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Discrete-event switching control for buck converter based on the FPGA

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ABSTRACT

This paper presents a discrete-event switching control of DC–DC converters which belong to a particular class of hybrid systems. Taking advantage of the energetical properties of these converters, Lyapunov function is proposed. This function, which is systematically deduced from the physical model, allows the creation of various stabilizing switching sequences. From a theoretical point of view, asymptotic stability can be obtained. The digital control is implemented by FPGA system, with additional A/D peripherals. Experimental results for digitally controlled synchronous buck converter show the effectiveness of the proposed approach.

1. Introduction

The switch-mode power supplies are switched circuits used to transfer power from a DC input to point-of-load. They are used in a large variety of applications because of their light weight, compact size, high efficiency and reliability. The control objective is to achieve output voltage regulation in the presence of an input voltage and output load variation (Mazumder, Nayfeh, & Boroyevich, 2001; Venkataramanan, Sabanovic, & Cuk, 1985), since the input DC voltage is unregulated and output power demand changes significantly over time (with time varying load). Interaction exists between continuous and discrete dynamics, due to a switch mode operation. In this case, DC–DC converters can be referred to as being hybrid by nature. When using the traditional methods, as in averaging methods, the hybrid nature of the systems is neglected and the systems are approximated by purely continuous dynamics. Consequently, they are controlled by the use of linear controllers with nonlinear procedures, such as pulse-width modulation (PWM) (Erickson & Maksimovic, 2000; Kassakian, Schlecht, & Verghese, 1991; Middlebrook & Cuk, 1977). The models used for controller design are the result of simplifications, which include the average behavior of the system over time (to avoid switching modelling) and linearizing around a certain operational point, acting without regard to any limitation. There are many approaches to the transient-state and steady-state analyses of switch-mode DC–DC converters. Firstly, there were two milestone papers written by Middlebrook and Cuk (1977) and Erickson, Cuk, and Middlebrook (1982), where the basic ideas of state-space averaging were introduced and the so-called small signal modelling was proposed for the purpose of control design. A switching converter system can be stable around the operating point, but may be unstable when the system undergoes sizeable disturbances or parameter variations. Therefore, small-signal models cannot predict all of the information on the stability of the system (Iannelli, Johansson, Jonsson, & Vasca, 2008; Sira-Ramirez, 1987; Venkataramanan et al., 1985).

Strategies for separate control of continuous and discrete dynamics of hybrid systems, separately, are clearly not the best choice. Although there are some well-known approaches, such as sliding mode control and bang-bang control, which deals with both continuous and discrete dynamics, but these techniques cannot be treated within a unified framework. Robust control can also be used to ensure the robustness to load and parameter changes (El Fadil & Giri, 2009), but a solid mathematical background and design tools are needed. Recently, several research results have shown more systematic ways of modelling, analyzing and controlling hybrid systems (Geyer, Papafotiou, & Morari, 2005; Sira-Ramirez & Silva-Ortigoza, 2002).

Hysteresis control is a fast and robust control approach, which is used mainly for simpler converter systems. In regard to such controllers, discrete-event systems open up a view that is more systematic and even enables the controller to design for nonlinear systems.

The goal of this paper is to present a more systematic design of hysteresis controllers from the viewpoint of discrete-event systems, so that it will be possible to benefit from their high robustness and dynamic response (Ramadge & Wonham, 1989).

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Several authors have recently reported the use of FPGA (field programmable gate array) in switching converters. Parallel operation of the FPGA allows for execution of the main processes and additional logic functions to run simultaneously, which differs from the sequential execution on DSP. The HDL (hardware description language) modelling system, used in design entry and simulation processes by FPGA programming, is based on the use of variables that represent logic values. Power mapping between FPGA hardware with HDL software and a mathematical model of an experimental switching converter and its nonlinear switching control is extremely important (Berto, Paccagnella, Ceschia, & Bolognani, 2003).

The aim of the presented paper is the application of a hybrid system in order to improve buck converter performance. Together with a control scheme based on control-Lyapunov function approach is proposed for the synchronous buck converter.

2. Synchronous buck converter design

Synchronous buck converters in comparison to the conventional buck converters can achieve a high efficiency in today's low-voltage applications, as they replace the freewheeling diode of buck converters with a MOSFET. When a MOSFET is used, instead of the diode, the conduction losses are reduced and bidirectional current flow is allowed. Thus, synchronous buck converter operates only in a continuous conduction mode. At high output currents, both synchronous and conventional buck converters stay in the continuous conduction mode (CCM). During light loads, the synchronous buck converter is maintained at the CCM, where the conventional buck converter enters the discontinuous mode of operation and the diode blocks negative current in the inductor. In the discontinuous conduction mode (DCM) operation, there is no conduction loss when the inductor current is zero. With the synchronous buck converter that operates in CCM, the conduction losses of MOSFET are still present in negative inductor currents. So the power dissipation at light loads can be relatively large and if stand-by efficiency is crucial for the application, this can present a drawback for synchronous buck converter. Synchronous buck converter operates with high efficiency at high output current but with low efficiency at low output power.

To enhance the efficiency of the synchronous buck converter at light load, a control circuitry is added. The aim of an additional control circuitry is to turn off the MOSFET when the current is zero, in order to block the negative inductor current with a diode. Hence, the MOSFET effectively functions as a diode that enables the operation of the synchronous buck converter to operate in DCM. To overcome the slow switching of the body diode and in order to improve the performance, an integrated fast freewheeling diode (Schottky diode) may be placed in parallel to the MOSFET. With the additional circuitry, the efficiency at low power is improved, although the converter's performance at high output currents is not affected.

3. State space converter modelling

To develop a state space model of the synchronous buck converter shown in Fig. 1, the model can be divided into three sets of state equations or modes of operation. These operational modes are obtained in relation to a switch position and conduction of the diode. In order to construct the state space equations, the derivatives of the inductor current and the capacitor voltage have to be defined, as well as equations for the output variables. With the inductor current i_L and capacitor voltage u_C as the state variables $\mathbf{x}=[x_1\ x_2]^T=[i_L\ u_C]^T$, the state space equation for buck converter is

$$\dot{\mathbf{x}} = \mathbf{A_k}\mathbf{x}+\mathbf{B_k}u \tag{1}$$

where $\mathbf{x}$ is the state vector. $\mathbf{A_k}$ and $\mathbf{B_k}$ are the state matrix and input matrix, respectively, $k=1, 2, 3$ is the mode of operation and $u=U_d$ is the input. The state space equation for the three operational modes is in general form expressed as

$$\dot{\mathbf{x}} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{du_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & p\cdot\frac{-1}{L} \\ p\cdot\frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \cdot \begin{bmatrix} i_L \\ u_c \end{bmatrix} + \begin{bmatrix} d\cdot\frac{1}{L} \\ 0 \end{bmatrix} \cdot U_d \tag{2}$$

Comparing (1) and (2) the system matrix $\mathbf{A_k}$ and $\mathbf{B_k}$ are

$$\mathbf{A_k} = \begin{bmatrix} 0 & p\cdot\frac{-1}{L} \\ p\cdot\frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \quad \text{and} \quad \mathbf{B_k} = \begin{bmatrix} d\cdot\frac{1}{L} \\ 0 \end{bmatrix} \tag{3}$$

where the variable d in matrix $\mathbf{B_k}$ represents the duty cycle function defined as follows:

$$d = \begin{cases} 1 & \text{where } s_1 = ON,\ s_2 = OFF \\ 0 & \text{where } s_1 = OFF,\ s_2 = ON \end{cases} \tag{4}$$

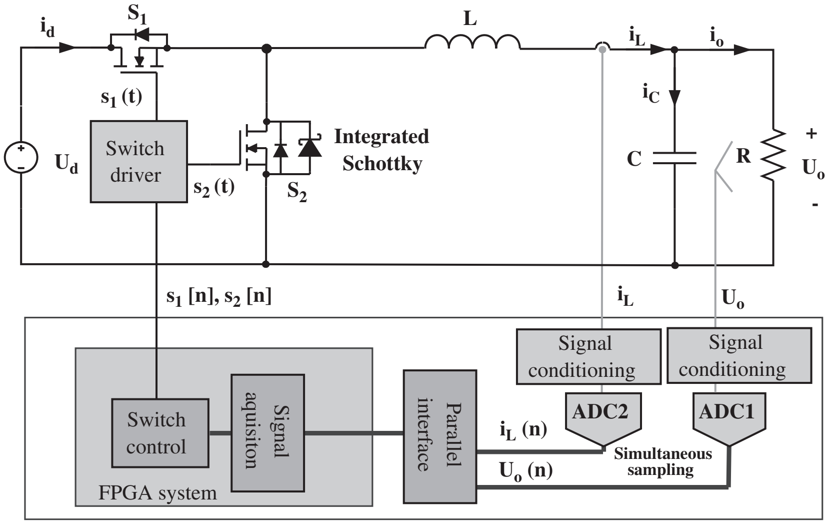

Fig. 1. Circuit diagram for synchronous buck converter with integrated Schottky diode.