Segmented, modular synchronous reluctance direct-drive minimising the drive-train costs

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Abstract: High-torque motors in direct-drive applications are advantageous especially with regard to the current trend of compact, cost-effective system integration. This paper discusses the concept of segmenting a synchronous machine and the resulting beneficial motor modularisation. Thereby, high-efficient, inverter-driven torque motors are possible, preferably for a speed range of up to 3000 rpm. The output power can be scaled from a few kilowatt up to higher power levels. This modularised, high-efficient motor enables a new dimension of system integration for many industries and applications. The motor segmentation, furthermore, allows an overall drive system cost optimisation while reducing the maintenance intensive components. How the drive-train cost changes when using a segmented motor is compared to a conventional belt-driven system.

1 Introduction

The digital factory, Internet of Things, system integration, and product modularisation are changing tomorrow’s production factories. Nowadays, the solution for industrial product diversification is met by a high diversity of mass produced motors in standard housings and sizes. However, attempts to reduce the high variance in part number has led to a focus on modular design throughout the power electronics and drives industry. To tackle the reduction of motor variance, while still being able to deliver system diversity, the segmentation and modularisation has to begin at the base of the electric motor.

A segmented direct drive is developed especially for high-torque applications, such as drum drives. A full rotor is mounted to the circumference of the drive, while the number of segmented stator modules is installed according to the required torque as shown in Fig. 1. The figure shows an arbitrarily chosen 90° segment. Thereby, with only one stator module, four different machines are possible leading to a reduced number of parts, while still offering a motor variance. In order to segment the stator modules as displayed in Fig. 1 and to reach a high motor utilisation while retaining low material cost, the motor is built as a synchronous reluctance motor. The segmented pancake motor is built with short-end windings utilising the machine’s volume as efficiently as possible [1]. The rotor material, thereby, is manufactured from inexpensive electrical steel and is able to sustain high temperatures and vibrations.

Scaling the power of the application by increasing the number of identical stator modules is beneficial for the entire system. This allows a similar scaling of parts for a whole number of applications with different power ratings. This scale-effect not only reduces costs for the customer because a lower amount of identical machines are necessary, but also the scaling-effect can be used in production resulting in a cost reduction of the machine.

First, the concept of segmenting a synchronous reluctance machine is presented, followed by the advantages of integrated direct drives. In Section 4, the benefit of the segmented drive in regard to drive cost is discussed. Thereafter, the scalable cost benefit is introduced. Furthermore, a case study using a saw-mill application is presented. In this case study, a conventional motor with a gear reduction, by means of a transmission or a belt drive similar to the one shown in Fig. 2 (left), and a direct-drive concept shown in Fig. 2 (right), is compared. The saw-mill application with a 900 mm roll diameter and 15 to 60 kW (single module to full machine) power rating is discussed and evaluated.

2 Segmented machine concept

The segmented machine is based on a synchronous reluctance machine with concentrated windings. In contrast to induction machines, synchronous reluctance machines have very low rotor losses, increasing its overall efficiency. Due to the reduced losses in comparison with induction machines, a compacter machine design at the same hot-spot temperature rise is possible [3]. Compared to permanent magnet synchronous machines the reluctance machine can be built from less expensive materials (i.e. no expensive rare earth materials) and the rotor is less prone to environmental influences such as temperature or vibrations. The benefit of higher efficiency and lower cost is partly compensated by the use of more copper in the windings and a lower power factor resulting in an increased inverter rating necessary.
higher design corner speed. It is clearly visible that the segmented experiments (DOE) method. The DOE provides a planned optimisation problem is handled by using a statistical design of the segment. The size of the stator segment can be chosen to best fit the application. Not only does segmenting a machine allow such a modular machine approach, but also adds an additional geometry freedom. Currently, the electrical machine always has to fit into a round volume, while with this concept, the size of the stator segment can be chosen to best fit the application and space available for the machine. Furthermore, how the cost optimum is influenced by the segmentation is presented and discussed.

Fig. 3 shows an exploded view of a single-stator module for an integrated installation. Scaling the power requirement is done by adding further stator modules to the rotor circumference. Thereby, the necessary power for a given application can be stacked from standard (catalogue) stator modules. Not only does segmenting a machine allow such a modular machine approach, but also adds an additional geometry freedom. Currently, the electrical machine always has to fit into a round volume, while with this concept, the size of the stator segment can be chosen to best fit the application and space available for the machine. Furthermore, how the cost optimum is influenced by the segmentation is presented and discussed in Section 4.

Fig. 4 shows the test bench with a 3 kW@600 rpm prototype. The prototype has a 150 mm rotor diameter and is built with a 360° stator module i.e. a full machine. On the left is an induction machine as a load machine, the higher power rating is due to its higher design corner speed. It is clearly visible that the segmented machine, with its larger rotor diameter, compared to the load machine is very short and compact. The following cost discussion uses the shown machine as its cost basis and scaling reference.

3 Advantages of integrated direct drives

Numerous industrial applications require drive systems based on medium speed (0–3000 rpm) electric machines coupled to a gear box with a certain transmission ratio to adapt the torque and speed to the demands of the application. Using a high torque direct drive without a gear transmission can be advantageous if the transmission ratio can be compensated by a larger motor diameter. Using a direct drive reduces system complexity, maintenance effort (elimination of gears or drive belts), and can increase efficiency.

Substituting the gear box (or belt drive) is possible with two different direct drive concepts shown in Fig. 2. It is either possible to fixate a rotor to the applications shaft combined with a segmented stator module (Fig. 2 (bottom)) resulting in a partial integration into the system or use the benefit of the already present large diameter in the application and fixate the rotor directly to this diameter (Fig. 2 (top)) resulting in a fully integrated drive. The larger diameter used in the full integration scenario allows the use of a smaller stator module. The necessary torque for the given application is scaled by the number of modules as demonstrated in Fig. 1.

With the presented integration concepts, multiple synergy effects can be realised. Not only does integration reduce the space necessary for the entire system, but also weight and cost is saved by using components in dual function. The shaft, bearing, and housing already present in the application are used also for the motor, thus reducing the total number of components in the system. Furthermore, the machine driving the application is not a separate part which has to be added, but can become an integral part of the system.

Direct drive benefits:

- reduced system complexity
- reduced maintenance
- increased efficiency and reliability

4 Cost optimisation by segmentation

In order to be competitive in the motor market, drive-train cost is one criterion which has to be optimised. Normally, by increasing production quantity creates a scaling effect resulting in a cost reduction of the individual component. Therefore, component modularisation is used to increase the quantity of each part, to create scaling effects. In this aspect, a segmented motor is ideal, as the resulting modularisation causes a large number of equal parts. Furthermore, the goal is to keep product diversity and being able to serve multiple applications.

The use of a synchronous reluctance machine generates another cost benefit as this type of machine has a specific basis of cost introducing an interesting cost optimisation aspect. As a first cost base a 3 kW machine with 150 mm rotor diameter and 360° stator i.e. a full machine is used (Fig. 4). This machine is marked by a circle in Figs. 5 and 6.

Fig. 5 shows how the cost changes at a fixed machine power rating, when changing the rotor diameter. It is clearly visible that the cost optimum is at a larger rotor diameter around 300 to 400 mm. By increasing the diameter, the tangential force necessary for a certain power decreases as the radius increases. With the segmented synchronous reluctance machine, the stator module is the most expensive component. Therefore, increasing the rotor diameter reduces the stator module necessary and too the overall machine cost. However, if the rotor diameter is increased too much, then the cost for mechanical fixation and for the over dimensioned rotor becomes predominant and the overall machine cost increases again. Therefore, there exists an optimal rotor diameter for a power rating, where overall cost becomes minimised.

Along to optimising the rotor diameter in regard to cost, the segmentation angle can too be changed within a certain range to
Increasing the rotor diameter indefinitely is not possible as at a certain size in relation to the power rating the overall cost will again start to increase due to the cost of additional mechanical components.

5 Case study: cost-effective integration

To investigate different segmented direct-drive integration concepts and their influence on drive-train cost, a saw-mill application as shown in Fig. 7 is used. In the following, a conventional drive-train with a belt-drive (Fig. 7a) is compared to an integrated segmented modular direct drive with varying rotor diameters as shown in Figs. 7b and c. All three drives represent a 16 kW motor to drive the saw-mill. How the size of the motor changes according to the used motor (conventional, segmentation angle and rotor diameter) is clearly visible in the figures and is investigated in this section. The two integrated motors are discussed in regard to their cost benefits.

Table 1 contains the data used as basis for the case study. A roll diameter of 900 mm and a maximum blade speed of 1000 m/min for cutting wood is assumed. Therefore, the resulting maximum shaft speed of the work machine is 360 rpm. In the conventional drive system, an inverter-driven 2-pole pair induction machine is used, while the speed adaption from 1500 rpm to 360 rpm is done via the belt-drive transmission.

Different power ratings for different saw-mill sizes found on the market are given in Table 2. Exemplary, the power ratings have been divided into two different customer requirements. The power ratings are on the basis of different sawing applications. For high-precision sawing as for dry wood a high-speed drive is required. Instead, for hardwood applications, a higher power rating is needed. The roll diameter is commonly in the range of 500 to 900 mm. The roll space can be used to replace the belt pulley with the rotor of the direct drive. This will ensure the required inertia of the saw and enables the full motor integration. The segmented reluctance direct drive can overcome the variety of power demands by adapting the amount of stator segments per drive. With four segments of the motor, the stator modules can cover a power range from 16 to 64 kW. Furthermore, different speed requirements can be adapted by connecting the motor segments in parallel or series. In Table 3, the resulting weight is shown for the proposed modular drive. As a reference, the weight of a state of the art synchronous reluctance motor is given with 16 kW and 1500 rpm.

In Fig. 8, the cost of segmented machines are compared for different power ratings. The cost is normalised to a 16 kW motor with 150 mm rotor diameter and a 360° stator module similar to the motor shown on the test bench in Fig. 4. The reference machine is represented by an orange circle in Figs. 8 and 9. The connected solid lines in Fig. 8 represent a motor with a fixed rotor diameter and implicitly a varying number of stator segments (segmentation angle) and machine length according to the power rating. The figure demonstrates how the motor cost changes with increasing power rating and for various rotor diameters. The cost is given in per kW allowing a comparison of the machine costs at fixed power ratings.

It can be seen that the motor cost for a certain power rating decreases with increasing rotor diameter. Therefore, the cost of a 16 kW motor decreases by 23% when changing the rotor diameter from 150 to 300 mm. In the graph, when changing the rotor diameter.

**Table 1** Data used for saw-mill case study

| Parameter          | Value  |
|--------------------|--------|
| Saw blade speed    | 1000 m/min |
| Saw roll diameter  | 900 mm |
| Max shaft speed    | 360 rpm |

**Table 2** Product diversification with one stator segment

| Power Rating (1 seg.) | Customer 1 | Customer 2 |
|-----------------------|------------|------------|
| 16 kW                 | 16 kW      | 11 kW      |
| 32 kW                 |            | 22 kW      |
| 45 kW                 |            | 45 kW      |
| 60 kW                 |            | 60 kW      |
| Roll diameter         | 900 mm     | 800 mm     |
| Motor speed           | 1000 rpm   | 1500 rpm   |

**Table 3** Total weight of the segmented direct drives with increasing power rating

| Motor Diameter | 16 kW | 32 kW | 48 kW | 64 kW |
|----------------|-------|-------|-------|-------|
| Conventional   | 177 kg| -     | -     | -     |
| 450 mm         | 116 kg| 135 kg| 154 kg| -     |
| 600 mm         | 118 kg| 133 kg| 148 kg| 163 kg|

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diameter, the segmentation angle too changes from 360° to 180°. A further cost reduction is possible if the rotor diameter is changed from 300 mm to 450 mm and to 600 mm while decreasing the segmentation angle from 180° to 120° and to 90°. An overview of cost savings in percentage is given in Table 4. This specific cost correlation is due to the discussed cost base from Section 4 which is specific to this kind of direct drive setup.

In Fig. 9, the cost base change versus the stator segmentation angle is shown. The solid lines again represent a motor at a fixed rotor diameter with different number of stator modules according to the given power ratings 16 to 64 kW. The dashed purple lines connect motor configurations (rotor diameter and segmentation angles) of constant power. Thus, if a certain power rating is needed one has to move along the dashed line. However, if different power ratings should be covered by one machine size with varying number of stator modules, then one has to move along the solid lines.

Fig. 9 demonstrates that in this case study the largest rotor diameter with the smallest stator module is the cost optimised motor. This is only possible if space is available in the application for such a large diameter. Furthermore, the largest diameter in the given case also allows the highest flexibility to scale the power rating with one and the same rotor and stator modules over a wide power range.

Today's standard motors available are visible in Fig. 9 on the vertical axes where the segmentation angle is 360°. Thereby, the different power ratings are achieved by moving from one motor size to the next, i.e. 150 mm for 16 kW, 300 mm for 32 kW up to 600 mm for 64 kW. By using a motor with segmentation on the other hand, the same power ratings can be achieved by using one 600 mm motor with either 1, 2, 3, or 4 stator modules.

6 Conclusions

This paper shows that using a segmented direct drive can be cost-effective and a compact, integrated solution compared to a conventional gear-box or belt-drive system. Particularly, a partially equipped motor with a large rotor diameter can be more cost-effective than a standard motor with a smaller rotor diameter and a 360° stator. The presented segmented, modular synchronous reluctance direct drive allows not only a cost optimisation, but also the flexibility to equip applications with different power ratings with one and the same rotor and stator module i.e. motor. This reduces the number of different motors and peripheral components necessary. Furthermore, the integrated direct-drive results in a maintenance free gearless drive system with a high torque density and high energy efficiency.

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| Table 4 Cost reduction by increasing rotor diameter (from Fig. 7) |
|-----------------|---------|---------|---------|
| Motor diameter, mm | 16 kW, % | 32 kW, % | 48 kW, % |
| 150              | 100     | -       | -       |
| 300              | -23     | 100     | -       |
| 450              | -8      | -16     | 100     |
| 600              | -4      | -8      | -12     |
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