determine the gains of the voltage loop since sliding mode is a highly nonlinear method [2]. Furthermore, since SMC is only applied to current regulation, the voltage loop will be more sensitive to high frequencies phenomena and to uncertainties in the reference current. In order to improve the performances of the controller, a control mode based on a sliding surface which involves output voltage will be treated.

Let (V_{equ}, I_{equ}) be the desired equilibrium point, where V_{equ} is the output voltage, and I_{equ} is the inductor current peak at equilibrium point. The input current peak I_L can be expressed as [13]

$$I_L=\frac{\pi}{2}V_o\frac{(1-\alpha)}{R} \tag{2}$$

So, the equilibrium point becomes $(V_{equ}, I_{equ}=(\pi/2)V_{equ}((1-\alpha)/R)$, and the sliding surface shall be given according to the expression

$$S=\lambda_1(v_o-V_{ref})+\lambda_2(i_L-i_{ref}) \tag{3}$$

where λ_1 and $\lambda_2 \in R^+$.

The control by current imposes the average power passed to the load with the ideal PFC pre-regulators [13].

$$P=\frac{V_{SM}I_{ref}}{2}=v_o i_o \tag{4}$$

The reference current peak depends on the operating point; it can be taken as

$$\frac{V_{SM}I_{ref}}{2V_{ref}}=\frac{i_o}{(1-\cos 2\omega t)}=\frac{v_o}{R(1-\cos 2\omega t)} \tag{5}$$

$$I_{ref}=\frac{i_o}{(1-\cos 2\omega t)}=\frac{2v_oV_{ref}}{V_{SM}R(1-\cos 2\omega t)} \tag{6}$$

Sliding surface coefficients (λ_1, λ_2) should be chosen such that the sliding mode exists at least around the desired equilibrium point, and the dynamics of the system will reach the surface and lead toward the equilibrium point.

3.1. Existence condition

The existence condition of sliding mode implies that both $\dot{S}$ and $\dot{S}$ will tend to zero (when $t\to\infty$), which means that the system dynamics remains on the sliding surface. The existence condition of the sliding mode is $S\dot{S}<0$ (when $S\to 0$); achieving this