The Four-Pole Planetary Motor

Richard Spießberger, Andreas Brunner, Manfred Schrödl

Technische Universität Wien, Institute of Energy Systems and Electrical Drives, Austria

Corresponding author: Richard Spießberger, richard.spiessberger@tuwien.ac.at

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
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).

\[
\begin{align*}
\frac{i_{u11}}{i_{w11}} & = -\frac{i_{w21}}{i_{u21}} & \frac{i_{u12}}{i_{w12}} & = -\frac{i_{w22}}{i_{u22}} \\
\frac{i_{v11}}{i_{w11}} & = -\frac{i_{w21}}{i_{v21}} & \frac{i_{v12}}{i_{w12}} & = -\frac{i_{w22}}{i_{v22}} \\
\frac{i_{w11}}{i_{w11}} & = -\frac{i_{u21}}{i_{w21}} & \frac{i_{w12}}{i_{w12}} & = -\frac{i_{u22}}{i_{w22}}
\end{align*}
\]

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
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.

![Diagram of a planetary gear system]

The gear ratios of the two gears are given by

\[ i_1 = \frac{r_{1,3}}{r_{\text{sun}}} \]  \hspace{2cm} (5)
\[ i_2 = \frac{r_{2,4}}{r_{\text{ring}}} \]  \hspace{2cm} (6)

with \( r_j \) the radius of planet \( j \), \( r_{\text{sun}} \) the radius of the sun gear and \( r_{\text{ring}} \) 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 Table 1 lists some of the main parameters of the machine.

![Prototype of a four-pole Planetary Motor with four rotors]

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed (main shaft)</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Rated torque (main shaft)</td>
<td>130 Nm</td>
</tr>
<tr>
<td>Rated current</td>
<td>106 A pk</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>1 : 9.33</td>
</tr>
</tbody>
</table>

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

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


