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On the limit cycle stabilization of a DC/DC three-cell converter

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ABSTRACT

This paper investigates a new state feedback controller design for DC/DC three-cell converter. The high dynamic performances of the converter have been translated into a desired limit cycle stabilization problem. The state feedback is established using hybrid automaton formalism, which allows us to design independently a transitory state and steady state control schemes. Finite-time convergence of the trajectory to the steady state and the local asymptotic stability of the desired limit cycle under the proposed controller are proved analytically. Simulation and experimental results confirm the theoretical results and show the effectiveness and robustness of the hybrid controller in spite of load variations.

1. Introduction

Power converters are nonlinear systems that exhibit an abundance of nonlinear phenomena such as: bifurcation, limit cycle and chaos, which are mainly due to the converter structure and/or the used control method. These nonlinear behaviors have raised interesting questions in the last decades to provide knowledge of how one can investigate them, use them, or avoid them depending on the application purpose (Sastry, 1999; Banerjee & Verghese, 2001). Traditionally, conventional models for power converters based on averaging process or sampled-data model have been elaborated for the analysis and control design. However, these mathematical models give little insight about the nonlinear behavior of the converter and the ability to predict important nonlinear phenomena is generally lost (Banerjee & Verghese, 2001). Recently, hybrid models for DC/DC power converters have been proposed to overcome the shortcomings of conventional models (Senesky, Eirea & Koo, 2003; Papafotiou, Geyer & Morari, 2004; Sreekumar & Agarwal, 2007, 2008; Benmansour, Benalia, Djemaï & de Leon, 2007; Hongbo & Quanyuan, 2009; Almer, Mariethoz & Morari, 2010; Cormerais, Buisson, Richard & Morvan, 2008; Benmiloud & Benalia, 2013; Salinas, Ghanes, Barbot, Escalante & Amghar, 2015). Nonetheless, most of the developed control strategies do not take into account the steady state cyclic behavior of the converter in the control design, which may limit considerably the closed loop performance (Patino, Riedinger & Iung, 2008; Benmiloud & Benalia, 2015). In this paper, a new control scheme design for three level DC/DC multicellular converter (also called flying capacitor converter) will be investigated using hybrid dynamical systems theory. The converter choice is motivated by the interesting practical benefits offered by its topology compared to standard ones (Benmiloud & Benalia, 2015; Meynard & Foch, 1991; Martins, Meynard, Roboam & Carvalho, 1998; Pinon, Fadel & Meynard, 1998; Gatteaux, 1999; Gateau, Fadel, Maussion, Bensaid & Meynard, 2002; Meynard et al., 2002; Bethoux & Barbot, 2002; Defaÿ, Llor & Fadel, 2008; Patino, Riedinger & Iung, 2009; Patino, Riedinger & Ruiz, 2010; Djemai, Busawon, Benmansour & Marouf, 2011; Defoort, Djemai, Floquet & Perruquetti, 2011; Gorp, Van, Defoort & Djemai, 2011; Amet, Ghanes & Barbot, 2011; Patino et al., 2011; Kamri, Bourdais, Buisson & Larbes, 2012; Hauroigne, Riedinger & Iung, 2012; Shafiyi, Khederzadeh, Sadeghi & Khani, 2012; Liu, Laghrouche, Harmouche & Wack, 2014). During this last decade, these systems become more and more attractive to industrial applications, especially in high-power applications (Meynard et al., 2002). Indeed, the harmonic contents of the output signal are improved compared to the classical two levels converter technology using the same switching frequency (Gatteaux, 1999). Furthermore, this structure enables the reduction of the losses due to commutations of power semiconductors while allowing low cost-components (Gatteaux, 1999; Bethoux & Barbot, 2002). For multicellular converters, the classical methodology lies on the use of average models, and continuous control design techniques implemented via Pulse-Width-Modulation (PWM) (Gatteaux, 1999;

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Gateau et al., 2002). Direct control techniques, addressing explicitly the design of binary signals, have been proposed in (Gorp et al., 2011; Amet et al., 2011), where a sliding mode control was proposed, in (Benmansour et al., 2007; Salinas et al., 2015), where hybrid control scheme was given, and in (Patino et al., 2009, 2011) where an optimal formulation problem has been suggested and solved. Passivity control, practical stabilization and quadratic stabilization have been addressed in Cormerais et al. (2008), Patino et al. (2011), Kamri et al. (2012), Hauroigne et al. (2012) and Benmiloud and Benalia (2013) respectively.

In Patino et al., (2008) and (2011), a predictive control approach based on optimal limit cycle for three-cell converter has been developed. The limit cycle has been obtained by a minimization of a quadratic cost-function. Although, no mathematical proof concerning limit cycle stability under the suggested controller has been performed. The authors in Benmiloud and Benalia (2015); Pinon et al. (1998) and Bethoux and Barbot (2002) suggested controllers that guarantee the asymptotic stability of a predefined limit cycle of two-cell converter.

In this paper, the high dynamic performances of the three-cell converter are formulated as a desired limit cycle stabilization problem. A transitory state controller is elaborated based on hybrid automaton formalism, which ensures a finite-time convergence of the converter trajectory to the steady state within three commutations. A steady state controller is developed to guarantee the local asymptotic stability of the desired limit cycle. Mathematical proofs have been presented and confirmed by simulation results. An experimental validation is also presented to show the effectiveness and the robustness of the proposed controller despite load conditions.

The remainder of the paper is organized as follows. In Section 2, hybrid modeling and problem formulation for three-cell converter are presented. In Section 3, a state feedback based on hybrid automaton is developed through geometric analysis of the converter dynamics. Local asymptotic stability of the desired limit cycle under the proposed state feedback is proved in Section 4. Simulation and experimental results are reported in Section 5. Conclusions and future works are outlined in Section 6.

2. Problem formulation

In high voltage applications, the voltage constraints can easily exceed the range that the semiconductor device can handle or unsatisfactory performances are obtained mainly due to the limited switching frequency. To meet the constraints in voltage using the classical converters, multiple power devices can be associated in series to obtain a macro-component having satisfactory characteristics in voltage. Although this solution seems to be attractive, a non-straightforward synchronous control of the multiple elements must be ensured (Gatteaux, 1999; Wang, 2009). Furthermore, only two output voltage levels can be delivered by the converter (Patino et al., 2011). An innovative solution has been proposed at the beginning of the 1990s using the concept of commutation cells (Meynard & Foch, 1991). Fig. 1 depicts the topology of the three-cell converter associated with an inductive load (R-L). Each commutation cell is composed of a pair of complementary switches. Its state is controlled by a binary input signals $u_k \in \{0, 1\}$, $k = 1, 2, 3$ where $u_k = 1$ ($u_k = 0$) indicates that the kth upper switch is closed (open) and the kth lower switch is open (closed). Depending on the cell states, one can distinguish eight configurations, which offer four output voltage levels at the converter equilibrium (see Table 1).

One can remark from the converter topology in Fig. 1, the coexistence of continuous variables (capacitor voltages v_{c1}, v_{c2} and load current i_L) and discrete variables (cell states). Accordingly, it is worthwhile to consider a hybrid model for the analysis and control design.

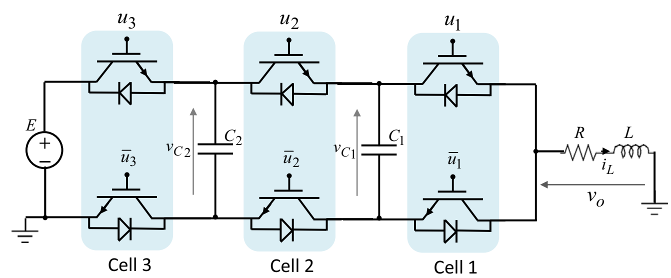

Fig. 1. Topology of a three-cell converter associated to an inductive load.

Table 1
The discrete modes of three-cell converter.

Discrete modes	Cells' signals			State evolution			Output voltage
	u_1	u_2	u_3	v_{c_1}	v_{c_2}	i_L	v_o
q_1	0	0	0	→	→	↘	0
q_2	1	0	0	↘	→	↗↘	v_{c1}
q_3	0	1	0	↗	↘	↗↘	$v_{c2} - v_{c1}$
q_5	0	0	1	→	↗	↗↘	$E - v_{c2}$
q_4	1	1	0	→	↘	↘↗	v_{c2}
q_7	0	1	1	↗	→	↘↗	$E - v_{c1}$
q_6	1	0	1	↘	↗	↘↗	$E + v_{c1} - v_{c2}$
q_8	1	1	1	→	→	↗	E

One of the main modeling formalisms used in hybrid system theory is the hybrid automaton (Lunze & Lamnabhi-Lagarrigue, 2009), which is formulated below for the three-cell converter,

$$H = (Q, X, S_c, T, G, Init), \quad (1)$$

where:

- $Q = \{q_i, i \in \{1, \ldots, 8\}\}$ is a set of eight discrete modes. Each one corresponds to a specific topology of the converter obtained by the cell states (see Table 1).
- $X = \{x \in \mathbf{R}^3 / 0 \le v_{ck} \le E \wedge 0 \le i_L \le I_{\max}, k = 1, 2\}$ is the continuous state space that characterizes the operating states of the converter, with $I_{max} = E/R$ is the maximum current that can be delivered by the converter.
- S_c is a subclass of dynamic systems where $S_i \in S_c = \{S_1, \ldots, S_8\}$ is defined by the following equation:

$$\dot{x}(t) = f_{q_i}(x(t)) = A_i x(t) + B_i, \; q_i \in Q, \quad (2)$$

where $x = [v_{c1} \;\; v_{c2} \;\; i_L]^T$ is the continuous state corresponding to the capacitor voltages and load current. For each discrete mode, one can replace the corresponding cells' signals, reported in Table 1, in the following state matrices,

$$A_i = \begin{bmatrix} 0 & 0 & \frac{u_2 - u_1}{c_1} \\ 0 & 0 & \frac{u_3 - u_2}{c_2} \\ \frac{u_1 - u_2}{L} & \frac{u_2 - u_3}{L} & -\frac{R}{L} \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{E}{L} u_3 \end{bmatrix}$$

- $T = \{T_{ij}, i, j \in \{1, \ldots, 8\}, i \neq j\}$ presents all possible transitions between discrete modes.
- $G: T \to 2^X$ is the guard condition (switching surface), which is associated with each transition. It describes a region in the state