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Fractional order controller of a stand alone wind energy system with battery storage

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***Abstract*—This paper presents fractional order controller FOPID for variable speed wind turbine coupled to a permanent magnet synchronous generator (PMSG). This controller is derived using fractional regulation parameters denoted λ and μ used to control accurately the mechanical speed and to extract maximum torque when wind speed is less or above the rated speed. Our proposed FOPID is synthesized to guarantee a constant DC link voltage. Actuator model of the pitch control, the turbine linearzed model and the bloc diagram of the proposed speed controller are simulated by MATLAB-Simulink Software prove the effectiveness of the robust FOPID controller.**

***Index Terms*—dc-dc converter, battery storage, FOPID controller ,closed loop control**

I. INTRODUCTION

In recent years due to global environmental concerns associated with conventional generation and potential worldwide energy storage, renewable energy are one of the most used solution which has received considerable attention. Among these renewable energies, wind energy records the most promising one with a high level of interest because of its potential in electricity generation [1]. The technological process of this renewable energy using electrical machines, converters and power electronics led to a great improvement of variable speed Wind Turbine (WT). WT is one of the fastest growing generation technologies worldwide in recent decades. It gives the possibility to produce the maximum power on a wide range of variation of the wind speed. Because of the variable and the uncertain output of the wind, it is necessary to include an energy storage system as an essential component of future energy system. In order to protect them from strong winds and to have a continuous production , WT are generally limited rotational speed and power [2]. Many control techniques have been developed to control WT such as fuzzy controller, DTC based on sliding mode control, and so on. Recently new method has been proposed in the literature named FOPID ($PI^{\lambda}\ D^{\mu}$)controller , which can get over of the conventional PID which they often encountered an extra degree of freedom in many experimental application.For several decades, proportional integer derivative (PID) controller have been widely used for process control applications [3]. Recently the increasing interest to the performance of PID, leads many researchers to develop the standard form of the PID algorithms and using their fractional order. The aim of this paper is to develop a new fractional order controller to extract maximum power point tracking (MPPT) of the WT and allowing the PMSG to operate at an optimal speed [4]. DC link voltage is also controlled via a buck boost converter associating with the lead acid battery bank. A given system can be illustrated by Fig.1 which presents a generation system corresponding to a topic of wind energy system composed by a speed controller, mechanical actuator, storage system and a grid connected system.

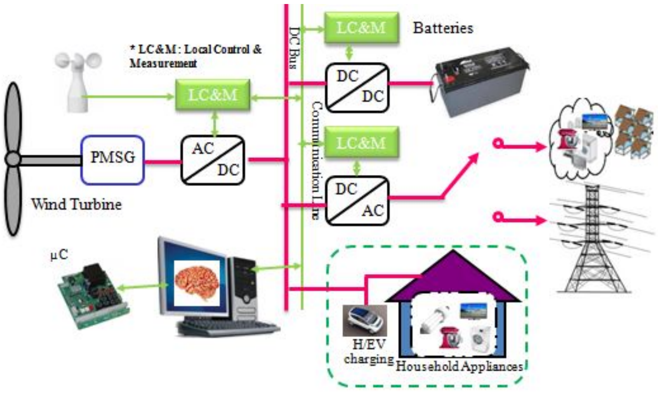

Fig. 1. System under study

II. MODELING OF THE PROPOSED SYSTEM

A. Wind Turbine model

The mechanical power P_{mec} (W) deduced from the aerodynamic can be written as [5]

$$P_{mec} = \frac{1}{2}\rho S V_w^3 C_p(\lambda,\beta) \tag{1}$$

Where S: blade swept Area(m^2),ρ: air specific density (Kg/m^3),V_w: wind speed(m/s),C_p: power coefficient. C_p is a nonlinear function depending on the tip speed ratio (λ) and the pitch angle of the rotor blades β. The ratio of the tangential velocity is defined as :

$$\lambda = \frac{R_t \Omega_t}{V_w} \tag{2}$$

One of the expression given to the power coefficient $C_p(\lambda,\beta)$ is given by:

$$C_p(\lambda,\beta) = 0.53\left[\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right] exp\left(\frac{-18.4}{\lambda_i}\right) \tag{3}$$

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where

$$\lambda_i = \frac{1}{\dfrac{1}{\lambda - 0.02\beta} - \dfrac{0.003}{\beta^3 + 1}} \tag{4}$$

The mechanical equation of the turbine coupled directly to the PMSG is given by:

$$\frac{d\Omega_t}{dt} = \frac{1}{J}(T_t - T_{em} - f\Omega_t) \tag{5}$$

Ω_t(rad/s) is the mechanical speed of the rotor torque(Nm), J is the moment of inertia (Kgm^2), f is the coefficient of the viscous friction $(Nmsrad^{-1})$ and T_{em} is the electromagnetic torque developed in the PMSG rotor axis.

B. PMSG model

The commonly electrical model of PMSG given by the park transformation is expressed by [6]:

$$\begin{pmatrix} V_{sd} \\ V_{sq} \end{pmatrix} = -R_s \begin{pmatrix} I_{sd} \\ I_{sq} \end{pmatrix} - \frac{d}{dt}t \begin{pmatrix} L_d I_{sd} \\ L_q I_{sq} \end{pmatrix} + p.\Omega_t \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} L_d I_{sd} + \phi_m \\ L_q I_{sq} \end{pmatrix} \tag{6}$$

The electromagnetic torque is given by:

$$T_{em} = p\phi_m I_{sq} \tag{7}$$

The quadrature current I_{sq} is given by the PMSG speed controller and the direct current I_{sd} is maintained to be at zero.

C. The Battery model

Lead acid battery is the most used storage in renewable energy. In the literature, the battery has been largely described by many authors such as Monegon, Facinelli, Hyam and CIEMAT. The model given by CIEMAT [7] which includes C_b and C_s that represented respectively the volume capacity and the surface capacity of the battery [8].The given model is illustrated by Fig.2:

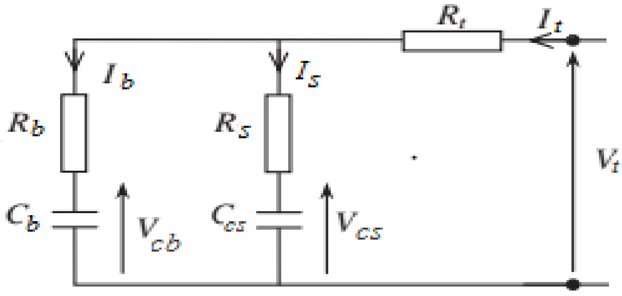

Fig. 2. Electrical model of a battery

By applying Kirchhoff's laws , the electrical circuit yields the following system:

$$\begin{cases} V_t = I_t R_t + I_b R_b + V_{cb} \\ V_t = I_t R_t + I_s R_s + V_{cs} \end{cases} \tag{8}$$

The state equation can be developed by the following matrix equation:

$$\begin{pmatrix} \dot{V}_{cb} \\ \dot{V}_{cs} \\ \dot{V}_t \end{pmatrix} = \begin{pmatrix} A_{(1,1)} & A_{(1,2)} & 0 \\ A_{(2,1)} & A_{(2,2)} & 0 \\ A_{(3,1)} & 0 & A_{(3,3)} \end{pmatrix} \cdot \begin{pmatrix} V_{cb} \\ V_{cs} \\ V_t \end{pmatrix} + \begin{pmatrix} \dfrac{R_s}{C_b(R_b + R_s)} \\ \dfrac{R_b}{C_s(R_b + R_s)} \\ B_{(3,1)} \end{pmatrix} I \tag{9}$$

where

$$A_{(1,1)} = \frac{-1}{C_b(R_b + R_s)}$$

$$A_{(1,2)} = \frac{1}{C_b(R_b + R_s)}$$

$$A_{(2,1)} = \frac{1}{C_s(R_b + R_s)}$$

$$A_{(2,2)} = \frac{-1}{C_s(R_b + R_s)}$$

$$A_{(3,1)} = \frac{-R_s}{C_b(R_b + R_s)^2} + \frac{R_b}{C_s(R_b + R_s)^2} - \frac{R_s^2}{C_b R_b (R_b + R_s)^2} + \frac{R_s}{C_s(R_b + R_s)^2}$$

$$A_{(3,3)} = \frac{R_s}{C_b R_b (R_b + R_s)} - \frac{1}{C_s(R_b + R_s)}$$

$$B_{(3,1)} = \frac{R_b^2}{C_s(R_b + R_s)^2} - \frac{R_s R_t}{C_b(R_b + R_s)} + \frac{R_s R_b}{C_s(R_b + R_s)^2} + \frac{R_t}{C_s(R_b + R_s)}$$

The considered storage system considered is a battery of $240V$ (composed of twenty lead acid batteries of $12V$) which have 60% as Depth of discharge limits DOD_{MAX} and an efficiency $\eta_{BAT} = 85\%$. The given Table.1 resume the battery specifications

TABLE I
BATTERY SPECIFICATIONS.

Battery specifications	Value
Nominal capacity (Ah)	50
Voltage (V)	240
DOD $(\%)$	60
η_{BAT} $(\%)$	85
Lifetime(year)	5

III. DESIGN OF THE PROPOSED FOPID CONTROLLER

The proposed strategy based on fractional order controller is elaborated to control variable speed operation of WT coupled to a PMSG with storage battery system via DC-DC bidirectional converter. This kind of controller characterized by the addition of external fractional regulation parameters λ and μ. Due to this two knobs. Fractional order controller denoted by $PI^{\lambda}D^{\mu}$ turn to be more flexible and robust [9]. The most usual definition for fractional differential integral is introduced by Reimann-Liouville (RL) [10]. $PI^{\lambda}D^{\mu}$ is presented by the following equation:

$$\alpha D_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_{\alpha}^{t} (t-\tau)^{n-\alpha-1} f(\tau) d(\tau) \quad (10)$$

where α is a constant with $n-1 < \alpha < n$ and $\Gamma(.)$ is the Euler's gamma function. The Laplace transform of RL fractional derivative is expressed as follows:

$$\alpha D_t^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_{\alpha}^{t} (t-\tau)^{\alpha-1} f(\tau) d(\tau) \quad (11)$$

where aD_t^{α} is the fractional operator. The Laplace transformation of Riemann–Lowville definition for the fractional derivative is expressed as follows:

$$L \ \alpha D_t^{\alpha} f(t) = S^{\alpha} F(S) - \textstyle\sum_{k=0}^{n-1} S_{\alpha}^{0} D_t^{\alpha-k-1} f(t) t = 0 \quad (12)$$

Through the Laplace transformation, the transfer function of the fractional order controller is shown as follows:

$$G_c = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} (\lambda, \mu > 0) \quad (13)$$

The conventional proportional integral derivative (PID) contains proportional integral derivative gains respectively K_p, K_i, K_d, when FOPID controller contains in addition two extra parameters integral order and differential order respectively λ and μ. With them the FOPID can be presented as a general order of the PID and expands it from point to a plan leading more flexibility and more accuracy to the system control.

IV. CONTROL STRATEGY

In this section, we derive the mechanical turbine speed control from pitch-blade angle actuator and wind speed behavior and the DC link voltage from a buck-boost converter.

A. Fractional control of WT

1) Pitch controller: For strong speed, the aerodynamic is operated. The pitch angle is activated and the PMSG works at a constant power, beyond the nominal output of the WT. For low or medium wind speed, the pitch control allows WT to operate at its optimum conditions. Whereas, it is active when the value of the wind speed is higher than the nominal value V_n. The blade pitch angle β increases until the wind turbine generator is at the rated velocity [11]. The diagram of the implemented pitch angle FOPID controller is shown in fig 3 where the P_g is the generator power. Taking into consideration the blade's orientation system, a transfer function of the first order is introduced :

$$\beta = \frac{1}{1+\tau_b s} \beta_{ref} \quad (14)$$

with τ_b is the sampling time $\tau_b = 10^{-3} s$

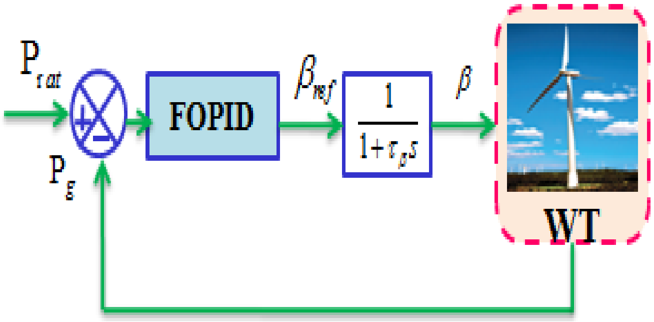

Fig. 3. FO-Pitch angle control

2) Fractional order MPPT with speed control: Taking account into the relative difficulty of the speed control for high inertia values of the WT turbine, a control of mechanical speed is proposed. The FOPID speed controller trakcs the speed reference of the rotor by controlling the generated electrical power [11], [12]. Therefore the torque, by imposing the equality between the electromagnetic torque and its optimal reference. The WT speed should be adjusted to the reference speed Ω_{ref}. This is obtained if $\lambda = \lambda_{opt}$ ($\lambda_{opt} = 8.1$) and $C_p = C_{pmax}$ ($C_{pmax} = 0.47$) and $\beta = \beta_{ref} = 0$. The aim of this control is to search the maximum power point tracking by imposing the electromagnetic torque reference T_{emref} given by the relation in below:

$$T_{emref} = (K_p + K_i S^{-\lambda} + K_d S^{\mu})(\Omega_{ref} - \Omega_{mec}) \quad (15)$$

where $K_p, K_i, \lambda, K_D, and \mu$ are the FOPID controller parameters. As shown in Fig 4, the main advantage of FOPID controller is to extract the maximum of power at each operating wind speed. The WT is coupled to a smooth pole

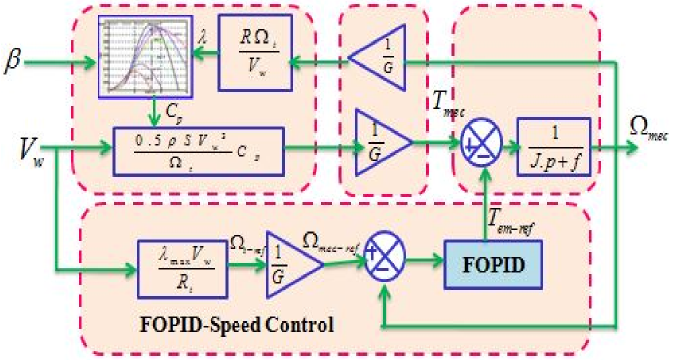

Fig. 4. MPPT-pitch angle control with FOPID controller

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PMSG. The maximum power technique consists on applying a vector control to the PMSG. This control results on the regulation of the quadrature current which is directly related to the $T_{emref}$by the following expression.

$$I_{sqref} = \frac{Temref}{p\Phi m} \tag{16}$$

and the direct current component to a null reference $I_{sd} = 0$.

3) Control of the DC bus voltage: The DC link voltage is carried out by the DC/DC converter and connected to the storage battery system. The task of the FOPID controller is to maintain a constant DC voltage. This control is ensured by using a control loop based on FOPID controller [3]. The reference current is expressed by the following equation:

$$Idc^* = (K_p + K_i S^{-\lambda} + K_d S^{\mu})(Udc^* - Udc) \tag{17}$$

Recharge and discharge mode of the batteries when there is a deficiency or excess of energy are combined with the FOPID algorithm in order to maintain a constant DC link voltage. This means that when there is a lack of DC voltage level, the discharge process of batteries is launched to overcome the voltage gap and they are in recharge mode when the DC link voltage get over its reference [13].

V. SIMULATIONS AND RESULTS

In order to validate the proposed FOPID control strategy,we aplied to the WT system a wind profile during 120s as shown in Fig 5. Optimum mechanical power is extracted by using FOPID-pitch control algorithm, and in the same time mechanical speed is controlled in order to reach the same speed reference profile. Fig.6 illustrates the mechanical speed on the shaft and Fig.7 shows the optimized mechanical power. We can noted that the power is maintained at its nominal value (3.9KW) when it exceeds this level. This limitation is guaranteed by the FOPID controller used in the pitch actuator like illustrated in Fig.8. Simulation results show that the power ration C_p is well adapted to the wind speed variation. C_p depends on both of the tip ration λ and the pitch angle as shown in Fig.9. The error between quadrature torque current and its reference remain null during the application of the wind profile as shown the electromagnetic torque in Fig.10.

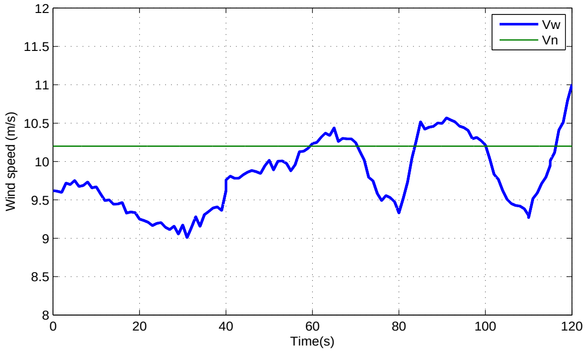

Fig. 5. Wind profile

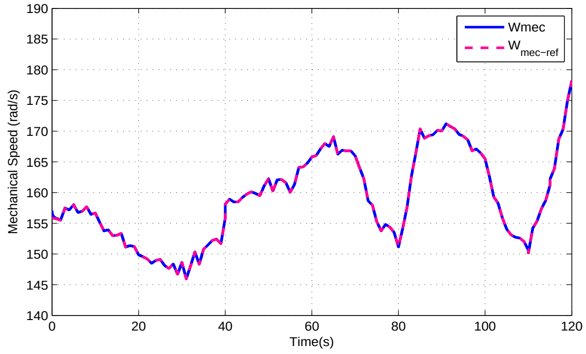

Fig. 6. Mechanical speed

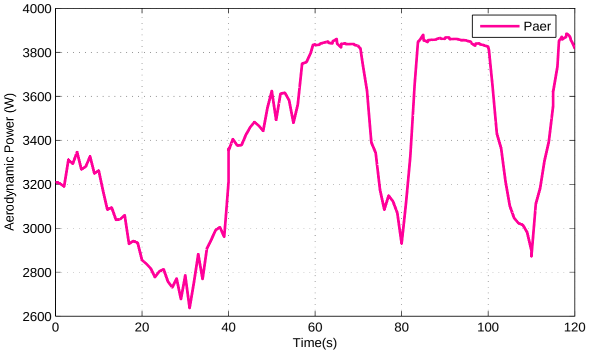

Fig. 7. Mechanical power delivred by the wind

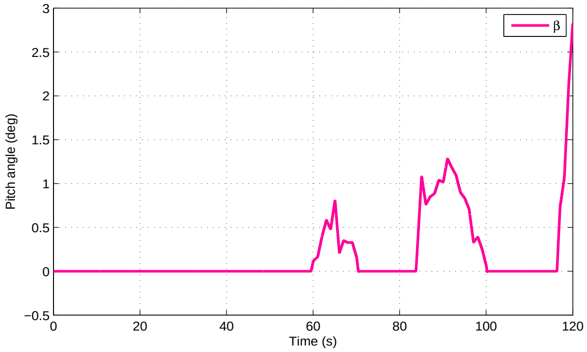

Fig. 8. Pitch angle

To maintain a DC link voltage constant, we have introduced a batteries storage system which can adjust the power level during the load variation. By using the bidirectional behavior of a buck boost converter we can guard a constant DC voltage by the help of discharge-recharge cycle of the batteries according to the load power demand. Fig.11 shows a profile of a varying time load demand and Fig.12 illustrates load current, batteries current and the current provided by the wind generator. We can observe teh behavior of the load current that ensure a constant DC link voltage.

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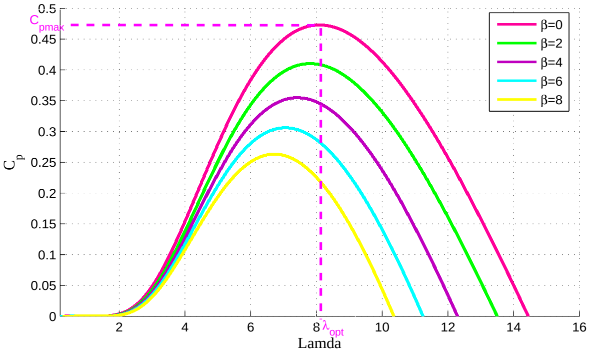

Fig. 9. Power coefficien

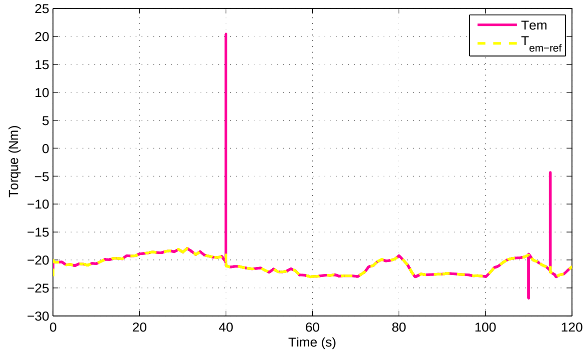

Fig. 10. Electromagnetic torque

VI. CONCLUSION

A novel control strategy of a WT based on FOPID was proposed in order to extract a maximum power from the wind at the same time a DC link voltage is maintained constant regardless the load demand. A large range of wind speed was taken and a pitch control loop with FOPID controller was presented to limit the mechanical power in case of overtaking of the wind speed level. As the pitch control loop, FOPID controller was proposed to control the DC link voltage to a constant value with the help of the battery storage system. The present results confirm the effectiveness of the FOPID controller and prove its accuracy of tracking.

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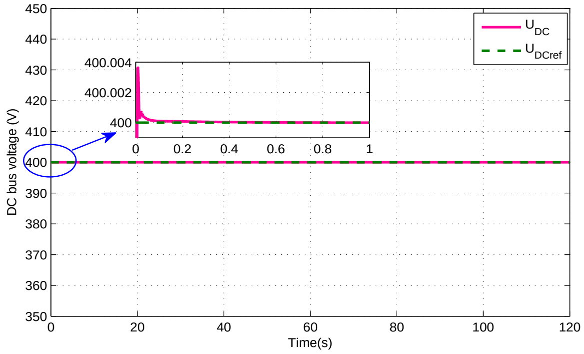

Fig. 11. DC bus voltage

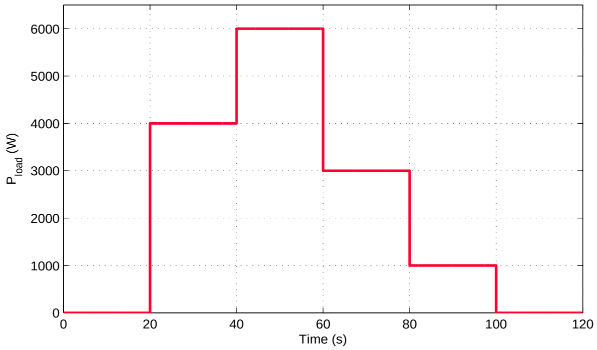

Fig. 12. Power load demand

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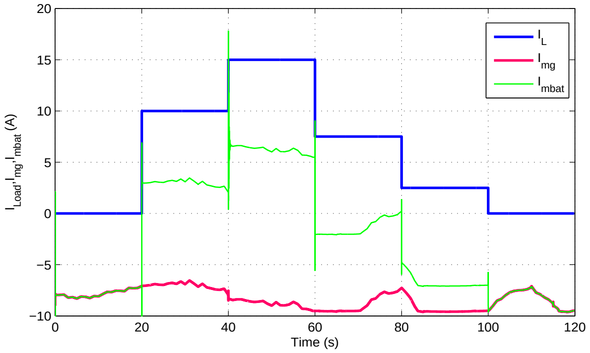

Fig. 13. Currents assessment

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