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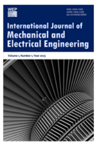

Energy Management Strategy for Electric-Driven Lifting Systems in Heavy Agricultural Machinery

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ABSTRACT

In this paper, an innovative method for energy recovery and management of the electronically controlled suspension system is proposed and simulated using MATLAB/Simulink, with the aim of enhancing energy efficiency and environmental sustainability. This method employs an integrated control approach based on force-position for tillage depth control. When the tractor suspension is positioned above the soil surface and descending, the PMSM switches to generator mode and uses the PMSM for energy recovery. The simulation results demonstrate the viability of energy recovery in heavy agricultural machinery, offering novel ideas and techniques for effective energy management in such equipment.

KEYWORDS

Energy Recovery; Agricultural Machinery; Force-position Control; Electric Drive Lifting System.

1. INTRODUCTION

The conventional heavy-duty tractor's hydraulic suspension lifting system, during ground operations, necessitates frequent lifting and dropping actions. This results in a significant conversion of load potential energy into heat within the lifting hydraulic system. This not only represents a considerable waste of energy but also poses limitations on the duration of single-shift lifting operations. Furthermore, it can easily lead to lubrication failures due to the excessive heat generated, causing thermal fatigue in various components and other related issues [1-21].

This paper presents the design of an electric lifting system focused on energy recovery and its intelligent control research. To cater to the unique characteristics of heavy-duty tractors, including their multiple power outputs, diverse operating modes, and intricate working conditions, this system utilizes an electric motor (generator) as the primary power source. In conjunction with energy storage devices like batteries and super capacitors, an intelligent electric-driven lifting system is designed, emphasizing energy recovery capabilities. Subsequently, the design of an electric lifting system incorporating energy recovery and its intelligent control research are meticulously conducted. By leveraging intelligent energy recovery devices and management strategies, this approach aims to significantly reduce energy waste and enhance energy utilization in agricultural machinery. This not only improves the operational economy and power of agricultural machinery but also helps mitigate carbon emissions and pollutants, ultimately ensuring timely and efficient agricultural operations.

2. LIFTING SYSTEM DESIGN

The electric drive lifting system with energy recovery function is designed in this study and the details are shown in Figure 1. Instead of relying on the conventional hydraulic lifting method for agricultural machine suspension, this device employs an electric motor-driven lifting approach. Integrated within the system are various components that enable energy recovery, including a super capacitor, a force/position sensing system, a DC/DC converter, an AC/DC converter, a power battery, and an ECU controller. These components collectively facilitate precise control over the position and operating depth of agricultural implements. Furthermore, they efficiently convert, recover, and utilize the potential energy generated during the landing of agricultural implements, thereby enhancing the overall efficiency of energy utilization. This not only improves the energy utilization efficiency but also extends the operating range of agricultural machinery.

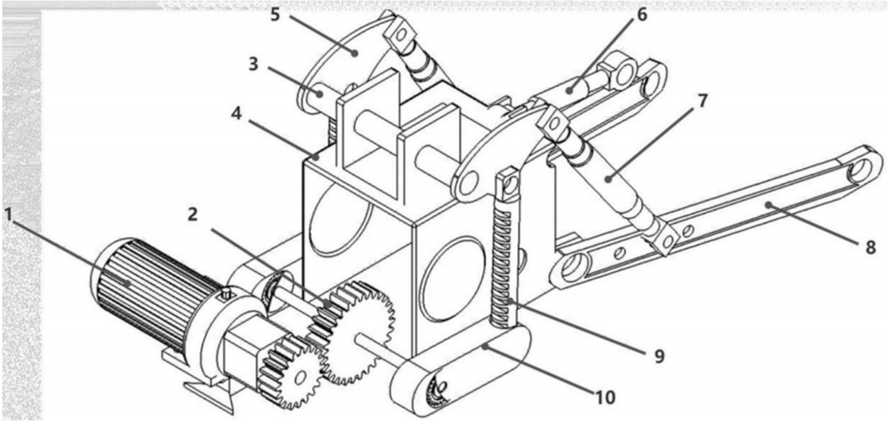

Figure 1. Schematic diagram of energy recovery device for lifting system

The working principle of the device involves converting the permanent magnet synchronous motor into a generator to produce electricity when the rear suspension descends. This conversion is triggered by judging and selecting the appropriate adjustment amount for the plowing depth. Conversely, when the rear suspension is lifted upward or encounters resistance during downward movement, the permanent magnet synchronous motor transforms into an electric motor, generating an upward lifting force and downward thrust force accordingly.

3. RESEARCH METHODOLOGY

Currently, the primary control methods for plowing depth encompass position control, force control, and force-position integrated control. Position control and force control primarily focus on regulating a single aspect of the operation, but they may fall short when dealing with complex, varying terrain, potentially resulting in inadequate plowing. Conversely, the force-position integrated control approach offers a comprehensive solution that better conserves energy and enhances the consistency of plowing depth. This paper delves into the strengths and weaknesses of these three methods, as well as their suitability for different terrain types.

Figure 2 illustrates the adjustment process of plowing depth in position control. When encountering undulating soil terrain during plowing, as the relative position between the tractor and the suspended implement remains constant, a rigid connection is established between them. This means that changes in soil-specific resistance, arising from differences in soil composition, will not affect the uniformity of plowing depth. However, such variations can lead to significant fluctuations in the tractor's engine load, resulting in poor fuel economy. In scenarios with significant terrain undulations, the tractor's front-to-rear movement can compromise the uniformity of plowing depth. Therefore, position adjustment is most suitable for level, dry fields, and paddy fields, as well as operations where implements are suspended at a fixed height.

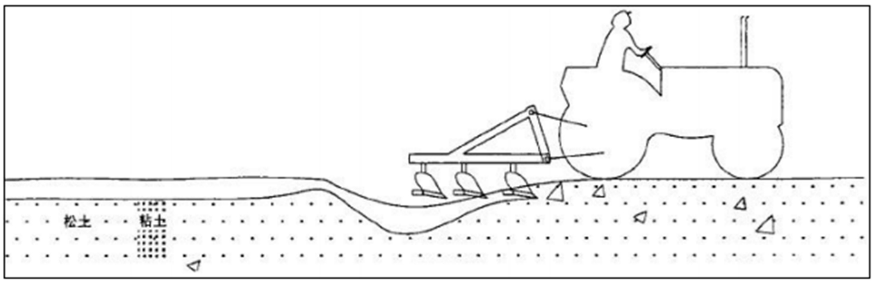

Figure 2. Tillage depth adjustment based on position control

Figure 3 depicts the plowing depth during force regulation. In instances where the undulation of the soil terrain is not significant, changes in soil-specific resistance occur. To maintain the stability of the tractor's engine load, the suspension system continuously adjusts its position up and down in response to these resistance changes. The magnitude of these adjustments is substantial, directly affecting the uniformity of plowing depth. However, in terrain with larger undulations and uniform soil composition, force regulation exhibits a certain degree of shape-imitating adjustment, resulting in better uniformity of plowing depth. Therefore, force regulation is suitable for various operating environments such as plowing, opening fields, and deep tilling.

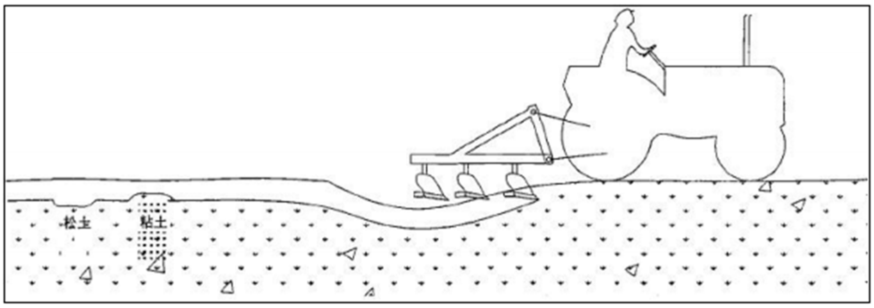

Figure 3. Tillage depth adjustment based on force control

Figures 4 and 5 illustrate the plowing depth achieved through the process of integrated force-level adjustment. In scenarios where the soil composition exhibits significant variations and the terrain is uneven, this method ensures both high-quality plowing and stable engine load. The flexibility of the integrated force-level adjustment allows it to be effectively applied to various operating environments, as mentioned previously.

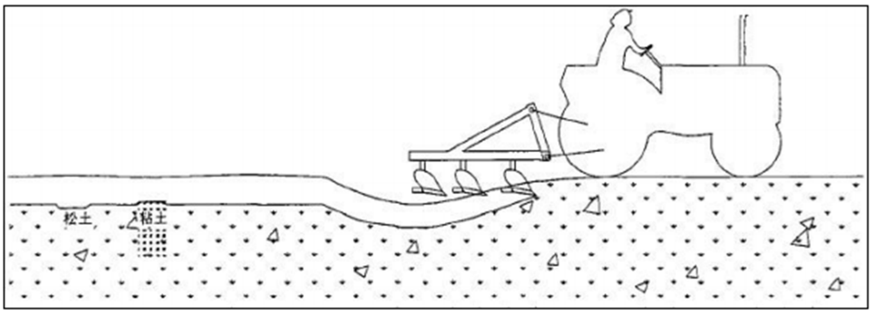

Figure 4. Tillage depth adjustment based on force-position integrated control

The amount of tillage depth adjustment in the integrated control of force level is obtained by the following formula:

$$H = \frac{F_o - F_m}{kb\beta}\omega + (H_s - H_m)(1 - \omega) \tag{1}$$

where, H_s is the set plowing depth, mm; H_m is the actual plowing depth, mm; F_o is the target traction force, N; F_m is the resistance detection value, N; ω is the weight coefficient; k is the soil specific resistance, according to the relevant soil survey and determination, take 6 N/cm^2; b is the operation width, mm.

The relationship between H, H_1, H_2 and tillage depth adjustment in force position comprehensive control is shown as follows:

$$H = H_1(1-\omega) + H_2 \cdot \omega \tag{2}$$

$$\mathrm{H}_1 = H_s - H_m \tag{3}$$

$$H_2 = \frac{F_o - F_m}{kb\beta} \tag{4}$$

When the weight coefficient ω falls within the range of 0 to 1, the system functions as a force-position integrated regulation system. It simultaneously performs both force and position regulation, with the proportion of position regulation in the overall regulation being determined by the magnitude of ω. The actual value H is derived from H_1 and H_2 by operation, H_1 is the plowing depth measured by the plowing depth sensor, H_2 is the plowing depth value transformed by force, as shown in Figure 5.

During the tillage process of a tractor, if the soil resistance increases and results in a higher force measured by the force sensor, based on the principle of force regulation participating in the comprehensive regulation, H_2 will increase accordingly. Consequently, the actual depth of tillage, H will also increase, exceeding the preset tillage depth. In response, the system will automatically adjust to decrease the tillage depth until the target value aligns with the actual comprehensive value. In areas with significant terrain fluctuations, if the tractor's body tilts forward, causing a shallower tillage depth, the tillage depth sensor may still record the same value, but the force measured by the force sensor will decrease. Under these conditions, H_1 remains unchanged, while H_2 decreases, leading to a decrease in H. When the target tillage depth exceeds the actual depth, the system adjusts to increase the tillage depth. Therefore, this method effectively regulates both varying soil resistance and uneven ground conditions.

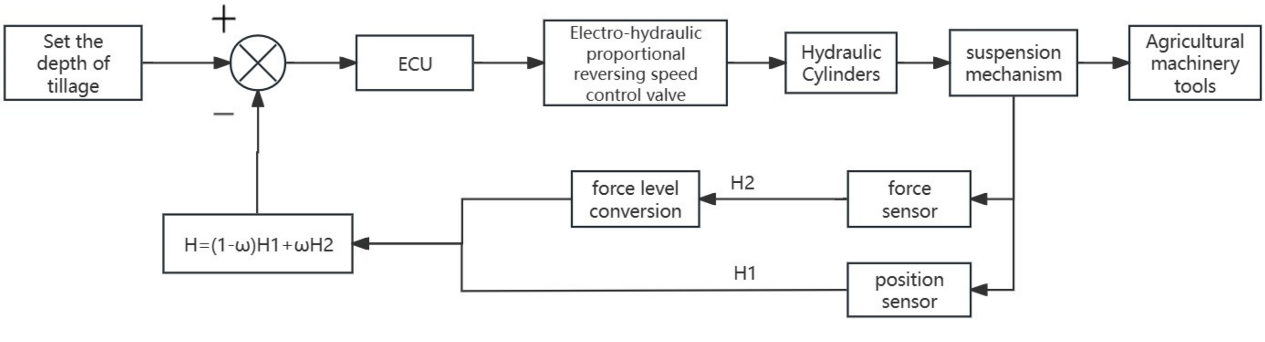

Figure 5. Schematic diagram of force-position integrated control

After comparing various control methods for adjusting plowing depths, this paper ultimately opts for the integrated force-position adjustment control method as the basis for both theoretical analysis and simulations.

Illustrated in Figure 6, the synchronous permanent magnet motor in the MATLAB/Simulink model can seamlessly transition between motor mode and generator mode by adjusting the torque. In this study, we employ the force and position integrated control approach to convert the required adjustment in plowing depth into torque data. This control mode involves separate assessments of force and position, with the analyzed data subsequently informing the operational mode (power consumption or generation) of the permanent magnet synchronous motor. The resulting torque is then fed into the motor, enabling either power generation or consumption. Specifically, the position is calculated as the difference between the actual value from the position sensor and the target value, while the force corresponds to the measurement obtained by the force sensor.

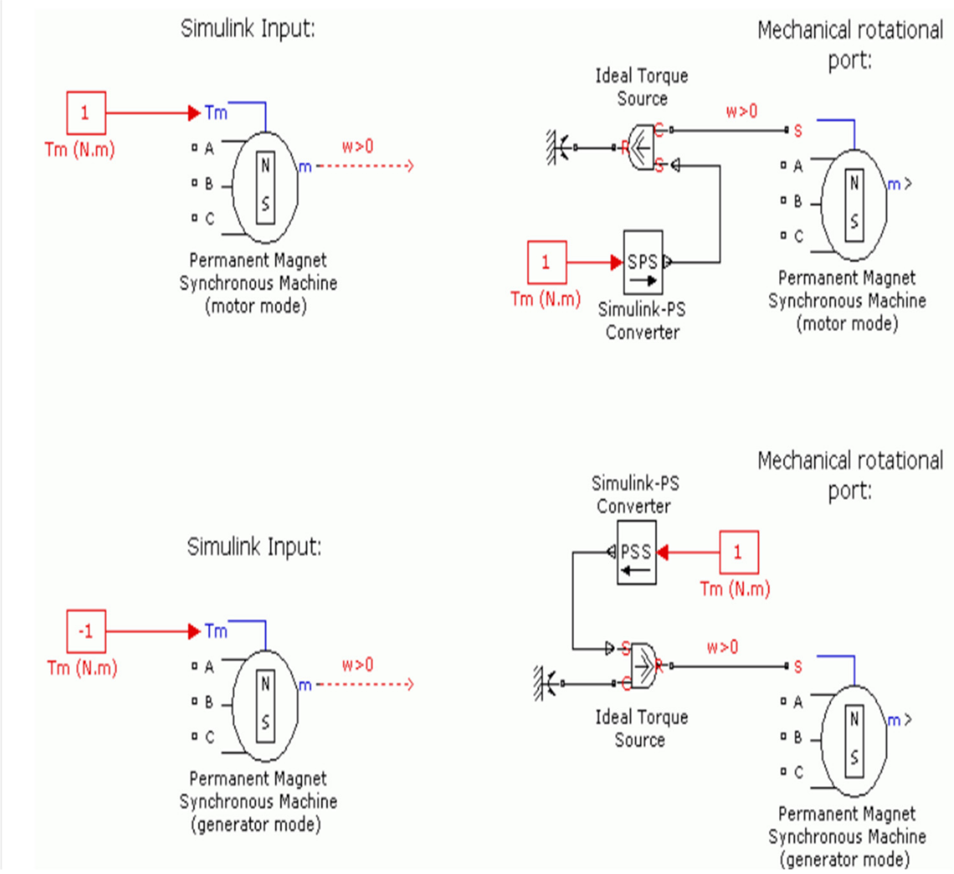

Figure 6. Schematic diagram of motor conversion mode

The decision-making process is summarized in Table 1. The permanent magnet (PM) synchronous motor converts into a generator and generates electricity only when the force sensor measures 0 and the position amount is negative. In all other modes, the PM synchronous motor functions as a motor, consuming electricity.

Table 1. Permanent magnet synchronous motor mode judgment

Position **Power**	**>0**	**=0**
<0	Electric motor	Dynamo
>0	Electric motor	Electric motor
=0	Electric motor	Electric motor

4. MODELING AND SIMULATION RESULTS

4.1. Simulation Model

The mathematical model and simulation model of electric drive lifting system and tillage depth control are established. The simulation block diagram is shown in Figures 7 and 8.

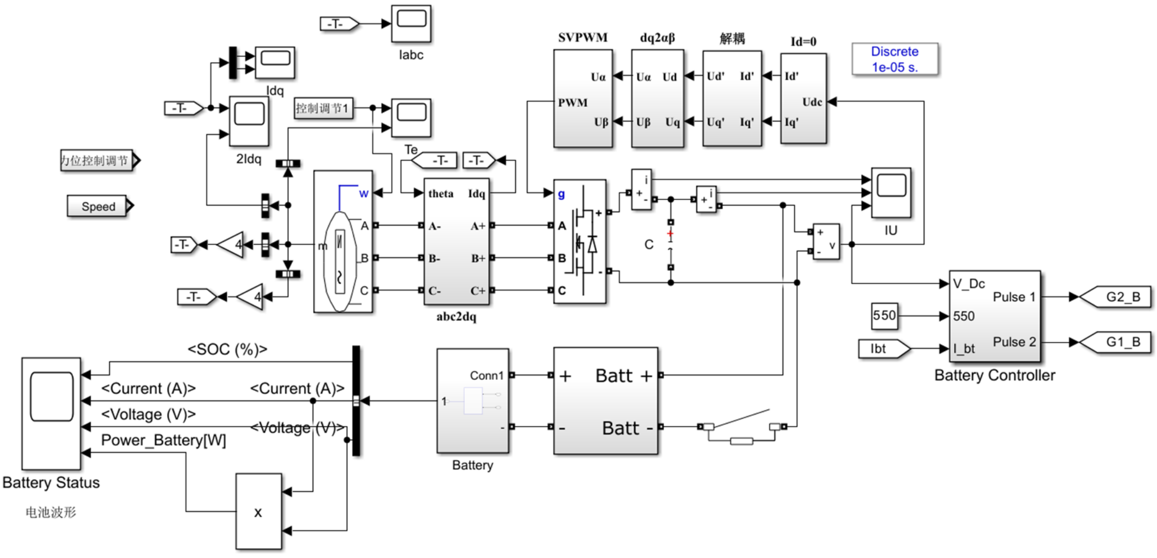

Figure 7. Schematic diagram of energy recovery device

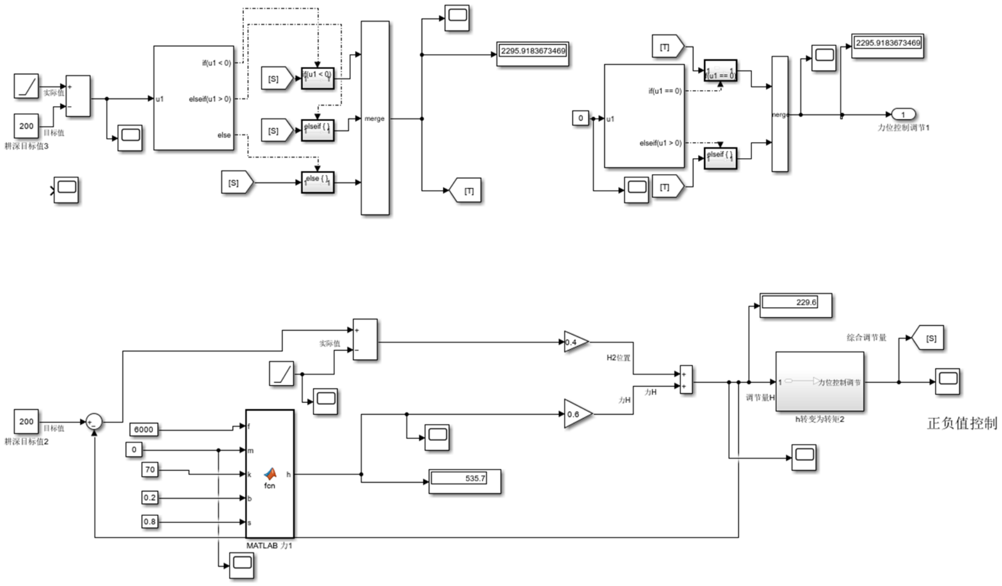

Figure 8. Schematic diagram of tillage depth adjustment

4.2. Simulation Results

In the simulation, we set specific operational parameters to simulate the farming process. The specific parameters are as follows:

Table 2. Simulation parameters

Depth of tillage	Traction force	Soil specific resistance	Working width	Comprehensive degree coefficient ω	Ground height
0 to 200	6	6	200	0.6	0
mm	kN	N/cm²	mm	1	mm

To examine the influence of the suspension system's descent at various heights on the battery's state of charge (SOC), simulations were conducted. These simulations modeled the gradual descent of the suspension system from three distinct initial heights: 200mm, 150mm, and 100mm, respectively, down to the ground level. The results of the simulations are presented in Figures 9, 10, and 11, which illustrate the variations in battery SOC during the descent of the suspension system from different heights. These visualizations facilitate a comparative analysis of the influence of suspension height on the battery's state of charge.

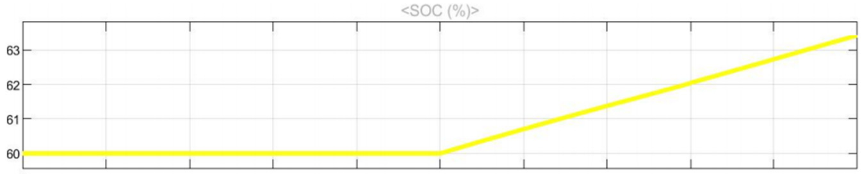

Figure 9. Results of SOC simulation when the suspension height is 200mm

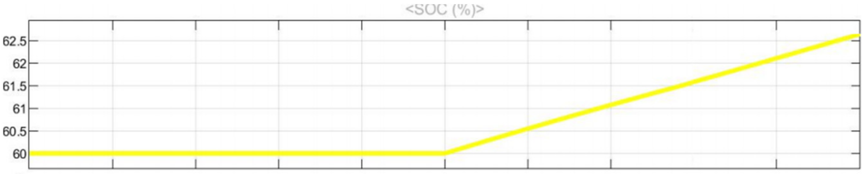

Figure 10. Results of SOC simulation when the suspension height is 150mm

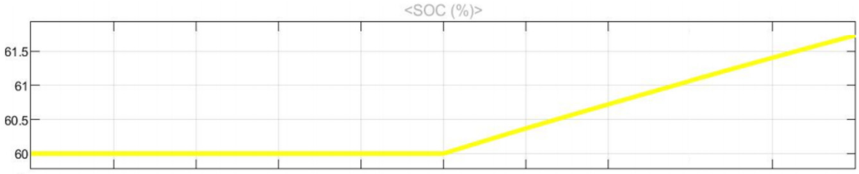

Figure 11. Results of SOC simulation when the suspension height is 100mm

When the suspension is positioned on the ground, the controller initiates its descent, during which only gravity acts to lower the suspension. As the suspension descends, the permanent magnet synchronous motor transitions into generator mode, effectively converting the gravitational potential energy into electrical energy. This results in a noticeable increase in battery power, indicating the successful recovery of energy.

5. CONCLUSION

In this paper, a novel method for energy recovery and management is introduced. This innovative approach capitalizes on the gravitational potential energy of a heavy agricultural machine, effectively transforming it into electrical energy via a motor. This transformation is facilitated by the precise control of the plowing depth, achieved through a suspension system. The electric motor seamlessly transitions between generator and motor modes, converting the gravitational potential energy into electrical energy for storage during the downward movement of the rear suspension. Simulations conducted across varying soil specific resistances reveal that maintaining the entire suspension system in a power generation state results in variations in energy recovery values. Furthermore, the simulation results pertaining to different suspension heights indicate that as the suspension height decreases, the battery energy recovery value also declines. This finding validates the practicality of energy recovery in heavy agricultural machinery. The presented approach provides novel insights and methodologies for energy recovery and management in heavy agricultural equipment, offering a significant contribution to the field.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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