Article

Current sensorless robust voltage regulation discontinuous control for DC-DC buck converter

Control discontinuo robusto sin sensor de corriente para regulación de voltaje en un convertidor reductor

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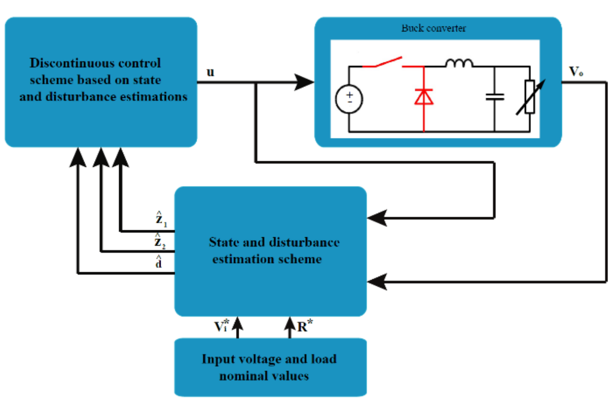
Abstract

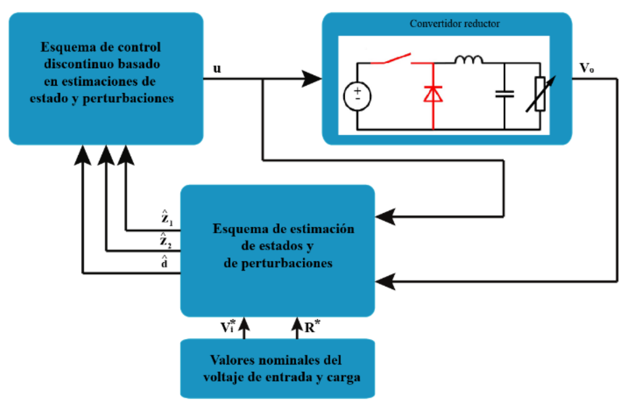
This paper presents the development of a robust discontinuous controller based on the super twisting algorithm and a simultaneous state and disturbance estimation scheme to regulate efficiently output voltage of a DC-DC converter in buck topology under load and input voltage variations. Such changes are handled by an appropriate rearranging of the system and the use of an Extended State Observer scheme to estimate the disturbance of the new model. This observer scheme also allows the estimation of the system states which permits the elimination of the current sensor reducing the overall system cost. The stability of the proposed robust discontinuous controller based on disturbance and state estimations is ensured using Lyapunov stability concepts. Simulation tests of the proposal in contrast to classic control techniques are presented to verify its adequate performance



Robust control, Power electronics, Disturbance estimation

Resumen

En este artículo se presenta el desarrollo de un controlador discontinuo robusto basado en el algoritmo Super Twisting y en un esquema de estimación simultanea de estados y perturbaciones para regular de forma eficiente el voltaje de salida de un convertidor CD-CD en topología reductora bajo cargas y voltajes de entrada variantes. Tales cambios son incluidos en el modelo mediante una reestructuración del sistema y el uso posterior de un Observador de Estados Extendido que permita estimar la perturbación acoplada del nuevo modelo. Este esquema de estimación tambien permite la estimación de estados lo cual permite la eliminación de un sensor de corriente reduciendo con esto el costo total del sistema. La estabilidad del controlador robusto discontinuo basado en estimaciones de estado es asegurada mediante conceptos de estabilidad de Lyapunov. Se presentan pruebas de simulación del control propuesto en comparación con técnicas de control clásicas para verificar su efectividad.



Control robusto, Electrónica de potencia, Estimación de perturbación

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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1. Introduction

Nowadays, with the great advance and development that has been carried out globally in the field of renewable energies, the use of DC-DC converters in their different topologies has become an essential part of the processes of generation and conversion of energy based in renewable sources. A known example of this can be found in photovoltaic systems, which require of these types of converters to guarantee operation in optimal conditions that ensure maximum extraction of the available energy at every moment, through the use of maximum power point tracking algorithms as shown in [13].

Therefore, it is a necessity to have control schemes that allow operating DC-DC converters in an efficient way under various situations specific of each particular application. A typical operation scenario of a system fed by DC-DC converters is the load change, which may affect the voltage regulation of the converter output deteriorating the overall system performance. For such scenario, various proposals can be found in the literature. In [18] a scheme model-based predictive control (MPC) is proposed for systems subject to disturbances, where a disturbance observer (DO) is developed for estimating disturbances value and using it in the output prediction to correct errors caused by disturbances and uncertainties. A fuzzy sliding control scheme is presented in [3], obtaining a better performance in comparison to conventional schemes based on Proportional Integral (PI) controllers.

A passivity-based controller with PI complementary control was developed in [19], guaranteeing a proper output voltage regulation, stability and fast response against load changes. Some other control schemes for output voltage regulation under load changes can be found in [15], [14], [4], [8]. Nevertheless, the previous control strategies show an efficient operation, most of them are complex techniques that entail a high computational burden which can limit its application, especially in low cost applications. In order to cope with this limitation a common robust control approach used for power converters control is sliding modes control theory [16].

Several proposals based on sliding modes can be found in the literature as the ones shown in [12], [17], [10], [9] achieving an efficient output power regulation even under disturbances along with easy implementation. Although sliding modes controllers have proved to be an excellent alternative to DC-DC converters, its major drawback is the high frequency commutation generated in the control signal, known as chattering, which can deteriorate severely the actuators. The Super Twisting control is a sliding modes technique that reduces chattering while keeping the robustness against disturbances [7]. To reduce the overall cost of the system it is a common practice the use of observation schemes that allow us to dispense of physical sensors to make measurements of the variables of interest, particularly for the buck converter the desired variables to estimate are the inductor current and the disturbances.

To estimate inductor current, several methods have been developed, in [1] and [11] such estimation is performed by means of observer schemes but this approach require additional measurements of load current, inductor voltage and output voltage. In [2] a method based on estimation of inductor's resistance and inductance parameters is proposed. Disturbance observers (DO) based methods only performs the estimation of disturbance without considering system states [6], [5] so it is required to carry out a scheme which estimates simultaneously both parts.

This work proposes the design of a simultaneous estimation scheme for states and disturbances that allows the elimination of sensors and at the same time operates efficiently under disturbance scenarios related to load and input voltage changes. To this end, the load and input voltage changes are modeled into a coupled term which can be estimated by an ESO, and use such estimation to attenuate disturbance effects. State and disturbance estimations are used to design a ST controller that ensures output voltage regulation in desired values. To guarantee system stability a Lyapunov analysis is performed. The remainder of the paper is organized as follows: Section II presents the mathematical model of the buck converter, Section III analyzes the design conditions for the ESO estimation scheme, Section IV describes the ESO based ST controller, Section V shows the results of simulation tests and finally Section VI states the main conclusions of the work

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2. Mathematical model of the buck converter

A step-down converter, also called buck converter, is a DC-DC converter topology that, as its name indicates, allows you to reduce the input voltage. A typical buck converter configuration is shown in Figure 1, where v_i, i_L, v_o are input voltage, inductor current and output voltage respectively. The converter components are denoted by R, L, C. This basic structure is affected mainly by two uncertainty sources, namely, input voltage variations and load changes.

Box 1

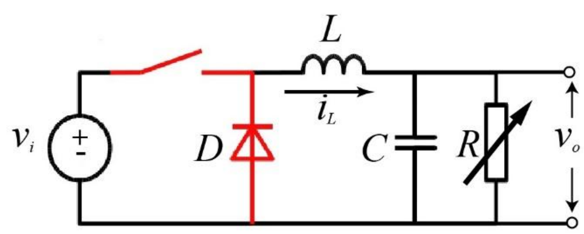

Figure 1
Buck converter topology

Depending on the Switch state the converter can be analyzed as two different circuits.

When S=ON (switch is closed), the current will increase, the inductor generates an opposing voltage in response to the change of current. This reduces the voltage across the load. The equations describing this scenario are:

$$\frac{di_L}{dt} = \frac{(v_i - v_o)}{L} \quad [1]$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC} \quad [2]$$

When S=OFF (switch is open), the voltage source will be removed from the circuit, and the current will decrease. The equations for this case are:

$$\frac{di_L}{dt} = \frac{-v_o}{L}$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC}$$

Using the state–space averaging method [20], [21], the dynamic model of the buck converter can be written as:

$$\frac{di_L}{dt} = \frac{-v_o}{L} + \frac{v_i}{L}u \quad [3]$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC} \quad [4]$$

where u is the duty ratio of the converter.

3. ESO estimation scheme

The model described by (3-4) can be transformed to include the load and input voltage changes as

$$\dot{z}_1 = z_2 \quad [5]$$

$$\dot{z}_2 = -n_{11}n_{21}z_1 - n_{23}z_2 + n_{11}n_{21}v_i(u + w) \quad [6]$$

with

$$n_{11} = {}^{1}\!/_{L},\ n_{21} = {}^{1}\!/_{C}$$
$$n_{22} = {}^{1}\!/_{RC} - {}^{1}\!/_{R^*C},\ n_{23} = {}^{1}\!/_{R^*C}$$
$$w = \frac{1}{n_{11}n_{21}v_i}\left[-n_{11}n_{21}v_{ref} + n_{11}n_{21}(v_i - v^*)u - n_{23}\dot{v}_{ref} - n_{22}\left(z_2 + \dot{v}_{ref}\right) - \ddot{v}_{ref}\right]$$

where $z_1 = v_o - v_{ref}$ and R^*, v^* describe the load nominal value and input voltage nominal value respectively. System (5-6) can be rewritten in matrix form as

$$\dot{z} = Az + Bu + B_w w \quad [7]$$

with

$$\dot{z} = [z_1\ z_2]^T,\ A = \begin{bmatrix} 0 & 1 \\ -n_{11}n_{21} & -n_{23} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ n_{11}n_{21}v_i \end{bmatrix},\ B_w = B$$

An extended variable $z_{n+1} = w$ is added to linearize system (7), so the extended system is described as [22]

$$\begin{cases} \dot{\bar{z}} = A_e\bar{z} + B_e u + Dh \\ y = C\bar{z} \end{cases}$$

where

$$\bar{z} = \begin{bmatrix} z \\ z_{n+1} \end{bmatrix},\ h = \dot{w}$$

$$A_e = \begin{bmatrix} 0 & 1 & 0 \\ -n_{11}n_{21} & -n_{23} & n_{11}n_{21}v_i \\ 0 & 0 & 0 \end{bmatrix}$$

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$$B_e = \begin{bmatrix} 0 \\ n_{11}n_{22}v_i \\ 0 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, C_e = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}^T$$

An ESO scheme for system (8) can be designed as

$$\begin{cases} \dot{\hat{\bar{z}}} = A_e\hat{\bar{z}} + B_e u + L(y - \hat{y}) \\ \hat{y} = C_e\hat{\bar{z}} \end{cases} \quad [9]$$

where $\hat{\bar{z}}$ is the vector of estimations of $\bar{z}$ and $L = [L_1\ L_2\ L_3]^T$ is the observer gain matrix.

4. Controller design

For the discontinuous control scheme design, the ST algorithm is selected considering the following surface

$$s = c_1\hat{\bar{z}}_1 + c_2\hat{\bar{z}}_2 \quad [10]$$

where $c_1, c_2 > 0$. The surface dynamics is described as

$$\dot{s} = c_1\dot{\hat{\bar{z}}}_1 + c_2\dot{\hat{\bar{z}}}_2$$

$$\dot{s} = c_1\hat{\bar{z}}_2 + L_1(\bar{z}_1 - \hat{\bar{z}}_1)c_1 + c_2[-n_{11}n_{21}\hat{\bar{z}}_1 - n_{23}\hat{\bar{z}}_2 + n_{11}n_{21}v_i(u + \hat{w}) + L_2(\bar{z}_1 - \hat{\bar{z}}_1)] \quad [11]$$

Considering a quadratic Lyapunov function

$$V(s) = \frac{1}{2}s^2$$

the condition $\dot{V} = s\dot{s} \leq 0$ must be fulfilled to guarantee system stability. Therefore, the proposed discontinuous control has the form

$$u = \frac{1}{n_{11}n_{21}v_i}\left(-\frac{c_1}{c_2}\hat{\bar{z}}_2 - L_1c_1(\bar{z}_1 - \hat{\bar{z}}_1) + n_{11}n_{21}\hat{\bar{z}}_1 + n_{22}\hat{\bar{z}}_2 - L_2(\bar{z}_1 - \hat{\bar{z}}_1) - n_{11}n_{21}v_i\hat{w} + v\right) \quad [12]$$

where v is the ST algorithm defined as

$$v = -\alpha\|s\|^{1/2}sign(s) - \beta\int sign(s)\,dt \quad [13]$$

Finally, by using (12) in (11), the surface dynamics results in

$$\dot{s} = v$$

then

$$\dot{V} = s\left[-\alpha\|s\|^{1/2}sign(s) - \beta\int sign(s)\,dt\right] \quad [14]$$

and by using the relation $\|s\| = sign(s)s$, the last equation can be transformed as

$$\dot{V} \leq -\alpha\|s\|^{1/2}\|s\| - \beta\int\|s\|\,dt \quad [15]$$

which ensures that $\dot{V} < 0$ if $\alpha + \beta > 0$.

5. Results

To verify the performance of the proposed control scheme, simulation tests have been developed using Simulink and the Simscape/Power Systems libraries. The selected parameters of the buck converter are shown in Table 1. The proposed controller parameters are presented in Table 2 which were selected empirically based on the condition (15). The proposed controller performance is compared with a PI control scheme and a first order sliding mode controller. The simulated scenario consists of an input voltage signal that changes from 20V-24V at $t = 6s$ and has small sinusoidal variation as shown in Figure 2. The desired output voltage is selected as 10V and a load change is presented at $t = 1s$ from 25Ω to 9.75Ω.

Box 2

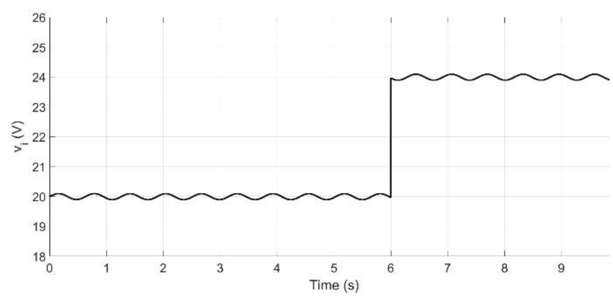

Figure 2
Input voltage signal

The output voltage regulation is illustrated in Figure 3. It can be seen that the 3 schemes perform an adequate regulation around the 10V reference but the proposed scheme shows an oscillation of lower magnitude. The load change at $1s$ generates a greater oscillation from the current increment, which is better handled by the proposed controller. The other disturbance effects produced by the input voltage change is also attenuated in a more accurate way by the proposed controller than the other schemes.

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Box 3

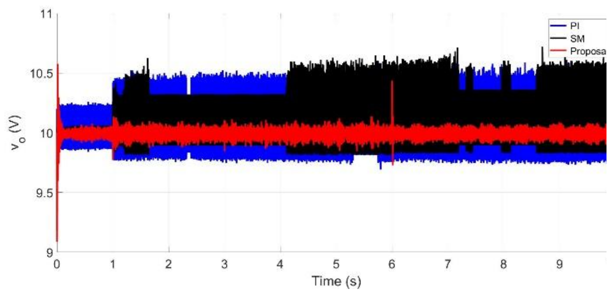

Figure 3
Output voltage

Figure 4 depicts the inductor current behaviour, which shows similar characteristics to the one seen for the output voltage case with a more accurate response for the proposed controller.

Box 4

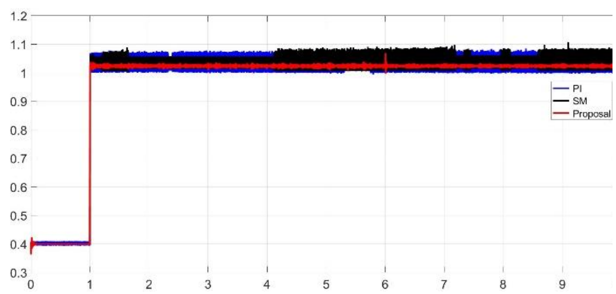

Figure 4
Inductor current

The control signal is shown in Figure 5. The three control signals keep his values in the desired range from 0 to 1.

Box 5

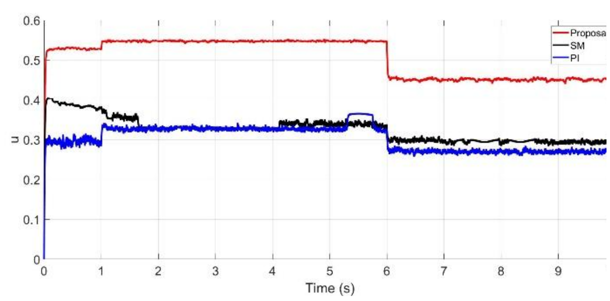

Figure 5
Control signal

The estimation error of the first state corresponding to the output voltage error $\left(v_o - v_{ref}\right)$ is presented in Figure 6, a very low error is generated which contributes to the proper performance of the proposed controller.

Box 6

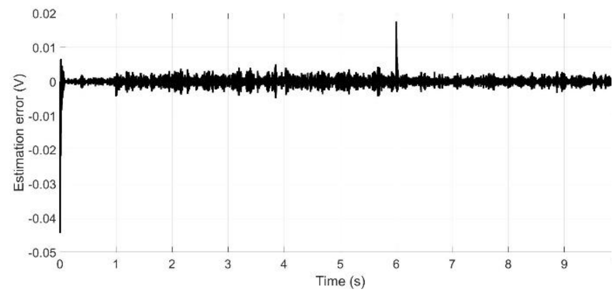

Figure 6
Estimation error of state $\hat{\tilde{z}}_1$

6. Conclusions

The proposed robust discontinuous control scheme using a ST controller based on ESO is able to effectively regulate the output voltage of the selected DC-DC buck converter under load changes and input voltage variations. The ESO scheme for simultaneous estimation of states and disturbances operates with low estimation errors contributing to an adequate voltage regulation. It was demonstrated system stability of the proposed controller by means of Lyapunov analysis. Simulation tests shown that the proposed controller has a better performance that conventional PID based schemes and is capable of handle disturbances generated from load changes and input voltage variations. It is possible to enhance the controller response in a future work by implementing an appropriate gain selection method which allows a more precise control of the desired variables.

Annexes

Box 7

Table 1
Buck converter parameters

Parameter	Value
Nominal load (R*)	11 Ω
Inductance (L)	200 μH
Capacitance (C)	220 μF
Input voltage (V_i)	20V

Box 8

Table 2
Proposed controller parameters

Parameter	Value
α	21
β	15
L_1	5000
L_2	1000
L_3	1000

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Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

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Availability of data and materials

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Abbreviations

DC	Direct Current
DO	Disturbance Observer
ESO	Extended State Observer
MPC	Model Predictive Control
PID	Proportional Integral Derivative
ST	Super Twisting

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