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ORIGINAL ARTICLE

External rotor gearless elevator machine: a new design with flanged shaft

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Abstract

The design of an external rotor gearless elevator machine (ERGEM) with a flanged shaft for elevator traction systems is presented in this paper. The machine is designed with two distinct shafts. The fixed shaft with stator is one, and the flanged shaft turns with the rotor is the other. The ERGEM's rotational movement has been reduced to a flanged shaft, and a novel motor design has been obtained that fits the market's traction pulleys and brake mechanisms. The flanged shaft provides traction by rotating with the pulley. Instead of making grooves on the rotor surface, an external pulley is used. The loads on the pulley have a negligible effect on the rotor because it is located between two fixing plates. With the plates on the right and left sides of the pulley, a symmetrical load distribution has been achieved. Finite element analyses (FEA) were performed using the maximum static load values. After the final design was approved, the prototype was built and experimental tests were conducted.

Keywords Elevator traction machine · External rotor · Gearless motor · Permanent magnet synchronous motors · Traction machine · Elevator systems

1 Introduction

Nowadays, there are mainly 4 different elevator types. These are electric elevators, hydraulic elevators, pneumatic elevators and maglev elevators. The most commonly used elevator systems are electrically driven geared or gearless elevator systems. In gearless PM synchronous motors, 40–50% lower power motor can be achieved for the same traction power requirement compared to geared motors. Thus, systems with lower power gearless motors can be installed with the same speed and carrying capacity as induction motors. With the reduction in the motor size, it is also possible to reduce the size of the drive, switch, machine brake, cable, and other components at the same rate. As a result, it helps to reduce energy consumption by reducing the system's size and weight. The ability of gearless traction motors to be connected in elevator systems via direct drive without the use of a reducer eliminates losses caused by gearboxes. The most important advantage of gearless elevator traction motors over geared induction motors is this energy saving (Duru et al. 2005).

Various roping ratios (suspension type) are used in elevator systems according to the loads and traction motors. It has been observed that the most used roping ratios are 1:1 and 2:1. Depending on the desired elevator car speed, the speed of the gearless motor also changes in different roping ratios. Therefore, roping ratio selection is an important parameter in terms of traction motor design. In gearless elevator systems, the most common roping ratio is 2:1 (Soyaslan 2020). As a result, in this study, 2:1 roping ratio was chosen for the elevator system. Various elevator suspension types are shown in Fig. 1.

Many different designs of gearless elevator motors have been released to the market for many years. Although most

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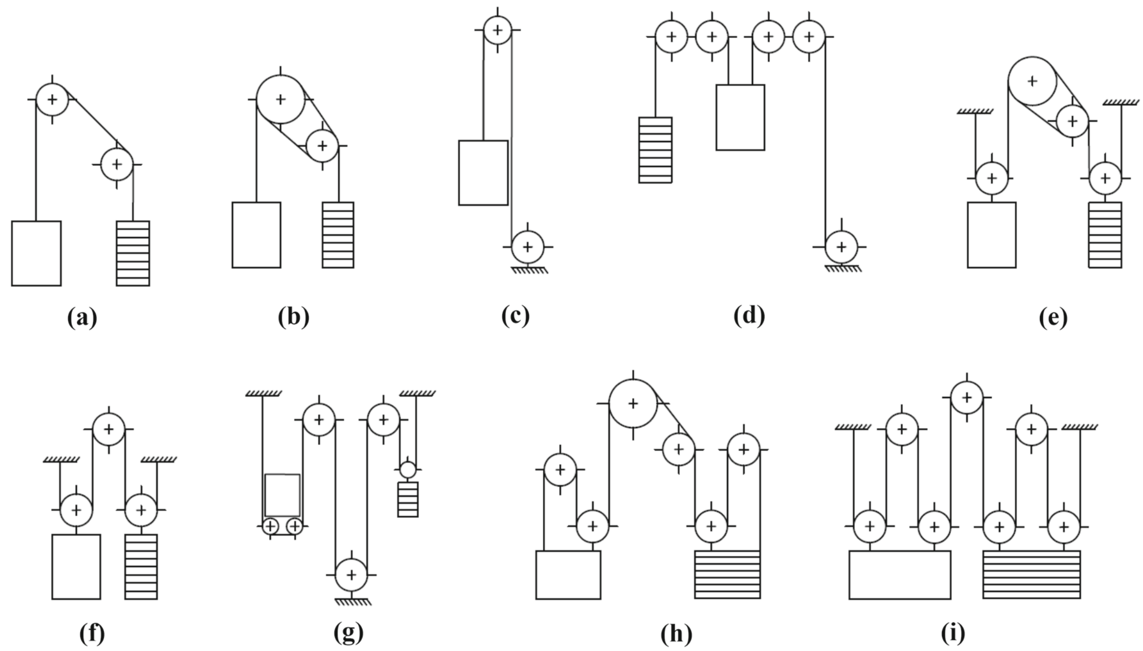

Fig. 1 Elevator suspension types **a** 1:1 Half wrap, **b** 1:1 Full wrap, **c** 1:1 Drum winding, **d** 1:1 Drum winding, **e** 2:1 Full wrap, **f** 2:1 Half wrap, **g** 2:1 Half wrap, **h** 3:1 Half wrap, **i** 4:1 Half wrap (Abdalla and Al-Jarrah 2011)

of these designs include internal rotor and radial flux motor structure, some designs are produced as external rotor or axial flux (Soyaslan et al. 2019). Some of the examined studies are related to the stator, rotor or magnets of the motor, while some of them contains innovations about fasteners and shapes, motion transmission systems, brake mechanisms, etc. Moreover, some studies have been investigated in which the length of the motor stack is reduced in order to reduce the magnet costs, and the stator tooth structure is changed to obtain larger winding areas (Rüger et al. 2014).

In this study; instead of an internal rotor structure, a novel gearless motor with an external rotor has been designed taking into account the static loads. The designed external rotor elevator motor differs from other designs in that the pulley is located between the fixing plates, the rotor's rotation movement is transmitted to the pulley via a flanged shaft, and the motor brake is connected axially to the fixing plate. Although there are designs in external rotor elevator motors with the pulley on the side, an external rotor elevator motor with the pulley between the fixing plates and the rotation movement of the rotor transmitted to the pulley with a flanged shaft has not been observed. The lifting capacity of the designed ERGEM is 630 kg, torque is 240 Nm and rated speed is 159.2 rpm. There are two different shafts in the machine. One of them is the fixed shaft which is located in the stator hub. The other is the flanged shaft which turns with the rotor drum. The rotor's rotational movement of the ERGEM has been reduced to the flanged shaft, and a novel motor design has been produced

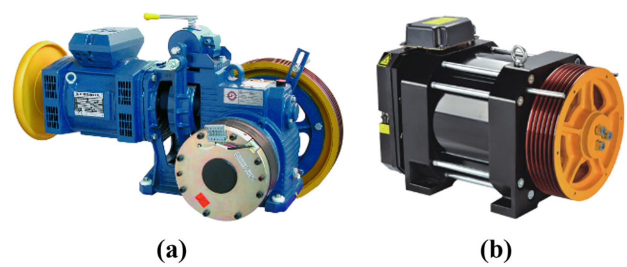

Fig. 2 Geared and gearless elevator traction motors: **a** Montanari Giulio (2014), **b** Sag Motor (2016)

that is compatible with the traction pulleys and brake systems available in the market.

1.1 PMSM type elevator traction systems

One of the most important component affecting energy efficiency in elevator systems is the traction motor. By year of 2018, 5.95 million elevators are used in European countries (Nyman 2018). In Germany, one of the developed countries in Europe, approximately 0.5% -0.8% of the total energy use is used by elevators (Hirzel et al. 2010). In developing countries, this rate rises to 2% and above. The main reason for this situation is the frequent use of PMSM type motors with high energy efficiency in developed countries, and the widespread use of geared induction motors with low energy efficiency in

Table 1 Classification of gearless elevator machines

Feature	Types
Flux	Radial flux, axial flux
Rotor	Inner rotor, external rotor
Brake	Disc brake (mono or multi), Block brake (mono or multi)
Pulley	External pulley (mono or multi), Pulley grooves with on the rotor (rotor is used for pulley)
Stator Rotor	Mono stator-mono rotor, Multi stator-multi rotor, Mono stator-multi rotor, Multi stator-mono rotor
Magnets	Have bedding on the rotor–No bedding, Skewed magnets–Straight magnets, Step skewed magnets–Aligned magnets
Traction	Rope drive, Belt drive

developing countries. In Fig. 2, examples of geared and gearless elevator traction motors are shown Soyaslan (2020). A gear traction elevator is made up of a motor and a gearbox. Gears' primary function is to provide power to the pulley that moves the ropes. A gearless traction elevator does not have a speed regulation gear system. The efficiency of gearless elevator motors with direct drive has also increased. These motors require a lot of torque at low speeds (Soyaslan et al. 2023). As a result of literature researches, the classification of PMSM type elevator traction systems has been achieved and presented in Table 1.

1.2 ERGEM features

When compared with inner rotor designs, external rotor designs have some advantages and disadvantages. Electrical motor designers must select motor types while considering constraints such as inertia, torque, performance, noise, and operating areas (Soyaslan et al. 2019). External rotor designs have the following advantages over inner rotor designs (Allied Motion Technologies Inc 2017);

- They have high inertia and low cogging torque.
- They provide the opportunity to obtain maximum torque with the possibility of a wider air gap.
- They have more stable low-speed performances.
- They are ideal for quiet environments due to low operating noise.
- For the same performance level, external rotor designs are axially shorter than inner rotor designs.

The external rotor designs have the following disadvantages as well (Soyaslan et al. 2019; Belkhadir et al. 2023);

- They have higher heating rates.
- They have bigger flux densities.
- Lack of turn faults in the stator windings can be occurred.
- They have disadvantages in terms of fault tolerance.

The slot-pole ratio is one of the most important parameters to consider when designing a high-performance motor. Although determining this ratio, care should be taken that there are no unbalanced magnetic forces. When the number of slots per pole per phase (q) presented in (1) is not chosen correctly, significant unbalanced magnetic forces arise due to the asymmetric placement of slots and windings (Tanç 2014). In (1), N_{slot} represents the slot number, p the number of poles, and n_f the number of phases.

$$q = \frac{N_{\text{slot}}}{p \cdot n_f} \tag{1}$$

Designs where q value is between 1/2 and 1/3 generally produce high performance, low cogging torques and high winding factor (k_{wf}) values (Salminen 2004). In order to have high flux distribution and torque density, the number of slots and poles are kept as close to each other as possible. There are many fractional slot/pole combination options that can be used for elevator systems. These need to be eliminated and a number of studies need to be optimised. The number of slots per phase (N_{slot}/n_f) must be even number in order to avoid unbalanced magnetic forces. Combinations with the number of slots two more or two less than the number of poles refer to machines with high flux distributions and high torque densities for electric motors (Wang et al. 2008). Accordingly, slot and pole numbers that have a relationship like in (2) give the most suitable motor designs.

$$N_{slot} = p \pm 2 \tag{2}$$

The use of double-layered winding in electric motors reduces eddy current losses, torque fluctuations, space harmonic components of magnetomotive force (MMF) and electromotive force (EMF) (Bianchi et al. 2006; El-Refaie et al. 2008). To provide a low cogging torque, a slot-pole combination with a bigger least common multiple (LCM) of N_{slot} and p should be determined (Avsar et al. 2023). Owing to its high efficiency and low cogging torques, double-layer winding structure was preferred in this study. Designs where the greatest common divisor (GCD) of the slot-pole combinations are even numbers should be selected for achieving low net radial forces (El-Refaie and Jahns 2005). In the elevator design for this study, the stator stack length and diameter must be in limits. As a result, high slot numbers, which result in increased motor diameter dimensions, were avoided. According to the knowledge obtained from the literature, 12/10, 12/14, 18/16, 18/20, 24/22 and 24/26 slot/pole structures are suitable combinations. Winding factors (k_{wf}) for these particular slot/pole combinations are given in Table 2

Table 2 Winding factors for harmonics

N_{slot}/p	Wound teeth	$n=1$	$n=3$	$n=5$	$n=7$
12/10	All	0.933	0.5	0.067	0.067
	Alternate	0.966	− 0.707	0.259	0.259
12/14	All	0.933	0.5	0.067	0.067
	Alternate	0.966	− 0.707	0.259	0.259
18/16	All	0.945	− 0.577	0.14	0.061
	Alternate	0.945	− 0.577	0.14	0.061
18/20	All	0.945	− 0.577	0.14	0.061
	Alternate	0.945	− 0.577	0.14	0.061
24/22	All	0.950	− 0.604	0.163	−0.096
	Alternate	0.958	− 0.653	0.205	0.158
24/26	All	0.950	− 0.604	0.163	−0.096
	Alternate	0.958	− 0.633	0.205	0.158

Table 3 Parameters of designed elevator machine

Feature	Designed ERGEM
Motor outer diameter (mm)	242
Stack length (mm)	150
Number of slots/poles	18/20
Suspension	2:1
Rated output power (kW)	4
Rated voltage (V)	380
Wire size (mm)	0.8
Circuit type	Y
Rated speed (rpm)	159.2
Torque (Nm)	240
Rated current (A)	7.18
Frequency (Hz)	26.53
Air Gap (mm)	1
Weight (kg)	141
Brake	Mayr Roba-twinstop 250
Encoder	Fenac FNC SC2048

(Wang et al. 2008). n represents the harmonic order number. Winding factors for fundamental and low-order harmonics can be seen from Table 2.

In the light of the information given and taking into account the optimum q, LCM and GCD values and the dimensions of the ERGEM, it was decided to have a slot-pole ratio of 18/20 which also validated with FEM analyses. Thus, the q value is 0.3, the k_{wf} value is 0.945, the LCM value is 180, and the GCD value is 2. Diameter and length of the designed motor was kept the same as a motor of the same power and torque used in the market. Table 3 shows some of the ERGEM designed parameters.

2 Novel ERGEM design

2.1 External rotor gearless elevator machines

Over the years, many different designs of gearless elevator motors have been introduced. Although the majority of these designs are produced as inner rotor and radial flux motors, some are also produced as external rotor or axial flux motors (Soyaslan 2020). Ziehl-Abegg, Partzsch, Leroy Somer, Ningbo Xinda Elevator and Otis have been known as the leading manufacturers of ERGEM products in the elevator industry. Figure 3 shows the external rotor machines in the market.

Although some patent researches involves innovations related to the stator, rotor, or magnets of the motor, others concern fasteners and shapes, motion transmission systems, and brake mechanisms. Some of these designs have the pulleys on the rotor, while others have the pulley on the side. Brake mechanisms are constructed out of block or disc structures (Ningbo Xinda Elevator 2011; Elevator 2015; Canon 2016; Mitsubishi Electric 1990; Swiss Traction Ag 2005). A stator with bidirectional teeth and a motor with both an inner and an external rotor were designed in Somer (2005). The inner and external rotors are coupled, have the same number of poles, and move in tandem. The purpose of this model is to increase the motor's power density. Reference Canon (2016) has a similar design with different drive pulleys on both the right and left sides. As a result of connecting the traction ropes from the right and left sides, a high-powered elevator system emerges. Another design for increasing power includes a stator inside and outside, as well as a rotor between the stators (Somer 2009). Step skewing of magnet method is used to reduce cogging torque in the smooth movement and quiet operations like elevators, vehicles etc. Cooling through shaft or cooling systems with rods are generally used in order to

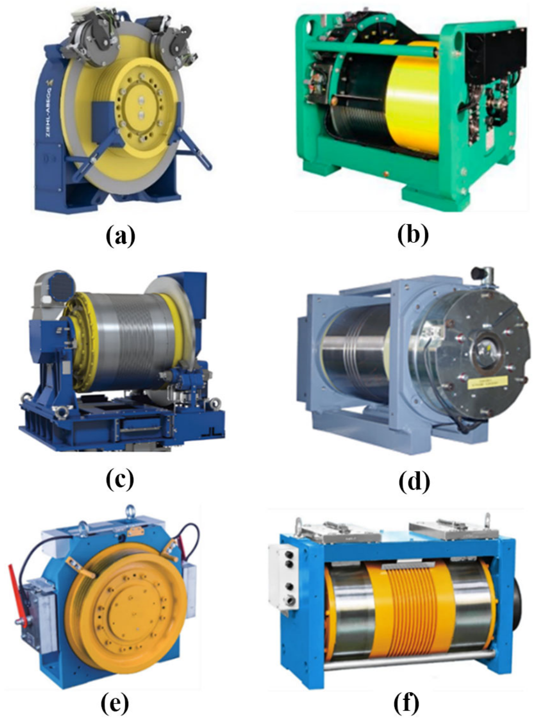

Fig. 3 External rotor gearless elevator machines: **a** Ziehl Abegg-ZAsyn, **b** Leroy Somer Z Range, **c** Otis SkyMotion 800, **d** Swiss Traction-Zefir, **e** Ningbo Xinda Elevator Mini, **f** Ningbo Xinda Elevator Diana

solve the heating problems. Special apparatuses are used for fixing the magnets, or stator teeth are produced separately and combined with an apparatus in some designs.

2.2 Flanged shaft design

The external rotor gearless machines used in elevator systems and their properties are mentioned in Sect. 2.1. According to literature, there are several designs that use the rotor drum as a pulley (Ningbo Xinda Elevator 2011; Elevator 2015; Canon 2016; Mitsubishi Electric 1990; Swiss Traction Ag 2005). This provides a cost advantage since there is no need to use a separate pulley. However, this kind of design could cause abrasions at the rope slots. Also the rotor must be thick enough for lifting the static and dynamic loads of the whole system. Abrasions at the rope slots could cause a deformation of rotor drum and deflection may pass the yield stress limits. To avoid these problems and make a modular design, a novel external rotor design with pulley was made as shown in Fig. 7. The advantages of using a separate pulley for external rotor gearless PMSM are listed as follows;

- The loads at the rotor drum has a negligible effect.
- The air-gap dimension will be always in its determined value, because there are less significant loads on the rotor.

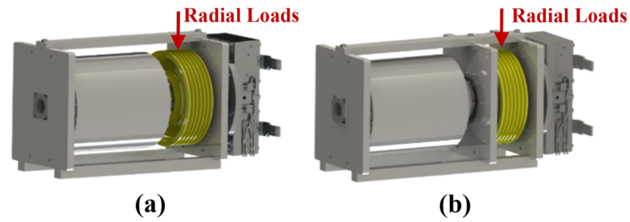

Fig. 4 The first and second ERGEM design trials with a rectangular profile, **a** without a middle fixing plate, **b** with a middle fixing plate

- The pulley's dimension can be changed according to implementation of gearless elevator motor.
- A belt pulley can be used for belt drive ERGEMs.
- The motor brake does not act to the rotor drum radially. Therefore, the forces acting to rotor drum and shaft by the brake are neutralized.

The rotating part of the ERGEM is the rotor and there are magnets on it. The rotational motion is transferred from rotor to the flanged shaft. Various geometries were studied while the machine was being designed. In the first design experiment without the fixing plate in the middle (Fig. 4a), radial loads were acting on the rotor. In order to eliminate the relatively high stresses that occur in the rotor geometry under these loads and to obtain a symmetrical load distribution, it was decided to place a fixing plate on the left side of the pulley, as shown in Fig. 4b. In addition, in the structural analysis of the first design trials (especially in the torsion analysis), it was decided to have the final model of the machine in a cage structure in order to reduce the stresses on the rectangular parts connecting the fixing plates. Therefore, the geometry and positions of the joining parts in the second design study (Fig. 4b) were also changed. The bending and torsional moment analyses results of the first design trials are shown in Figs. 5 and 6, respectively. In the FEA simulation setup, blended curvature-based mesh method with 16 Jacobian points was used. High mesh quality with 2 mm minimum and 14 mm maximum element size and surface to surface bonding method was used for interactions. Forces and torques was applied to the parts from the appropriate places and analyses results were taken. In the elevator machine design, the factor of safety was taken as 5 (TS1812 1988). The first design trials did not provide this safety factor and the model with a cage structure and middle fixing plate was selected as the final model.

The torsional moment of the cabin and counterweight and also rotor's torque are trying to rotate and bend the body of the machine. As the results of the analyses show, the connection parts of the first and second design did not compensate these bending and torsional moments according to safety factor. Since the connection parts of the first and second design are on the outsides of the plates and they are not placed at

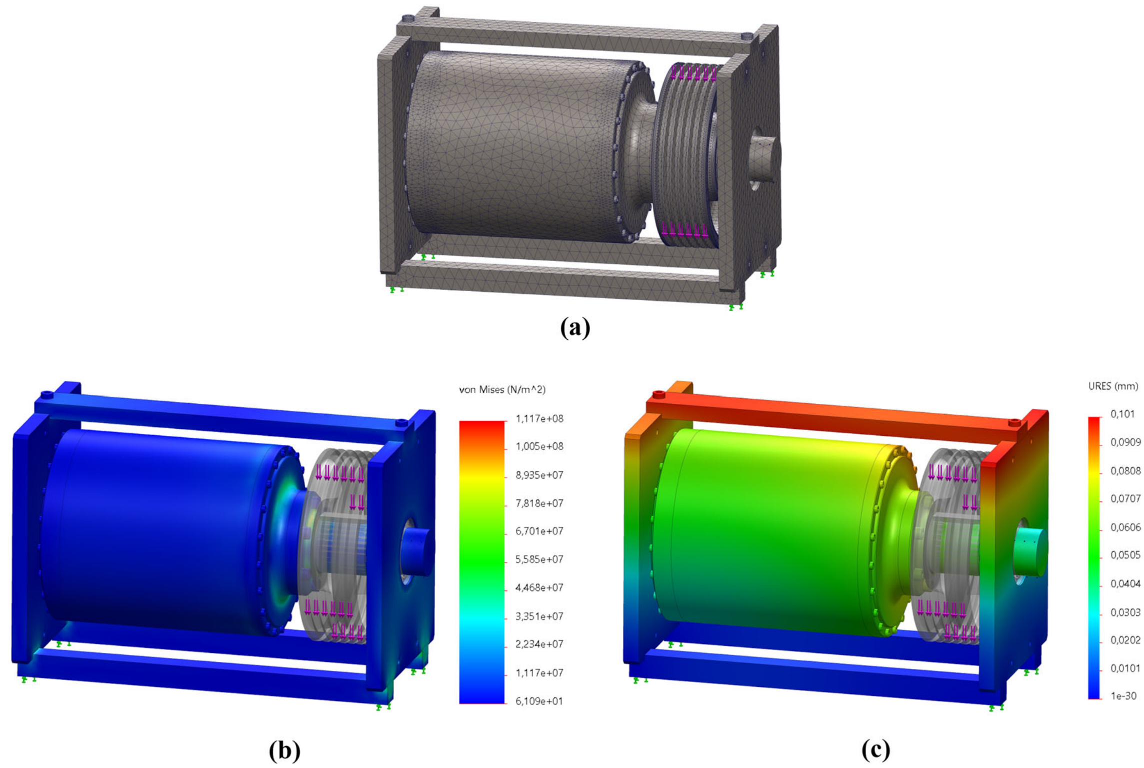

Fig. 5 Bending moment analysis results of first design; **a** Mesh structure, **b** Von Mises stress analysis results, **c** displacement analysis results

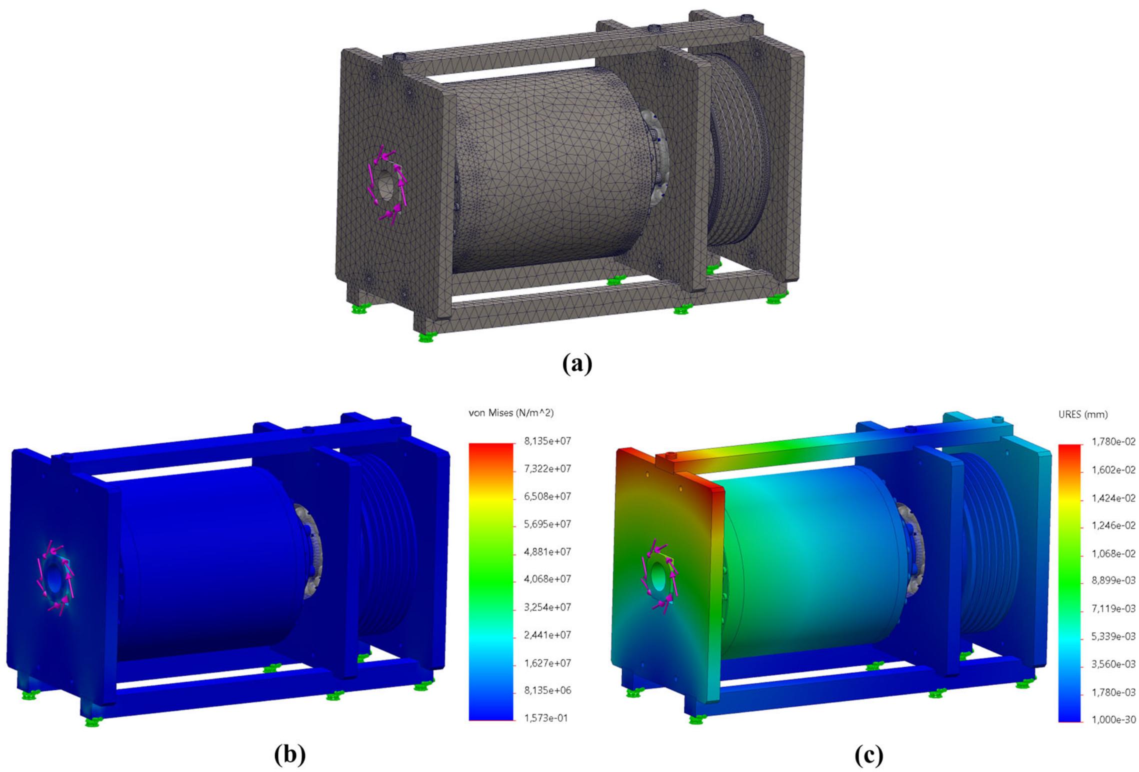

Fig. 6 Torsional moment analysis results of second design; **a** Mesh structure, **b** Von Mises stress analysis results, **c** displacement analysis results

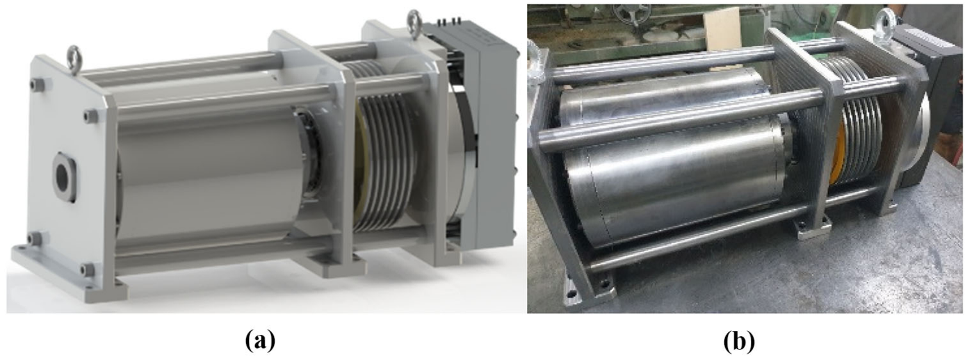

Fig. 7 **a** The final model of novel ERGEM, **b** manufactured machine

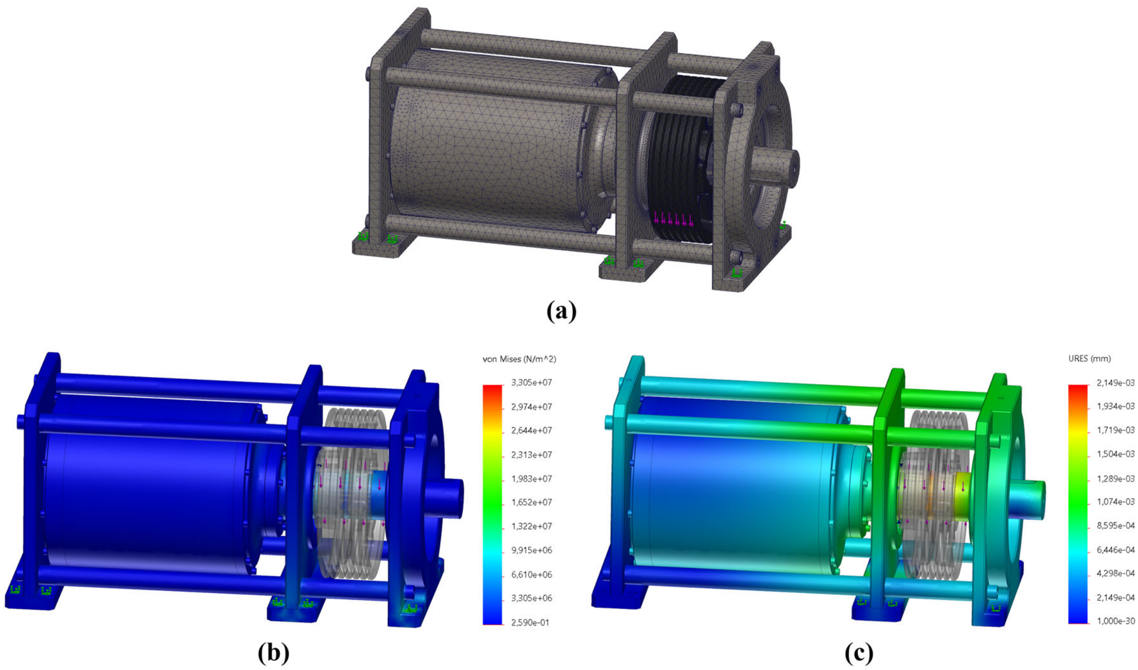

Fig. 8 Bending moment analysis results of the final design; **a** Mesh structure, **b** Von Mises stress analysis results, **c** displacement analysis results

four corners of edges, the torsional moment may cause the body a distortion. To prevent this distortion, the connection parts of the final design are placed on the corners of the edges and moved to the inner points of the fixing plates to increase the body's stability. The loads on the pulley have a negligible effect on the rotor since the flanged shaft is situated between two mounting plates in the final design depicted in Fig. 7. A symmetrical load distribution has been achieved by placing plates on the right and left sides of the pulley. Furthermore, the cage structure reduces the motor's distortion due to torsion. Bending and torsion analyses results of the final design are shown in Figs. 8 and 9, respectively. Despite the fact that the final model's body provided the safety factor, bending and torsional moment analyses were performed on the flanged shaft as well. Since the flanged shaft is the most critical and important part of the machine for elevator loading, it was detaily analyzed in Sect. 2.3.

2.3 Stress analysis of flanged shaft

The loads at the flanged shaft will be maximum 2500 kg and the FEA stress analysis is done according to this value. Section view of the machine, mesh structure and the results of the stress analysis under bending moment are shown in Figs. 10 and 11, respectively. The shaft material is selected AISI 1010 steel (hot rolled bar) in the SolidWorks Simulation analysis. The part names of ERGEM are given in Table 4. In the FEA simulation setup of the flanged shaft, blended curvature-based mesh method with 16 Jacobian points was used. High mesh quality with 1.2 mm minimum and 5 mm maximum element size was used. The number of total nodes of the mesh is 104,544 and total elements is 70,952. As it can be seen from Fig. 10; the radial loads on the pulley is located between the fixing plates and bearings. Hence, the

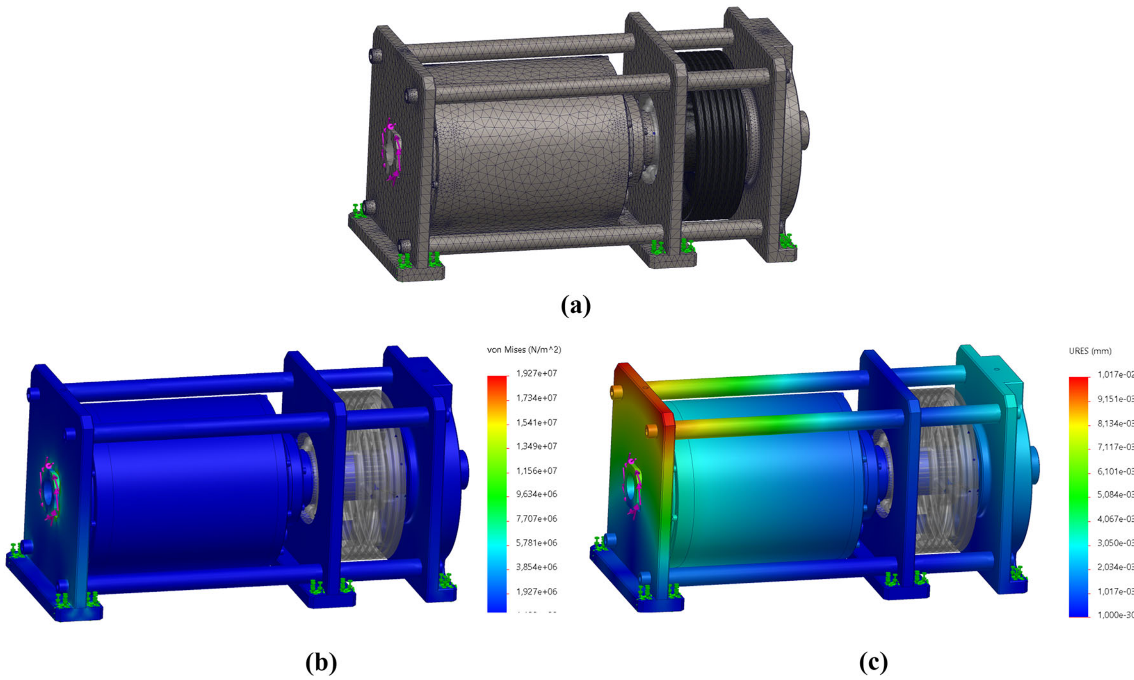

Fig. 9 Torsional moment analysis results of the final design: **a** Mesh structure, **b** Von Mises stress analysis results, **c** displacement analysis results

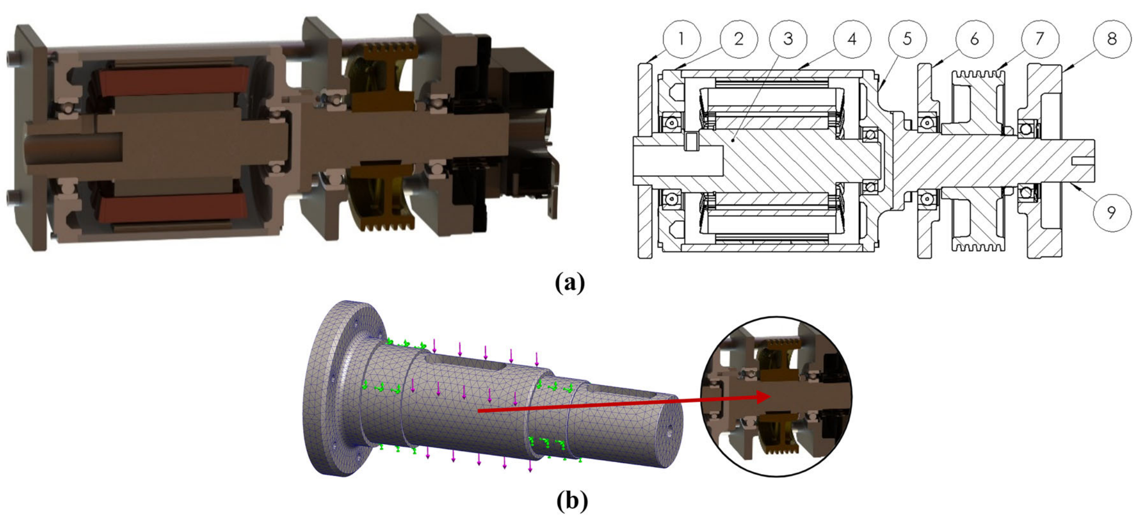

Fig. 10 **a** Section view of the ERGEM, **b** Mesh structure of flanged shaft under 25 kN force

loads on the pulley have a negligible effect on the rotor since the flanged shaft is situated between two mounting plates.

When the analysis results are examined; the maximum von Mises stress value is obtained 19.17 MPa under 25 kN load force. This number is significantly lower than the yield strength value of the specified shaft material, which is 180 MPa. The shaft's safety factor is 9.389, according to bending moment analysis results. Furthermore, the maximum displacement is 2.042 µm, which is a very low value.

A torsional moment of 240 Nm, which is the maximum output torque of the motor, is applied to the flanged shaft. The connection points of the rotor right cover and flanged shaft were taken as fixed points and the torsional moment was applied from the end of the flanged shaft. The mesh structure of the flanged shaft under the applied torsional moment is shown in Fig. 12, von Mises stress results and the displacement results are shown in Fig. 13.

When the analysis results are examined; the maximum von Mises stress value is obtained 16.11 MPa under 240 Nm torsional force. While analyzing the torsion effect, the shear yield strength of the material is taken into account. This is approximately 0.58 times the yield strength for bending

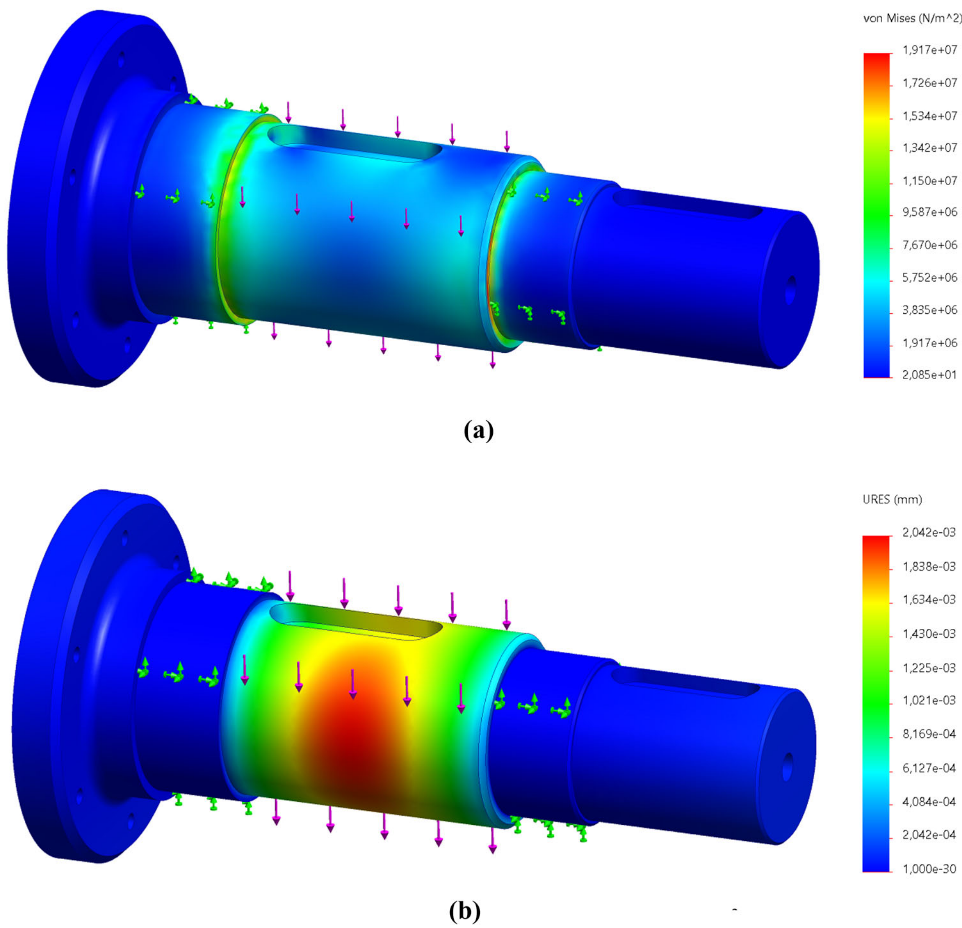

Fig. 11 Bending moment analysis of flanged shaft, **a** Von Mises stress analysis results (N/m^2) **b** displacement analysis results (mm)

Table 4 Part names of ERGEM

Part no	Part name
1	Left fixing plate
2	Left cover
3	Fixed shaft
4	Rotor
5	Right cover
6	Middle fixing plate
7	Pulley
8	Right fixing plate
9	Flanged shaft

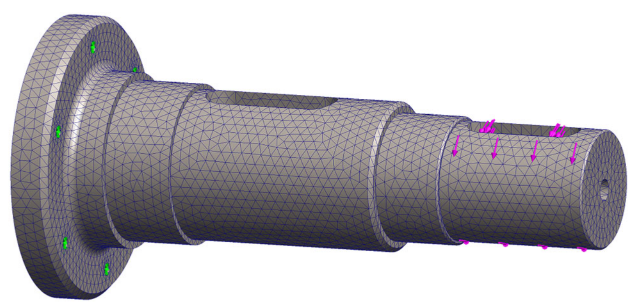

Fig. 12 Mesh structure of the flanged shaft under 240 Nm torsional moment

(Shear Strength 2007). In this case, the shear yield limit of the material is 104.4 MPa. Thus, the flanged shaft was 6.48 times safe under the effect of torsional moment. In the design calculations, the factor of safety was taken as 5. According to the deformation analysis, the maximum displacement was found to be 12.62 µm at the ends of the flanged shaft. As a result, the flanged shaft operates in the safe zone when forced to the maximum torsional moment.

2.4 Prototype manufacturing

The machine is approved for safe working conditions following FEA analyses. The prototype parts were then manufactured, as shown in Fig. 14. The loading tests were done with a test setup shown in Fig. 15. To determine the strength, 240 Nm torsional moment was applied to the shaft. The tests were completed successfully, and no shaft deformation occurred. The machine operated safely, and the prototype was approved.

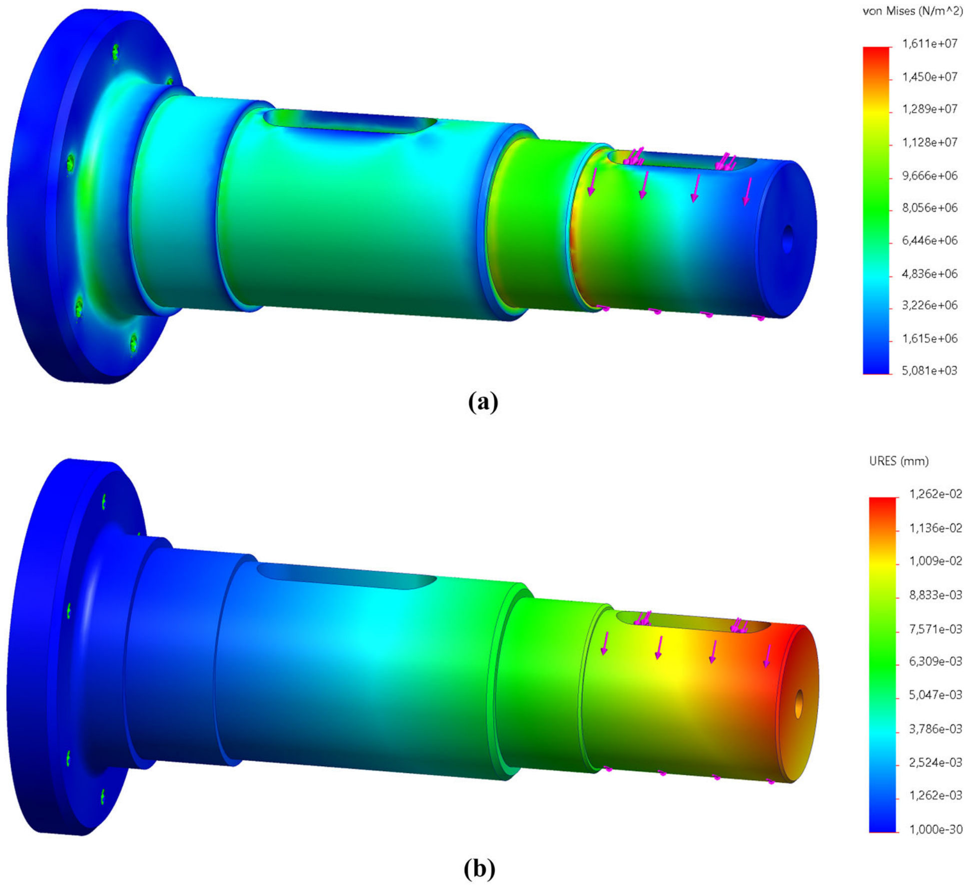

Fig. 13 Torsional moment analysis of flanged shaft, a) Von Mises stress analysis results (N/mm.^{2}) b) Displacement analysis results (mm)

Fig. 14 Prototype parts of the elevator machine

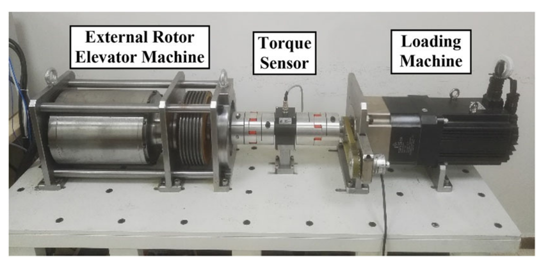

Fig. 15 Elevator machine test setup

3 Conclusion

The rotational motion of the ERGEM's rotor has been reduced to the flanged shaft, and a new motor design has been obtained that is suitable for market-available traction pulleys and brake mechanisms. As in other external rotor motors, the pulley was not formed by opening grooves on the rotor. A standard pulley was connected to the rotor drum with the flanged shaft. A similar motion transmission system in external rotor elevator motors has never been described in the literature. The external rotor motor can be converted into a belt-drive elevator motor by replacing the rope pulley with a belt pulley. According to the literature research, this design is being proposed for the first time within the scope of this study. FEA analyses and experiments showed that the manufactured elevator machine with a flanged shaft design is suitable for elevator systems.

Visual inspection was made and no cracks, fractures or deformations were detected in any part of the machine. Also the dimensions and fixing points are measured and they were same with the starting values. There are several defect detection methods. In the elevator systems, visual inspection is generally enough for crack or deformation detection. If any of the parts fails, the measurement results will change, and this will be obvious. The dimensions' changes also can be followed by the torque sensor, current sensor and tachometer data. In the test results, the data of the sensors were stable and that show us the parts worked in the limits.

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Author contributions MS: Conceptualization, Methodology, Writing-Original draft preparation, Visualization, Software, Writing-Reviewing and Editing OE: Validation AF: Supervision YA: Investigation.

Declarations

Conflict of interest The authors declare no competing interests.

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