The Four-Pole Planetary Motor

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Abstract

Electric drive systems usually gain their high power density by using a motor with a high rotational speed at a certain torque. To increase the output torque the motor needs to be equipped with an additional gearbox. The speed and therefore the output power are often limited by the mechanical strength of the rotor material. This paper proposes a multi-rotor drive system, which allows to further increase the maximum output power by splitting the motor into several partial motors. The structure of the multi-rotor machine, which behaves like a single three-phase motor, is derived for the case of using four-pole permanent magnet rotors. To verify the operating principle a prototype is built and measurements are presented.

1 Introduction

In numerous industrial and automotive applications electric drive systems with a high power to size ratio are needed due to restrictions to the weight or the construction size. Since the torque mainly defines the size of an electric machine, a high power density is usually reached with a high rotational speed at a certain torque [1]. An additional reduction gearbox is used to increase the torque on the output shaft and simultaneously reduce the speed. Nevertheless, the maximum rotor speed and therefore the maximum power are often limited by the mechanical strength of the rotor material. Typically, circumferential velocities of 100 m/s to 200 m/s can be achieved economically [2].

A solution to further increase the maximum rotational speed is to split the conventional motor into several partial motors with smaller rotor diameters. Due to the lower circumferential velocity of the partial rotors the maximum speed and therefore the maximum total output power can be increased. A special gear set is needed to combine the power of all rotors to the main output shaft. This approach of using multiple separated motors as a joint drive has already been a topic of research and is already applied in industrial applications, see e.g. [3], [4], [5], [6].

In contrast to using separated motors, in this paper a multi-rotor drive system, called Planetary Motor, is presented, where multiple rotors are integrated into a common stator. This leads to a simplified stator structure in comparison to the structure of separated stators. The interconnection of the motor coils results in a three-phase winding system and therefore the motor can be driven by a three-phase inverter with conventional control strategies (e.g. field-oriented control). The structure of the Planetary Motor with two-pole permanent magnet rotors was already presented in [7].

This paper is organized as follows. In Section 2 the motor structure with four-pole permanent magnet rotors is derived. The mechanical coupling of the rotors is explained in Section 3. Measurement results of a prototype with four rotors are shown in Section 4. Conclusions are drawn in Section 5.

2 Motor structure

2.1 Stator

The derivation of the stator structure starts with two identical four-pole permanent magnet motors with concentrated stator windings shown in Fig. 1. The goal is to simplify the structure and integrate the rotors into one shared stator. At first only the magnetic field distribution produced by the permanent magnets is investigated, the current in the stator winding system is zero. For the given

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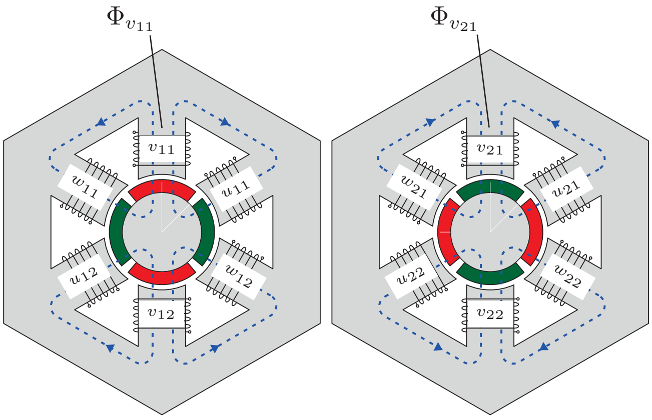

Fig. 1: Four-pole permanent magnet synchronous motor

rotor positions depicted in Fig. 1 the magnetic flux $\Phi_{v_{11}}$ through the stator tooth v_{11} of the left motor is the same as the flux $\Phi_{v_{21}}$ through the tooth v_{21} of the right motor, but in opposite direction. Similar conditions can be observed for other pairs of stator teeth which are given in Eq. (1).

$$\begin{aligned} \Phi_{u_{11}} &= -\Phi_{w_{21}} & \Phi_{u_{12}} &= -\Phi_{w_{22}} \\ \Phi_{v_{11}} &= -\Phi_{v_{21}} & \Phi_{v_{12}} &= -\Phi_{v_{22}} \\ \Phi_{w_{11}} &= -\Phi_{u_{21}} & \Phi_{w_{12}} &= -\Phi_{u_{22}} \end{aligned} \tag{1}$$

Without changing the behaviour of the individual motors, pairs of stator teeth with equal flux (but opposite direction) can be connected. This leads to the structure shown in Fig. 2. It should be noted, that Fig. 2 only shows a schematic structure which might look more steel intensive than the original structure shown in Fig. 1. By putting the rotors and the stator teeth closer together the structure can be simplified.

So far, the simplification of the stator structure was only investigated for a single position of the two rotors. As shown below, the conditions given in Eq. (1) can also be met in the case that both machines are rotating if a constraint between the two rotor positions is fulfilled. Assuming that the permanent magnets produce a sinusoidal flux density distribution in the air gap, the flux through the stator teeth can be calculated by

$$\begin{aligned} \Phi_{u_{i1}}(\gamma_i) &= \Phi_{u_{i2}}(\gamma_i) = \hat{\Phi}_m \cos(2\gamma_i) \\ \Phi_{v_{i1}}(\gamma_i) &= \Phi_{v_{i2}}(\gamma_i) = \hat{\Phi}_m \cos(2(\gamma_i - \pi/3)) \\ \Phi_{w_{i1}}(\gamma_i) &= \Phi_{w_{i2}}(\gamma_i) = \hat{\Phi}_m \cos(2(\gamma_i - 2\pi/3)) \end{aligned} \tag{2}$$

with γ_i the mechanical rotor position of motor i ($i = 1, 2$) and $\hat{\Phi}_m$ the amplitude of the flux. Note

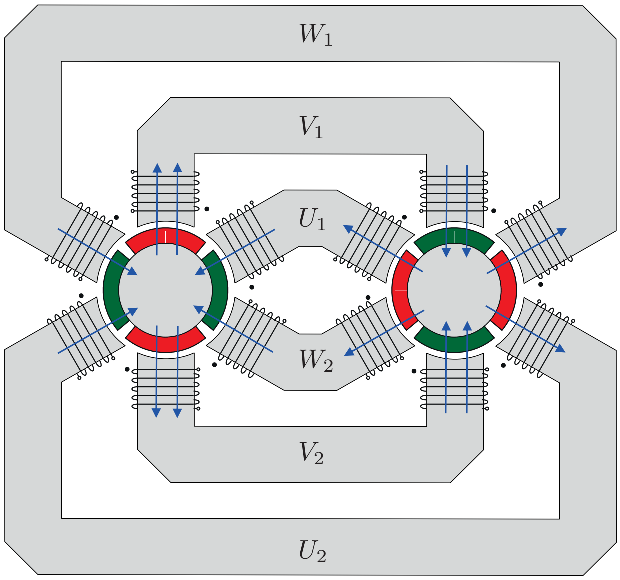

Fig. 2: Schematic structure of a four-pole Planetary Motor with two rotors

that $\gamma_i = 0$ is the position where the d-axis is aligned with the stator tooth u_{i1}. Insertion of Eq. (2) into Eq. (1) yields to a constraint between the two rotor positions, which is given in Eq. (3).

$$\gamma_2 \overset{!}{=} \frac{\pi}{6} - \gamma_1 \tag{3}$$

That means that the d-axes of the rotors need to be at a certain angle to each other. The time derivation of Eq. (3) gives $\omega_2 = -\omega_1$, so the rotors must move with the same speed but in the opposite direction. When installing the rotors into the stator, they need to be initially placed in the correct orientation. A special gear set, which is described in Section 3, keeps the rotors synchronised to each other, so that the constraint given in Eq. (3) is fulfilled automatically.

The magnetic flux through the stator teeth which is produced by the coils leads to an additional constraint to the currents in the stator winding systems in order to fulfill Eq. (1).

$$\begin{aligned} i_{u_{11}} &\overset{!}{=} -i_{w_{21}} & i_{u_{12}} &\overset{!}{=} -i_{w_{22}} \\ i_{v_{11}} &\overset{!}{=} -i_{v_{21}} & i_{v_{12}} &\overset{!}{=} -i_{v_{22}} \\ i_{w_{11}} &\overset{!}{=} -i_{u_{21}} & i_{w_{12}} &\overset{!}{=} -i_{u_{22}} \end{aligned} \tag{4}$$

A detailed mathematical derivation of these constraints can be found in [8]. As a result of

Eq. (4) the two stator winding systems have a different phase order (left motor u, v, w and right motor w, v, u). Therefore, the rotary fields in the two air gaps are rotating in opposite directions. Consequently, the torque of the two rotors is also oriented in the opposite direction, confirming the different directions of rotation from Eq. (3).

2.2 Electrical interconnection

An easy way to meet the constraints given in Eq. (4) is to connect the two coils on each merged stator tooth in series. In other words, the two coils can be combined to a new coil with twice the number of turns. Thus, the number of coils of the new stator structure is reduced from 12 to 6. Now each phase (u, v, w) consists of two coils which can be connected in series or parallel. Furthermore, the three phases can be connected in star or delta connection. In Fig. 3 an example with two coils per phase in series and star connection of the three phases is shown.

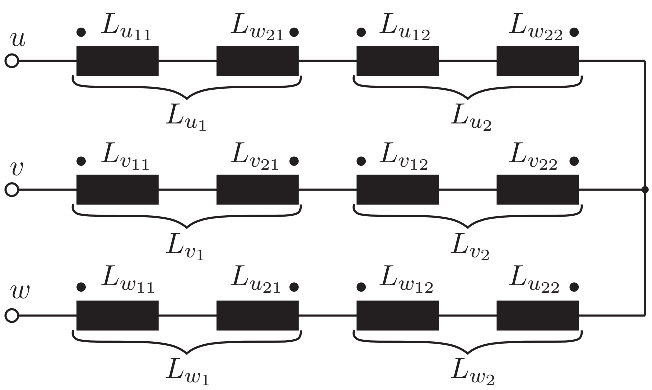

Fig. 3: Star connection of the phases and series connection of the phase coils

The interconnection of the motor coils results in a three-phase winding system. Thus, the Planetary Motor behaves like a conventional permanent magnet synchronous machine at the motor terminals. Therefore, conventional inverters and control strategies (e.g. field-oriented control) can be used. A position sensorless control of a four-pole Planetary Motor is presented in [9].

2.3 Extension to several rotors

Adaptions of the structure with two rotors shown in Fig. 2 allow to build motors with a higher number of rotors (4, 6, etc.). As an example, a Planetary Motor with four rotors can be derived by placing two identical Planetary Motors with two rotors one above the other. Similar simplification steps, which were done in Section 2.1, lead to the common stator structure shown in Fig. 4. The interconnection of the 12 stator coils results in a three-phase winding system again. Also note that adjacent rotors move in opposite directions.

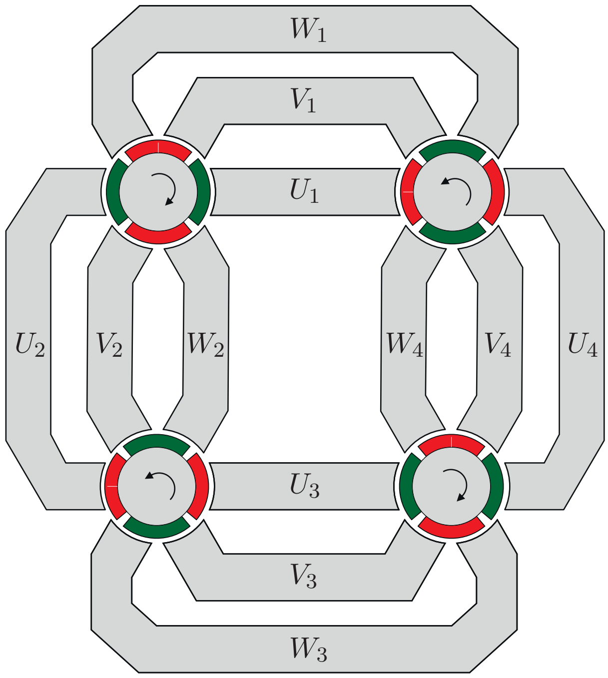

Fig. 4: Four-pole Planetary Motor with four rotors [9]

By interpreting the Planetary Motor with four rotors as a series connection of two Planetary Motors with two rotors, structures with a high number of rotors can be derived.

3 Gearbox

To combine the power of all rotors and transmit it to the main shaft a gearbox is needed. As already discussed in Section 1, the partial rotors usually operate at high speed and low torque, which allows to reduce the construction size. Thus, the gearbox is additionally needed to increase the torque on the main shaft.

This section proposes a gearbox for a motor with four rotors, which is also used for the prototype. The mechanical coupling of the four rotors, which are rotating in different directions (see Fig. 4), is achieved by a modified planetary gear set shown in

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Fig. 5. Note, the planets of a conventional planetary gear are rotating in the same direction. The rotors of the partial motors are connected to the planets of the gear set. Two opposite planets (1 and 3) interact with a central sun gear and the other two planets (2 and 4) are connected to the outer ring gear. This arrangement allows that adjacent rotors can rotate in opposite directions while the sun and ring gear rotate in the same direction. As depicted on the left side of Fig. 5 the sun and ring gear need to be placed in two axially shifted planes to ensure that the gears do not interfere. A solution to avoid the axial shift of the two gears and to reduce the construction size of the gearbox is to put the axes of the four rotors (planets) on the corners of a rhombus instead on the corners of a square.

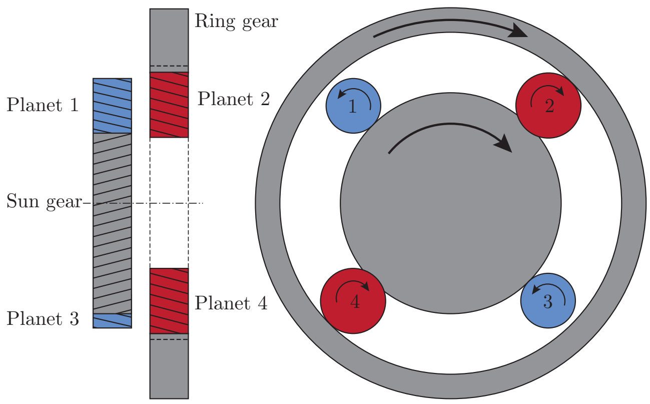

Fig. 5: Mechanical coupling of the four rotors [8]

The gear ratios of the two gears are given by

$$i_1 = \frac{r_{1,3}}{r_{sun}} \tag{5}$$

$$i_2 = \frac{r_{2,4}}{r_{ring}} \tag{6}$$

with r_j the radius of planet j, r_{sun} the radius of the sun gear and r_{ring} the radius of the ring gear. By choosing the same gear ratio ($i_1 = i_2$), the sun gear and the ring gear rotate at the same angular velocity and can be mechanically connected to the main shaft.

4 Measurements on a prototype

In order to verify the operating principle of the derived motor structure, a four-pole Planetary Motor with four rotors was built and first measurements were carried out. Figure 6 shows the prototype and Tab. 1 lists some of the main parameters of the machine.

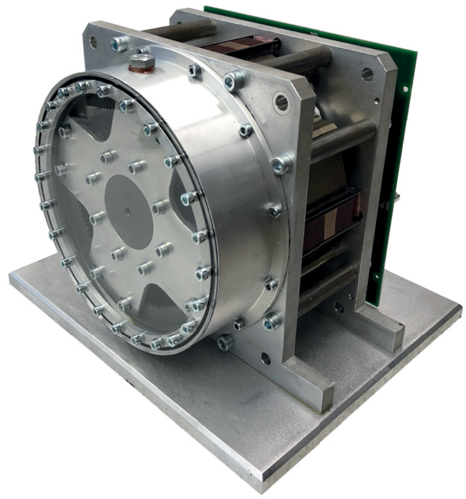

Fig. 6: Prototype of a four-pole Planetary Motor with four rotors

Term	Value
Rated speed (main shaft)	$1000\,\mathrm{rpm}$
Rated torque (main shaft)	$130\,\mathrm{N\,m}$
Rated current	$106\,\mathrm{A}_{pk}$
Gear ratio	$1:9.33$

Tab. 1: Main parameters of the prototype

The motor was driven by a conventional three-phase voltage-source inverter and a field-oriented control was implemented. To be able to investigate the behaviour of the machine at different operating points the Planetary Motor was mechanically coupled with a load machine. To prove that the motor behaves like a conventional three-phase system with three symmetrical and 120 degree phase shifted terminal voltages, the no load terminal phase voltages were investigated. Figure 7 shows the measurement results at 10% of the rated speed. The induced voltages include a small content of harmonics which can be further reduced by optimising the stator and rotor geometry.

Further, the total output torque on the main shaft as a function of the quadrature axis current I_q was investigated. The direct axis current I_d was controlled to be zero. The measurement results are presented in Fig. 8. Due to magnetic saturation

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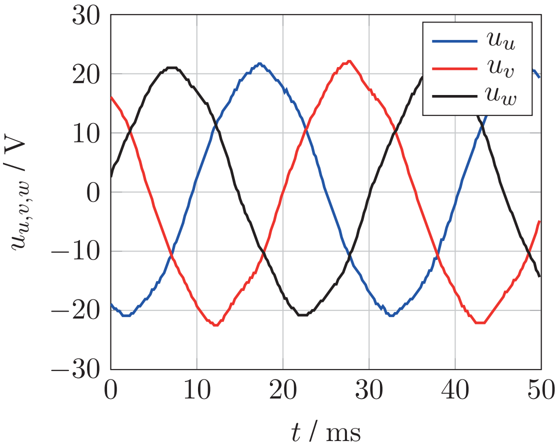

Fig. 7: Terminal phase voltages at no load and 100 rpm

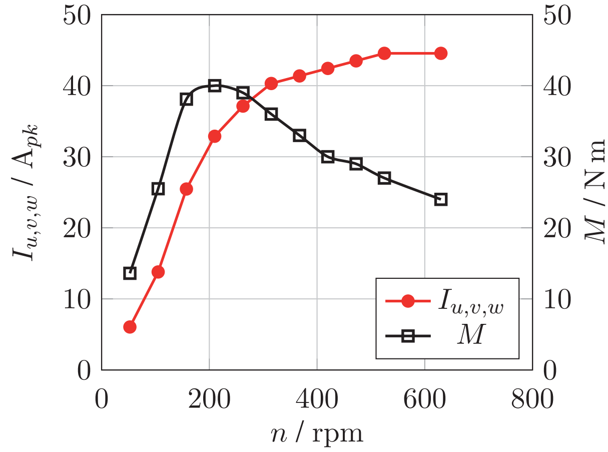

Fig. 9: Phase currents and total output torque in the case of a three-phase short circuit

the slope of the torque curve is decreasing at high currents.

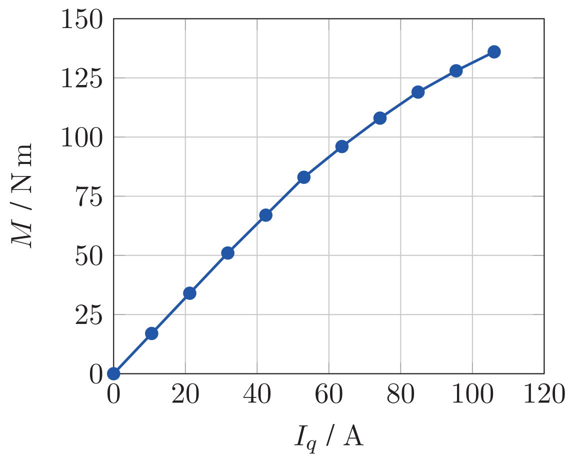

Fig. 8: Total output torque on the main shaft as a function of quadrature axis current I_q ($I_d = 0$)

A short circuit fault of a permanent magnet synchronous machine can lead to a dangerous behaviour in terms of high currents which can thermally destroy the stator winding system or a high torque which yields to a high mechanical stress to the gear wheels. To verify the short circuit behaviour of the prototype the torque and the phase currents were measured at different speeds in the case of a three phase short circuit of the winding system. The measurement results are depicted in Fig. 9. Due to the high stator inductance of the prototype the steady state current and therefore the torque are significantly below the rated values.

5 Conclusion

This paper presents a multi-rotor drive system where several rotors are integrated into a common stator. Starting with two separated four-pole permanent magnet synchronous machines the common stator structure with two four-pole rotors was derived. The basic structure with two rotors can be extended to a higher number of rotors. The construction of the magnetic circuit requires that adjacent rotors move in opposite directions. Thus, a special gearbox is used to combine the power of all rotors and transmit it to the main output shaft. The Planetary Motor behaves like a classical three-phase system at the motor terminals and therefore conventional inverters and conventional control strategies (e.g. field-oriented control) can be used. To verify the operating principle a prototype with four rotors was built and first measurements were done.

A detailed comparison of the new multi-rotor design and a conventional motor design will be done in further investigations.

References

[1] A. Binder, “Elektrische Maschinen und Antriebe”, in. Springer Verlag, 2012, ch. 4, pp. 210–214. DOI: 10.1007/978-3-540-71850-5.

[2] F. Viggiano, “Aktive Magnetische Lagerung und Rotorkonstruktion Elektrischer Hochgeschwindigkeits-Antriebe”, PhD thesis, ETH Zürich, 1992.

[3] S. Lee and I.-W. Park, “Mechanical and Electrical Design of a Biped Humanoid Which Has Multiple Motors on Each Lower Body Joint”, *Intell. Serv. Robot.*, vol. 9, no. 1, pp. 49–61, Jan. 2016. DOI: 10.1007/s11370-015-0184-z.

[4] F. Zhang, G. Liu, Y. Shen, and F. Wang, “Characteristic study on a novel PMSM with opposite-rotation dual rotors”, in *2007 International Conference on Electrical Machines and Systems (ICEMS)*, 2007, pp. 805–809.

[5] Z. Li and J. Tang, “A novel approach of fixed joint multi-motor power balance control”, in *2008 International Conference on Electrical Machines and Systems*, 2008, pp. 1567–1570.

[6] H. Wu, J. Huo, W. Zhang, D. Zhu, and N. Hou, “An electromechanical coupling model of TBM’s main driving system”, in *2016 12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, 2016, pp. 1–6. DOI: 10.1109/MESA.2016.7587111.

[7] M. Schrödl, “Der (elektrische) Planetenmotor – Eine unkonventionelle Kombination von Elektromotor und Planetengetriebe”, *e & i Elektrotechnik und Informationstechnik*, vol. 134, no. 2, S. 170–176, 2017.

[8] A. Brunner, “Design and Construction of a Four-Pole Planetary Motor for Automotive Applications”, Master’s thesis, TU Wien, Jun. 2018.

[9] A. Brunner, R. Spießberger, and M. Schrödl, “Sensorless Control of a Planetary Motor”, in *PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2019.

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