Automatica 77 (2017) 344–352

Contents lists available at ScienceDirect

Automatica

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

Brief paper

# Hybrid cancellation of ripple disturbances arising in AC/DC converters[☆]

Andrea Bisoffi [b], Luca Zaccarian [a,b], Mauro Da Lio [b], Daniele Carnevale [c]
JET Contributors [d,1]

[a] CNRS, LAAS, 7 avenue du colonel Roche, F-31400 Toulouse, France and Univ. de Toulouse, LAAS, F-31400 Toulouse, France
[b] Dipartimento di Ingegneria Industriale, University of Trento, Italy
[c] Dipartimento di Ing. Civile e Ing. Informatica, University of Rome "Tor Vergata", Italy
[d] Culham Science Centre, OX14 3DB, Abingdon, UK

ARTICLE INFO

*Article history:*
Received 8 June 2015
Received in revised form
31 May 2016
Accepted 14 September 2016
Available online 17 January 2017

*Keywords:*
Hybrid dynamical system
Hybrid observer
Power system
Tokamak plasma
Ripple

ABSTRACT

In AC/DC converters, a peculiar periodic nonsmooth waveform arises, the so-called ripple. In this paper we propose a novel model that captures this nonsmoothness by means of a hybrid dynamical system performing state jumps at certain switching instants, and we illustrate its properties with reference to a three phase diode bridge rectifier. As the ripple corrupts an underlying desirable signal, we propound two observer schemes ensuring asymptotic estimation of the ripple, the first with and the second without knowledge of the switching instants. Our theoretical developments are well placed in the context of recent techniques for hybrid regulation and constitute a contribution especially for our second observer, where the switching instants are estimated. Once asymptotic estimation of the ripple is achieved, the ripple can be conveniently canceled from the desirable signal, and thanks to the inherent robustness properties of the proposed hybrid formulation, the two observer schemes require only that the desirable signal is slowly time varying compared to the ripple. Exploiting this fact, we illustrate the effectiveness of our second hybrid observation law on experimental data collected from the Joint European Torus tokamak.

## 1. Introduction

Many engineering applications require power electronics in their actuators and often these power electronics are equipped with AC/DC converters whose switching nature produces a peculiar ripple disturbance. A similar disturbance on the torque arises in the presence of split ring commutators on the shaft of DC motors. Ripple disturbances may have damaging effects on control design, not only because they affect the actuation signal (like in a DC motor), but also because they often affect the power supply, thus possibly affecting all sensor measurements due to the magnetic coupling. This phenomenon is especially noticed in high-power applications such as tokamaks and plasma control (Pironti & Walker, 2005). One of the important features of the ripple is that its frequency is typically a known parameter with little uncertainty, because it is a multiple of the utility frequency in the electrical power grid, which is in turn tuned very finely to the values of either 50 or 60 Hz. Due to this fact, it appears natural to address the problem of ripple estimation and rejection using linear (Francis & Wonham, 1976) or nonlinear (Isidori, 1995, Ch. 8) regulation theory.

However, the peculiar non-smoothness of ripple disturbances makes them less prone to be addressed with classical continuous-time approaches and makes it an interesting problem to be tackled using hybrid regulation theory (see, e.g., the preliminary work in Marconi & Teel, 2010 and the more recent results in Carnevale, Galeani, & Menini, 2012, Carnevale, Galeani, & Sassano, 2013, Cox, Marconi, & Teel, 2013, Marconi & Teel, 2013 and references therein). These works, as well as the approach adopted here, are based on the novel framework for the description of nonlinear hybrid dynamical systems in Goebel, Sanfelice, and Teel (2012) and Goebel, Sanfelice, and Teel (2009). In particular, the advantage of

---

[☆] The material in this paper was partially presented at the 53rd IEEE Conference on Decision and Control, December 15–17, 2014, Los Angeles, CA, USA.This paper was recommended for publication in revised form by Associate Editor Ricardo G. Sanfelice under the direction of Editor Andrew R. Teel.

*E-mail addresses:* andrea.bisoffi@unitn.it (A. Bisoffi), zaccarian@laas.fr (L. Zaccarian), mauro.dalio@unitn.it (M. Da Lio), daniele.carnevale@uniroma2.it (D. Carnevale).

[1] See the Appendix of F. Romanelli et al., Proc. of the 2014 IAEA Fusion Energy Conference, Saint Petersburg, Russia.

http://dx.doi.org/10.1016/j.automatica.2016.11.013
0005-1098/

adopting that framework will be evident here because it enables us to exploit important robustness properties following from suitable regularity of the dynamics. We make large use of the robustness results established in Goebel et al. (2012, Chap. 7) to specifically address a "ripple cancellation" problem, wherein the ripple corresponds to a high-frequency perturbation affecting a slowly varying signal within an available measurement. Then the goal of our design is to estimate the ripple component that can be suitably subtracted from the measurement signal. To this end, we consider a general context where an unknown *constant* bias affects the measurement, we take care of this constant bias by incorporating a band-pass filter in our ripple observer, and then rely on the robustness results in Goebel et al. (2012, Cor. 7.27) to apply the scheme in the presence of slowly varying signals.

Our approach is much inspired by the recent results in Forni, Teel, and Zaccarian (2013) and the machinery given in Teel, Forni, and Zaccarian (2013, Thm. 2) (also reported in Forni, Teel, & Zaccarian, 2013, Lemma 1 with a notation that resembles more closely the situation addressed here). We would also like to emphasize that a hybrid approach to tackle this problem does not seem to be the only viable one, because the ripple disturbance is indeed an absolutely continuous function and one may find ways to generate it with a nonsmooth continuous time approach (see, e.g., the results in Marconi & Praly, 2008 where a continuous-time exosystem is built that generates the absolute value of a cosine waveform). However, it remains unclear how to do this for the specific waveform characterized in here. Our results are also close in nature to those reported in Cox et al. (2013, Sec. 4.2), where a hybrid exosystem also generates the absolute value of a cosine waveform. However, as compared to that result, we focus here on ripple signals that perform commutations at phases *different* from $\pm\pi/2$ (see also Remark 1). Alternative methods that are relevant in the proposed context pertain to the scientific area of observer design for switched systems, because one may think of the ripple as being generated by a suitable switching system. Then, one may follow the approaches in Pettersson (2005) if the active mode (or, equivalently, the jump times among modes) is known, or rely on the approaches of Barbot, Saadaoui, Djemai, and Manamanni (2007), Petterson (2005), Pettersson (2006) and references therein, where the active mode is estimated online. In addition to requiring a reformulation of our model as a switched system (which seems to be possible due to the continuity of the ripple output), the problem with applying these switched observation laws is that it is unclear how to take into account the slowly varying signal affecting the output measurement. In our work we incorporate a band-pass filter to remove that component from our ripple observer, and then we use the robustness of our formulation to prove *rigorous* properties of our scheme under a reasonable timescale separation assumption. Conversely, within the active mode detection of the above works, this seems to be a nontrivial goal.

A preliminary version of this paper was presented in Bisoffi, Da Lio, and Zaccarian (2014). Here, as compared to Bisoffi et al. (2014), we give the proofs of our two main theorems, and we discuss the application of the proposed scheme to experimental signals from the Joint European Torus (JET) tokamak, whereas only simulation results were given in Bisoffi et al. (2014).

The paper is organized as follows: in Section 2 we introduce the hybrid model for the ripple generation and present the cancellation problem under consideration. In Sections 3 and 4 we illustrate the two proposed estimation schemes, and state and prove their desirable properties. Finally, in Section 5 we illustrate the effectiveness of the more general scheme on the experimental measurements from the JET tokamak. The notation used throughout the paper is that of Goebel et al. (2012). An illustrative survey of this approach can be found in Goebel et al. (2009) and a brief review in Nešić, Teel, and Zaccarian (2011, Sec. 2).

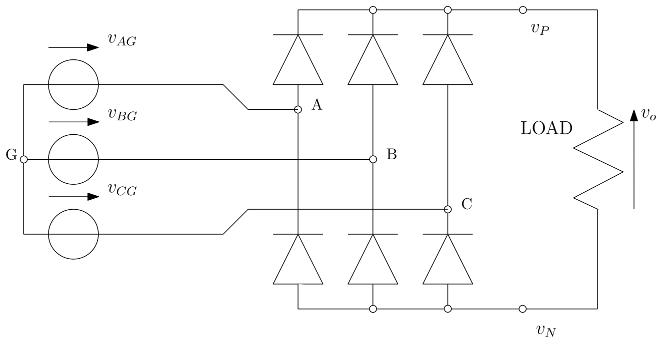

**Fig. 1.** A three phase diode bridge rectifier for AC/DC conversion, which results in a waveform affected by a ripple.

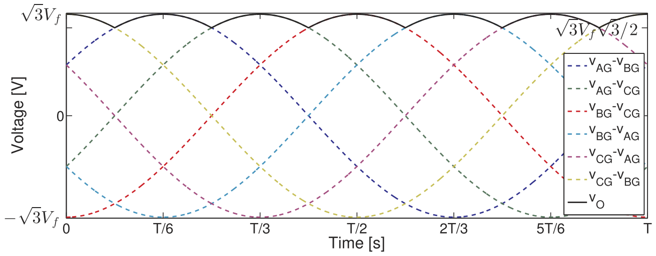

**Fig. 2.** Line-to-line voltages in a three-phase diode bridge rectifier.

## 2. A hybrid model for the ripple-induced noise in measurement signals

Let us consider a simple physical example where a ripple disturbance arises, i.e., the three phase diode bridge rectifier depicted in Fig. 1, where the valves are ideal diodes. This device converts a three-phase voltage to a mono-phase *almost* direct voltage, which is applied to a load, for example a resistor. The resulting voltage is *almost* direct because, due to the logic of conversion, a non smooth waveform, the ripple, is superposed to the ideal direct voltage.

Indeed, by denoting ground by $G$, the three phase voltages have the form:

$$\begin{aligned} v_{AG} &= v_A - v_G = V_f \sin(\omega t + \theta_0) \\ v_{BG} &= v_B - v_G = V_f \sin\left(\omega t + \theta_0 - \tfrac{2\pi}{3}\right) \\ v_{CG} &= v_C - v_G = V_f \sin\left(\omega t + \theta_0 - \tfrac{4\pi}{3}\right), \end{aligned} \tag{1}$$

and given the power supply in (1), the output voltage $v_o$ of the converter in Fig. 1 can be shown to be

$$v_o = v_P - v_N = \sqrt{3} V_f \max_{i\in\mathbb{Z}} \cos\left(\omega t + \theta_0 - i\tfrac{\pi}{3}\right). \tag{2}$$

This result follows easily from well-known circuit theory rules that establish the conducting diode, when more than one are connected at cathode or anode. Over an interval $[0, T] = [0, 2\pi/\omega]$, (2) can be equivalently obtained by taking at each time the maximum among the three line-to-line voltages and their opposites in sign, as depicted in Fig. 2.

Based on the hybrid system formalism in Goebel et al. (2012), we propose a different characterization of the ripple and we show in Proposition 1 how it represents equivalently the physical example we have just introduced. The flow and jump dynamics read

$$\begin{cases} \dot{x}_r = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} x_{r1} \\ x_{r2} \end{bmatrix} =: A_r x_r \\ \dot{\bar{b}} = 0 \end{cases}, \quad (x_r, \bar{b}) \in \mathcal{C} \tag{3a}$$

$$\begin{cases} x_r^+ = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x_{r1} \\ x_{r2} \end{bmatrix} =: J_r x_r \\ \bar{b}^+ = \bar{b} \end{cases}, \quad (x_r, \bar{b}) \in \mathcal{D}, \tag{3b}$$