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Hardware-In-the-Loop model design using the *ESA Control Toolbox* in MATLAB Simulink

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Abstract—The *ESA Control Toolbox* is a new MATLAB toolbox that offers a quick, efficient, and practical alternative for the implementation of digital controllers into Field Programmable Gate Arrays (FPGAs) for space applications. This paper demonstrates the versatility and viability of the toolbox by showcasing its effectiveness in developing Hardware-In-the-Loop (HIL) models on FPGAs. While the straightforward way for implementing such models is by coding them in a Hardware Description Language (HDL), those languages are not trivial and render a cumbersome and time-consuming process. MATLAB Simulink HDL Coder blocks offer a more efficient and intuitive approach, though several issues arise from the fact that there is no static equivalence between blocks and VHDL code. In order to address these issues, the presented toolbox provides blocks that are linked to static VHDL code, enabling the design and synthesis of any kind of HIL model in FPGAs. This paper demonstrates the application of the toolbox in a case study for modeling a Three-Level Active Neutral-Point-Clamped (3L-ANPC) converter. The proposed toolbox results are compared with a MATLAB Simscape model incorporating both open and closed-loop controllers, yielding identical results and thus confirming the reliability and functionality of the *ESA Control Toolbox* as an alternative for creating FPGA-based HIL designs.

Index Terms—Hardware-In-the-Loop model, FPGA, Digital controller, Power converter, MATLAB Simulink.

I. INTRODUCTION

Field Programmable Gate Arrays (FPGAs) have become recently the common approach for implementing digital controllers due to their higher level of reliability and faster computing capabilities compared with software-based solutions. However, a Hardware Description Language (HDL) such as VHDL/Verilog is needed for implementing those models into FPGAs (one example of such implementation can be seen in [1]). These languages are not trivial among power electronics engineers that are mainly acquainted with languages such as C or C++ for implementing controller algorithms, and often render the implementation task complex and time-consuming [2], [3].

One alternative to writing VHDL code without any previous knowledge of a HDL is given by the MATLAB Simulink HDL Coder, which converts Simulink models into synthesizable VHDL code [4]. Two advantages arise from this approach: Simulink is a well-known, established tool among digital controller designers, and the synthesized VHDL presents more efficient synthesis results than other alternatives such as the Xilinx Vivado HLS tool [5], [6]. However, the release of new versions of MATLAB tools means that the provided VHDL code will be updated, implying that the synthesized VHDL code must be tested and verified again. This presents an important challenge in the certification process for space applications. Furthermore, small changes in the designed algorithms may often result in a totally different VHDL code due to the internal simplification steps in HDL Coder.

In order to address the above points, a new MATLAB toolbox called *ESA Control Toolbox* has been developed and presented [7]. For each Simulink block, it provides static VHDL code that can be used in sensitive applications. As a result, there is no need for the designer to verify the performance of the synthesized VHDL code after a change in the algorithm or upon update of the MATLAB tools. The *ESA Control Toolbox* library consists of several subcategories, including blocks needed for controller design (PWM generators, registers, etc), facilitating the design of digital controllers [7]. Furthermore, it can also be implemented and used like any other Simulink library and it is integrated into MATLAB HDL Coder, allowing the user to incorporate HDL Coder blocks into the applications.

One particular application where the *ESA Control Toolbox* can be used with great results is in FPGA-based Hardware-In-the-Loop (HIL) simulation design, which involves testing the behavior of a controller in real time. In HIL simulations, the physical system being controlled is replaced by a simulated model which interacts in real time with the

physical controller. This approach enables engineers to test the controller's performance under a range of different conditions and scenarios without the need for a physical system, which may be expensive or difficult to set up.

The architecture of a HIL testing system that uses the toolbox is demonstrated in Fig. 1. As shown, the *ESA Control Toolbox* blocks (1) are encapsulated into a Subsystem block (2) in the parent Simulink file containing the HIL model (3). As we are discussing the functionality of the toolbox, no other blocks will be considered to be in the Simulink file, though a number of them could be incorporated as previously stated. The aforementioned subsystem block plays the role of the top module in the final VHDL implementation, i.e. the FPGA block. In turn, the HIL model then interacts in real time with the controller (4) through a Digital-to-Analog Converter (DAC).

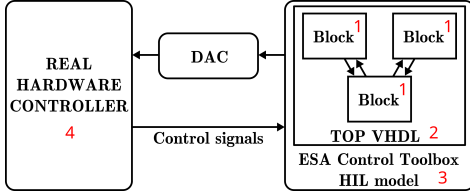


Fig. 1. Architecture of a HIL system using *ESA Control Toolbox*.

II. CASE STUDY

The *ESA Control Toolbox* blocks can be used to model any HIL plant circuit, and among them power converters. As a case study, a three-phase Three-Level Active Neutral-Point-Clamped (3L-ANPC) converter has been chosen to verify the performance of the proposed toolbox. In Fig. 2, the circuit schematic for the 3L-ANPC is presented, and values of the circuit elements are given in Table I.

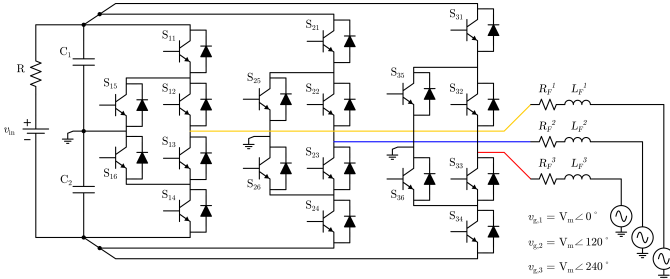


Fig. 2. The circuit schematic for a 3L-ANPC.

TABLE I
VALUES OF THE THREE-PHASE 3L-ANPC CIRCUIT ELEMENTS

v_{in}	R	V_m	L_F^1, L_F^2, L_F^3	R_F^1, R_F^2, R_F^3	C_1, C_2
1 KV	0.1 Ω	380 V	1 mH	0.5 Ω	1 mF

While it is true that each phase of the 3L-ANPC presents 2^6 switch combinations, discarding hazardous states and considering equivalent topologies yields a simplification like the one

presented in Fig. 3. From there, the equations of the model can be easily obtained and derived.

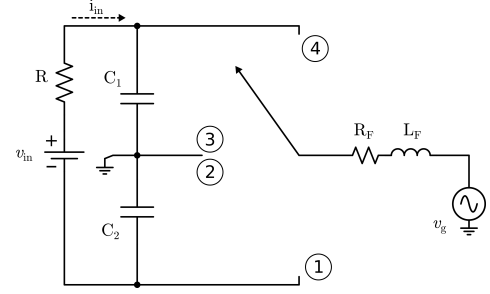


Fig. 3. Simplified schematic for one phase of the 3L-ANPC.

Ignoring parasitic components, the discretized inductor current can be formulated (using the forward Euler method) as:

$$i_L(k) = \frac{\Delta t}{L} v_L + i_L(k-1) \left[1 - R_F \frac{\Delta t}{L} \right]$$

A value of $\Delta t = 500$ ns will be assumed hereafter. Therefore, for each of the positions in Fig. 3:

$$i_L(k) = \begin{cases} \frac{\Delta t}{L} (-v_{C_2} - v_g) + i_L(k-1) \left[1 - R_F \frac{\Delta t}{L} \right] & \text{pos. 1} \\ \frac{\Delta t}{L} (-v_g) + i_L(k-1) \left[1 - R_F \frac{\Delta t}{L} \right] & \text{pos. 2/3} \\ \frac{\Delta t}{L} (v_{C_1} - v_g) + i_L(k-1) \left[1 - R_F \frac{\Delta t}{L} \right] & \text{pos. 4} \end{cases}$$

The voltage for each of the capacitors C_1 and C_2 , in turn, can be modeled by the following equations:

$$v_C(k) = v_C(k-1) + \frac{\Delta t}{C} i_C = \begin{cases} v_C(k-1) + \frac{\Delta t}{C} (i_{in} - P_4^A i_A - P_4^B i_B - P_4^C i_C) & \text{for } C_1 \\ v_C(k-1) + \frac{\Delta t}{C} (i_{in} + P_1^A i_A + P_1^B i_B + P_1^C i_C) & \text{for } C_2 \end{cases}$$

Where P_N^x takes value 1 if phase x is in position N (1, 2, 3 or 4, as per Fig. 3) and zero otherwise. Possible switch configurations for each of the three positions are given in Table II.

TABLE II
SWITCHING STATES FOR THE SIMPLIFIED ONE-PHASE 3L-ANPC

Position	S_1	S_2	S_3	S_4	S_5	S_6	Output voltage (V)
1	OFF	OFF	ON	ON	ON	OFF	$-v_{C_2}$
2	OFF	ON	OFF	ON	ON	OFF	0
3	ON	OFF	ON	OFF	OFF	ON	0
4	ON	ON	OFF	OFF	OFF	ON	v_{C_1}

From all the above, designing the 3L-ANPC circuit with the *ESA Control Toolbox* is just a matter of translating the derived equations into the Simulink block schema using the *ESA Control Toolbox* components. Simulink implementations commonly offer the flexibility to utilize diverse data types for inputs, with the output data type being inherited accordingly. However, meticulous attention is required to prepare

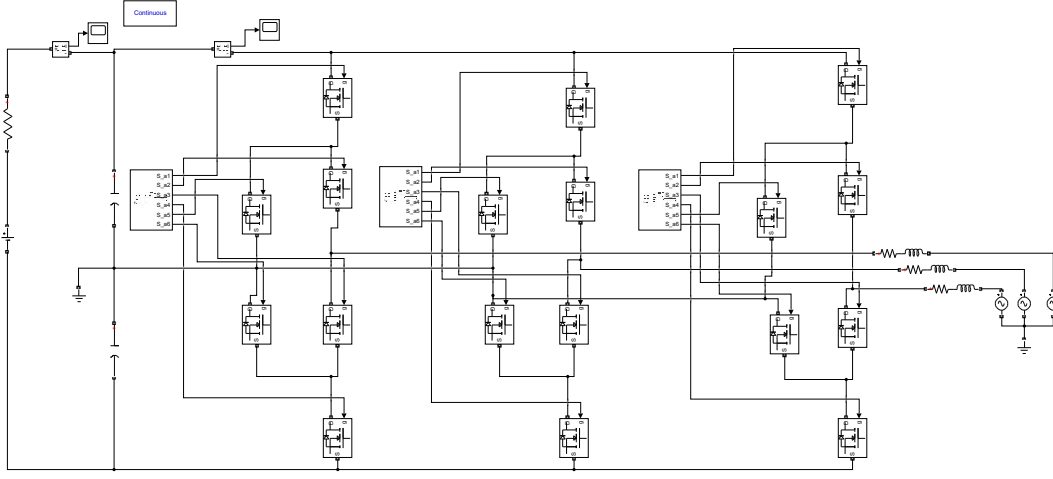


Fig. 4. Open-loop controlled Simscape three-phase 3L-ANPC model.

the system adequately for VHDL synthesis. VHDL implementations, in exclusive adherence to their specifications, rely upon signed and unsigned libraries which ultimately depend on either integer or fixed-point arithmetic. Therefore, to ensure a seamless translation process to VHDL and preempt potential complications, it is prudent to represent all data types as signed vectors, selectively incorporating fixed-point notation as deemed necessary. Further reading for optimization on this topic can be found in [1].

III. RESULTS

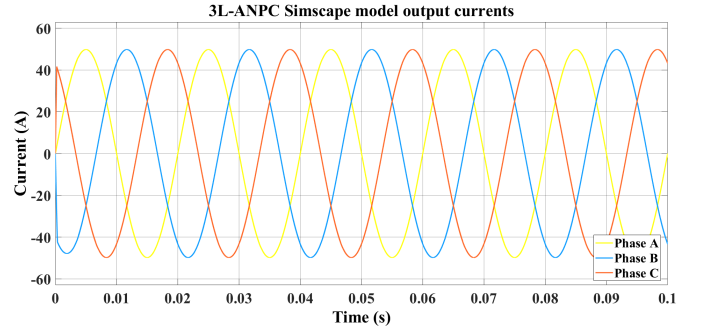
In order to verify the performance of HIL models designed with the *ESA Control Toolbox*, the 3L-ANPC model has also been simulated employing the Simulink built-in block library of Simscape as a reference for a comparison study. Although the blocks provided in the Simscape library do not present the advantages stated in Section I, the resulting Simulink model is visually clear (see Fig. 4) and offers a well-tested comparison point. Both models have then been simulated under the MATLAB Simulink environment both with a closed and open-loop controller.

As it was previously indicated, a time step of 500 ns has been chosen as the simulation step (Δt) for the *ESA Control Toolbox* model. In order to keep the consistency, the clock signal used in the register blocks has been therefore updated to the aforementioned value. *ESA Control Toolbox* can model applications with sampling steps of under 100 ns, but such high frequencies are not common in commercial HIL applications. Instead, a usual employed value is 500 ns (e.g. the default Typhoon HIL frequency [8]), which has been our final choice. Additionally, initial voltages of 520 V and 480 V have been chosen for C_1 and C_2 respectively, in order to check the correct balancing of the capacitors by the controller.

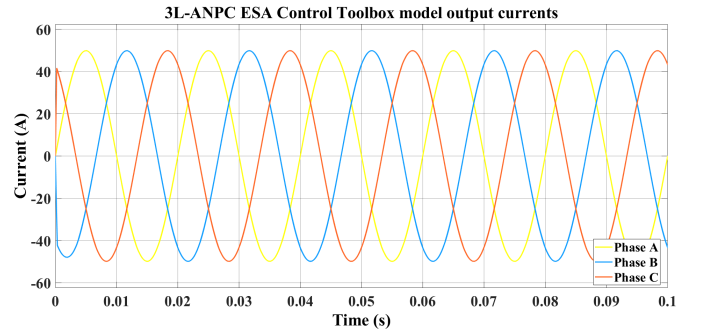
A. Closed-loop-controlled circuit

In this study, the Model Predictive Control (MPC) approach has been chosen for the closed-loop control of the 3L-ANPC

circuits. MPC is an advanced control strategy that uses mathematical models of a system to predict its future behavior and optimize control actions accordingly [9], [10]. This is to say, the cost of each action is anticipated by calculating the difference of the output from a reference value, and the minimum cost action is chosen at each step. Switching frequency will be inherited from the model at 500 ns, though a smarter take may make use of the Period Control Approach (PCA) as used in [11], [12].



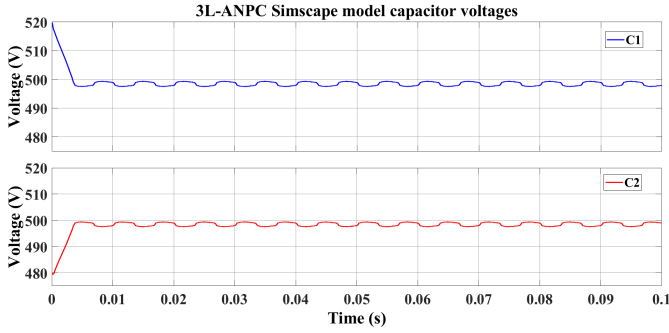
(a) Output currents for the Simscape model



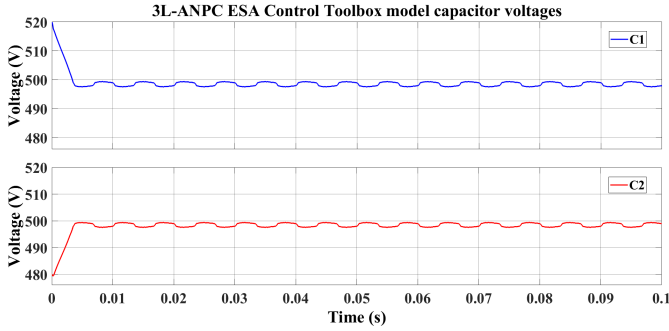
(b) Output currents for the *ESA Control Toolbox* model

Fig. 5. Output currents comparison.

With the equations presented in the previous section, a straightforward MPC controller that only takes into account



(a) Capacitor voltages for the Simscape model



(b) Capacitor voltages for the *ESA Control Toolbox* model

Fig. 6. Capacitor load balancing comparison.

the next step for the 3L-ANPC has been written using MATLAB code. Apart from the ease and time saved with such a high-level language, MATLAB code may be embedded in Simulink designs, making the models easily testable.

Figures 5 and 6 present side-by-side comparisons between the expected circuit behavior, modeled using Simscape, and the instance created with the *ESA Control Toolbox*. The comparisons include measurements of the output currents and the balancing of the capacitor load. In the two cases there are no apparent differences between the two models, with only small ripples at nanosecond level due to the continuous behavior of the Simscape solver versus the discrete *ESA Control Toolbox* simulation. As a further confirmation of the correct functioning of the model, the FFT (Fast-Fourier Transform) analysis of the harmonics of the currents are shown in Fig. 7.

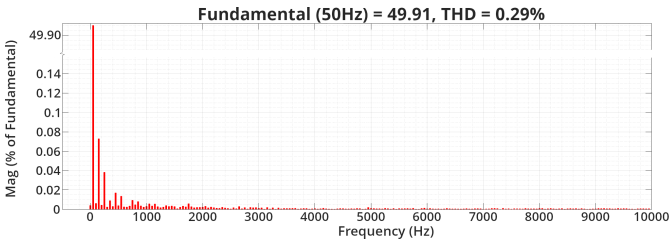


Fig. 7. Harmonic analysis for phase A current.

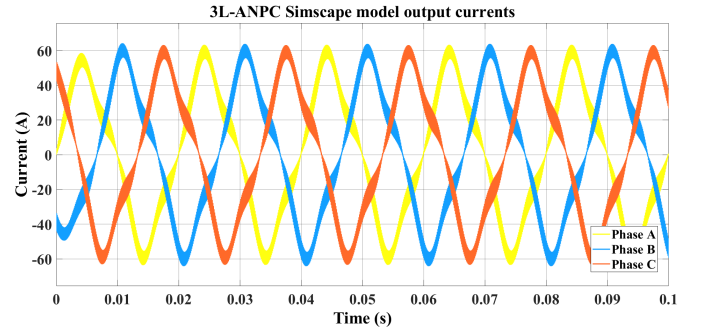
B. Open-loop-controlled circuit

Side-by-side comparison of the *ESA Control Toolbox* and the Simscape models has also been carried out with an open-

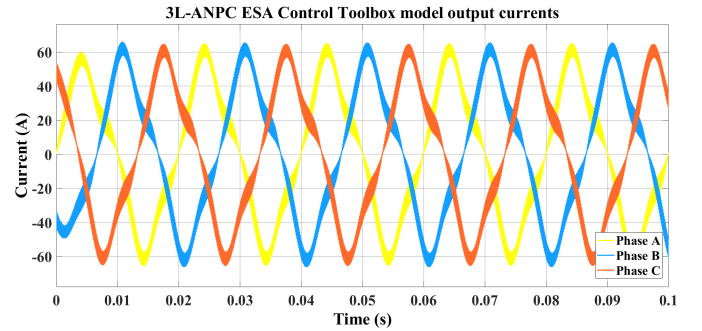
loop Pulse-Width Modulation (PWM) controller. In order to set the reference voltage signals for the controller, an FFT analysis of the output voltage from the MPC-controlled model has been carried out, and the corresponding values for the fundamental harmonic (at 50 Hz) therefore chosen for each phase. These values are shown in Table III. Additionally, the switching frequency has been chosen to be 10 kHz.

TABLE III
PARAMETERS OF THE REFERENCE VOLTAGE PWM SIGNAL

Phase	Amplitude	Phase difference
A	405.85 V	2.2°
B	405.85 V	242.3°
C	405.85 V	122.2°



(a) Output currents for the Simscape model



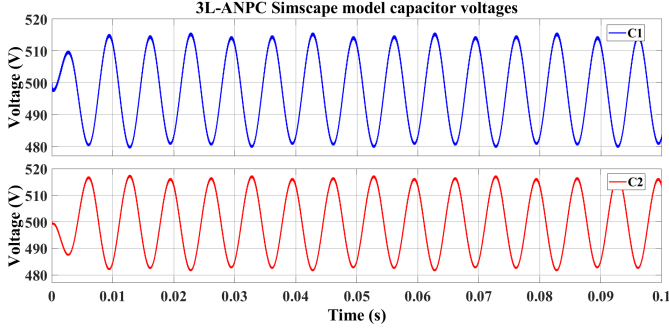
(b) Output currents for the *ESA Control Toolbox* model

Fig. 8. Output currents comparison.

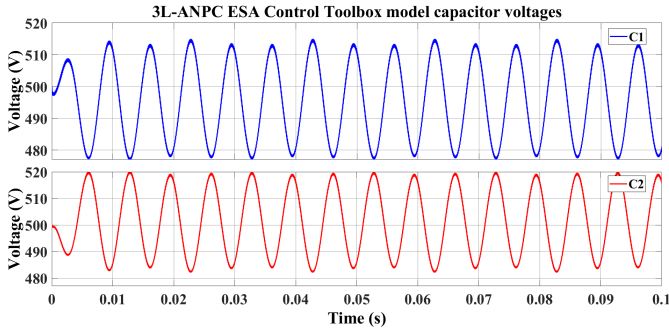
With the above parameters, Figures 8 and 9 present a side-by-side comparison of the output currents and the capacitor load balancing when simulating with the open-loop PWM controller. At a first glance, there is a striking difference to the MPC-controlled models, but then again open-loop control cannot “see” the state of the system and therefore correct any deviations from the expected outputs. With respect to the output currents, the approximation that PWM manages to obtain bears a clear resemblance with the target current signal, but its amplitude is a bit larger and it presents a more triangular shape. This is obviously due to the control approach: as PWM does not receive any inputs, it acts “blindly” over the converter, giving the switching signals as it considers more appropriate according to the reference voltage in each time step. However,

as far as we are concerned, both Simscape and *ESA Control Toolbox* models present the same behavior.

As for the capacitor voltages, the open-loop controller does not take into account their balancing and therefore oscillate much more than in the MPC-controlled version. However, both models show very similar waveforms, with the same peak-to-peak voltage. The only difference is a small offset between the two, which is easily explained as the *ESA Control Toolbox* HIL simulation does not model the small resistances in the MOSFET components, which do appear in the Simscape version and add up to that small difference.



(a) Capacitor voltages for the Simscape model



(b) Capacitor voltages for the *ESA Control Toolbox* model

Fig. 9. Capacitor load balancing comparison.

C. Synthesis results

As a further study, synthesis results for the *ESA Control Toolbox* 3L-ANPC model have been carried out using the Xilinx Artix-7 FPGA, specifically the model xc7a200tfbg676-2. This FPGA includes 33,650 slices, with every slice comprising four 6-input Look-Up Tables (LUTs) and eight flip-flops (FFs), and 740 Digital Signal Processing (DSP) blocks. The synthesis analysis has been performed in Vivado, with the results presented in Table IV. The last column, $T_{clk,min}$, indicates the minimum achievable clock period for the model. Note how, despite carrying out the previous comparison study with a time delta of 500 ns, it would have been possible to reduce that value up to around 15 ns, which presents a considerably higher clock frequency and therefore higher precision.

TABLE IV
FPGA RESOURCES USED BY THE SYNTHESIZED 3L-ANPC MODEL

Resources	LUTs	FFs	DSPs	$T_{clk,min}$ (ns)
Used	638	160	10	15.101
% of total	0.47	0.06	1.35	-

IV. CONCLUSIONS

Implementing HIL models in FPGAs by directly coding in a HDL presents a challenging and time-consuming task for HIL model developers. While the MATLAB Simulink HDL Coder provides a good alternative by converting Simulink models into synthesizable VHDL code, updating MATLAB tools or making small algorithm changes can result in the need to retest and verify the synthesized VHDL code.

The *ESA Control Toolbox* presented in this paper provides another Simulink-based approach for model generation in HIL testing. It addresses the possible drawbacks of MATLAB HDL Coder by providing static VHDL code for each Simulink block that can be used in sensitive applications, and thus eliminates the need to verify VHDL code performance after algorithm changes or MATLAB tool updates. In order to assess and verify the performance of the proposed toolbox, a case study modeling a 3L-ANPC converter circuit has been implemented and compared with an equivalent model designed with the MATLAB Simscape blocks. Using both open-loop and closed-loop controllers (such as MPC), similar behavior is observed.

To sum up, the *ESA Control Toolbox* presents not only a powerful tool for sensitive space applications but also a great alternative for HIL model implementation into FPGAs, providing a reliable choice for Hardware-In-the-Loop designers. Additionally, the synthesized code for the toolbox designed models is comparable in terms of area and speed to the equivalent hand-coded VHDL, ensuring high performance and reliability in FPGA implementations.

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