Comparative analysis of modular outer rotor and modular inner rotor permanent magnet flux switching machine

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ABSTRACT

A modular rotor is an advanced design in electric motor (EM) technology, offering enhanced performance and efficiency for various applications. Its segmented structure allows for optimized magnetic flux paths, reducing iron losses and improving energy efficiency. The modular rotors can be classified into modular inner rotors and modular outer rotors (ORs). While both have their applications, modular inner rotor permanent magnet flux switching machines (PMFSMs) face limitations, including lower torque density, inefficient magnetic flux operation, and reduced cooling capability, making them less suitable for high-torque applications. This paper presents an analysis of the comparison between a new modular OR and a modular inner rotor PMFSM. The outer OR-PMFSM offers higher torque density due to more efficient magnetic flux positioning, resulting in a better torque-to-weight ratio. The design and analysis are conducted using JMAG designer version 18 under no-load and load conditions to test the proposed design's effectiveness. Hence, the suggested design obtained an increment of torque and power of 6.06% and 5.4%, respectively. In conclusion, the modular OR produces higher torque and power than the modular OR. The proposed motor can be very useful in electric bike applications for practical high performance and low cost.

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1. INTRODUCTION

Electric motors (EM) are critical to developing environmental and economic innovation in the modern era. Consequently, tremendous advancements have been achieved in improving EM functioning to make it suitable for use in the aerospace and automotive industries. These advances include torque, power, effectiveness, speed range, reliability, and controllability [1]–[8]. High torque, high proficiency, high accuracy, low heat loss, low weight, low start-up energy consumption, and low tremor are required for automotive applications. Hence, lightweight fully electric vehicles (FEVs) and other automotive applications require high-torque EMs [9]–[11]. One way to preserve greenhouse vehicles and save energy is by using outer rotor (OR) motors [3]. The application torque and speed that EM offers are essential elements in this process of development and change [12]. The EM's torque defines its application category and performance. From this point, research into high-torque motors is important for supporting eco-friendly applications. Current exploration and advancement could result in numerous automotive applications with in-wheel high-torque EMs [13], [14].

Permanent magnet flux switching machines (PMFSMs) have excellent magnetic properties, such as high torque density, high torque, high efficiency, a broad speed range, and minimal upkeep requirements, making them ideal for automotive applications. Nevertheless, it finds the rotor's active ingredients [15]–[17]. Increased permanent magnet volume, restricted field weakening capability, smaller slot surface area, and significant thermal loss are some of PMFSM's disadvantages [18]–[20]. The benefit of free-loss excitation has drawn attention to PMFSM over the years. For various applications, PMFSM has available inner and OR variants. However, inner rotor FSMs are less ideal for applications requiring high torque density, efficient cooling, and mechanical robustness. The reference modular inner rotor produces relatively good torque but does not reach the torque required for the application, such as off-road E-Bikes. To overcome these problems, Fei *et al.* [21] suggested a three-phase OR-PMFSM requiring high torque density applications in the automotive industry. It consists of a C-stator core with segment stator teeth ensconced between PMs arranged circumferentially. The high density of OR-PMFSM is advantageous. However, using C-Core, which decreases armature slot area, impacts performance [22], [23]. Additionally, the motor's weight is a crucial factor in PMFSM configuration since it directly impacts manufacturing efficacy, mechanical integrity, installation, and thermal management. To address these challenges, a modular outer-rotor PMFSM topology is suggested to enhance motor performance, including torque density, power, efficiency, and weight.

A modular rotor can be used to minimize PMFSM iron losses, resulting in a marginal decrease in output torque for lightweight in-wheel applications [24]–[27]. Modular rotors also have the advantage of reducing rotor weight compared to conventional rotor topologies. To begin with, reluctance motors have been using modular rotors. Modular rotors reduce iron loss to provide a shorter flux path. Whereas the flux in conventional rotors is divided into the two adjacent rotor teeth, in modular rotors, the flux is forced to be dispersed toward the back of the iron.

This technical paper proposed a new structure of a modular OR compared to an existing modular inner rotor PMFSM, emphasizing increasing the torque capability for lightweight applications. This paper's contribution highlighted the advancement resulting in an increment of the torque and power of the modular ORPMFSM and the design restriction and formulation analysis elaborately. In addition, this manuscript is composed as follows. Section 1 is made for introduction. Section 2 presents the design restrictions and specifications. Section 3 describes the preliminary design of the proposed motor. Section 4 provides a performance comparison between the modular inner rotor and modular outer rotor configurations. Finally, section 5 concludes the paper.

2. DESIGN RESTRICTION AND SPECIFICATION

2.1. Geometric design of the proposed modular outer rotor

Figure 1 shows a modular rotor design. The initial design parameters were selected by the 80-85% split ratio for the stator radius and rotor outer radius [28]. Figure 1(a) shows the sectional view of the rotor structure based on the determined parameters, illustrating the segmented design of the modular OR, highlighting its key dimensions and geometric arrangement. Firstly, the dimension of the rotor's outer radius r_{ro} is set to 75 mm. The rotor's inner radius r_{ri} is calculated in (1). Meanwhile, the circumference of the OR, L_{ro}, and inner rotor, L_{ri}, are computed based on (2) and (3). Figure 1(b) depicts the enlarged of a single modular rotor structure, illustrating its distinctive segmented design. Each rotor segment is calculated to ensure optimal magnetic flux distribution while minimizing leakage. This structure enables shorter flux paths, reducing iron losses and improving energy efficiency. The segmentation also simplifies manufacturing and provides enhanced cooling capabilities, which are critical for high-performance applications.

$$r_{ro} = (85\% \times r_{ri}) \tag{1}$$

$$L_{ro} = 2\pi r_{so} \tag{2}$$

$$L_{ri} = 2\pi r_{si} \tag{3}$$

Afterward, the width of the rotor teeth, W_{rp}, can be calculated as in (4) and (5):

$$\frac{360}{N_r} = 72° \tag{4}$$

$$W_{rp} = \frac{72°}{5} = 14.4° \tag{5}$$

where N_r is the number of rotors, N_r=5.

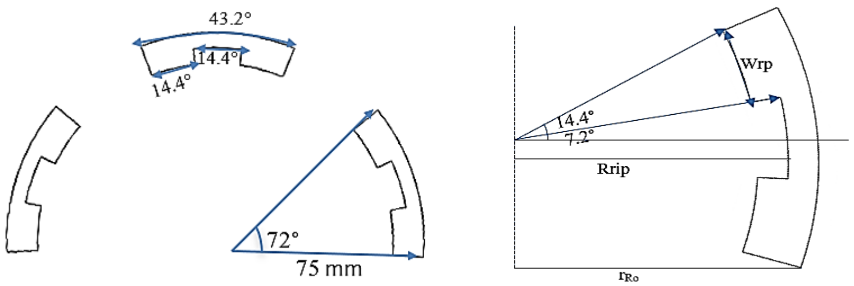
In (5), 5 refers to the rotor divided into parts to get equal rotor teeth. Then, the rotor's inner pole radius r_{rip} can be determined using (6):

$$r_{rip} = \left(\frac{r_{ro} - r_{ri}}{2}\right) + r_{ri} \quad (6)$$

The quantity of slot-pole pairs can be calculated using (7):

$$N_r = N_s\left(1 + \frac{k}{2q}\right) \quad (7)$$

where N_r represent the number of rotor poles, N_s denotes the number of stator slots, k is an integral range from 1 to 5, and q indicates the number of phases. N_r is selected based on k, N_s, and q of 1, 12, and 3, respectively.



(a) (b)

Figure 1. Modular rotor design: (a) sectional view of rotor structure and (b) enlarged modular rotor structure

Subsequently, the stator structure of the modular rotor PMFSM has been suggested based on the calculated parameters illustrated in Figure 2. Figure 2(a) highlights the sectional view of the stator, which plays a critical role in ensuring efficient magnetic flux transfer between the rotor and stator. Each stator component is split equally based on E-core sections, ensuring uniform flux distribution. This equal segmentation improves the motor's performance by minimizing flux imbalance and reducing potential losses. The design also features permanent magnets integrated into the stator structure, strategically placed to enhance torque production while maintaining compactness and mechanical stability. The outer radius of the stator, r_{so} is calculated based on (8). Where ag is the air gap is fixed to 0.3 mm, the inner radius of the stator, r_{si} is set to 30 mm [29] while the stator's outer radius, r_{so} is computed to be 63.45 mm. Figure 2(b) depicts the enlarged stator structure of the modular OR, showcasing its geometric configuration for efficient magnetic flux transfer. The stator components are divided into six slots aligned with the E-core sections. This symmetrical design ensures balanced flux distribution and consistent performance across all phases. The structure also incorporates permanent magnets within the stator slots, enhancing the torque and power output by providing a robust magnetic field source. It can be calculated based on (9) to determine the possible angle of the stator.

$$r_{so} = [85\% \times r_{ro}] - ag \quad (8)$$

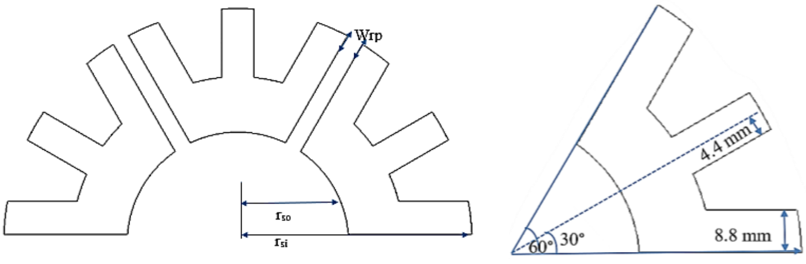
$$\frac{360°}{6} = 60° \quad (9)$$

Where (6) is the number of stator slots. The stator components are then split equally based on the E-core sections. This technique guarantees equal fluxes from the stator to the rotor and back again [30].
In addition, W_{PM} is the width of the permanent magnet, which can be determined based on (10):

$$W_{PM} = \frac{PM\ weight}{h \times SL \times PM\ density \times N_{PM}} \quad (10)$$

Where the mass of the permanent magnet is fixed to 0.5 kg, L is the length of the permanent magnet, W is the permanent magnet's width, SL is the stack length, which is fixed to 70 mm, and h is the height of the slot area. Since the permanent magnet material is NEOMAX 35-AH, its density is 7550 kg/m^2. The height of the slot area is calculated based on (11):

$$h = r_{so} - r_{si} \quad (11)$$



(a) (b)

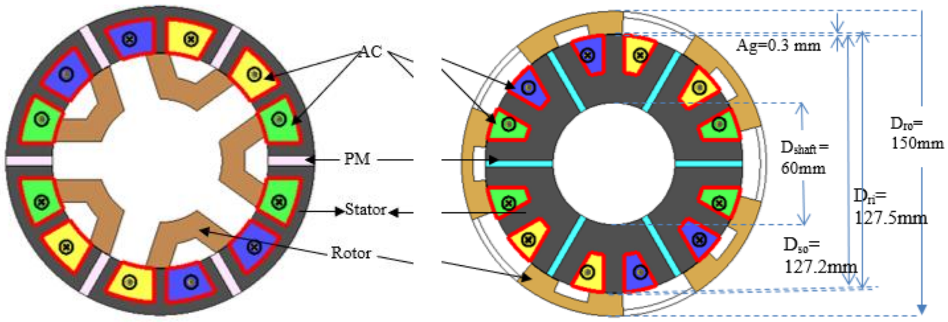
Figure 2. The suggested modular rotor PMFSMs stator structure: (a) sectional view of stator structure and (b) enlarged single stator structure

3. PRELIMINARY DESIGN OF THE PROPOSED MOTOR SPECIFICATION

Figure 3 compares an existing modular inner rotor and a proposed design for a new modular OR PMFSM. These designs illustrate the structural and functional differences that define their respective torque, power, and efficiency performance. Table 1 clarifies the design characteristics, limitations, and requirements for the suggested modular ORPMFSM. Moreover, the corresponding mechanical restrictions, such as motor size and stack length, are set to 75 mm and 70 mm, respectively. The 6 permanent magnets in the suggested motor are evenly spaced among the armature coils. To achieve direct drive, a wheel tire can be installed on the exterior of the rotor. The modular inner rotor in Figure 3(a) features a more compact rotor placement within the stator, while the modular OR in Figure 3(b) places the rotor around the stator, with permanent magnets positioned circumferentially.

Table 1. Comparison parameters of an existing inner rotor and new OR modular PMFSM

Parameter	Modular inner rotor [31]	Modular outer rotor
Rotor-outer (mm)	104.4	150
Rotor inner (mm)	60	127.5
Stator outer (mm)	150	60
Stator inner (mm)	105	60
Permanent magnet weight (kg)	0.35	0.5
Number of turns	50	35
Torque (Nm)	34	>34
Power (kW)	1.78	>1.78



(a) (b)

Figure 3. Design comparison: (a) modular inner rotor and (b) modular OR

4. PERFORMANCE COMPARISON AMONG MODULAR INNER ROTOR AND MODULAR OUTER ROTOR

This study examines the performance of a modular OR-PMFSM in terms of torque and power. The aim is to achieve better torque and power performance than the modular inner rotor. Initially, a study on the coil arrangement test is conducted to verify the operation of the suggested three-phase modular OR. The positions of each armature coil phase are rearranged to obtain a sinusoidal waveform. Therefore, the phase shift at 120° is associated with the flux linkage in various phases [31]. Figure 4 illustrates the first combination tested coil arrangement, using three distinct armature coil groupings. Armature coils 1 and 4 are grouped as U, the second combination, V, consists of armature coils 2 and 5, while armature coils 3 and 6 are combined to form W.

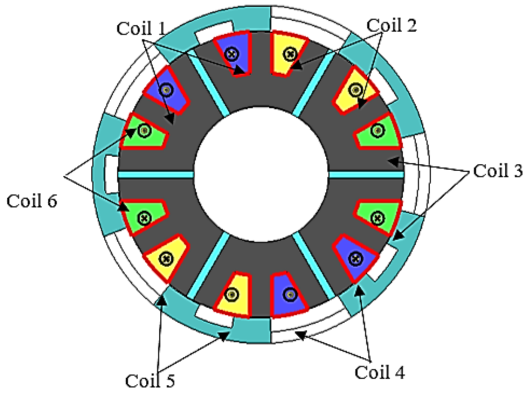


Figure 4. Coil arrangement test

Besides that, in electric machines, the back electromotive force (EMF), also known as induced voltage, arises when a similar motion occurs between the rotor magnetic field and the stator windings. The induced voltage of the proposed motor is examined at a speed of 500 r/min, which is an open-circuit situation. The motor will operate well with an induced voltage waveform that has less distortion. Figure 5 shows the induced motor produced by the inner and outer modular rotor PMFSM. The modular outer-rotor PMFSM displays about 31.54 V, while the modular inner-rotor PMFSM exhibits about 58.49 V. The graph shows the unbalanced harmonics that the distortions of the voltage or current may produce. It can be concluded that modular outer-rotor PMFSM has better back-EMF than modular inner-rotor PMFSM.

To generate internal power, cogging torque must offset the counteracting torque caused by the repulsive magnetic interaction between the stator's magnets, the rotor tooth and PM. Cogging torque increases the flux connection and results in a low torque for the motor engine. The proposed design machine is in an open-circuit condition. *Ja* is set to 30 Arms and no supply to the AC. So, it was observed that every 36° of rotor position equals 1 electric cycle. The largest cogging torque produces motor vibration, while the lowest cogging torque represents the ideal machine state. A comparison between modular outer-rotor PMFSM and modular inner-rotor PMFSM is presented in Figure 6. The modular outer-rotor rotor-based PMFSM has a peak-to-peak measurement of 64 Nm, whereas the modular inner-rotor PMFSM has a peak-to-peak measurement of about 16 Nm. It shows that the modular inner-rotor PMFSM produced much better cogging torque than the modular outer-rotor PMFSM. Changing the air gap distance between the rotor and stator can significantly lower cogging torque, according to the results of a prior [32]. In fact, rotor pole notching, rotor pole pairing, and rotor skewing could all further reduce cogging torque.

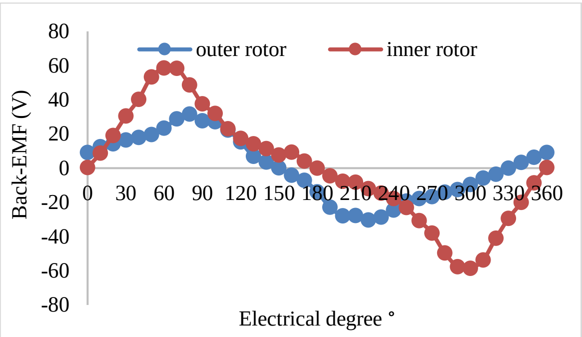


Figure 5. PMFSM modular rotor induced EMF

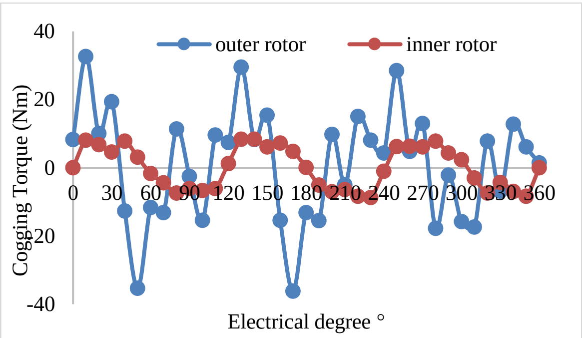


Figure 6. Modular rotor PMFSM cogging torque

For load analysis review, the current density of the armature coil, Ja, fed into the system ranges from *Ja* of 5 A_{rms}/mm^2 up to *Ja* of 30 A_{rms}/mm^2. By using information on the motor's speed and output torque, the output power of PMFSM machines may be determined. The previous analysis provided all the necessary data. In addition, (12) is used to determine the machine's power. The computed power of the motor is the sum of the torque and the rotational speed of the rotating component, and it is determined by (12)-(14):

$$P = \tau\omega \quad (12)$$

$$\omega = \frac{2\pi s}{60} \quad (13)$$

$$P = \tau\left(\frac{2\pi s}{60}\right) \quad (14)$$

Where *P* is power in kilowatts (kW), τ is torque in Newton meters (Nm), and *S* is speed in revolutions per minute (r/min). Consequently, Figure 7 highlights the suggested motor that uses 6S-10P modular inner-rotor PMFSM, contributing to the power of approximately 1.80 kW at *Ja*=30 A_{rms}/mm^2. In comparison, the modular outer-rotor PMFSM gives a maximum power of 2.07 kW at *Ja*=30 A/mm^2, higher than the modular inner-rotor. Most precisely, the graph illustrates how the power steadily rises to a maximum at a current density of 30 A_{rms}/mm^2.

Meanwhile, the current densities of torque vs. armature are displayed in Figure 7. The findings indicate that an alteration in Ja increases between 0 and 30 A_{rms}/mm^2 and changes output torque from minimal to maximal. It shows that the torque is maximum at 30 A_{rms}/mm^2, which is 34.4 Nm for the modular inner rotor PMFSM, while the modular OR can produce 39.56 Nm, higher than the modular inner rotor. Nevertheless, the output power magnitude varies as the armature current density increases from 0 A_{rms}/mm^2 to 30 A_{rms}/mm^2, as depicted in Figure 8. Accordingly, the suggested design can be optimized to improve even more, increasing the power and torque to a desirable value. Optimization refers to the process of adjusting design parameters in a sequential manner, part by part, and recurrently over the design to achieve the best possible performance of the machine, balancing factors like power, torque, and efficiency. Accordingly, the suggested design can be optimized to improve even more, increasing the power and torque to a desirable value [33].

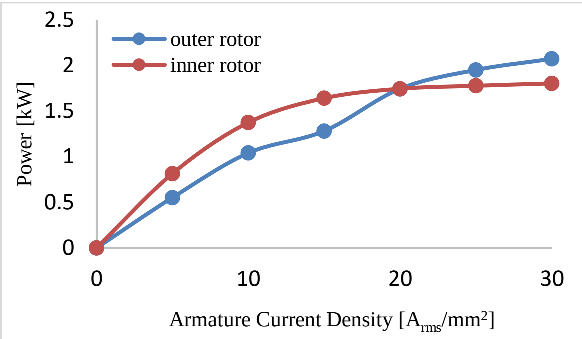


Figure 7. Power performance

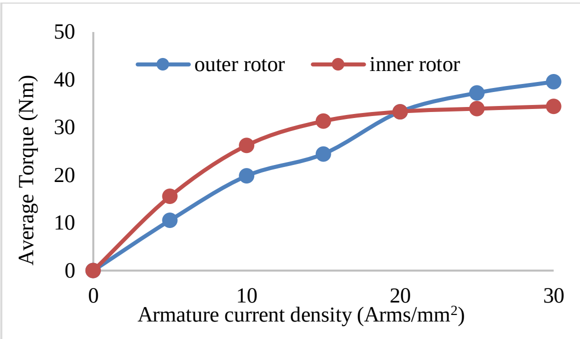


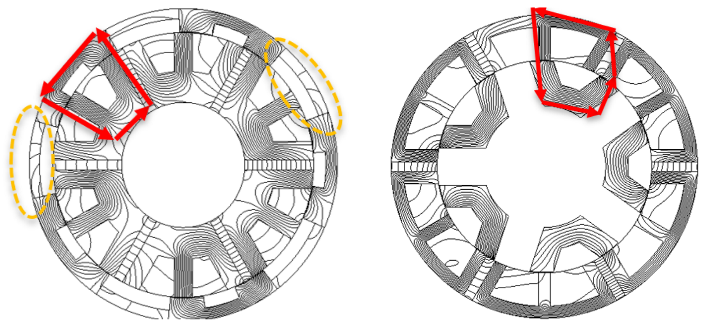
Figure 8. Torque AC performance

Recent observations indicate the proposed motor had better torque and power than the previous research, which a modular inner rotor PMFSM. The comparison result has been summarised in Table 2.

Table 2. Summary findings between modular inner rotor and modular OR-PMFSM

	Modular inner rotor	Modular OR
Back-EMF (V)	8	32
Cogging torque (Nm)	31.54	58.49
Average torque (Nm)	34.4	39.56
Power (kW)	1.8	2.07

In addition, the flux line is analyzed to determine the flux characteristics between the modular OR and modular inner rotor PMFSM. The flux line is the presence of a force field or energy flow through a surface in a particular physical medium referred to as flux. Figure 9 illustrates the magnetic flux lines for both designs, highlighting the presence of short flux lines completing a full cycle, marked in red between the stator and rotor teeth. In Figure 9(a), the modular OR design exhibits a higher flux density but also experiences increased losses, as indicated by the orange marks caused by the more complex flux paths. The flux is more concentrated in the stator, leading to flux transfer between the stator and rotor. In contrast, Figure 9(b) shows the modular inner rotor design, demonstrating a more balanced and smoother magnetic flux distribution throughout the entire magnetic structure.



(a) (b)

Figure 9. Magnetic flux lines for: (a) modular outer-rotor PMFSM and (b) modular inner-rotor PMFSM

5. CONCLUSION

This research aimed to investigate the comparative study of a new design modular OR and modular inner rotor PMFSM. This investigation has concluded that the proposed design has achieved higher torque and power than the modular inner rotor. As a result, the proposed motor produces an increment of 6.05% and 5.4% of torque and power, respectively, compared to the reference motor. It generates better torque, surpassing that of the modular inner rotor. However, the proposed motor produces a cogging torque that is quite high, which can lead to motor vibration effects on the motor's performance. In the future, several techniques can be implemented to reduce the cogging torque, such as rotor skewing, rotor pole notching, and rotor pole pairing, which can further enhance the motor's performance. Besides that, the development of a better cooling system to improve thermal resistance is essential to increase the motor's durability and efficiency. Additionally, exploring new materials for the rotor and stator can also contribute to reducing cogging torque and improving overall motor performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are openly available in IEEE Explore at https://doi.org/10.1109/I2CACIS.2019.8825010, reference number [31].

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