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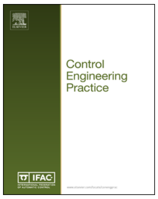

Digital memory look-up based implementation of sliding mode control for dc–dc converters

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A B S T R A C T

Switched power electronic converters involve different control actions for different system events. A local control strategy may be developed which reacts only to some local information available to each component without any communication between the different system components located far away in real time. The purpose of this paper is to present a low cost memory based control strategy in a dc–dc boost converter. The control employed in this work is based on a sliding-mode hysteretic control strategy where the sliding manifold is derived *a priori* and stored as a look-up table in digital memory hardware. The proposed control implementation strategy is low cost and offers a robust dynamic response that is used to mitigate many disturbances in the system.

1. Introduction

In modern day smart grids and microgrids, the usage of dc–dc power electronic converters has increased due to the requirement of various levels of dc voltages in home and office facilities (Liu, Wang, & Loh, 2011). Switching in the power electronics is a non-linear phenomena and application of the traditional linear control techniques is often not suitable (Guldemir, 2005). The classical linear control technique has limitations in large signal transients, such as step changes in the load or startup processes (Su, Chen, & Wu, 2002). Thus, there is a need for a control technique which is capable of dealing with non-linearities and wide variations in load, while ensuring uninterrupted operation and at the same time providing a good transient response (Dashtestani & Bakkaloglu, 2015; Mattavelli, Rossetto, & Spiazzi, 1995; Sira-Ramirez, 1987). This advanced capability often comes at the price of a complex and costly control hardware (Tarte, Chen, Ren, & Moore, 2006). Switching converters form a variable structure system and thus sliding-mode control is an effective and simpler technique (Alvarez-Ramirez, Espinosa-Perez, & Noriega-Pineda, 2001; Sira-Ramirez, 1989) than other robust control schemes which are computationally intensive (Guldemir, 2011; Shtessel, Zinober, & Shkolnikov, 2002). Previous work has been done on the development of sliding-mode control strategies in power electronics, which drive the system states to some reference (Banerjee & Weaver, 2012, 2014; Cid-Pastor et al., 2013; Guldemir, 2005; He & Luo, 2006; Mattavelli et al., 1995). The use of digital control in switching power converters has increased due to the decreased cost and increased computational capability of digital ICs (König, Gregorĉiĉ, & Jakubek, 2013; Liu & Jia, 2010; Marwali & Keyhani, 2004). Some work has been done with the digital implementation of a control strategy by using a predetermined surface inside a digital controller (Banerjee & Weaver, 2014; Pitel & Krein, 2009).

This work shows a method of implementing a digital sliding-mode hysteretic control technique in a switching power electronic converter. A dc–dc boost converter is chosen to validate the strategy. The stability analysis of various reference surfaces chosen for the controller is performed in this work. This work uses (Pitel & Krein, 2009) as the starting point and implements a digital sliding-mode hysteretic control method in a dc–dc boost converter where the sliding surfaces are predetermined and stored in a low-cost memory circuit, instead of using any form of software component, such as a Digital Signal Processor (DSP), in the design. The use of this control strategy eliminates the necessity of any analog tuning and communication. It is also shown that by using analog-to-digital converters (ADC) in the process, the control can be improved by eliminating the need to derive and implement a hysteresis band which limits the effective switching frequency (Pereira, Postolache, Dengchao, Viegas, & Girao, 2007). The inherent propagation delay in the ADC creates the required hysteresis band in the controller. Since the sliding surfaces are derived *a priori*, the system response time is reduced.

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2. Implementation of digital hysteretic sliding-mode controller in a dc–dc converter

The use of digital control in switching power converters has increased due to the decreasing cost of digital controllers, such as microcontrollers, DSPs and Electrically Erasable Programmable Read-Only Memory (EEPROM) (Liu & Jia, 2010). A sliding-mode control surface for power electronics can be implemented in all these devices. However, a EEPROM device has the lowest cost with the best response rate of all the mentioned devices. Different choices of reference surfaces can be calculated *a priori* and stored as a memory lookup table in the device. This memory table contains the complete surface and the switching law. An analog-to-digital conversion of the state feedback signals of dc–dc converter are used as the quantized digital addresses of the memory table. The proper switch states (1 or 0) are stored in the memory location according to the *a priori* calculations. A hysteretic band can also be introduced by feeding the current switch state back as an address component for the next switch state. The circuit of a dc–dc boost converter, along with the memory lookup table/EEPROM controller, is shown in Fig. 1. The sample times for the ADCs are 2.2 μs, 2.5 μs and 2.8 μs and these are the times used in the simulations and experiments.

3. Experimental apparatus

In Fig. 1 the analog signals from the power stage of the converter are converted into digital signals of M bits using parallel interface ADCs. The digital output of the ADCs is interfaced with a parallel EEPROM chip, which stores the switching surfaces based on the open-loop solutions for different desired response scenarios. The switching surfaces are stored as pixels in the address locations of the EEPROM. The output of the EEPROM is the switch state. Corresponding to each address in the memory, a switch state is programmed by an algorithm that compares the pixel for that address to the reference surface and computes the switch states. Therefore, in the EEPROM, the complete surface is stored as different addresses and each address has a switch state associated with it. Thus, the EEPROM forms the digital controller that outputs the switch state based on hysteretic sliding-mode control technique. From the two parallel digital devices an entire byte of data is transmitted. Therefore, when information from the analog signal of the power stage is converted to an M-bit digital signal at the output of the ADC the entire M-bit of data is transmitted to the parallel EEPROM at the same time. The physical address space is a p-dimensional look-up table (where p is the number of analog signals being fed into the ADC converters). Therefore, in Fig. 1, i_{in}, the input current, and v_{out}, the output voltage, are M-dimensional vectors with binary entries. This control scheme has a very fast response time when the ADCs with appropriate resolution and fast sampling rate EEPROMs are used. For implementing the hysteretic sliding-mode control of the power converters, an 8 bit ADC is used for each analog signal. This is a generic hardware set-up that can be used to control a switching power converter with any number of state-analog signals. The gain blocks shown in Fig. 1 are voltage dividers that step down the state analog signals to appropriate levels for the ADCs. This will depend on the maximum input voltage limit of the ADCs.

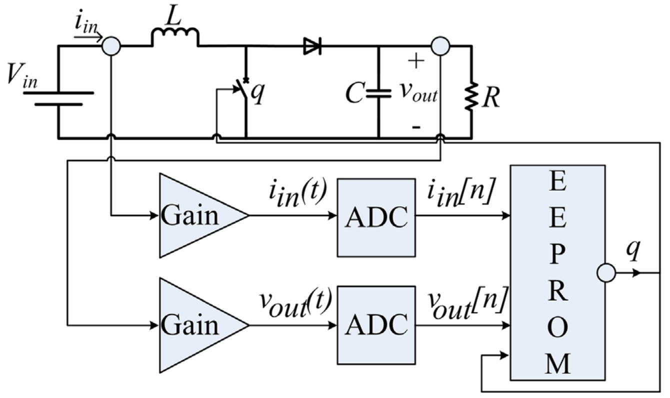

Fig. 1. Circuit for the implementation of the digital sliding-mode control strategy with two ADCs and a single EEPROM in a dc–dc boost converter.

4. Memory resolution analysis

The dc–dc boost converter depicted in Fig. 1 is based on the assumption of an ideal switch and diode to the dynamic system equations

$$L\dot{i}_{in} = V_{in} - (1-q)\,v_{out}$$
$$C\dot{v}_{out} = (1-q)\,i_{in} - \frac{v_{out}}{R}, \tag{1}$$

where i_{in} is the input current, v_{out} is the output voltage, V_{in} is the input voltage, q is the switch state, L and C are energy storage elements and R is a constant resistive load. An ideal switch for the dc–dc converter is considered for mathematical modeling and simulation. The state space representation of (1) gives

$$\dot{x}(t) = \begin{bmatrix} 0 & -\dfrac{1-q}{L} \\ \dfrac{1-q}{C} & -\dfrac{1}{CR} \end{bmatrix} x(t) + \begin{bmatrix} \dfrac{V_{in}}{L} \\ 0 \end{bmatrix} \tag{2}$$

where

$$x(t) = \begin{bmatrix} i_{in}(t) \\ v_{out}(t) \end{bmatrix}. \tag{3}$$

The system parameters and the states are combined into $\lambda = [R, L, C, V_{in}]^T$ and $x(t) = [i_{in}, v_{out}]^T$ respectively. The switch state q is generated from a digital hysteretic sliding-mode controller. The system state trajectories are first attracted towards a reference sliding surface given by

$$s = 0 \tag{4}$$

based on the switching control law

$$q = \begin{cases} 0 & \text{if } s - \dfrac{h}{2} > 0 \\ 1 & \text{if } s + \dfrac{h}{2} < 0 \\ q & \text{else.} \end{cases} \tag{5}$$

Then they travel along s and finally limit cycles about the intersection of $s=0$ and a desired steady state operating point $x_e = [i_{inop}, v_{op}]^T$, within a band $h > 0$ known as the hysteresis band.

A dc–dc boost converter has a range of operating points depending on λ and $x(t)$. The load line results from the steady state condition of the system shown in (2) and can be given by

$$i_{in} = \frac{v_{out}^2}{RV_{in}}. \tag{6}$$

The sliding surface chosen for this analysis is a sloped linear surface in the state-plane. The reason for the choice of this surface is discussed in Section 6.2. The equation for the surface is

$$s = i_{in} - m + bv_{out} \tag{7}$$