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NONLINEAR MPPT CONTROL OF SQUIRREL CAGE INDUCTION GENERATOR-WIND TURBINE

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ABSTRACT

This paper presents a nonlinear control method to track the maximum power point of wind turbine equipped with Squirrel Cage Induction Generator (SCIG). Since the mechanical power of wind turbine is function of its shaft speed at a given wind velocity, the proposed controller provides the desired voltage at the output of Voltage Source Converter (VSC) so as to control the generator speed and then extracting maximum power from wind. The controllers exploit the backstepping scheme to calculate the required converter's control to eliminate the instantaneous errors of mechanical speed and flux. The proposed control laws are derived from the Lyapunov approach which is well suited for this nonlinear system. Finally, the simulation results verify the stability and effectiveness of the control strategy proposed.

Keywords: *Wind Power, SCIG, VSC, Nonlinear Control, Backstepping Controller, Lyapunov Approach, MPPT*

1. INTRODUCTION

Renewable energies are becoming increasingly important as alternative energy sources. Wind power is one of the most-effective systems available today to generate electricity from renewable sources. This energy is transformed into mechanical energy by wind turbine and then converted to electrical energy by electrical generator and a power converter [1]. To obtain maximum benefit from the wind energy, variable speed wind turbines are being used in general. Variable speed wind turbine systems produce variable voltage and frequency when no controller element is used. In order to extract maximum power in desirable values from variable speed wind generation systems, they must be operated together with the controller element [2]. The conventional back-to-back voltage source converter is usually used to connect the generator to the grid. The VSC can increase the system robustness and MPPT tracking control, many studies have been conducted to analyze, develop and improve the extraction of maximum power in literature [3-11]. Different types of generator can be used to realize a wind power generation (WPG). The common candidates for the generator are Doubly-fed Induction Generators (DFIG), Squirrel Cage Induction Generators (SCIG), and Permanent Magnet Synchronous Generators (PMSG). (WPGs) have so many uncertainties due to erratic nature of wind-based systems. Therefore, the controller should accommodate the effects of uncertainties and keep the system stable against a large variation of system parameters. The conventional PI-based controllers cannot fully satisfy stability and performance requirements. On the other hand, the system is highly nonlinear and has a large range of operating points. Thus, linearization around one operating point cannot be employed to design the controller. Nonlinear control methods can be used to effectively solve this problem [1] and [3].

In attempt to achieve high performances in the steady state as well as during the transients, a different nonlinear control structure must be applied. In the recent two decades, many modified nonlinear state feedback such as input-output feedback linearization, control based on sliding mode have been applied to more improve the induction machine control performances [12].

However, the behavior of the SCIG-wind turbine system using backstepping approach with "virtual contron" has not been tested. The objective of this paper is to implement the backstepping control to wind turbine equipped with SCIG, so as to regulate mechanical speed provides by MPPT algorithm and flux to their input references even during a wind speed conditions, and that a perfect conversion of wind power to electrical power.

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Dynamic modeling and simulation of the SCIG-wind turbine power generation system and backstepping controllers are performed by means of Matlab/Simulink. Behavior of SCIG-wind turbine depending on wind velocity variation is observed through the simulation study.

2. WIND TURBINE MODEL

2.1 System Configuration

The schematic diagram of the studied wind turbine equipped with SCIG is shown in Fig.1. The rotor shaft of the studied SCIG is coupled to the hub of turbine by through a gearbox for transforming low rotational speeds of turbine to the required higher rotational speeds of the SCIG. The mechanical energy is transforming to electrical energy by the generator. The nonlinear backstepping controller provides proper switching signals for the VSC so as to extract maximum power from the wind.

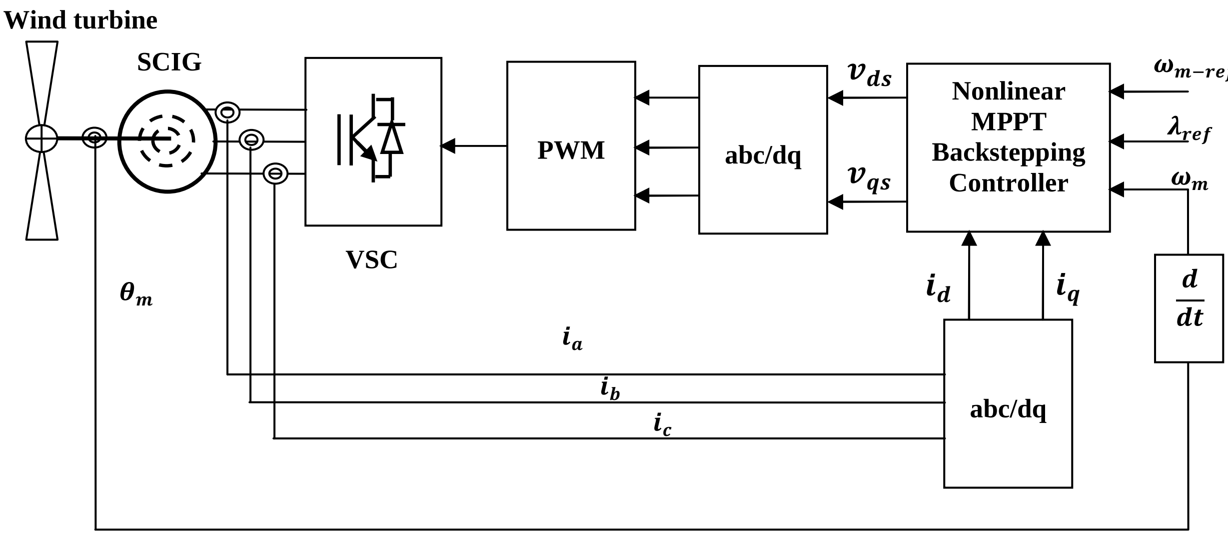

Figure 1 . The overall diagram of the proposed control

2.2 Wind Turbine

The wind turbine input power usually is

$$P_v = \frac{1}{2}\rho A v^3 \quad (1)$$

The output mechanical power of wind turbine is:

$$P_m = C_p P_v = \frac{1}{2} C_p(\delta,\beta)\rho A v^3 \quad (2)$$

where δ is defined as the ratio of the tip speed of the turbine blades to wind speed:

$$\delta = \frac{R\omega_t}{v} = \frac{R\omega_m}{Gv} \quad (3)$$

ω_t is the turbine speed, it is a function of mechanical speed ω_m and gear ratio G.

We consider a generic equation to model a power coefficient C_p, based on the modeling turbine characteristics described by [13]:

$$C_p(\delta,\beta) = 0.5109\left(\frac{116}{\delta_i} - 0.4\beta - 5\right)\exp\left(\frac{-21}{\delta_i}\right) + 0.0068\delta \quad (4)$$

$$\delta_i^{-1} = \left[\frac{1}{(\delta + 0.08\beta)} - \frac{0.035}{(\beta^3+1)}\right]$$

In order to make full use of wind power, in low wind speed β should be equal to zero [14]. Fig. 2 illustrates the wind turbine power curve when β is equal to zero. From the Fig.2 we can see there is one specific mechanical speed (or generator speed) at which the output power of wind turbine is optimal. Connected all the maximum power point of each power curve, the optimal power curve ($P_{m\text{-}opt}$ curve) is gotten. When the wind turbine is in the $P_{m\text{-}opt}$ curve, the turbine will get the maximum power P_{max}. In this case, the maximum value of power coefficient C_p is C_{Pmax}=0.47, is achieved for β=0° and δ_{opt}=8.1, Fig. [3].

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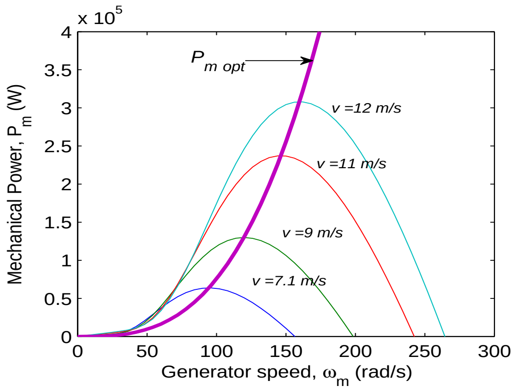

Figure. 2. Wind turbine power curve

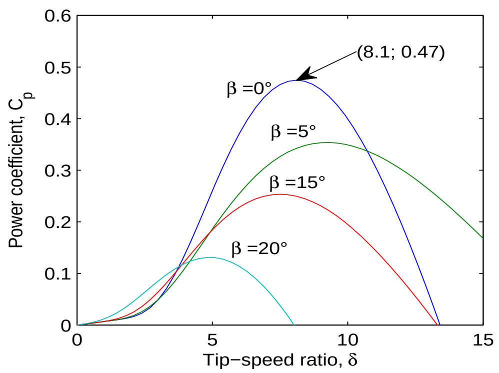

Figure. 3. Characteristics Cp vs δ, for various values of pitch angle β

2.3 Squirrel Cage Induction Generator Model

The SCIG mathematical model can be expressed in a reference frame rotating with arbitrary angular speed by the following equations [14]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\ v_{qs} = R_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \\ v_{dr} = 0 = R_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - \omega_r \lambda_{qr} \\ v_{qr} = 0 = R_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} + \omega_r \lambda_{dr} \end{cases} \quad (5)$$

where subscripts 's' and 'r' refer to the stator and rotor side respectively, subscripts 'd' and 'q' refer to the d-axis and q-axis respectively. R_s and R_r are, respectively, the stator and rotor phase resistances, ω is the electrical speed, λ is the rotor-flux

The stator and rotor flux can be expressed as [14]

$$\begin{cases} \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \\ \lambda_{dr} = L_r i_{dr} + L_m i_{ds} \\ \lambda_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (6)$$

where i_{ds}, i_{qs}, i_{dr}, i_{qr} are, respectively, the direct and quadrature stator and rotor currents and L_m is the mutual inductance.

The electromagnetic torque can be calculated as [14]

$$T_{em} = \frac{pL_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) \quad (7)$$

where p, is the pair-pole number

The voltage and flux equation can be supplemented by the mechanical equation for the drive train (gearbox) by (8) to complete the model of generator used in this paper

$$J\frac{d\omega_m}{dt} = T_m - T_{em} \quad (8)$$

where T_m is the mechanical torque. J is the total inertia, it can be calculated as:

$$J = \frac{J_t}{G^2} + J_g \quad (9)$$

where J_t and J_g are respectively the turbine inertia and the generator inertia

The above model (5) to (9) can be presented as differential equations for the stator currents and rotor flux vector components under the following form:

$$\frac{di_{ds}}{dt} = -a_1 i_{ds} + \omega_s i_{qs} + a_2 \lambda_{dr} + a_3 \omega_m \lambda_{qr} + a_4 v_{ds} \quad (10)$$

$$\frac{di_{qs}}{dt} = -a_1 i_{qs} - \omega_s i_{ds} + a_2 \lambda_{qr} - a_3 \omega_m \lambda_{dr} + a_4 v_{qs} \quad (11)$$

$$\frac{d\lambda_{dr}}{dt} = a_5 i_{ds} - a_6 \lambda_{dr} + (\omega_s - p\omega_m)\lambda_{qr} \quad (12)$$

$$\frac{d\lambda_{qr}}{dt} = a_5 i_{qs} - a_6 \lambda_{qr} - (\omega_s - p\omega_m)\lambda_{dr} \quad (13)$$

$$\frac{d\omega_m}{dt} = a_7(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) - a_8 \omega_m - a_9 T_m \quad (14)$$

Where:

$$a_1 = (L_r^2 R_s + L_m^2 R_r)/\sigma L_s L_r^2 \ ; a_2 = R_r L_m/\sigma L_s L_r^2$$

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$a_3 = pR_r/\sigma L_s L_r$; $a_4 = 1/\sigma L_s$; $a_5 = R_r L_m/L_r$;

$a_6 = R_r/L_r$ $a_7 = pL_m/JL_r$; $a_8 = f/J$; $a_9 = 1/J$

3. NOLINEAR MPPT CONTROL STRATEGY FOR SCIG-WIND TURBINE

The basic idea of the backstepping design is the use of the "virtual control" quantities to decompose systematically a complex non-linear control structure problem into simpler and smaller ones. Backstepping design is divided into two various design steps. In each one we deal with an easier and single-input-single-output design problem and each step provide a reference for the next design step [9] From the presented above model it seen that the squirrel cage induction generator is a nonlinear multivariable system with coupling between direct and quadrature axis.

This model is dependent on the stator electrical speed ω_s , this variable can be calculated if dq reference frame synchronized with rotor flux.

Fixing the d-axis of the rotating reference frame on the rotor flux vector, we have $\lambda_{dr}=\lambda_r$ and $\lambda_{qr}=0$. In this case, two state variables have been proposed for describing the SCIG model in order to extracting maximum power from turbine, mechanical speed and rotor flux, as follows:

$$\dot{\omega}_m = a_7\lambda_{dr} i_{qs} - a_8\omega_m - a_9 T_m \quad (15)$$

$$\dot{\lambda}_{dr} = a_5 i_{ds} - a_6\lambda_{dr} \quad (16)$$

Therfore, the error is defined using the rotational speed $e_\omega = \omega_{m-ref} - \omega_m$ and rotor flux $e_\lambda = \lambda_{ref} - \lambda_{dr}$ and the first Lyapunov function is defined as

$$V = \frac{1}{2}e_\omega^2 + \frac{1}{2}e_\lambda^2 \quad (17)$$

The time derivative of V is given by

$$\dot{V} = \dot{e}_\omega e_\omega + \dot{e}_\lambda e_\lambda \quad (18)$$

i_{ds} and i_{qs} are considered to be the virtual controls input. Thus, there references are obtained as:

$$i_{sq}^* = \frac{1}{a_7\lambda_{dr}}\left[\dot{\omega}_{m-ref} + a_8\omega_m + a_9 T_m + k_\omega e_\omega\right] \quad (19)$$

$$i_{sd}^* = \frac{1}{a_5}\left[\dot{\lambda}_{ref} + a_6\lambda_{dr} + k_\lambda e_\lambda\right] \quad (20)$$

k_ω and k_λ are positive design constants that determine the closed loop dynamics.
Equations (19) and (20) indicate that the virtual controls should be in order to satisfy the control objectives. So they provide the references for the next step and try to make the signals i_{ds} and i_{qs} behave as desired. So, we define again the error signals involving the desired variables in (19) and (20):

$$e_{ids} = i_{ds}^* - i_{ds} \quad (21)$$

$$e_{iqs} = i_{qs}^* - i_{qs} \quad (22)$$

Finally, we extended the Lyapunov function in (17) to include the states variables e_{ids} , e_{iqs} as:

$$V_e = \frac{1}{2}(e_\omega^2 + e_\lambda^2 + e_{i_{ds}}^2 + e_{i_{qs}}^2) \quad (23)$$

Control laws are derived by differentiating the Lyapunov function with respect to time.

$$v_{ds} = \frac{1}{a_4}\left(\frac{di_{ds}^*}{dt} - \left(-a_1 i_{ds} + \omega_s i_{qs} + a_2\lambda_{dr}\right) + a_5 e_\lambda + k_{i_{ds}} e_{i_{ds}}\right) \quad (24)$$

$$v_{qs} = \frac{1}{a_4}\left(\frac{di_{qs}^*}{dt} - \left(-a_1 i_{qs} - \omega_s i_{ds} - a_3\omega_m\lambda_{dr}\right) + a_7\lambda_{dr} e_\omega + k_{i_{qs}} e_{i_{qs}}\right) \quad (25)$$

In this case, the Lyapunov function derivative is given by

$$\dot{V}_e = -k_\omega e_\omega^2 - k_\lambda e_\lambda^2 - k_{i_{ds}} e_{i_{ds}}^2 - k_{i_{qs}} e_{i_{qs}}^2 \leq 0 \quad (26)$$

The controller of nolinear MPPT is implemented by (24) and (25) which is introduced in Fig. 4 and simulated by using Matlab/simulink.

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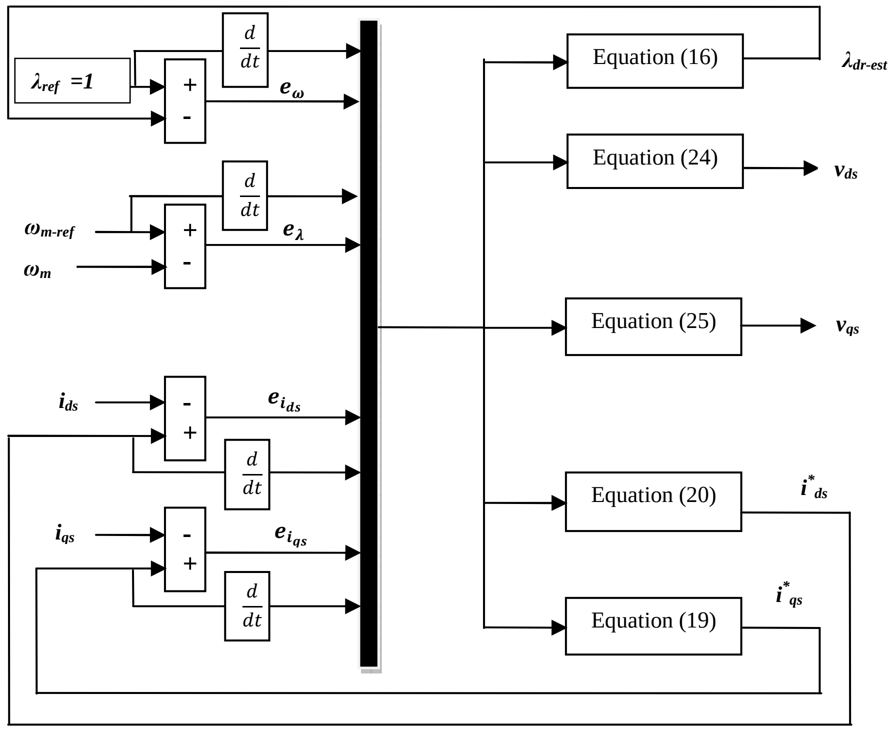

Figure 4. Detailed diagram of the nonlinear backstepping controller scheme

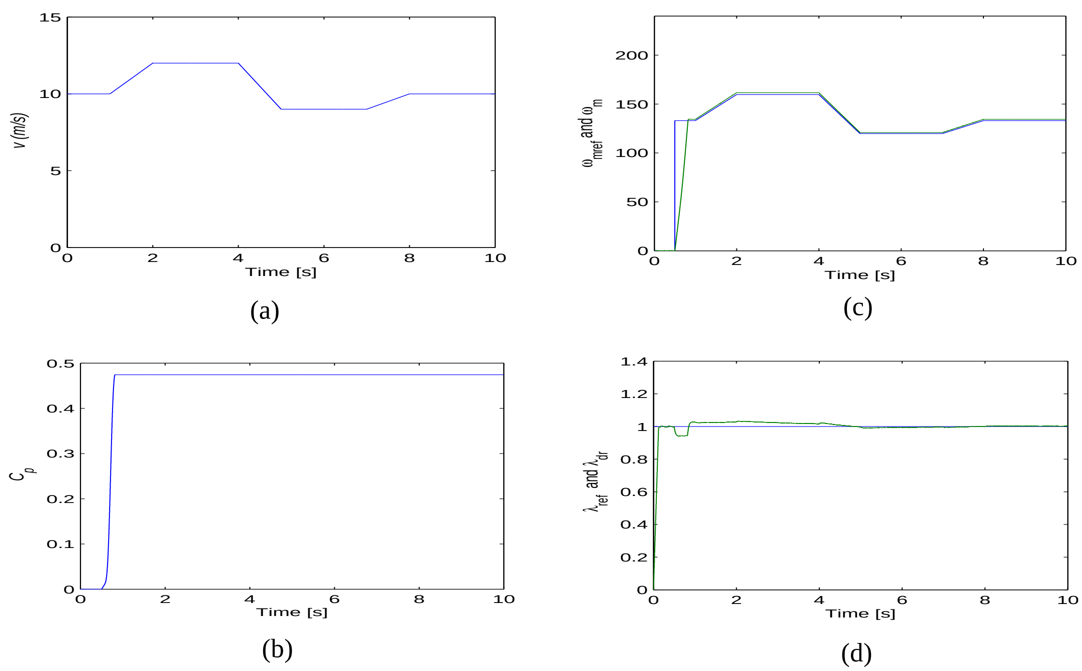

Figure 5. SCIG wind power performances with nonlinear Backstepping control

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4. SIMULATIONS RESULTS

The model of the SCIG based variable speed wind turbine system of figure 1 is built using MATLAB\SIMULINK dynamic system simulation software. The parameters of the turbine and SCIG used are given in appendix, respectively in Table I and Table II. The VSC and the nonlinear backstepping control algorithm are also implemented and included in the model. The PWM VSC is operated at 10 kHz.

Figure (5) shows the response of the system for a change of wind velocity, from 10 m/s to 12 m/s to 9 m/s and then comes back to 10 m/s. Fig (a) shows the wind velocity profile imposed. At t=0.5 s the mechanical speed reference provides by MPPT is applied. During test, the power coefficient C_p is kept at their optimal value (C_P=0.47), simulation result is shown in Fig (b).

Fig (c) illustrates the mechanical speed tracking trajectory for a change in the wind velocity with the proposed nonlinear backstepping controller, according to the wind turbine characteristics, the optimal mechanical speed of SCIG is calculate as:

$$\omega_{m-ref} == \frac{Gv\delta_{opt}}{R} = \frac{23 \times 8.1 \times v}{14}$$

So, SCIG mechanical speed reference is $\omega_{m-ref} = 14 \times v$.

According to $\omega_{m\text{-}ref}$, when wind velocity v is 10 m/s, the optimal mechanical speed is 140 rad/s, and when wind velocity v is 12 m/s, the optimal mechanical speed is 168 rad/s, etc. It is seen that in MPPT control, the generator speed has to change to keep at any wind velocity maximum power coefficient (C_p=0.47) and so, extraction of maximum power.

Fig (d) shows the rotor flux, as desired, the direct rotor flux component is perfectly tracked to their input references with the proposed nonlinear control strategy. As can be seen, the adopted control strategy is capable of providing accurate tracking for mechanical speed and flux references and, meanwhile, keeping good decoupling of electromagnetic torque and flux regulations, finally, an excellent MPPT control is achieved.

5. CONCLUSION

This paper presented a nonlinear backstepping approach for maximum power point tracking MPPT of SCIG-wind turbine generation system. MATLAB/similink simulation results show the stability and effectiveness of this strategy of control. The validity of this proposed method is confirmed by theoretical analysis and simulation results. The nonlinear backstepping control theory can be easily exploited in the wind power generation systems equipped with SCIG-based variable speed.

APPENDIX:

TABLE I
PARAMETERS OF THE TURBINE

Item	Symbol	Value
Density of air	ρ	1.22 kg/m3
Area swept by blades	A	615.8 m2
Speed-up gear ratio	G	23
Base wind speed	v_n	12 m/s
Turbine inertia	J_t	50 kg.m2

TABLE II
PARAMETERS OF THE SCIG

Item	Symbol	Value
Rated power	P_n	300 kW
No. of poles	p	2
Rated speed	ω_n	158.7 rad/s
Stator resistance	R_s	0.0063 Ω
Stator inductance	L_s	0.0118 H
Mutual inductance	L_m	0.0116 H
Rotor resistance	R_r	0.0048 Ω
Rotor inductance	L_r	0.0116 H

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