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SMC CONTROL APPLIED TO A BUCK CONVERTER: COMPARISON TO A PID CONTROLLER

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ABSTRACT

This paper aims to control the output voltage of a buck converter using a Sliding Mode Controller (SMC) on an AVR experimental setup. The controller has been implemented with SIMULINK followed by simulations in order to check its convergence and to compare SMC's robustness to PID's. We have shown that the designed SMC reaches convergence and is more robust than the classic PID controller. We also pointed out that the robustness of the SMC is widely variable from one noised parameter in the Buck converter model to another. Complementary work can be done to explain this variation of the robustness offered by the SMC.

KEYWORDS: Sliding mode control, buck converter, robustness, AVR.

1. INTRODUCTION

Buck converter is very used today because of the solution it provides for a large range of application. On the other hand, when parameters of linear systems can suffer wide variation, classical commands such as PID, perform poorly [1] because of their lack of robustness. Then, the slide mode control (SMC) shows itself as an interesting alternative.

The classical PID type control laws are very effective in the case of linear systems with constant parameters [1]. For systems nonlinear or linear systems whose parameters may be subject to large variations, these control laws may be insufficient because they are not robust enough especially when the demands on precision and system speed are strict as is often the case in an industrial environment. Control laws insensitive to variations in parameters, perturbations and nonlinearities are then necessary. The command to a variable structure by sliding mode constitutes a solution to this problem.

The principle of sliding modes has a very important interest in requires variable structure systems. Power converters and in particular DC-DC converters are characterized by a variable structure and are, more specifically, considered to be switched systems due to of the change in the topology of their circuits according to the passing and blocked states switches and diodes.

This principle has often been studied on converters DC-DC and has shown good reliability. It was also used to design robust nonlinear observers [2]–[15]. It is therefore very interesting to study the summary of control laws by sliding modes, accompanied by observations authors based on the same methodological approaches.

The goal pursued is to design an SMC controller which converge and to show it has greater robustness than PID and to achieve to control a buck converter with SMC.

General principles of Sliding Mode Controller

Sliding Mode Control (SMC) is a methodological approach to nonlinear control [16], [17] used for many applications, in particular for nonlinear systems with various structures such as power converters. Compared to other non-linear control strategies, its design can be envisaged by limiting complexity and, at the same time, making it possible to guarantee robustness in the stability. However, its application to the different topologies of power converters is difficult to generalize and must be adapted for each architecture. Like most control methods, SMC was applied to basic DC-DC converters [18]–[20] and complex [2], [21]–[24]. Although most parts of the authors mention the generalization of the methods developed on high order converters, the difference in circuit

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topology may change the behaviour of the system completely, even if they are the same order. The use of synthetic approaches must be adapted accordingly.

2. MATERIALS AND METHODS

Buck converter modelling

Figure 3. *1* shows the electrical circuit of a buck converter.

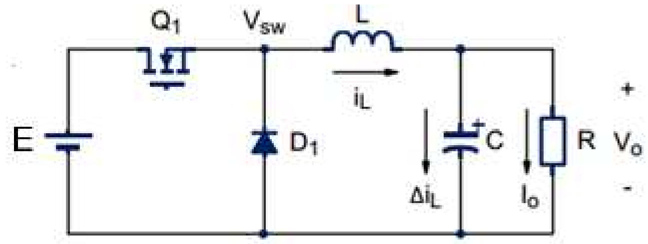

Figure 3. 1 Buck converter

The behavior of the buck converter is entirely described by two equations. The first one is obtained thanks to Kirchhoff's second law:

$$E.u = L\frac{di_L}{dt} + V_o \quad (1)$$

with
E : the input voltage of the converter,
u : the duty cycle,
i_L : the current through the inductor,
V_o : the output voltage of the buck converter.
This equation can be rewritten:

$$\frac{di_L}{dt} = \mathrm{i}'_\mathrm{L} = -\frac{1}{\mathrm{L}}\mathrm{V_o} + \frac{\mathrm{E}}{\mathrm{L}}\mathrm{u} \quad (2)$$

The second equation is derived from the first law of Kirchhoff:

$$\mathrm{i_L} = \mathrm{C}\frac{\mathrm{dV_o}}{\mathrm{dt}} + \frac{\mathrm{V_o}}{\mathrm{R}} \quad (3)$$

It can also be rewritten:

$$\frac{dV_o}{dt} = V_o' = \frac{1}{C}i_L - \frac{1}{RC}V_o \quad (4)$$

From those equations, we can derive the mathematic model of the buck converter:

$$\begin{cases} i_L{}' = -\frac{1}{L}V_o + \frac{E}{L}u \\ V_o{}' = \frac{1}{C}i_L - \frac{1}{RC}V_o \end{cases} \quad (5)$$

Implementation of the SMC
Sliding surface
Given the SMC is of the first order, the commutation function is [2]:

$$s = e' + K.e \quad (6)$$

with
K : a parameter of the controller and

$$e = V_{ref} - V_o \quad (7)$$

with
V_{ref} : the setpoint voltage.
Thus :

$$e' = -V_o' \quad (8)$$

Given (4), we can write:

$$s = -V_o' + K\left(V_{ref} - V_o\right) = -\frac{1}{C} i_L + \frac{1}{RC} V_o + K.V_{ref} - K.V_o \quad (9)$$

And we can reduce it as :

$$s = \frac{-1}{C} i_L + \left(\frac{1}{RC} - K\right) V_o + K.V_{ref} \quad (10)$$

Designing the Equivalent part of THE SMC controller

We get to derive the sliding surface:

$$s' = \frac{-1}{C} i_L' + \left(\frac{1}{RC} - K\right) V_o' \quad (11)$$

Then by replacing i_L' and V_o' by their expressions, we have:

$$s' = \frac{-1}{C}\left(-\frac{1}{L} V_o + \frac{E}{L} u\right) + \left(\frac{1}{RC} - K\right)\left(\frac{1}{C} i_L - \frac{1}{RC} V_o\right) \quad (12)$$

$$s' = \left(\frac{1 - KRC}{RC^2}\right) i_L + \left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o + \left(-\frac{E}{LC}\right) u \quad (13)$$

And we find u_{eq} :

$$u_{eq} = \frac{LC}{E}\left[\left(\frac{1 - KRC}{RC^2}\right) i_L + \frac{LC}{E}\left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o\right] \quad (14)$$

Which can be simplified:

$$u_{eq} = \left(\frac{L - KRLC}{RCE}\right) i_L - \left(\frac{L - KRLC - R^2C}{R^2CE}\right) V_o \quad (15)$$

And by posing,

$$A = \frac{L - KRLC}{RCE}$$

$$B = \frac{L - KRLC - R^2C}{R^2CE}$$

We get to write:

$$\begin{cases} u_{eq} = A.i_L - B.V_o \\ A = \dfrac{L - KRLC}{RCE} \\ B = \dfrac{L - KRLC - R^2C}{R^2CE} \end{cases} \quad (16)$$

Designing the discontinuous part of the SMC controller

It's obtained thanks to the attractivity condition [3]:

$$ss' < 0$$

Let's replace *s'* by its (13) expression:

$$s\left[\left(\frac{1 - KRC}{RC^2}\right) i_L + \left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o + \left(-\frac{E}{LC}\right) u\right] < 0$$

And do the same with *u*:

$$s\left[\left(\frac{1 - KRC}{RC^2}\right) i_L + \left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o + \left(-\frac{E}{LC}\right)\left(u_{eq} + u_n\right)\right] < 0$$

According to (16) :

$$s\left[\left(\frac{1 - KRC}{RC^2}\right) i_L + \left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o + \left(-\frac{E}{LC}\right)\left\{\frac{LC}{E}\left[\left(\frac{1 - KRC}{RC^2}\right) i_L + \left(-\frac{L - KRLC - R^2C}{R^2C^2L}\right) V_o\right] + u_n\right\}\right] < 0$$

Thus :

$$s(-u_n) < 0 \quad (17)$$

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A solution of that inequation is:
$u_n = H.sign(s)$
With H a strictly positive real.

Mathematical expression of the SMC command
The final expression is the sum of the two previous parts forecasted:

$$\begin{cases} u = A.i_L - B.V_o + H.sign(s) \\ A = \dfrac{L - KRLC}{RCE} \\ B = \dfrac{L - KRLC - R^2C}{R^2CE} \\ H > 0 \end{cases} \qquad (18)$$

This expression has been implemented using the « function » bloc of SIMULINK.

Implementation under SIMULINK

Presentation of the bloc diagram
It's made of four mains blocs: a « process », a « controller », a « setpoint » and a « parameter ». Figure 5. 1 shows it under SIMULINK.

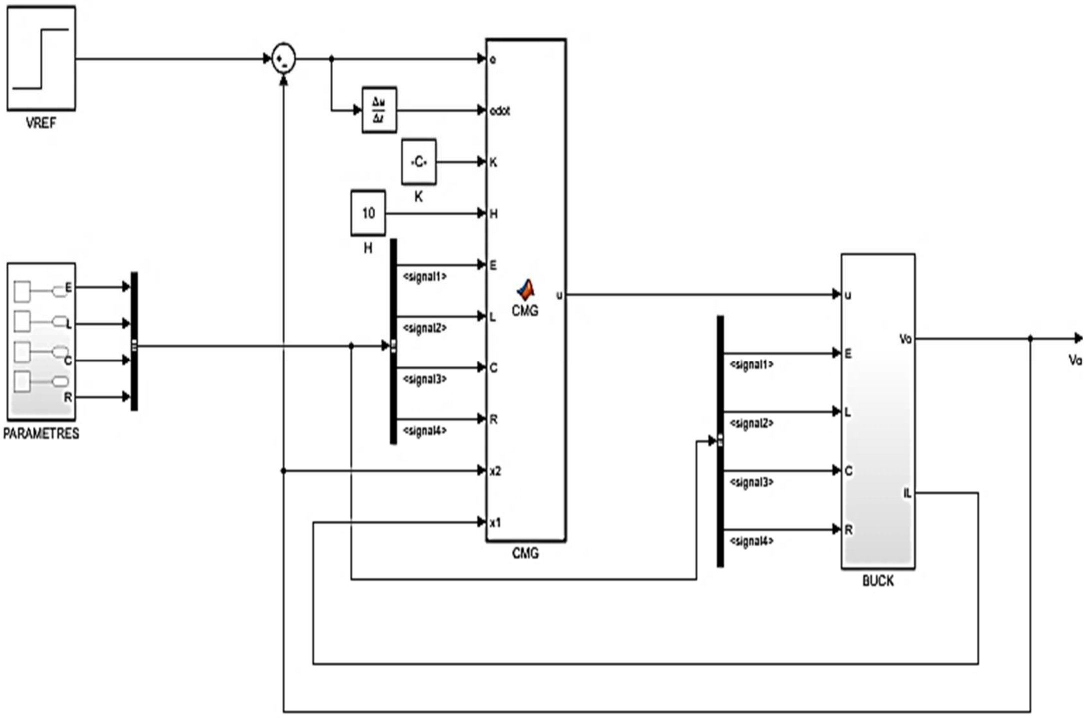

Figure 5. 1 Bloc diagram under SIMULINK

The values used for model parameters are filled in

Table *5.1*:

Table 5.1: Buck Converter parameters values

Parameters	Values
Input voltage	30 V
Inductor	30 mH
Capacitor	10 µF

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Output resistor	220 kΩ

Parameters values choice

Values of parameters *K* and *H* have a direct impact on the performance of the system controlled by SMC. So, the ones we've chosen offer good performance to the system without though awakening chattering problem inherent to the sliding mode. The PID controller have been tuned using "PID Tuner" toolbox under SIMULINK.

Table 5.2 shows SMC's and PID's parameter used.

Table 5.2: Parameters used in SMC and PID controller.

SMC's parameters	Values	PID's parameters	Values
K	100000	P	0,55
		I	498,77
H	10	D	$1{,}47.10^{-4}$
		N	1343402,12

Robustness tests under SIMULINK

It's been about varying the system internal parameters. A single has been changed at the time. All parameters (E, L, C) have been shrinked to 50% of their initial value while the resistor have been replaced by a 20Ω one. All these changes took place at five milliseconds after time origin.

3. RESULTS AND DISCUSSION

Results of convergence test

The convergence test results are shown on Figure 6. *1*.

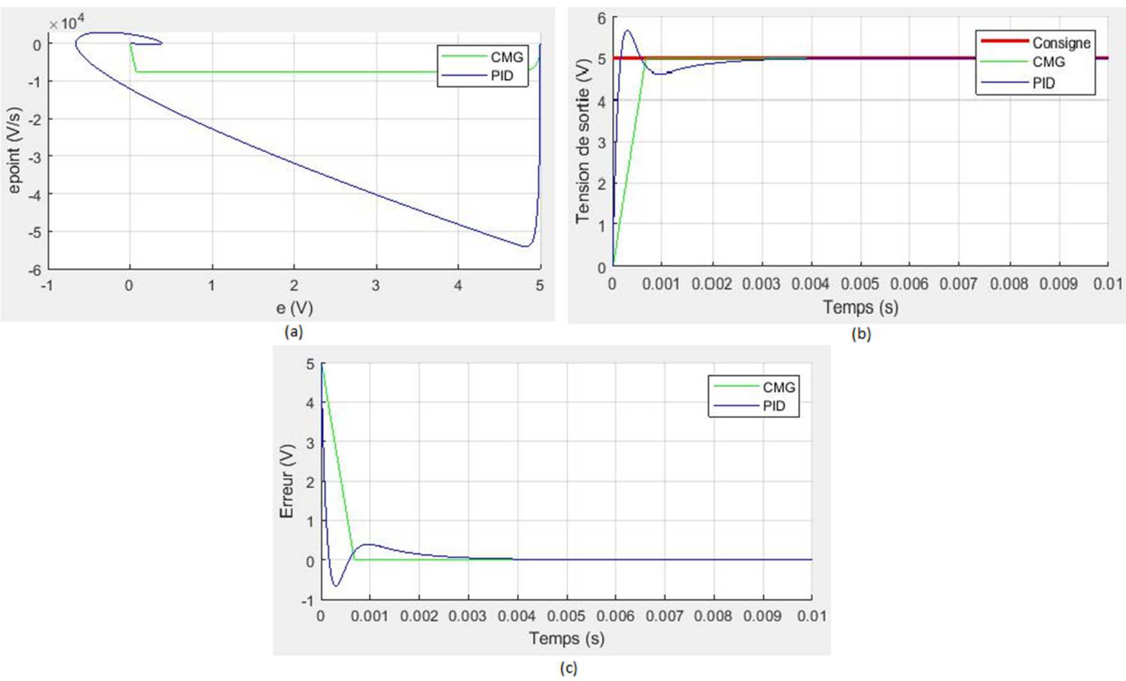

Figure 6. 1 (a) Phase plot with SMC and PID (b) Setpoint tracking with SMC and PID (c) Error with SMC and PID

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Figure 6.1 (a) reveals that the system controlled using SMC reach a sliding surface and stabilize itself at the desired state. Figures 6.1 (b) and 6.1 (c) reveals that error disappear and the setpoint is reached after a finite time.

All these have us to conclude the convergence of the system indeed toward the desired state in a finite time. H. Guldemir, in [25], got similar results applying SMC to Buck-boost converter.

Results of robustness tests

Figure 6. 2 shows the behavior of the system when applying SMC and PID to control it and then varying its internal parameters.

- ❖ Variation of input voltage

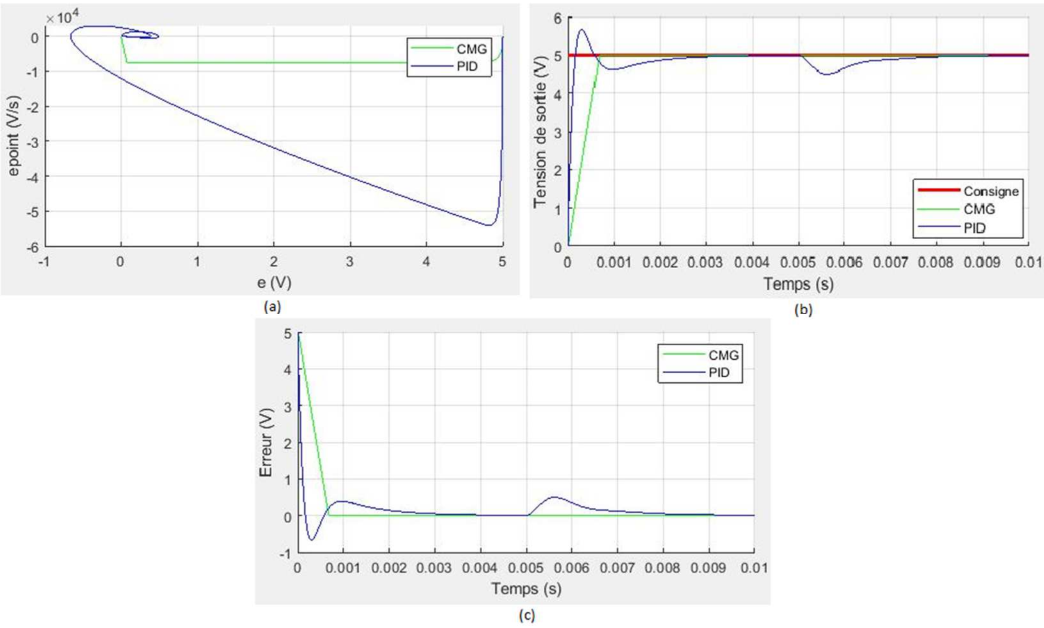

Figure 6. 2 (a) Phase plot with SMC and PID (b) Setpoint tracking with SMC and PID (c) Error with SMC and PID

- ❖ Variation of the inductor

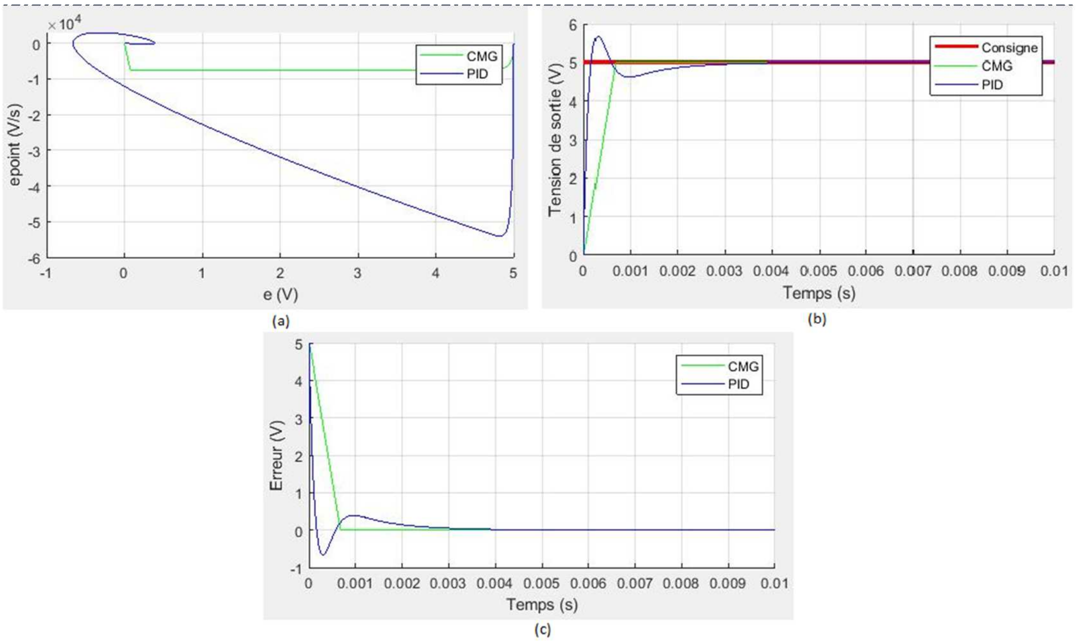

Figure 6. 3 (a) Phase plot with SMC and PID (b) Setpoint tracking with SMC and PID (c) Error with SMC and PID

- ❖ Variation of the output resistor

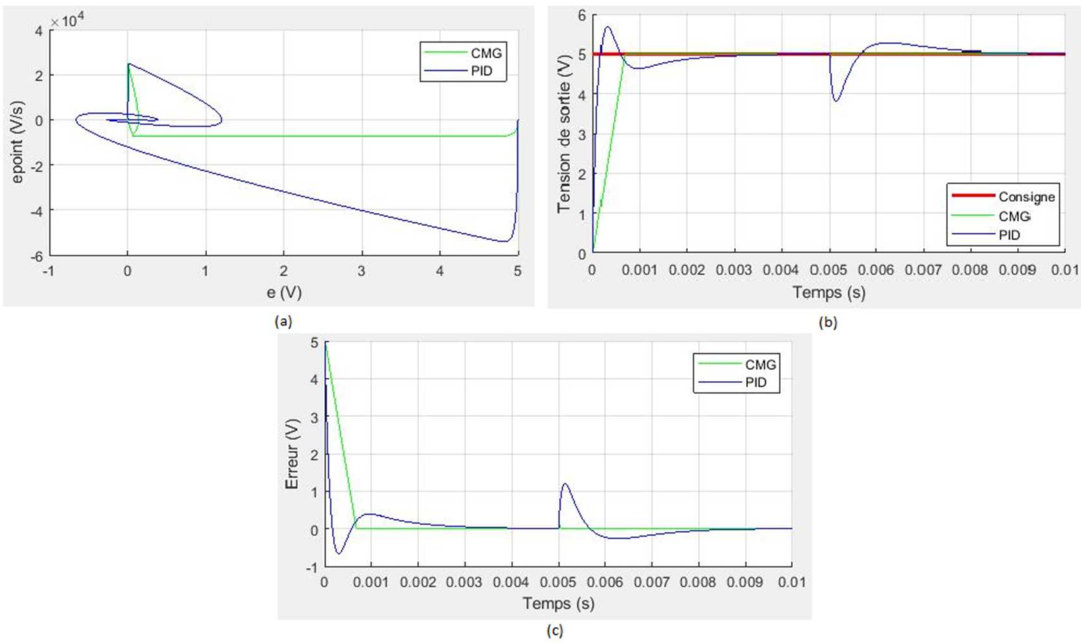

Figure 6. 4 (a) Phase plot with SMC and PID (b) Setpoint tracking with SMC and PID (c) Error with SMC and PID

Phase plots figure 6. 2 a figure 6. 3 a figure 6. 4 a show that when disturbing the system controlled with PID leave the desired state and start a second convergence toward it. In the case of SMC thus the system is either insensible figure 6. 2 figure 6. 3 or it reaches a second sliding surface so as to converge figure 6.4a also with the system controlled by SMC output voltage never suffers from overshooting figure 6.2, figure 6.3 and figure 6.4 finally reaction time before reaching the desired state for the second time is way shorter when the control is performed by SMC figure 6.4a we can conclude that the system controlled by SMC is clearly more robust than the same system controlled by PID. similar results have been obtained by h. Guldemir [25] when varying the input voltage and the output resistor of its buck-boost converter and by Hashim in [26] who compared the robustness of an SMC controlled dc motor by varying its load to a PI controlled DC motor in the first time and repeating the operation varying then it inertia moment. Here too there are some values of parameters which can bring one to a slightly different conclusion. We can remark that the system controlled with SMC is almost insensible to the input voltage inductor value variation and little more to output resistor variation. Our guessing is that the nearer the parameter is relatively to state variable less the system is responsive to its variation. Futures work have to be done in order to explain this difference in the responsiveness of the system to parameters variation.

4. CONCLUSION

Results enable us to conclude firstly of the convergence of the SMC controlled system and secondly of its superior robustness compared to PID. Then SMC seems more suited for a system subject to a large variety of their internal parameters as often required in the industrial field. Tough different parameters values for SMC or PID can bring to different results. We've gotten to notice a large difference of the responsiveness of the system to perturbation depending on the parameter causing it. We would want further experimentation to try to provide an explanation of this behaviour.

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