



Accurate Control Method of Vane Direction Based on Pressure Difference Feedback in Active Yaw System for Wind Turbines

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In this paper, an active yaw system with valve-controlled hydraulic motor is designed. Correspondingly, the accurate control method of vane direction based on pressure difference feedback is presented. Then the simulation analysis is conducted in AMESim[®]. The simulation results show that the control method presented in this paper is efficient. Moreover, the control accuracy can be improved by decreasing the friction torque or adding a friction compensation link into the controller. At last, an experimental platform is built to verify the feasibility of the control method presented. The achievements provide theoretical and practical guidance for the design of wind turbine active hydraulic yaw systems.

Keywords: Wind turbines, active yaw, differential pressure feedback, accurate control method of vane direction

Target audience: Energy Industry, Wind Generator, Hydraulics

1 Introduction

The wind turbines yaw systems, including passive and active systems, can align the vane direction to the wind direction rapidly and steadily, which improves the generating efficiency. The passive yaw system is only adopted on small off-grid wind turbines. Although having a complicated structure, the active yaw system makes the yaw process controllable. So it has been widely used^[1,2]. Usually, the motors are used as the driving unit of active yaw systems. Besides, the hydraulic cylinders and hydraulic motors can also be adopted.

Because of the varying wind direction, there exists some errors in the anemoscope detection results, which makes the active yaw system difficult to control the rotation position of engine room. That reduces the utilization rate of wind energy and exerts asymmetric force on symmetric vanes of wind turbines, which results in engine room's vibration and vane fatigue^[3,4].

To eliminate the negative influence from the error of anemoscopes, the traditional method is to introduce power control within small control angles (usually within 15 degrees). Though a better control effect can be achieved, the power control method needs a complicated control strategy, which increases the difficulty in system design and control^[5]. Aimed at the deficiency of traditional methods, an active yaw system with valve-controlled hydraulic motor is designed. Correspondingly, the accurate control method of vane direction based on pressure difference feedback is presented. Then the simulation analysis and experimental verification are conducted. It provides theoretical and practical guidance for the design of active hydraulic yaw systems and accurate control methods of vane direction.

2 Hydraulic design of the active yaw system

2.1 Load calculation of the active yaw system

When wind blows the vane, the kinetic energy of wind per unit of time can be expressed as follows:

$$P_F = \frac{1}{2}mv^2$$

where, m — wind mass flow (kg/s)

v — wind speed (m/s).

The wind mass flow per unit of time can be expressed as follows:

$$m = \rho Av$$

where, ρ — air density (kg/m³)

A — swept area of the wind wheel in one rotation (m²)

The energy transferred to wind wheel per unit of time can be expressed as follows:

$$P_Y = C_P P_F$$

where, C_P — wind energy efficiency of wind wheel

The average pressure on the swept area of wind wheel is expressed as follows:

$$P_H = \frac{P_Y}{Av}$$

Combine equation (1)-(4), the following result can be obtained:

$$P_H = \frac{1}{2}C_P \rho v^2$$

The wind blows the vane with a certain angle, the force diagram of wind wheel is shown in Figure 1.

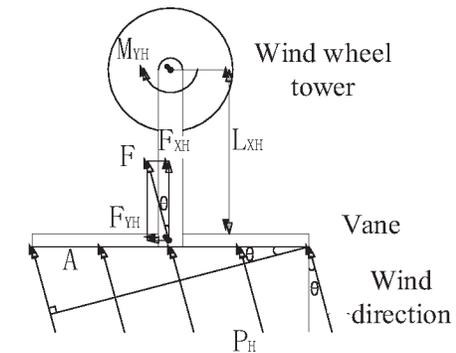


Figure 1: Force diagram of wind wheel.

The torque exerted on the wind wheel tower can be reached:

$$M_{YH} = F_{YH}L_{XH} = P_H A \cos\theta \sin\theta L_{XH} = \frac{1}{2}P_H A L_{XH} \sin 2\theta$$

where, L_{XH} — friction torque (Nm);

M_v — viscous torque (Nm);

I_M — inertia moment on the axis of wind wheel tower (m⁴);

α — angle accelerate of cabin while yawing (rad/s²);

M_a — other torques during yawing, including the eccentric torque resulted from aerodynamic force and the torque caused by gust load (Nm)

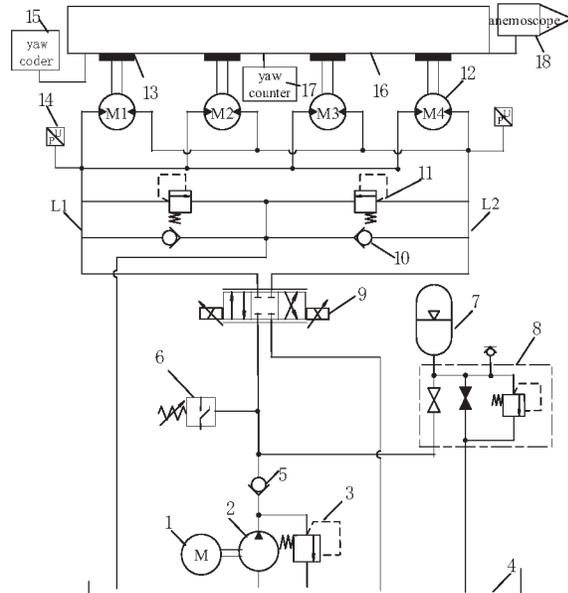
2.2 Hydraulic principles of active yaw system

The active yaw control can align the vane direction to the wind direction automatically when the wind speed is available and make the vane direction vertical to the wind when the wind speed is unavailable. Besides, the function of untwisting the cables automatically is also required to make wind turbines operate steadily and efficiently. The relative parameters of 850kW wind turbine is shown in Table1.

Parameter	Symbol	Value	Unit
Rated generation power	p_r	850	kW
Rated wind speed	v_r	13	m/s
Best aerodynamic coefficient	$C_{p\ max}$	0.4496	
Swept area of vanes and wind wheel hub	A	1559.9	m ²
Vertical distance between the center of Tower and wind wheel	L_{XH}	3.177	m

Table 1: Parameters of 850kW wind turbine.

According to the load calculation result and the requirement of active yaw, a hydraulic system is designed according to the parameters of 850kW wind turbine. The system principle diagram is shown in Figure 2.



1. motor 2. pump 3. relief valve 4. tank 5. check valve 6. pressure relay 7. energy accumulator 8. valve bank for energy accumulator 9. proportional direction valve 10. check valve 11. relief valve 12. hydraulic motor 13. yaw gears 14. pressure sensor 15. coder 16. cabin internal-gear ring 17. counter 18. anemoscope

Figure 2: Principle of active yaw hydraulic system.

In parallel connection, four hydraulic motors (12) with low speed and big torque can provide enough torque to rotate the cabin through internal-gear ring (16). Energy accumulator (7) provides the system with hydraulic power. The start and stop of the motor are controlled by the pressure relay which comes after the energy accumulator (7). This can realize the oil supply for the energy accumulator (7). Relief valve (17) is used to ensure the safety and check valve (10) is used to avoid the lower pressure cavity from sucking air.

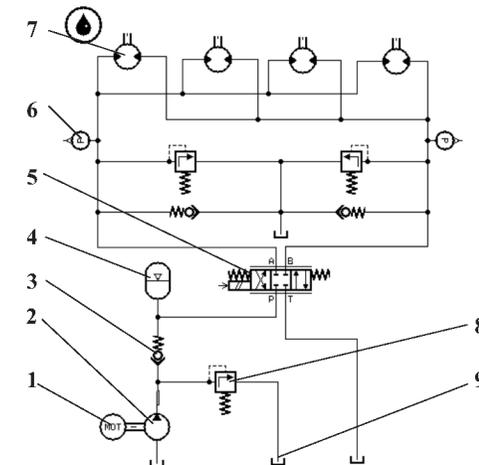
To achieve position closed loop control, the yaw system uses proportional valve-controlled hydraulic motors. According to the error between coder (15) and the detective values of anemoscope (18), the opening gap of proportional valve (9) is controlled to align the vane direction to the wind direction rapidly. The system will untwist the cables automatically when counter (17) give the corresponding signal; when the wind speed detected by anemoscope (18) is beyond the available scale, the system will stop generating.

If there is a certain nonzero angle between vane direction and wind direction, the force on the swept plane of vane will lead to a pressure difference between the two ends of hydraulic motors. According to the pressure difference between pipe L1 and pipe L2 detected by pressure sensor (14), the proportional valve (9) is controlled to align the vane direction accurately.

3 The simulation model of active yaw hydraulic system

3.1 AMESim® simulation model of hydraulic system

According to the hydraulic principle diagram, a simulation model shown in Figure 3 is built in AMESim® software.



1. motor 2. fixed displacement pump 3. check valve 4. energy accumulator 5. proportional direction valve 6. pressure sensor 7. hydraulic motor 8. relief valve 9. tank

Figure 3: AMESim® simulation model of active yaw hydraulic system.

3.2 AMESim® simulation model of load

According to the torque on wind wheel tower exerted by wind, the load simulation model of the system is built in AMESim® with the consideration of the gear transmission ratio, system inertia, friction and viscous damping etc. The model is shown in Figure 4.

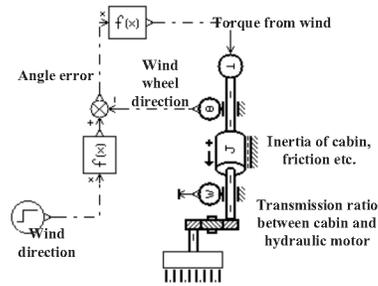


Figure 4: Load AMESim® simulation model of hydraulic system.

3.3 AMESim® model of accurate vane direction control

The accurate vane direction control is achieved based on the detection of the pressure difference between both ends of the hydraulic motor. An inertia link is designed to eliminate the influence from the medium-high frequency noise of pressure signals. The dead zone is designed to stop the vane direction control within the permissible error. PID control method is adopted in the system. Meanwhile, the amplitude limitation of the control signals and the dead zone of proportional direction valve are also considered. The AMESim® simulation model of accurate vane direction control is shown in Figure 5.

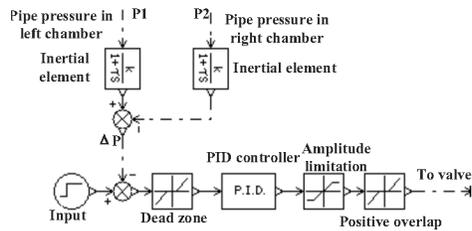


Figure 5: AMESim® simulation model of accurate control method for the wind.

3.4 AMESim® simulation model of the whole system

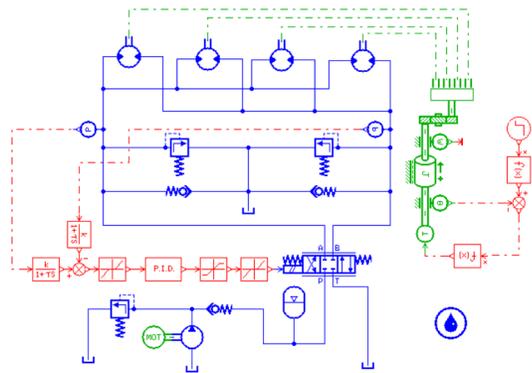


Figure 6: AMESim® simulation model of the whole system.

3.5 Parameters in AMESim® simulation model

In the simulation model, the friction torque is simplified to a constant. Some factors such as the extra eccentric torque, the gust torque and the leakage of hydraulic motors are also ignored. The simulation sampling time is 10ms and the simulation duration is 20s. Other parameters are shown in Table 2.

Parameter	Value
Transmission ratio (actual value)	16.7
Inertia torque of cabin and axis of wind wheel tower (calculated from the 3D model)	$8.96 \times 10^5 \text{ kgm}^2$
The mass of vane and wheel hub (calculated from the 3D model)	$1.14 \times 10^4 \text{ kg}$
Total mass of wind wheel and cabin (calculated from the 3D model)	$4.5 \times 10^4 \text{ kg}$
Motor speed	990 r/min
Pump displacement	4ml/r
Rate volume of energy accumulator	30 L
Opening pressure of check valve	0.15 MPa
Rate flow of proportional direction valve	8 L/min
Displacement of hydraulic motor	940 ml/r
System pressure	25 MPa
Parameters of pipes	Estimated according to the actual situation
oil	Software default

Table 2: Parameters of AMESim® Simulation model.

4 Simulation analysis of accurate vane direction control

4.1 The influence of the angle between wind and vane on system characteristics

The friction torque during yaw is estimated as 5000N^[6]. The initial angle between vane direction and wind direction is zero. Then the step change signals, which are set as 5, 10 and 15 degrees, are input into the system respectively. Using the accurate control method of vane direction, the variation curves of the pressure in both cavities of hydraulic motors and the angle between vane direction and wind direction are achieved, which are shown in Figure 7 and Figure 8.

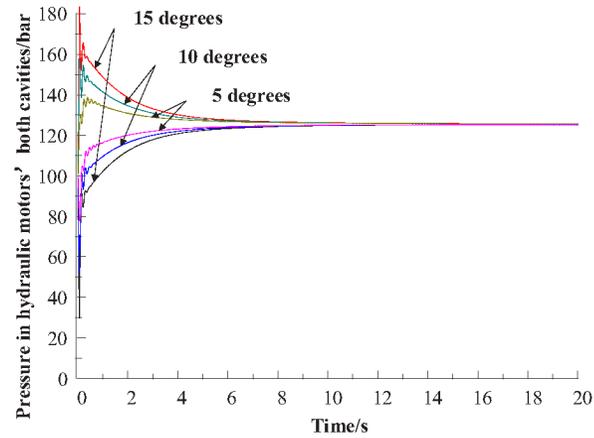


Figure 7: Pressure curves of hydraulic motor cavities.

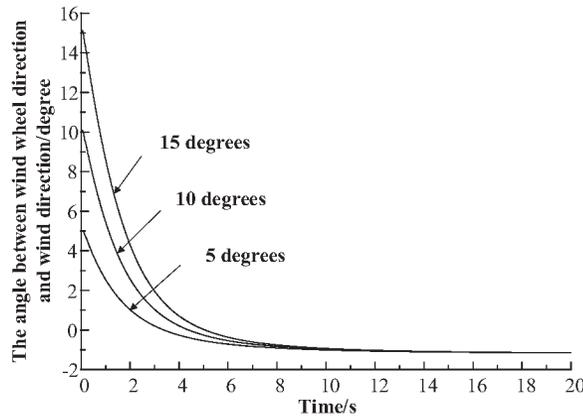


Figure 8: Angle curves between wind and wind wheel.

The following things can be seen from the curves. Because of the angle between vane direction and wind direction, the inclined wind flow exerts a torque on engine room, which results in the pressure difference between hydraulic motor's two cavities. The larger the angle is, the bigger the pressure difference is. The vane direction control method based on pressure difference feedback is applied to control the pressure difference between hydraulic motor's two cavities by adjusting the opening gap of the proportional valve. The less pressure difference means the smaller angle error between vane direction and wind direction, which achieves the accurate vane direction control.

Moreover, when the step changes of the initial angle are 5, 10 and 15 degrees, the adjust time of vane direction is 5.1s, 6s and 7s respectively. It meets the performance requirement of control speed.

4.2 The influence of engine room's friction torque on system control accuracy

The pressure difference between hydraulic motor's two cavities resulted from friction torque leads to system overshoot. So simulations with friction torques of 7000Nm, 5000Nm and 3000Nm are conducted, from which the curves of the angle between wind wheel direction and wind direction are obtained. It can be seen from the curves in Figure 9 that friction torque has great effect on vane direction control accuracy. The smaller the friction torque is, the higher the control accuracy is.

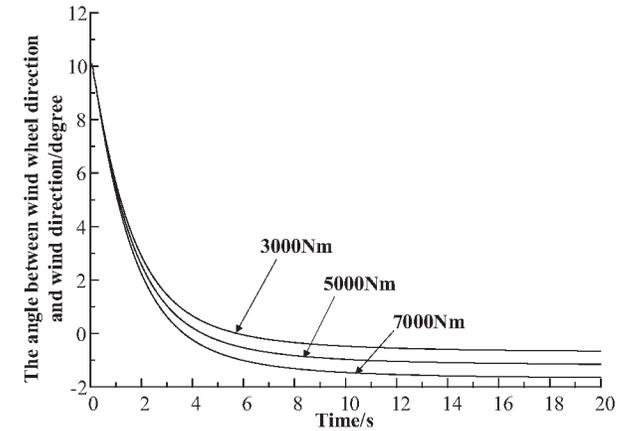


Figure 9: Angle curves between wind and wind wheel.

4.3 Compensation control of friction torque

The friction torque is estimated as 5000Nm. The influence on the pressure of hydraulic motor's two cavities is calculated. The friction torque direction is confirmed by detecting the rotation direction of engine room. The friction compensation link is added between dead zone link and PID controller. The simulation model of friction compensation link is shown in Figure 10.

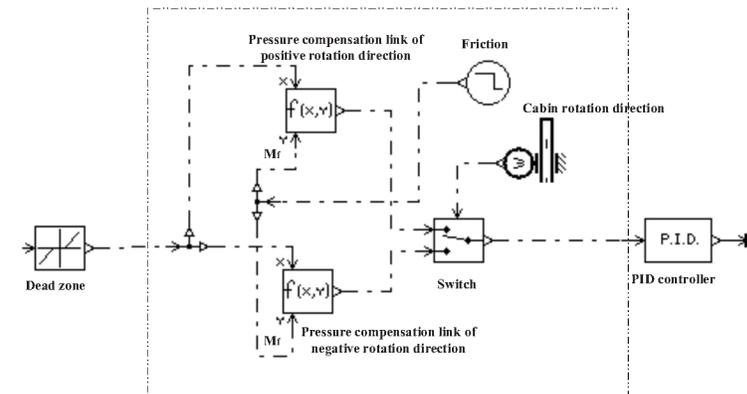


Figure 10: AMESim[®] simulation model of friction torque compensation.

Conduct the simulation with friction compensation link, the angle curves shown in Figure 11 can be achieved. It can be seen from the curves that the friction compensation link can eliminate the steady-state error and improve the system accuracy.

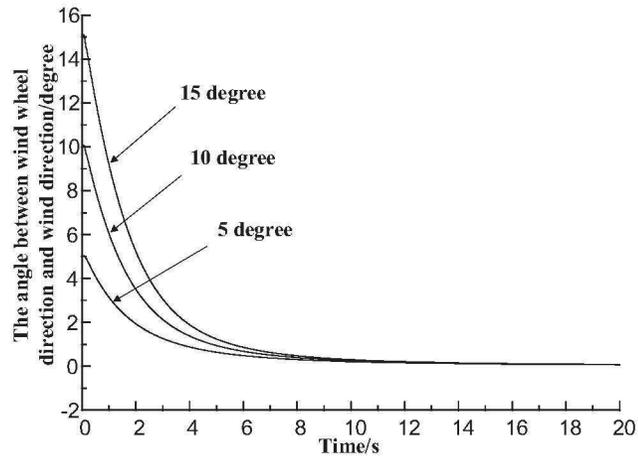


Figure 12: Angle curves between wind and wind wheel.

5 Simulation experiments of accurate vane direction control

A simulation experiment platform of 850kW hydraulic wind turbine yaw system is built to verify the feasibility of the vane direction control strategy.

5.1 Hardware composition of simulation experimental platform

The experimental platform is composed of load simulation system, yaw system, control system and detection system. The overall structure is shown in Figure 12.

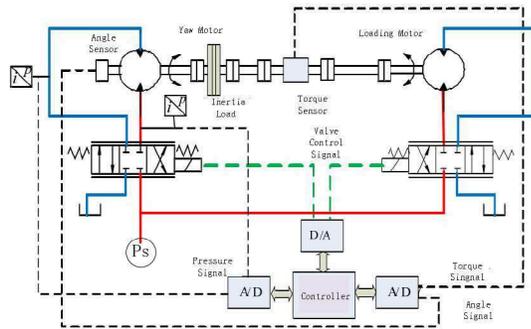


Figure 12: Overall schematic of the simulation experimental platform.

5.1.1 Detection system of wind turbine yaw simulation

The wind direction is decided by the input signal. The vane direction is detected by angle sensor. Driven by wind, the wind wheel generates a yaw load, which is detected by the torque sensor. The pressure of both ends of hydraulic motor is detected by pressure transmitter. The adopted sensors are shown in Figure 13.



Figure 13: Adopted sensors.

5.1.2 Hydraulic system of experimental platform

The yaw simulation hydraulic system is composed of a variable pump, a constant delivery pump with low speed and large torque, hydraulic control valves, a control system, detection components, valve blocks and pipes. Its semi-physical simulation experimental platform is shown as Figure 14.

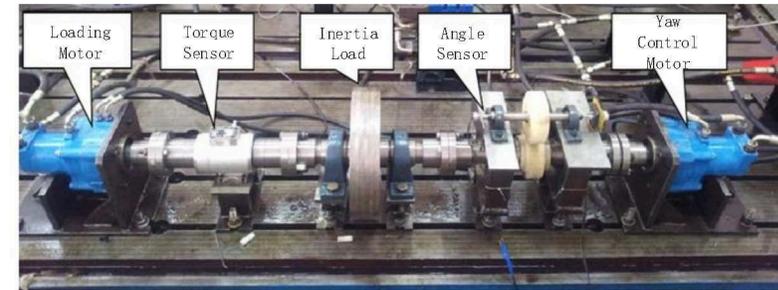


Figure 14: Structure schematic of the hydraulic system of the simulation experimental platform.

5.1.3 Control system of experimental platform

The system control and data collection are conducted on dSPACE system, which is composed of industrial personal computer, data collection card and dSPACE controller. The picture of dSPACE system is shown in Figure 15.

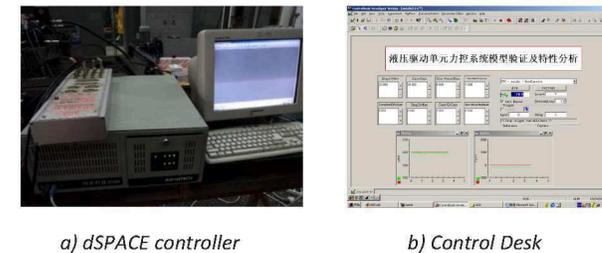


Figure 15: Structure schematic of the hydraulic system of the simulation experimental platform.

5.2 Experimental scheme of accurate vane direction control

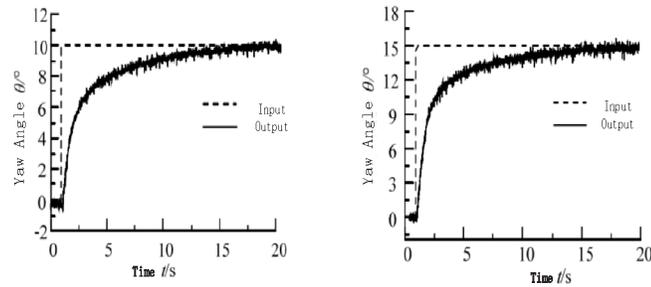
On the yaw simulation experimental platform, when wind direction changes a small angle, the pressure difference feedback principle is used to control the vane direction. The specific step is expressed as follows:

- (1) Different signals of small angles are input into the system. Then a yaw torque is generated and it produces the pressure in both ends of hydraulic motors.
- (2) The pressure is output to computer through pressure transmitter. Then the pressure difference between both ends of hydraulic motors is calculated. The difference control signal is achieved by comparing that pressure

difference with the normal difference without wind. That signal is input into the control system to align the accurate control on vane direction.

5.3 Experiments of accurate vane direction control simulation

The system pressure is set to 10MPa. When the input angle signal is 10 degrees and 15 degrees, the yaw angle curves of the simulation yaw system are shown in Figure16.



a) An input angle signal of 10 degrees b) An input angle signal of 15 degrees

Figure 16: Experimental curves of accurate control of vane direction.

In Figure16, there is a step change of wind direction at 2s. By using pressure difference feedback control method, the yaw process lasts about 13s. The steady-state angle error meets the accuracy requirement. The accurate control of vane direction is achieved.

6 Conclusions

1. An accurate vane direction control method is presented and it is verified to be efficient through simulation and experiments.
2. The larger angle between vane direction and wind direction brings the larger pressure difference in two cavities of hydraulic motor and longer yaw time.
3. Engine room's friction torque has great effect on control accuracy. The smaller the friction is, the higher the control accuracy is. The friction torque can be reduced by improving the lubrication of yaw bearings.
4. The pressure difference signal in friction compensation link can be obtained by measuring the actual friction torque in wind turbines. An appropriate friction compensation torque can greatly improve the system accurate.
5. Based on the principle of pressure difference feedback, the accurate vane direction control strategy is verified to be feasible and efficient.

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