Voltage Stabilization of dc/dc Converter-driven Constant Power Loads via Feeding-back the Output Measured Current

Panos C. Papageorgiou* Antonio T. Alexandridis*

**Department of Electrical and Computer Engineering, University of Patras, Rion-Patras, 26504, Greece.
(e-mail: papageorgiou@ece.upatras.gr; a.t.alexandridis@ece.upatras.gr).*

Abstract: A new approach and a novel solution to the voltage control problem of a dc/dc boost converter feeding an arbitrary constant power load (CPL) is developed. Particularly, as CPLs exhibit negative incremental resistance, a fact that in combination with the nonlinear nature of a converter/CPL system creates *ad hoc* stability problems, a nonlinear control design is proposed with main purposes: i) to be effective on regulating the output voltage regardless of the power absorbed, ii) to be easily implemented as a feedback loop from measurable states and outputs. In the feedback loop the measurable current at the power load side is fed back diminishing the need to apply any adaptation or other complicated mechanism for estimating the power absorbed by the CPL. Hence, the proposed controller analysis is based on the complete closed-loop nonlinear model instead of using standard linearized techniques and asymptotic stability is proven by applying suitable Lyapunov methods. This design approach extends the controller validity in a wide range while in practice it can be easily realized. The stable and good performance of the controller is finally evaluated by simulations taken with various CPL levels.

Keywords: Application of power electronics, Power systems stability, Control system design

1. INTRODUCTION

In modern power system applications, the use of power converters in feeding different kinds of loads is becoming increasingly popular. Especially in the case of low/medium voltage distribution systems [Pavlovic et al. (2013)] or small, closed electric circuits like the ones designed for aircrafts, vehicles and ships [Rivetta et. Al. (2006); Sudhoff et al. (1998); Haibing and Yan (2014)], the ac/dc or dc/dc power converters are being extensively used. Specifically for dc applications, the employment of the dc/dc boost converter is still the most common one, as a mean to increase and regulate the voltage supplied on a power load. Certainly, many efficient control methods and techniques have been proposed in cases where simple resistive or resistive-inductive loads are fed by controlled power converters [Alexandridis and Konstantopoulos (2014)]. However, it is a standard sense in power systems to characterize electric loads by their absorbed power instead of considering them as passive impedances. A commonly used type of power loads is the constant power loads (CPLs), which introduce a clearly unstable behaviour in the system [Magne et al. (2012)]. Therefore, the fundamental problem met in many practical applications is to feed a CPL by a controlled power electronic device in constant voltage, regardless of the power level. This still constitutes a significant challenge [Khaligh (2008)], although remarkable attempts have been made to confront the problem of designing a stabilizing controller [Rahimi and Emadi (2009)].

In fact, a CPL exhibits adverse damping characteristics, since an increase of the voltage supplied on it results in a decrease of the load current, which in turn means that the CPL introduces a negative dynamic resistance. The effect of this action is more evident in cases where the power load is high and therefore, it clearly leads to instability and serious abnormal system performance. Obviously, such configurations involve hard nonlinearities in their dynamic model and the design of an appropriate control scheme for their efficient drive is also expected to be of a nonlinear type. Having this in mind, it is important to notice that the stable action of these controllers may be verified by a nonlinear stability analysis performed with a rigorous manner.

Several studies have dealt with the issue of analyzing the CPL electric behaviour and have utilized a great deal of techniques in order to examine and ensure system stability, by considering different types of dc/dc converters. In [Anun et al. (2015)], the authors have adopted the circular switching surface technique to achieve stabilization for buck-boost converters feeding a CPL. A sliding-mode control scheme has been designed in [Zhao et al. (2014)], for the topology of a buck converter-CPL interface to cope with the problem of system instability over a large operating range. Another study proposed a composite nonlinear disturbance observer to stabilize the response of a boost converter feeding a CPL by also including a feedforward compensation along with a backstepping algorithm [Xu et al. (2019)]. A nonlinear feedback control scheme involving cancellation of system-model terms has been also introduced in [Rahimi et al. (2010)], in order to lead to stable operation of CPL fed by dc converters. The passivity-based technique has also been extensively used to study the stability of systems comprising both buck-boost [He et al. (2018)] and boost converters [Zeng et al. (2014)]. Although these studies feature nonlinear
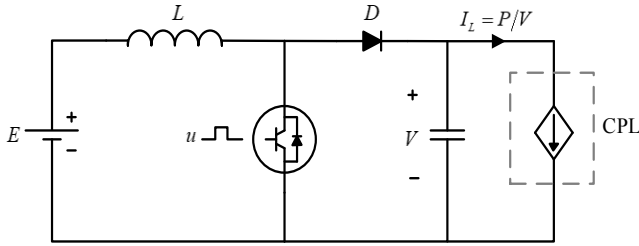
Fig. 1. Model of a boost converter feeding a CPL.

control scheme designs, they ultimately consider linear stability analysis apart from [He et al. (2018)], which, however, considers a tracking algorithm technique to deal with the unknown CPL power problem. To the best of the authors' knowledge, the majority of studies dealing with this kind of systems involve the design of complicated control schemes, accompanied by unwieldy stability analysis procedures under strong assumptions. Furthermore, many of them employ adaptation- or tracking-based designs in order to achieve better system behaviour under uncertainties, but do not account for tracking errors with variations of the operating point. It is, however, worth noting that as the design becomes more complex, it also complicates the implementation of the controller in practical applications.

In this paper, a novel controller is formulated and proposed, which is capable of regulating the output voltage level of a dc/dc boost converter feeding an arbitrary CPL in a manner that guarantees stability at the desired equilibrium. Due to the extremely nonlinear nature of the problem and the unknown equilibrium of the system caused by the supplied arbitrary CPL, a model-based design is adopted in contrary to the standard used small signal analysis. In order to achieve an easily implemented scheme, the proposed controller does not need the exact value of any system parameter, as for example is needed in the case of using cancellation terms [Rahimi et al. (2010)]. In the proposed approach, only accessible and easily measurable states and outputs, namely the boost inductance current, as well as the boost output (at the CPL side) load current and voltage are used in the feedback loop. In fact, this means that the action of the control scheme remains valid and accurate in any case where the CPL can take arbitrary levels. It is clear that even if the actual or estimated value of the CPL is known, the design of voltage controllers is still complicated; furthermore, the design becomes unnecessarily more complicated when additional loops, such as the adaptation schemes proposed in [He et al. (2018)] are involved in the case of an unknown CPL, a fact avoided in the present work. Nevertheless, since the closed-loop system as derived from the implementation of the control scheme remains nonlinear, the use of nonlinear stability analysis tools is required. Thus, without the need to consider hard and restricting assumptions, well-known Lyapunov-based techniques are applied. The analysis proves that the particular regulator guarantees stability of the system and convergence to an equilibrium inside a permitted domain of attraction. The controller design and the theoretical results of this analysis are verified by simulations which include the response of the system under unknown CPL by considering

either the mean-value dynamic model of the dc/dc boost converter or the real time switching-based accurate one.

The remainder of the paper is organized as follows. In Section 2, the dynamic model of the examined system is provided and the problem formulation is presented in detail, along with the control design procedure. In Section 3, a closed-loop system stability analysis is performed, while in Section 4, the system behaviour is examined by conducting extensive simulations. Finally, in the last Section 5, the results emerged from this analysis are summarized.

2. SYSTEM MODELING AND OPEN-LOOP CHARACTERISTICS

In this section, the model of the dc/dc boost converter feeding a CPL is provided. For the analysis and control design purposes, it is a standard supposition to adopt the mean value model of power converters, a fact that allows us to handle systems with power electronic devices as continuous-time systems [Krein et al. (1990); Ortega et al. (1998)]. Therefore, the system model also for our case is deployed in this frame, enabling us to consider the duty-ratio signals as the system input functions. By taking into account the CPL in the dc/dc boost converter model, a preliminary open-loop analysis is presented which aims to clarify the unstable performance introduced by the particular nature of such a configuration. Indeed, this highlights the fact that the system cannot operate effectively under the CPL action and exhibits the importance of designing an appropriate regulator in order to compensate the open-loop system instabilities; a process presented in the context of the next section.

2.1 Model of a dc/dc Boost Converter Feeding a CPL

The system under consideration is depicted in Fig. 1. A boost converter comprises an input inductor signified by L, a diode which is denoted by D and an output capacitor C. The mean value dynamic model of the system operating in conduction current mode (CCM) is given as in [Zeng et al. (2014)]:

$$L\dot{I} = -(1-u)V + E \qquad (1)$$

$$C\dot{V} = (1-u)I - \frac{P}{V} \qquad (2)$$

where E, I and $V \in \mathbb{R}_{>0}$ represent the input dc-voltage source, the current flowing through the input inductor and the output voltage at the load side, respectively. Also, $P \in \mathbb{R}_{>0}$ denotes the constant power absorbed by the CPL. Finally, the control input is defined as $u \in [0,1)$ representing the duty-ratio signal function acting on the switching component. The CPL can actually be modeled as a voltage-controlled current source, as in [Emadi et al. (2006)], where its dynamic behaviour is described by:

$$I_L = \frac{P}{V} \qquad (3)$$

with I_L being the current supplied to the CPL.

It is pointed out that the CPL as inserted in (2) provides an additional nonlinearity in the system model. As it is shown in the following subsection, this term is of particular interest and has a great impact on the stability properties of the system model.

2.2 Open-loop Instabilities

If one neglects the dependence of I_L from the output voltage, as considered in (3), then can easily establish the misleading result that a linear relationship exists between the current source being drawn by the CPL and the output voltage of the boost converter. However, the real influence of a CPL introduces a negative resistance [Wu and Lu (2015)], since the dynamic behaviour of the CPL is represented by:

$$\frac{dV}{dI_L} = P\frac{d(1/I_L)}{dI_L} = -P\frac{1}{I_L^2} = -\frac{V}{I_L} = -R_{CPL} \qquad (4)$$

where R_{CPL} represents the resistance of the CPL around steady-state conditions.

It is worth mentioning that by observing (3), one can also easily reach to the conclusion that at any given time of operation, the instantaneous value of resistance is positive (as $V/I_L > 0$). However, this is not true for the corresponding incremental change (where $dV/dI_L < 0$). This fact actually constitutes one of the main reasons for instability in such configurations.

An important consideration that one has to take in mind when dealing with this kind of systems is that the CPL action naturally drives the system to instability in the absence of a closed-loop control. On the contrary, this does not hold true when a typical set-up of a dc/dc converter is connected to a resistive or any constant-current load. As described for example in [He et al. (2018)], in the case of a buck-boost converter feeding a CPL, the open-loop system is unstable; a fact which will be proven also for our case, where a system of a dc/dc converter and CPL configuration is considered. To proceed with an analogous analysis for the present case, we firstly consider (1) and (2) in steady state, to obtain the unique assignable equilibrium set of the system:

$$S : \left\{ (I,V) \in \mathbb{R}_{>0}^2 \mid \frac{V}{I} - \frac{VE}{P} = 0 \right\}. \qquad (5)$$

Now, deriving from (1) and (2) the small-signal model around this equilibrium set, this is given by

$$L\dot{\tilde{I}} = -(1-U)\tilde{V} + \tilde{u}V^* + \tilde{E} \qquad (6)$$

$$C\dot{\tilde{V}} = (1-U)\tilde{I} - \tilde{u}I^* + \frac{P}{(V^*)^2}\tilde{V} \qquad (7)$$

with $U \in [0,1)$ being an arbitrary open-loop command input, $\tilde{I}, \tilde{V}, \tilde{u}$ denote the new small-signal variables and I^*, V^* the

steady-state values of the inductor current and capacitor voltage, respectively.

Then, the transfer function of the output voltage with respect to the duty-ratio input, can be directly derived from (6) and (7) as follows

$$G(s) = \frac{\tilde{V}}{\tilde{u}} = \frac{-LI^*s + (1-U)V^*}{LCs^2 - \left[PL/(V^*)^2\right]s + (1-U)^2}. \qquad (8)$$

It is easily established from (8) that the open-loop system of (1)-(2) is unstable, since the poles of the transfer function (8) have positive real part.

Taking this fact into consideration, the system can reliably operate only under the action of a closed-loop control scheme. To this end, a novel regulator has to be designed in order to drive the system to a stable equilibrium, as described in the next section.

3. CONTROL DESIGN AND STABILITY ANALYSIS

3.1 Controller Design

The main aim of the developed control scheme is to regulate efficiently the output voltage of the dc/dc boost converter to a desired reference value by compensating the unstable impact of the CPL. In that case, the current flowing to the CPL is expected to reach a constant value, as determined by (3) and in turn, the inductor input current should also take a constant value at steady state.

Defining the dc output voltage error around an arbitrary positive reference value as

$$\bar{V} = V - V^* \qquad (9)$$

where $\bar{V}$ represents the error between the actual output voltage and the desired reference at steady-state V^*, then, the following feedback control law is proposed to be applied on the duty-ratio input of the dc/dc boost converter

$$u = 1 - \frac{E}{V^*} + \left[\frac{\bar{V}}{V^*I}\left(\frac{P}{\bar{V}+V^*} + \xi\right)\right] \qquad (10)$$

where ξ is an additional input, to be defined later on.

It is obvious that the implementation of this particular regulator requires measurement or estimation of the unknown power absorbed by the CPL, while the fed back states V, I are clearly accessible and measurable. Fortunately, under the reasonable assumption that the output current of the feeding dc converter, I_L, is measurable, the control law (10) becomes

$$u = 1 - \frac{E}{V^*} + \left[\frac{\bar{V}}{V^*}\left(\frac{I_L}{I} + \frac{\xi}{I}\right)\right]. \qquad (11)$$

In accordance to control law (11), the regulator action remains accurate for any considered CPL, since there is no

dependence from the value of the actual supplied power. As it is proven in the sequel, the proposed controller is capable of compensating the instability inserted by the CPL, with the extra input ξ determined as follows, in order to achieve output voltage regulation to the desired reference value

$$\xi = -k_P I^2 (V - V^*) \tag{12}$$

where k_P is a constant positive gain.

Notably, the proposed control law is based on a feedback loop of the measurable states V and I, as well as the output load current I_L. Also, the known constant input voltage E and the reference of the output voltage V^* are both inserted in the control law but no other system parameter or inaccessible variable is needed. The implementation of the regulator (11)-(12) in the system of (1)-(2) yields the following closed-loop system formulation, as depicted also in Figure 2

$$\begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \dot{I} \\ \dot{\bar{V}} \end{bmatrix} = \begin{bmatrix} 0 & -(1-u-a) \\ (1-u-a) & -k_P I^2 \end{bmatrix} \begin{bmatrix} I \\ \bar{V} \end{bmatrix} \tag{13}$$

where now

$$a = \frac{I_L}{I} + \frac{\xi}{I}. \tag{14}$$

One can easily observe that the proposed regulator affects the original structure of the system by inserting a damping term: $-k_P I^2$ and eliminates the external uncontrolled inputs, while simultaneously renders its basic characteristics.

To proceed with the analysis, the closed-loop system is examined for its stability. The aim is to prove that the implemented controller drives the system to the desired output voltage by asymptotically converging the states of the closed-loop system to a unique equilibrium independently from the power absorbed by the CPL.

3.2 Closed-loop Stability Analysis

For the system of the form of (14), the following positive definite Lyapunov function is proposed

$$H = \frac{1}{2} L I^2 + \frac{1}{2} C \bar{V}^2. \tag{15}$$

The derivative of the storage function (15) is easily calculated as

$$\dot{H} = -k_P I^2 \bar{V}^2 \le 0. \tag{16}$$

Inequality (16) indicates that the system is Lyapunov stable, which means that $\bar{V}$ and I are bounded. It is additionally implied convergence either at $\bar{V} = 0$ or $I = 0$. However, for any nonzero output voltage reference, the case of the convergence to $I = 0$ equilibrium, would result in $\dot{I}$ to take nonzero values which in turn leads I to deviate from zero.
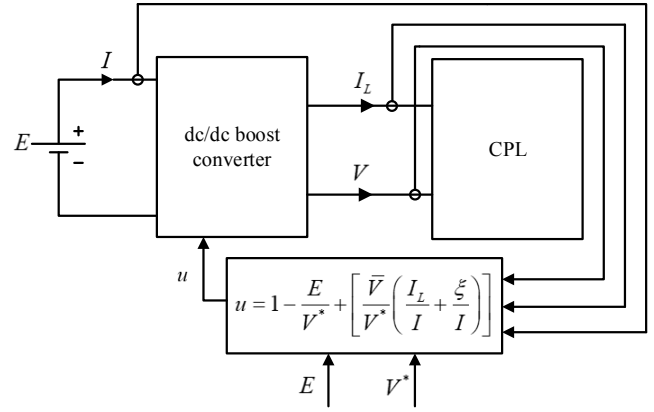

Fig. 2. The closed-loop system under consideration.

This fact does not contradict the previously stated boundedness condition only if the equilibrium of current I is of no zero value. This result is absolutely compatible with CCM operation of the boost converter [Gusseme et al. (2007)], since the energy stored in the inductor cannot be zero at any time instant and hence the input current cannot be eliminated in steady state. This practically means that condition $\dot{H}(I, \bar{V}) = 0$ is satisfied only if $\bar{V} = 0$. To proceed now with the LaSalle's invariance principle [Khalil (2002); Slotine and Wu (1991)], we start by determining the unique assignable equilibrium that results from the steady-state condition of (13) under the control given by (11) and (12). In that case, the equilibrium is found to be

$$(I^*, \bar{V}^*) = (\frac{I_L V^*}{E}, 0) = (\frac{P}{E}, 0). \tag{17}$$

It is important to note that the above equilibrium obviously lies within the permitted region of the duty-ratio $u \in [0,1)$ which leads to the following permissible region for the states $I, \bar{V}$:

$$S_1 : \left\{ (I, \bar{V}) \in \mathbb{R}^2_{>0} \mid \bar{V}(\frac{I_L + \xi}{I}) < E \right\}. \tag{18}$$

The main aim of the performed stability analysis is to prove that there exists an even smaller, local domain of attraction in which the unique equilibrium (17) belongs. The local stability is ensured by showing that inside this area, the system state trajectories converge to the largest invariant set.

Particularly, since H is positive definite and radially unbounded, there exists a compact, positively invariant set $\Omega_c = \{ I, \bar{V} \in \mathbb{R}^2 \mid H \le c \}$ with c being a sufficiently small positive constant. Furthermore, since Ω_c is bounded and $\dot{H} \le 0$ in Ω_c, the choice of $S_1 = \Omega_c$ is an obvious one. In accordance to the previous discussion, all conditions required by the LaSalle theorem are satisfied for the largest invariant set inside the set given by: $E = \{ I, \bar{V} \in \Omega_c \mid \bar{V} = 0 \}$. Since for $\bar{V} = 0$ the unique equilibrium is determined by (17), every system trajectory starting within Ω_c approaches E as $t \to \infty$, and asymptotic convergence occur, i.e.

$$(I(0), \overline{V}(0)) \in \Omega_c \Rightarrow (I(t), \overline{V}(t)) \in \Omega_c, \forall t \geq 0$$

and
$$\lim_{t \to \infty} (I(t), \overline{V}(t)) = (I^*, \overline{V}^*).$$

Indeed, the proposed controller (11), (12) guarantees asymptotic stability of the closed-loop system for every admissible power value drained by the CPL.

4. SIMULATION RESULTS

The efficiency of the implemented control scheme and the system stability were evaluated by conducting thorough simulations. In particular, the configuration of a boost dc/dc converter feeding a CPL as presented in Fig. 2 was modeled by considering both the average and the accurate switching-based converter models. The controlled system response was studied under several changes, including CPL power variations, as well as a step change in the controlled dc-voltage output reference value, i.e. V^*. The considered boost converter parameters, along with the applied dc-voltage in its input, the gain k_P of the ξ-term involved in the control scheme of (11) are given in Table 1.

Table 1. System parameters, voltage input and gains

Symbol	Quantity	Value
L	Inductance of the boost converter	0.2mH
C	Capacitance of the boost converter	1.2mF
E	DC input voltage	20V
k_P	ξ-gain	0.04
f_s	Switching frequency (accurate model)	10kHz

The simulation scenario features an initial CPL of $P = 5.5\,\text{W}$, whereas power variations are set to occur at time instants $t_1 = 25s$ and $t_2 = 50s$, corresponding to $P = 8\,\text{W}$ and 4W, respectively. In addition, the dc-voltage output of the boost converter is originally defined to follow the reference value of $V^* = 40\text{V}$, while at $t_3 = 80s$ this value is increased by 2.5%.

The closed-loop system response is presented in Figures 3 to 7. In particular, Fig. 3 presents the voltage output of the boost converter. It is easily observed that the steady-state values are achieved in a smooth and accurate manner. The voltage applied on the CPL presents significantly low overshoots, without any long transient phenomena that may be taking place during changes forced into the system. In Fig. 4, the load current I_L supplied to the CPL is provided. Apart from its smooth response, a careful examination of I_L with respect to the dc-voltage presented in Fig. 4, reveals that, indeed, the CPL operation as voltage dependent current source, shown in (3), holds true. An important note is also extracted by observing the current flowing through the inductor at the input of the boost converter, as illustrated in Fig. 5, that is a fast and smooth convergence to a nonzero equilibrium (CCM operation).

Finally, Fig. 6 and Fig. 7 present the system responses as provided by testing the real time switching-based model of the

boost converter. Specifically, Fig. 6 depicts the boost converter dc-voltage output. The reference value of the voltage is achieved in a very fast and precise manner, although some ripples are observed, mainly due to the losses introduced in this case.
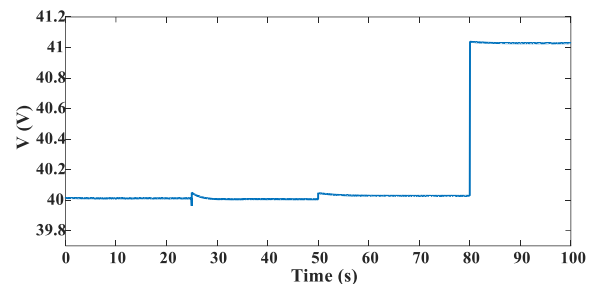

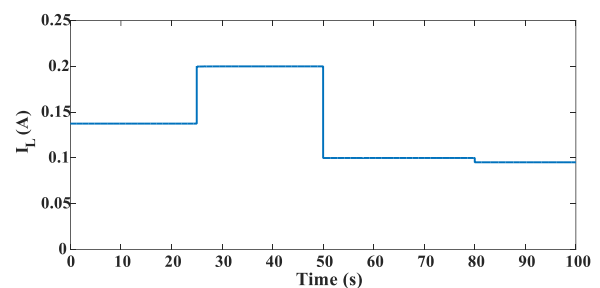Fig. 3. Boost converter dc-voltage output.

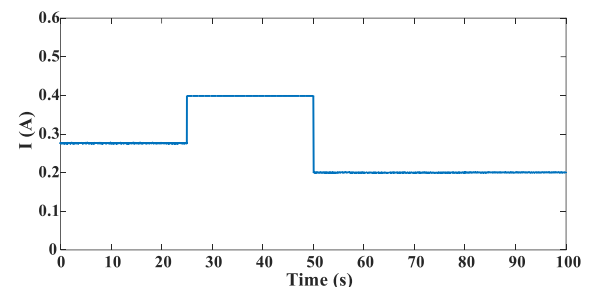Fig. 4. Current supplied to the CPL.

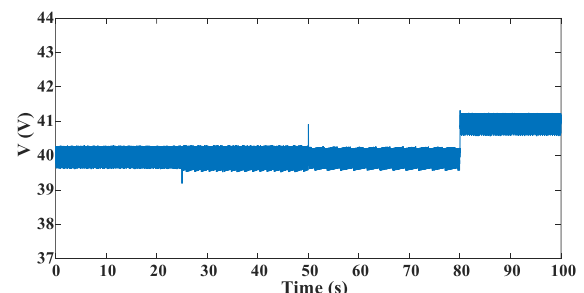Fig. 5. Boost converter input current.

Fig. 6. Boost converter dc-voltage output (accurate model).

Similarly, the current supplied to the CPL, as illustrated in Fig. 7, exhibits a smooth behaviour, reaching the desired steady-state values with significant accuracy. As expected, a small difference is observed in the dynamic response of the system when the mean-value or the accurate model is used. Nevertheless, it is to be noted that an increase in the switching frequency leads to better matching between the responses of the two simulated models.
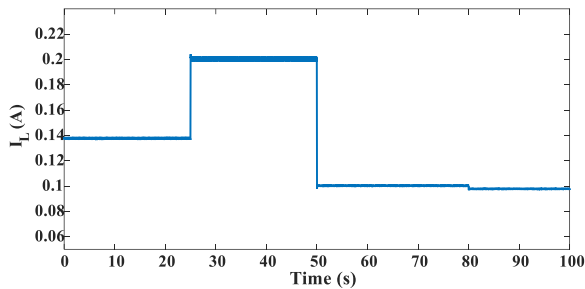
Fig. 7. Current supplied to the CPL (accurate model).

The controlled system performance exhibits exceptional regulation of the dc-voltage output of the boost converter, while the overall system behaviour remains stable at all times. In both considered cases, the one using the average converter model and the second one based on the accurate switching model, the results fully verify the proposed design approach. Both the tasks imposed for the controller, i.e. to compensate the instabilities introduced by the CPL action and to effectively regulate the output voltage, are satisfied. Moreover, the system responses are all very satisfactory and within the operating limits as defined by standard technical constraints of this kind. During the simulated operating time, the system state trajectories of the controlled system remain in the bounded domain of attraction. This is an expected fact, satisfying the local stability conditions discussed in the analysis of Section 3. Therefore, a general result coming from the simulations is that all the system responses agree with the performed analysis and the applied control scheme leads to a very good performance of the boost converter/CPL system.

5. CONCLUSION

An easily implemented nonlinear controller design is presented and analyzed that effectively confronts the problem of compensating the instabilities inserted by a CPL fed by a dc/dc boost converter. As shown by a theoretical analysis and verified by the implementation presented, the proposed controller drives asymptotically the system at the stable equilibrium and regulates the output voltage at any desired value. As discussed in previous sections, the main contribution of the present design approach is that it results from a nonlinear analysis of the original system, without requiring any kind of approximations, while its structure is easily implemented as it is free from the system parameters and it is only dependent from the measurable states and outputs of the system. In a future work, a challenging issue may be an attempt to generalize the proposed controller to include other power electronic devices with CPL loads.

REFERENCES

Alexandridis, A.T., and Konstantopoulos, G.C. (2014). Modified PI speed controllers for series-excited dc motors fed by dc/dc boost converters. *Control Eng. Practice*, 23, 14-21.

Anun, M., Ordonez, M., Zurbriggen, I.G., and Oggier, G.G. (2015). Circular Switching Surface Technique: High-Performance Constant Power Load Stabilization for Electric Vehicle Systems. *IEEE Trans. Power Electron.*, 30(8), 4560-4572.

Emadi, A., Khaligh, A., Rivetta, C.H., and Williamson, G.A. (2006). Constant power loads and negative impedance instability in automotive systems: Definition, modeling, stability, control of power electronic converters and motor drives. *IEEE Trans. Veh. Techn.*, 55(4), 1112–1125.

Gusseme, K.D., Van de Sype D.M, Van den Bossche, A.P.M., and Melkebeek, J.A. (2007). Input-Current distortion of CCM boost PFC converters operated in DCM. *IEEE Trans. Ind. Electron.*, 54(2), 858-865.

Haibing, H., and Yan, X. (2014). Design considerations and fully digital implementation of 400-Hz active power filter for aircraft applications. *IEEE Trans. Ind. Electron.*, 61(8), 3823–3834.

He, W., Abraham Soriano-Rangel, C., Ortega, R., Astolfi, A., Mancilla-David, F., and Li, S. (2018). Energy Shaping Control for Buck-Boost Converters with Unknown Constant Power Load. *Control Eng. Practice, 74*, 33-43.

Khaligh, A. (2008). Realization of Parasitics in Stability of DC–DC Converters Loaded by Constant Power Loads in Advanced Multiconverter Automotive Systems. *IEEE Trans. Ind. Electron.*, 55(6),2295-2305.

Khalil, H.K. (2002). *Nonlinear Systems*, 3rd ed. Upper Saddle River, NJ: Prentice-Hall.

Krein, P.T., Bentsman, J., Bass, R.M., and Lesieutre, B.L. (1990). On the Use of Averaging for the Analysis of Power Electronic Systems. *IEEE Trans. Power Electron.*, 5(2), 182-190.

Magne, P., Marx, D., Nahid-Mobarakeh, B., and Pierfederici, S. (2012). Large-Signal Stabilization of a DC-Link Supplying a Constant Power Load Using a Virtual Capacitor: Impact on the Domain of Attraction. *IEEE Trans. Ind. App.*, 48(3), 878-887.

Ortega, R., A. Loria, A., Johan Nicklasson, P., and Sira-Ramirez, H. (1998). *Passivity-based Control of Euler-Lagrange Systems*, Springer-Verlag, Berlin, Germany.

Pavlovic, T., Bjazic, T., and Ban, Z. (2013). Simplified Averaged Models of DC–DC Power Converters Suitable for Controller Design and Microgrid Simulation. *IEEE Trans. Power Electron.*, 28(7), 3266-3275.

Rahimi, A.M., and Emadi, A. (2009). Active Damping in DC/DC Power Electronic Converters: A Novel Method to Overcome the Problems of Constant Power Loads. *IEEE Trans. Industrial Electron.*, 56(5), 1428-1439.

Rahimi, A.M., Williamson, G.A., and Emadi, A. (2010). Loop-Cancellation Technique: A Novel Nonlinear Feedback to Overcome the Destabilizing Effect of Constant-Power Loads. *IEEE Trans. Veh. Techn.*, 59(2), 650-661.

Rivetta, C.H., Emadi, A., Williamson, G. A., Jayabalan, R., and Fahimi, B. (2006). Analysis and control of a buck DC-DC converter operating with constant power load in sea and undersea vehicles. *IEEE Trans. Ind. App.*, 42(2), 559-572.

Slotine, J.J.-E., and Li, W. (1991). *Applied Nonlinear Control*, Prentice Hall.

Sudhoff, S.D., Corzine, K.A., Glover, S. F., Hegner, H.J., and Robey, Jr. H.N. (1998). DC link stabilized field oriented control of electric propulsion systems. *IEEE Trans. Energy Conv., 13*(1), 27–33.

Wu, M., and Lu, D. D.-C. (2015). A novel stabilization method of LC input filter with constant power loads without load performance compromise in DC microgrids. *IEEE Trans. Ind. Electron.*, 62(7), 4552–4562.

Xu, Q., Zhang, C., Wen, C., and Wang, P. (2019). A Novel Composite Nonlinear Controller for Stabilization of Constant Power Load in DC Microgrid. *IEEE Trans. Smart Grid*, 10(1), 752-761.

Zeng, J., Zhang, Z., and Qiao, W. (2014). An Interconnection and Damping Assignment Passivity-Based Controller for a DC–DC Boost Converter With a Constant Power Load. *IEEE Trans. Ind. App.*, 50(4), 2314-2322.

Zhao, Y., Qiao, W., and Ha, D. (2014). A sliding-mode duty-ratio controller for DC/DC buck converters with constant power loads. *IEEE Trans. Ind. App.*, 50(2), 1448–1458.