Control Engineering Practice 74 (2018) 33–43

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Energy shaping control for buck–boost converters with unknown constant power load

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A R T I C L E I N F O

Keywords:
Buck–boost converter
Constant power load
Interconnection and damping assignment passivity-based control
Immersion and invariance

A B S T R A C T

We develop in this paper an adaptive passivity-based controller for output voltage regulation of DC–DC buck–boost converter with an unknown constant power load. This control problem is theoretically challenging since the average model of the converter is a bilinear second order system that, due to the presence of the constant power load, is non-minimum phase with respect to both states. A solution to the problem was recently reported in Wei et al. (2017), however, the resulting control law is extremely complicated to be of practical interest. The purpose of this paper is to present a new, significantly simpler, controller that can be easily implemented in applications. The key modifications introduced in the new design are the use of a change of coordinates and a partial linearization that transform the system into a cascade form, to which an adaptive energy-shaping controller is applied. Another advantage of the proposed controller, besides its simplicity, is that it is amenable for the addition of an outer-loop PI that improves its transient and disturbance rejection performances. Simulations and experimental results are provided to assess the improved performance of the proposed controller.

1. Introduction

DC–DC power converters are widely employed in power distribution systems to achieve the regulation of voltage between the DC source and the load (Wang, Li, Wang, & Li, 2017). Generally speaking, the DC–DC buck–boost power converter is more advantageous due to the fact that it possesses the ability of step-up and step-down modes. Although the control of these converters in the face of classical loads is well–understood, in some modern applications the loads do not behave like standard passive impedances, instead they are more accurately represented as constant power loads (CPLs), which correspond to first–third quadrant hyperbolas in the loads voltage–current plane. This scenario significantly differs from the classical one and poses a new challenge to control theorist, see Barabanov, Ortega, Grino, and Polyak (2016), Emadi, Khaligh, Rivetta, and Williamson (2006), Marx, Magne, Nahid-Mobarakeh, Pierfederici, and Davat (2012), Mosskull (2016) and Du, Zhang, Zhang, and Qian (2013) for further discussion on the topic and Singh, Gautam, & Fulwani (2017) for a recent review of the literature. It should be underscored that the typical application of this device requires large variations of the operating point—therefore, the dynamic description of its behavior cannot be captured by a linearized model, requiring instead a nonlinear one.

Several techniques have been proposed for the voltage regulation of the buck–boost converter with a CPL in the power electronics literature. However, to the best of the authors' knowledge, none of them provides a rigorous stability analysis for the nonlinear model. In Rahimi and Emadi (2009), the active-damping approach is utilized to address the negative impedance instability problem raised by the CPL. The main idea of this method is that a virtual resistance is considered in the original circuit to increase the system damping. However, the stability result is obtained by applying small-signal analysis, which is valid only in a small neighborhood of the operating point. A new nonlinear feedback controller, which is called "Loop Cancellation", has been proposed to stabilize the buck–boost converter by "canceling the destabilizing behavior caused by CP" (Rahimi, Williamson, & Emadi, 2010). The control problem turns into the design of a controller for the linear system by using loop cancellation method. However, the construction is based

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https://doi.org/10.1016/j.conengprac.2018.02.006
Received 26 September 2017; Received in revised form 31 December 2017; Accepted 9 February 2018

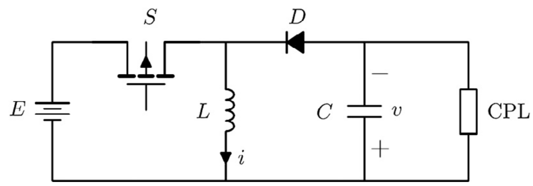

Fig. 1. Circuit representation of the DC–DC buck–boost converter with a CPL.

on feedback linearization that, as is well-known, is highly non–robust. A sliding mode controller is designed in Singh, Rathore, and Fulwani (2016) for this problem. However, for the considered nonlinear system, the stability result is obtained by adopting linear system theory. In addition, as it is widely acknowledged, the drawbacks of this method are that the proposed control law suffers from chattering and its relay action injects a high switching gain. The deleterious effect of these factors is clearly illustrated in experiments shown in Singh et al. (2016), which exhibit a very poor performance. In He, Ortega, Machado, and Li (2017) an adaptive interconnection and damping assignment passivity-based controller (IDA-PBC) (Ortega & Garcia-Canseco, 2004; Ortega, Van Der Schaft, Maschke, & Escobar, 2002), with guaranteed stability properties, was proposed. Unfortunately, the resulting control law is relatively complex styming its potential application in a practical scenario. In Soriano, Wei, Cisneros, Mancilla, Ortega, and Li (2017) an approximation of the control law was implemented in an experimental benchmark. A consequence of the controller reduction was that the tuning procedure for its gains turned out to be quite critical—yielding a below par performance.

The main objective of this paper is to propose a new, simpler, controller that can be implemented – without approximation – in a practical scenario. A second objective of the paper is to prove that it is possible to add a PI action to the PBC, a modification that is always required in this kind of applications to improve the transient and disturbance rejection properties of the closed-loop system.

The remaining of the paper is organized as follows. Section 2 gives the model of the system and the problem formulation. Section 3 presents the proposed controller assuming the extracted load power is known. In Section 4 an on–line power estimator is presented, while some simulations carried out by MATLAB and experimental results are included in Section 5. This paper is wrapped–up with some concluding remarks in Section 6.

2. System model and problem formulation

In this section, the average model of a buck–boost converter feeding a CPL and the control problem addressed in the paper are given. Also, introducing a scaling in the state coordinates and the time, we present a normalized representation of the system model that simplifies the calculations.

2.1. Model of buck–boost converter with CPL

The topology of a buck–boost converter feeding a CPL, is shown in Fig. 1. Under the standard assumption that it operates in continuous conduction mode (CCM), the average model is given by

$$\begin{aligned} L\frac{di}{dt} &= -(1-u)v + uE, \\ C\frac{dv}{dt} &= (1-u)i - \frac{P}{v}, \end{aligned} \tag{1}$$

where $i \in \mathbb{R}_{>0}$ is the inductor current, $v \in \mathbb{R}_{>0}$ the output voltage, $P \in \mathbb{R}_{>0}$ the power extracted by the CPL, $E \in \mathbb{R}_{>0}$ is the input voltage and $u \in [0,1]$ is the duty ratio, which is the control signal.

Some simple calculations show that the assignable equilibrium set is given by

$$\mathcal{E} := \left\{ (i,v) \in \mathbb{R}^2_{>0} \mid i - P\left(\frac{1}{v} + \frac{1}{E}\right) = 0 \right\}. \tag{2}$$

Now, the stability problem for an *open-loop* buck–boost converter with a CPL is discussed. Since the system (1) is nonlinear, to analyze its behavior, the following small-signal equations are derived

$$\begin{aligned} L\dot{\tilde{i}} &= -(1-U)\tilde{v} + \tilde{u}v_\star + U\tilde{E} + \tilde{u}E, \\ C\dot{\tilde{v}} &= (1-U)\tilde{i} - \tilde{u}i_\star + \frac{P\tilde{v}}{v_\star^2}, \end{aligned} \tag{3}$$

where $i_\star, v_\star$ are the equilibrium and U is an open-loop control input. Solving the above equations the transfer function of the output voltage versus duty cycle is given by

$$T(s) = \frac{\tilde{v}}{\tilde{u}} = \frac{-Li_\star s + (1-U)(v_\star + E)}{LCs^2 - \frac{PL}{v_\star^2}s + (1-U)^2}. \tag{4}$$

It is clear that the poles of the transfer function $T(s)$ have positive real part. Hence, the DC–DC buck–boost converter is unstable when it operates in *open-loop* due to the effect of the CPL.

Remark 1. As stated in Section 2.1, it is assumed that the DC–DC buck–boost converter with a CPL works in CCM. Hence, the present work does not consider the discontinuous conduction mode.

2.2. Control problem formulation

Consider the system (1) verifying the following conditions.

Assumption 1. The power load P is *unknown* but the parameters L, C and E are *known*.

Assumption 2. The states i, v are *measurable*.

Fix a *desired output voltage* $v_\star \in \mathbb{R}_{>0}$ and compute the associated assignable equilibrium point $(i_\star, v_\star) \in \mathcal{E}$. Design a static state-feedback control law with the following features.

(F1) $(i_\star, v_\star)$ is an asymptotically stable equilibrium of the closed-loop with a well–defined domain of attraction.
(F2) It is possible to define a set $\Omega \subset \mathbb{R}^2_{>0}$ which is *invariant* and inside the domain of attraction of the equilibrium. That is, a set inside the first quadrant verifying

$$\begin{aligned} (i(0), v(0)) \in \Omega &\Rightarrow (i(t), v(t)) \in \Omega, \forall t \geq 0 \\ \lim_{t\to\infty} (i(t), v(t)) &= (i_\star, v_\star). \end{aligned}$$

2.3. A normalized model

To simplify the notation, and without loss of generality, in the sequel we consider the normalized model of the system, which is obtained using the change of coordinates

$$\begin{aligned} x_1 &:= \frac{1}{E}\sqrt{\frac{L}{C}}i \\ x_2 &:= \frac{1}{E}v, \end{aligned} \tag{5}$$

and doing the *time scale* change $\tau = \frac{t}{\sqrt{LC}}$ that yields the model

$$\begin{aligned} \dot{x}_1 &= -(1-u)x_2 + u \\ \dot{x}_2 &= (1-u)x_1 - \frac{D}{x_2} \end{aligned} \tag{6}$$

where

$$D := \frac{P}{E^2}\sqrt{\frac{L}{C}},$$