Journal of Intelligent Systems and Control
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Efficiency Improvement of Induction Motors Based on Rotor Slot and Tooth Structures

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Received: 02-12-2023 **Revised:** 03-08-2023 **Accepted:** 03-14-2023

Citation: H. B. Duc, C. P. Do, M. D. Cong, and V. D. Quoc, "Efficiency improvement of induction motors based on rotor slot and tooth structures," *J. Intell Syst. Control*, vol. 2, no. 1, pp. 13-22, 2023. https://doi.org/10.56578/jisc020102.

Abstract: Due to simple structure, easy maintenance and low cost, induction motors (IMs) are widely applied in various industries, accounting for 60-80% alternating current (AC) motors used in industry. However, the efficiency of IMs is very low, and even small improvement can result in significant energy saving. For instance, 1% efficiency increase saves billions of kilowatt hours. Therefore, this paper aimed to improve the efficiency of IMs, thus reducing energy consumption and greenhouse gas emissions. For an IM with 7.5kW rated power and IE3 energy efficiency, the efficiency is improved by making various changes. Sequential quadratic algorithm and fmincon function are proposed to change the rotor slot and teeth structures, realizing nearly 91% motor efficiency, which is a significant improvement over the original efficiency. It is worth noting that improving the efficiency of IMs saves a lot of energy, especially in cases where IMs account for a large proportion of AC motors.

Keywords: Induction motors; Optimization design; Sequential quadratic algorithm; Fmincon function; Efficiency

1. Introduction

Electrical energy plays an important role in our life, and the majority of the electricity consumed in the industrial sector is used for electric motors, with induction motors being the most widely used type. These motors are cost-effective, easy to maintain, reliable, and can be operated directly from the power grid. However, their low efficiency is a significant drawback, as the losses associated with their operation can account for a substantial portion of the total cost of usage. Induction motor (IM) losses can be categorized into several types, including rotor and stator copper losses, core losses, friction and windage losses, and other losses. While efforts have been made to minimize these losses through various studies, the efficiency of these machines can vary significantly, ranging from 70% to 95% depending on the power [1]. Designing electric motors for maximum efficiency at rated values is essential to ensure that they operate efficiently (Table 1). Energy-efficient induction motors have power factors and higher efficiencies at high speeds and can provide the same output with lower input (Figure 1). When IMs operate at lower voltages for extended periods, stator and rotor temperatures increase, resulting in higher copper losses [2, 3]. The production of highly efficient electric motors, particularly IMs, is critical to reducing energy costs in industrial applications. While IMs offer several advantages over other types of motors, their low efficiency remains a significant issue that must be addressed to improve overall energy efficiency and reduce costs [4].

Table 1. Efficiency levels of electric motors [5]

Efficiency Class	Minimum Efficiency	Applicable Motor Types
IE1	Standard Efficiency	All motor types
IE2	High Efficiency	All motor types
IE3	Premium Efficiency	Three-phase motors
IE4	Super Premium Efficiency	Three-phase motors

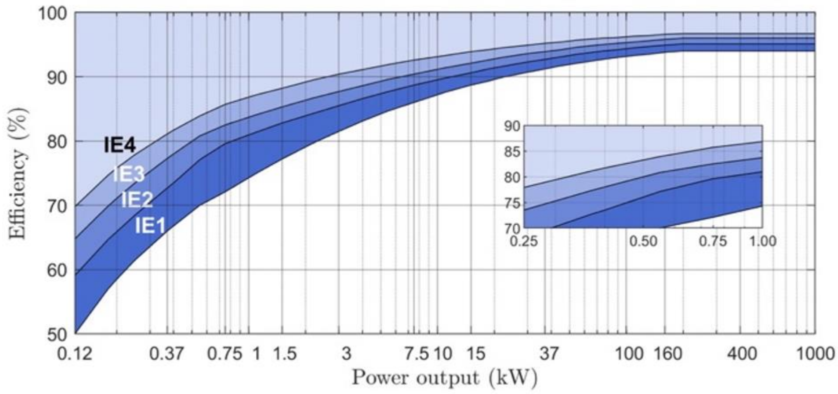


Figure 1. Efficiency levels of electric motor with the output powers [5]

Recently, many researchers have developed different approaches to improve the performances of IMs. It can be listed as follows: the control strategy based on the slip power back to the rotor of a slip ring induction motor was developed to improve the electromagnetic torque and efficiency of a three-phase IM [6]. The copper rotor cage and premium steel were replaced by standard steel and aluminum cage, with standard and higher stack length to improve the efficiency of a three phase IM of 7.5kW [7]. In this paper, the prototypes of induction motors with the mixed material was also presented to verify the improvement of efficiency. The performance of the IM was improved by changing the stator and rotor slot shapes [8]. A control technique with a constant frequency was developed for a three-phase induction motor to improving the power density and efficiency [9]. In this development, the silicon controlled rectifier, a semiconductor component, was considered to adjust the voltage phase trigger. A finite element method (FEM) associated with the genetic algorithms was introduced to improve the performance of the IM [10]. The performance was improved by using the high magnetic flux materials [11, 12]. A new approach was proposed for a variable speed IM drive for reducing copper and iron losses and improving the the efficiency [13]. A swarm optimization method was developed for the efficiency evaluation of IM [14]. An optimization approach based on a simple off-line identification algorithm was developed for the IM [15, 16]. The developed method allows to identify all parameters of the IM such as rotor and stator resistances, rotor and stator leakage inductances, mechanical inertia and friction coefficient, mutual inductance.

In this paper, a new approach is proposed to improve the efficiency and reduced weight of an IM with a rated power of 7.5kW and and IE3 energy efficiency. In this proposed method, the rotor slot and teeth structures are optimized by using the sequential quadratic algorithm (SQA) and fmincon function. These optimizations led to a motor efficiency of nearly 91%, which is a significant improvement over the original efficiency of the motor. It is worth noting that improving the efficiency of an IM can lead to substantial energy savings, especially when you consider that these motors account for a large percentage of AC motors used in various industry applications.

2. Analytical Model

2.1 Theorical Background

The Methodology In this study, the Matlab tool is presented to define an optimization function (fmincon function). The calculation process is expressed via the diagram structure as shown in Figure 2.

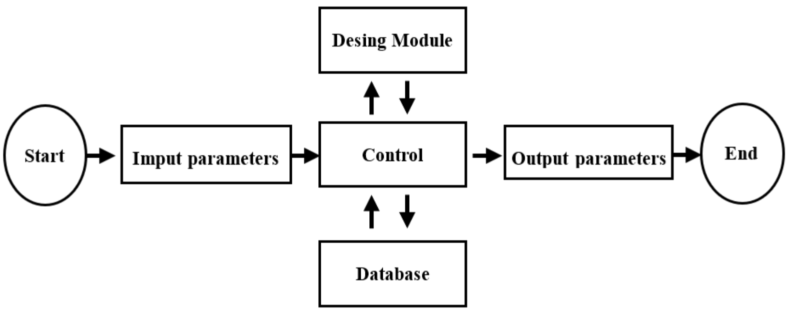


Figure 2. Calculation process of the IM

The moduls in Figure 2 are described as follows:

- *Imput parameters*: This modul consists of the voltage, powers, frequency and optimization sizes.
- *Data base*: This modul is to save the motor information such as type steels, power loss, weight, magnetic field and magnetic flux density.
- *Design module*: This modul is presented to design/define main parameters of the proposed IM.
- *Control module*: Based on the database and design modul, this modul will perform a optimization calculation to obtain a maximum efficiency with the satisfied constrain conditions.
- *Output parameters*: This modul gives optimization values corresponding to different input parameters.

2.2 Computation of Slots and Tooth of the Rotor

The detailed geometry of slots and teeth of the rotor is pointed out in Figure 3. The area of rotor slots is defined as [17].

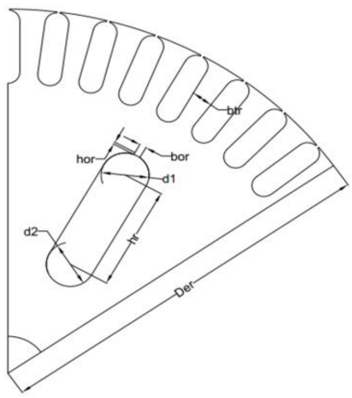


Figure 3. Structure of rotor slots and tooth

$$A_b = \pi \times \frac{d_1^2+d_2^2}{8} + \frac{1}{2} \times (d_1 + d_2) \times h_r, \tag{1}$$

where d_1, d_2 are respective the slot diameters and h_r is the height of slot.

The refferred resistance (R_r^S) from the rotor to stator is defined [18, 19]:

$$R_r^S = 2m \times (W_1 \times K_{w1})^2 \times \frac{\rho_{Al} \times \frac{L \times K_r}{A_b} + l_{er}}{A_{er} \times N_r \times \sin^2\left(\frac{\pi \times p_1}{N_r}\right)}, \tag{2}$$

where m is the large slot diameter, W_1 is the small slot diameter, K_{w1} is the slot height, ρ_{Al} is the electrical resistivity of alumimum at 80°C, L is the stator length, K_r is the skin effect, A_b is the rotor area, l_{er} is the length of short slip ring, A_{er} is the area of short slip ring, p_1 is the number of pole pairs and N_r is the number of rotor slots.

The power loss on the rotor is defined as [1-3, 18, 19]:

$$p_{Al} = 3(R_r')_{Sn} K_I^2 I_{1n}^2, \tag{3}$$

where I_{1n} is the rated current.

For the starting case, the R_r^S can be written as

$$R_r^{S=1} = 2m \times (W_1 \times K_{w1})^2 \times \frac{\rho_{Al} \times \frac{L \times K_r}{A_b} + l_{er}}{A_{er} \times N_r \times \sin^2\left(\frac{\pi \times p_1}{N_r}\right)}, \tag{4}$$

The starting current is then:

$$I_{LR} = \frac{V_{ph}}{\sqrt{(R_s + R_r^{S=1})^2 + (X_{s1}^{S=1} + X_{r1}^{S=1})^2}}, \tag{5}$$

where R_s is the stator resistance, $X_{s1}^{S=1}$ is the leakage reactance of stator. The reffered resistance ($R_r^{S=1}$) for the starting motor can be expressed as [1, 18]:

$$R_r^{s=1} = (\rho_{Al})_{80^oC}\left[\frac{L.}{A_b}K_R + \frac{l_{\mathrm{er}}}{2A_{\mathrm{er}}\,sin^2\left(\frac{\pi p_1}{N_r}\right)}\right]. \tag{6}$$

The expression of the starting torque is defined as [18]

$$T_{LR} = \frac{3R_r^{S=1} \times I_{LR}^2 \times p_1}{2\pi f}. \tag{7}$$

The rotor weight of the teeth is then computed:

$$G_{tr} = \gamma_{iron} \times L \times K_{fe} \times N_r\left(h_r + \frac{d_1 + d_2}{2}\right) \times b_{tr}, \tag{8}$$

where γ_{iron} is the stator weight, $\mathrm{K_{fe}}$ is the compaction factor and b_{tr} is the rotor teeth width.
In the same way, the weight of rotor magnetic circuit is defined:

$$G_r = \gamma_{iron}L\left(\frac{D_{re}^2 \times \pi}{4} - N_rA_b\right), \tag{9}$$

where D_{re} is the rotor diameter.
The loss due to the pulsation is expressed as [17, 18]:

$$p_{iron}^s = 0{,}5 \times \frac{f}{p_1} \times \left[\left(N_s \times k_{ps} \times B_{ps}\right)^2 \times G_{t1} + \left(N_r \times k_{pr} \times B_{pr}\right)^2 \times G_{tr}\right], \tag{10}$$

where N_s is the stator slots, G_{t1} is the weight of stator teeth and G_{tr} is the weight of rotor teeth.
The mechanical loss is then defined as:

$$p_{iron}^1 = \left(K_t \times B_{ts}^{1,7} \times G_{t1} + K_y \times B_{cs}^{1,7} \times G_{y1}\right) \times \left(\frac{f}{50}\right)^{1,3} p_{10}, \tag{11}$$

where p_{10} is electrical resistivity of the iron.
The total losses is finally computed as:

$$\sum p = p_{Al} + p_{Cu} + p_{iron}^1 + p_{iron}^s + p_{mv} + p_{stray}, \tag{12}$$

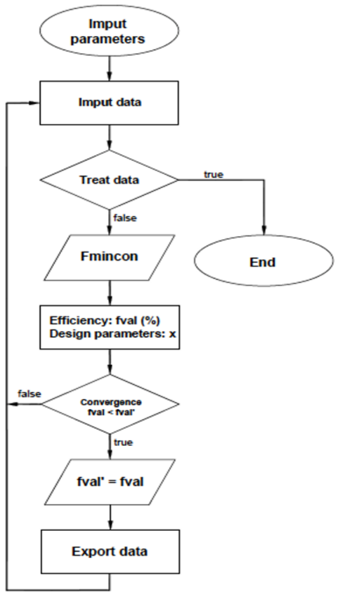
where p_{Al} is the loss of conducting bars, p_{Cu} is the copper loss, p_{mv} is the friction loss and p_{stray} is the auxiliary loss. The efficiency of the motor is then expressed as:

$$HS = \frac{P_n}{P_n + \sum p} \times 100\%. \tag{13}$$

The structure of rotor teeth affects directly the weight of the total irons. The iron losses depend on the steel type and the weight of iron core. The structure of the rotor loss also affects to the loss of aluminum bars. In order to obtain the optimal goal of efficiency and weight, the structure of rotor slots and teeth is checked with different steel types. However, changing these components will also lead to changes in the fundamental characteristics of the motor such as starting current, multiple maximum torque, and mechanical characteristics. Thus, the optimization problem has to take care of these constraint components.

3. Squential Quadratic Algorithm and Fmincon Function

The SQA is developed to solve single-objective optimization problems with nonlinear constraints. The algorithm for optimazation design is shown in Figure 4.



$x_0 = [x_1\ x_2\ x_3\ x_4]$,

Figure 4. Algorithm for optimazation design

Here, the fmicon function is proposued to get a convergen solution. This function consists of two objectives: $f_1(x)$ is the efficiency and $f_2(x)$ is the weight of the magnetic circuit. The optimal parameters are: the outer teeth diameter of rotor (x_1:d_1); the inter teeth diameter of rotor (x_2:d_2); the teeth height of rotor (x_3:d_3); the number of rotor slots (x_3: N_r). The constraint condition are given as:

$$c(x) < 0,\ c_{eq}(x) = 0,\ Ax < b,\ A_{eq}x = b_{eq},\ lb < x < ub,$$

where:

- c, c_{eq} are the nonlinear vector functions including multiple starting curent (i_{LR}), multiple starting torque (t_{LR});
- A, A_{eq} are the matrixes;
- b, b_{eq} are the vectors;
- lb, ub are respecitively the below and above limitations of vectors, and are define as:

$$lb = [1.0\ 0.0\ 10.0\ x_4],$$

$$ub = [10.0\ 10.0\ 30.0\ x_4].$$

The initial vector values are defined as

$$x_0 = [x_1\ x_2\ x_3\ x_4],$$

where $x_1\ x_2\ x_3\ x_4$ are respectively discrete variables. A fmicon function is then determined as:

- Options = optimal options (**'fmincon','Display','iter','Algorithm','active-set'**);
- [**x, fval, exitflag, output, lamda, grad, hessian**] = fmincon (**'goal', *x*₀, *A*, *b*, *A*_{eq}, *b*_{eq}, *l*_b, u_b, 'constraint', options**).

It should be noted that the imput parameters of the motor are the voltage, powers and frequency. The output parameters are: the minimization value of objective function (fval); the convergence of algorithm (exitflag).

4. Application Test

The test problem is an IM of 7.5kW with main parameters given in Table 2. The steel here is used with different types of TATA steel [20]. The comparison of efficiency and weight between conventional and optimal solutions with diferent steel types is shown in Figure 5 and Table 3. It can be seen that for the same steel type of M235-35A, the significant efficiency and weight of the motor obtained after doing an opimization are respectively 90.2% and 28kg, while the conventional efficiency and weight are 89,7% and 29kg. The obtained optimal results are checked to the starting current and torque multiples, maximum torque multiples as shown in Table 2. The values of conventional and optimal starting current multiples with different steel types are presented in Figure 6 and Table 4. It can seen that the starting current multiple after doing an optimization can be acceptable and approximately equal to the initial constraint condition. In addition, the slip factor is also improved. The starting torque multiple for different steel types before and after optimization is pointed out in Figure 7 and Table 5. The optimal value of 1.90 is bigger than initial constraint condition 1.51. Similarly, Figure 8 and Table 6 also show the results of the maximum torque for different steel types before and after the optimization. The maximum torque multiple increased by 1.1% in comparison with the initial value and satisfied the constraint condition.

Table 2. Basic parameters of IM

No.	Rated parameters	Unit	Value
1	Nominal voltage	V	380
2	Rated current	A	18.01
3	Rated frequency	Hz	50
4	Rated power	kW	7,5
5	Rated speed	rpm/min	1462
6	Starting torque multiple		1.42
7	Maximum torque multiple		3.07
8	Starting current multiple		5.72
9	Weight of the magnetic circuit	kg	29.05
10	Efficiency		89.94

Table 3. Comparison of efficiency between conventional and optimal solutions with diferent steel types

No	Steel types	Optimal efficiency	Reference solution
1	M235-35A	90.16	89.71
2	M250-35A	90.12	89.66
3	M270-35A	90.07	89.59
4	M300-35A	89.95	89.50
5	M330-35A	89.77	89.31
6	M250-50A	90.12	89.64
7	M270-50A	89.99	89.56
8	M290-50A	89.95	89.51

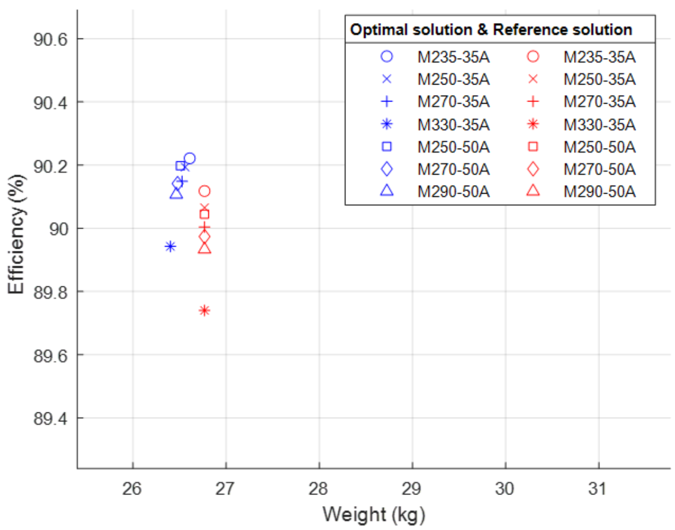


Figure 5. Comparison of efficiency between conventional and optimal solutions with different steel types

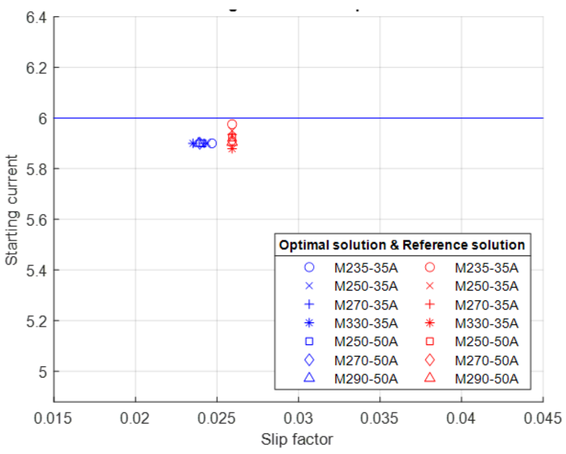


Figure 6. Conventional and optimal starting current multiples with different steel types

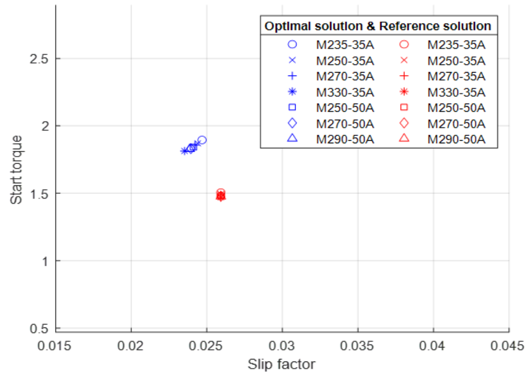


Figure 7. Conventional and optimal starting torque multiples with different steel types

Table 4. Results of conventional and optimal starting current multiples with different steel types

Steel types	Starting current multiples (A)	
	Optimal solution	*Reference solution*
M235-35A	5.90	5.98
M250-35A	5.90	5.95
M270-35A	5.90	5.93
M300-35A	5.90	5.88
M330-35A	5.90	5.92
M250-50A	5.90	5.91
M270-50A	5.90	5.90
M290-50A	5.90	5.98

Table 5. Results of conventional and optimal starting torque multiples with different steel types

Steel types	Starting torque multiples (Nm)	
	Optimal solution	*Reference solution*
M235-35A	1.90	1.51
M250-35A	1.87	1.49
M270-35A	1.86	1.49
M300-35A	1.81	1.47
M330-35A	1.84	1.48
M250-50A	1.83	1.48
M270-50A	1.83	1.48
M290-50A	1.90	1.51

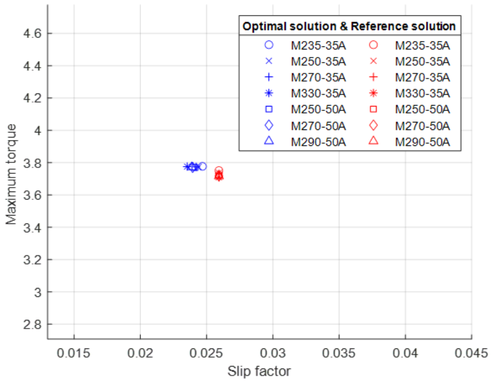


Figure 8. Conventional and optimal maximum torque multiples with different steel types

Table 6. Results of conventional and optimal maximum torque multiples with different steel types

Steel types	Maximum torque multiples (Nm)	
	Optimal solution	***Reference solution***
M235-35A	3.78	3.75
M250-35A	3.77	3.74
M270-35A	3.77	3.73
M300-35A	3.78	3.71
M330-35A	3.77	3.72
M250-50A	3.77	3.72
M270-50A	3.77	3.72
M290-50A	3.78	3.75

The mechanical and current characteristics of conventional and optimal motors with different slip factors is presented in Figure 9. It shows that the starting torque after optimization increased by 1.57 times and the starting current descreased by 5% compared to the initial values. Figure 10 shows the output power of conventional and optimal motors. In the range of speed, the optimal solution is always is lower than the reference solution, indicating that the proposed method improved motor efficiency. However, the maximum power is reduced, this is completely suitable with the starting torque multiple. The obtained results have suggested that the use of optimization techniques and careful selection of steel types can lead to significant improvements in the performance of electric motors.

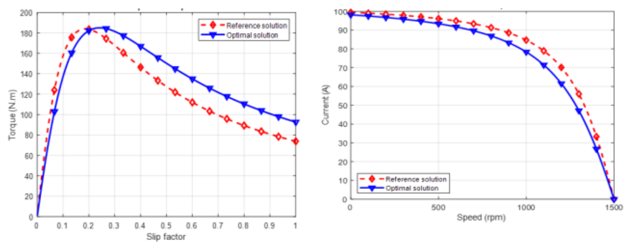


Figure 9. Mechanical and current characteristics of conventional and optimal motors

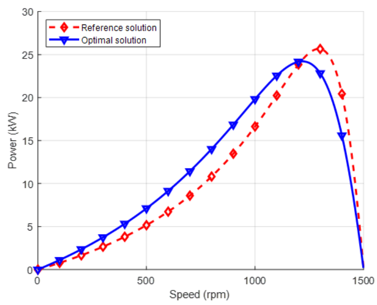


Figure 10. Output power characteristic of conventional and optimal solutions

5. Conclusions

This paper sucessfully presented a new approach to improve the effeciency and reduce the weight of the IM by changing rotor slots and teeth structrures. The obtained results showed that the efficiency increased to 90.16% for the steel type of M235-35A, corresponding to the IE3 motor class. Besides the obtained optimal efficiency and weight, the paper also checked the starting current, starting and maximum torque multiples and output power to verify the contraint conditions. Finally, this paper presented the mechanical and current characteristics and output power of conventional and optimal motors to validate the method. The results obtained in this paper will help manufacturers and designers to change the technology to improve the IM efficiency.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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