Brushless-DC Motor using Soft Magnetic Composites as a Direct Drive in an Electric Bicycle

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Keywords

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Abstract

Recent advances in materials research have produced soft magnetic composites that can be considered for use in electrical machines. New drive concepts are needed to fully take advantage of this new material. An electric bicycle with a new drive with very good performance and low cost is presented. A major part of this drive is a new brushless-dc motor using soft magnetic composites. The motor is also suitable for other drive applications.

Introduction

The paper presents an electric bicycle with a new brushless-dc motor. Soft magnetic composites are used for the motor that is installed as a direct drive in the front hub of the bicycle.

Powder metallurgy has been used for decades as a cost-effective material for DC and hard magnetic applications. However, it was only recently that research has developed soft magnetic composites with AC performance good enough to allow it to be competitive for use in electrical machines [1]. Because of the different electrical and mechanical characteristics as well as the different ways of production of the parts when compared with laminated steel, soft magnetic composites should not be used simply to replace the laminated steel in existing machines. New machine designs are needed to fully take advantage of its strong points. Given suitable design and the right machine type the possibilities offered by the material can actually outweigh the inferior magnetic properties [2] i.e. lower unsaturated permeability, lower saturation flux density and increased iron loss. Soft magnetic composites can carry magnetic flux in three dimensions, and allow net shaped parts to be built. Thus, they open a field of new machine concepts that is today widened further by the price-drop in the semi-conductor industry.

A brushless-dc motor, using soft magnetic composites, has previously been developed and installed as a direct drive in an electric bicycle [3]. The machine is a combined radial/axial motor with a toroidal, air gap winding and uses rare earth magnets. The research vehicle had proved the viability of the concept but also pointed out aspects needing further investigation.

This paper reports on a new electric bicycle that shows significant improvement as compared to the first generation. Following a presentation of the bicycle context the concept and performance of the direct drive are presented. Then, the new brushless-dc motor, using soft magnetic composites is explained. The paper closes with an outlook on further developments and conclusions.

Bicycle Context

Performance requirements and riding style influence the design of a drive for use in an electric bicycle system. Licensing speed limits in some countries are 25 kph. A typical operating cycle is shown in table I. Motor, batteries and control electronics need to be adapted to give reasonable range and driveability even on steep hills. Furthermore, the bicycle should be easy to ride and pleasing to look at.

As mentioned above, a new bicycle concept had been developed previously. Here, an outer-rotor motor built from soft magnetic composites was installed as a direct drive in the front hub, while the battery box and the control electronics were on the rear pannier [3]. This concept had proved to be very suitable. - No gears are needed and the drag with the motor is reduced, hence no free wheel is required. Therefore, the total cost is reduced in comparison with a conventional system. Furthermore, due to the even weight distribution and the reduction of components it meets the requirements towards driveability and elegance. Based on the experience with this bicycle, the new drive should further exploit the merits of this concept. The new electric bicycle is shown in figure 1.

Table I: Bicycle operating data

Riding conditions	Wheel	Power	Torque	Duty Cycle
	rpm	W	Nm	%
20 kph, flat road, no wind	160	50	3.0	70
20 kph, flat road, headwind	160	150	8.9	20
10 kph, 1:10 gradient	80	270	32.3	10
			total	100

Drive

The drive of the electric bicycle is composed of a new brushless-dc motor that is again installed in the front hub of the bike, rear pannier mounted batteries and control electronics. The electronics is based upon a current controlled, standard MOSFET three-phase bridge inverter operating in a torque demand mode by a handle bar twist grip.

The choice was made towards a full electric drive rather than an electrically assisted bike.

The motor is integrated in the front wheel with the spokes directly attached as shown in figure 2. It gives 9.5 Nm torque at the thermal limit and can give up to 12.5 Nm. The motor will be explained in detail below. It is fed from 40 Nickel-Metal-Hydride M cells, giving nominally 48 V, 18 Ah. Figure 3 shows the electrical system at 20 kph and rated load.

In pure cycling terms any weight penalty in the cycle itself is felt very much by the rider, particularly in a psychological sense. It is difficult to provide any sizeable assistance to the

Figure 1: New electric bicycle

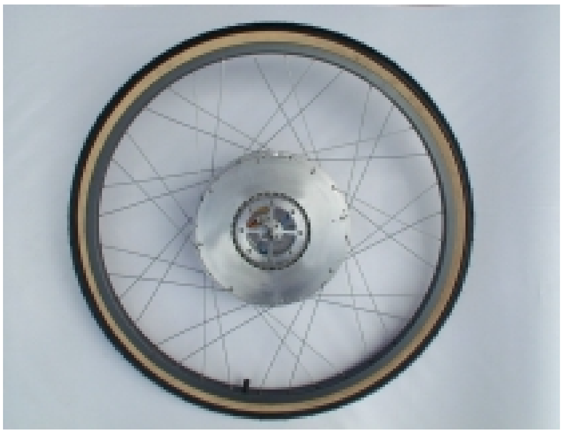

Figure 2: Front wheel with integrated motor

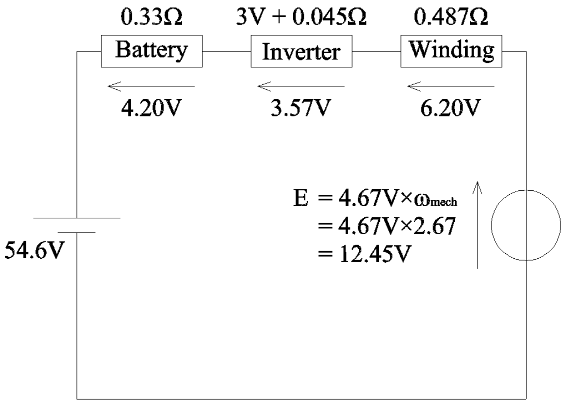

Figure 3: Electrical system at 20 kph and rated load

rider without a significant weight penalty. These considerations naturally lead to near full electric propulsion with rider assistance. The weight of the motor is 3.6 kg, but the batteries weigh 15.6 kg. These weights are large in comparison to modern bicycles but small in relation to the weight of the rider. The style of riding is not vigorous cycling but rather effortless cruising. In keeping with these trends the batteries provide enough energy for the bike to be driven over a longer distance even in windy conditions.

Installing the motor in the front wheel is very simple and does not impact on the existing chain drive. In addition it helps to even out weight distribution and perhaps surprisingly does not impinge on the handling capabilities of the bike.

The position of the batteries is important to the riding characteristics of the bicycle. In the first prototype the batteries were mounted atop the rear pannier. This high placing of the weight coupled to the deflection of the pannier support structure in a sideways direction lead to high inertia and a natural frequency in the sideways rocking mode close to that typical of the average cyclist. For this reason the batteries have been mounted in two halves low down on the sides of the pannier in the new bicycle reported here. As well as being stiffer the new position also offers considerably less inertia to the cyclist.

The performance data for two operating points – 20 kph, flat, no wind and headwind – are given in table II. Hence, when driven at 20 kph, the range of the bicycle is 250 km with no wind, and 47 km with a headwind.

Table II: Drive performance data

	Efficiency			
Riding conditions	**Motor**	**Inverter**	**Battery**	**Overall**
20 kph, flat road, no wind	0.96	0.85	0.96	0.78
20 kph, flat road, headwind	0.69	0.84	0.85	0.49

Motor

A radial/axial brushless-dc motor with toroidal airgap winding and surface mounted rare-earth magnets had been used in the first generation electric bicycle [3]. While the viability of such a concept could be shown, different aspects needed to be improved. These were notably the difficult winding arrangement, low electric loading, weight and cost (due to the large amount of magnets required).

Using this motor as a starting point, many different motor concepts were analysed on an analytic level. All were outer-rotor structure. The analysis was not limited to the bicycle application. Each concept was optimised in terms of material cost, volume and weight. When comparing the different concepts, the ease of manufacture was also taken into account. Details of the different types will be described below, when the elements of the final design are explained.

The models were validated and improved using three dimensional finite elements.

Optimisation was supported via the MATLAB toolbox genetic algorithms [4]. This toolbox is a powerful means to optimise complex problems. It imitates the natural selection process. A “population” is composed of a combination of the parameters that are to be determined out of a range given for each. The program evaluates the “fitness” of every member of the population concerning the given optimisation criteria. Based thereon, “off-springs” are created through imitation of the natural mutation process. This process is repeated the given times, the number of “generations”. The result is the best combination of the values of the parameters concerning the given optimisation criteria. In this case optimisation was done on the basis of material cost with constraints of performance weight and dimensions set by manufacturing limits.

The analysis of the different motor concepts had been done independently from the bicycle context. However, this application was chosen again for the prototype to be built.

The new motor is shown in figures 4 and 5. It is a radial field, outer rotor, single tooth winding machine with 3 phases, 24 poles and

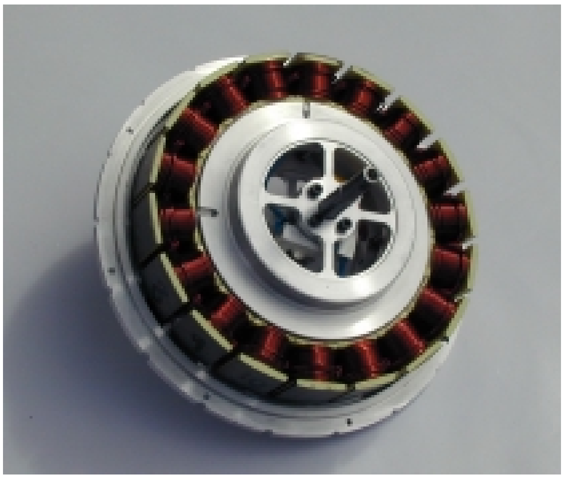

Figure 4: Stator of the new motor

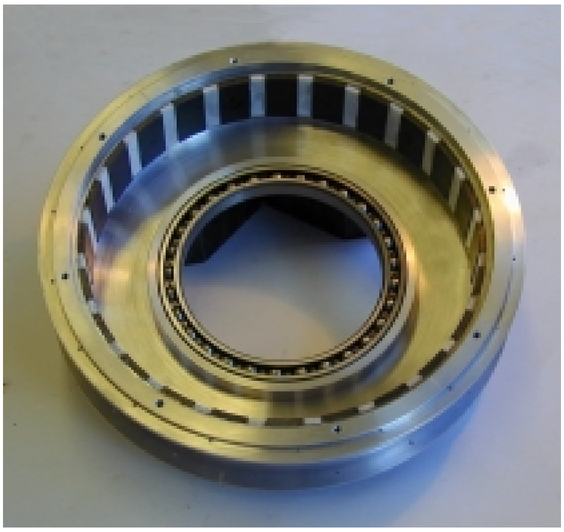

Figure 5: Rotor of the new motor

18 teeth. The armature core is manufactured from bobbin-shaped segments using soft magnetic composites. These tooth pitch sections are suitable for later mass production. Surface mounted, low cost ferrite magnets are used.

The measured nominal torque of 9.5 Nm is produced at the rated current of 12.75 A (corresponding to a measured winding temperature rise of 100 C). Figures 6 and 7 show measured torque and back EMF constant as a function of the load. Due to the demagnetisation limit of the magnets, the maximum current is set to 25 A. Hence, the motor gives a maximum torque of 12.5 Nm.

The line to line inductance measured statically with 100 Hz is 9.3 mH as compared to a finite element calculation of 9.8 mH with the rotor running synchronously. The measured inductance is naturally reduced by the eddy currents induced in the rotor magnets and solid core back at 100 Hz. To give some idea of the effect of this inductance, if the machine is viewed as synchronous (as opposed to its real mode of brushless dc), the inductance represents a voltage which is 0.5 pu of the battery supply (of nominally 48V) when running at 20 kph and thermal rated load of 12.75A.

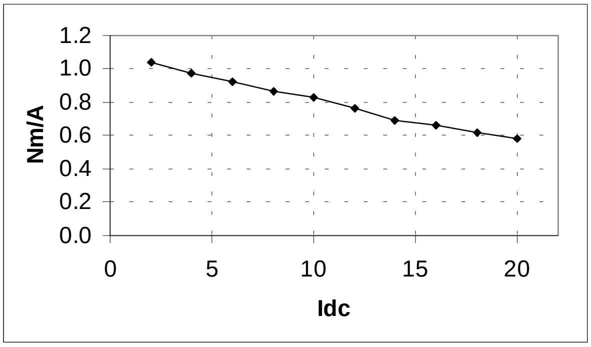

Figure 6: Load dependent torque constant

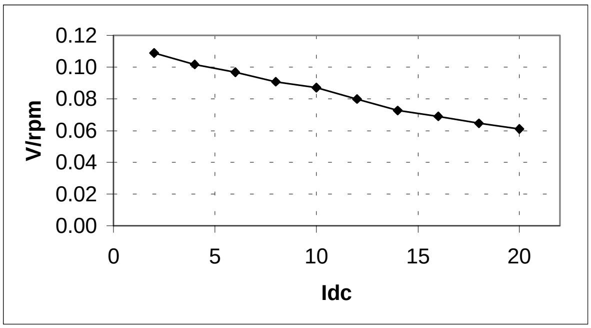

Figure 7: Load dependent back EMF constant

The weight of the motor is 3.5 kg, which shows clearly in the high torque to weight ratio for a surface ferrite magnet machine of 2.7 Nm/kg. This figure is well up to the performance that could be expected from a machine using Neodymium Iron Boron. A good part of the reason for this is the facility with which soft magnetic composite concentrates the low air gap flux density (commensurate with ferrite magnets) via its 3D magnetic field capability.

The stator pieces are bobbin-shaped. Figure 8 shows a single tooth without winding. The tooth tips are far longer axially than the tooth body which is the effective flux concentration mentioned above. The shape of the tooth sections make the motor easy to wind. A high fill factor can be achieved. Figure 9 shows a single tooth with winding. The fill factor of the motor is as high as 53%. The motor has a high ratio copper/mass of 35% that results in a high electric loading of 25 kA/m. The fill factor could still be increased, as the experiences gained while building the prototype show. This

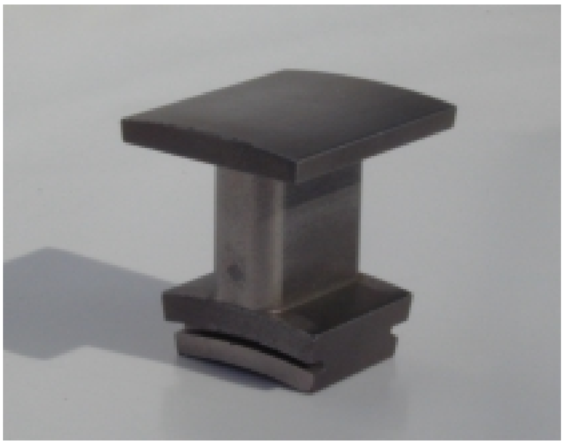

Figure 8: Tooth of the new motor

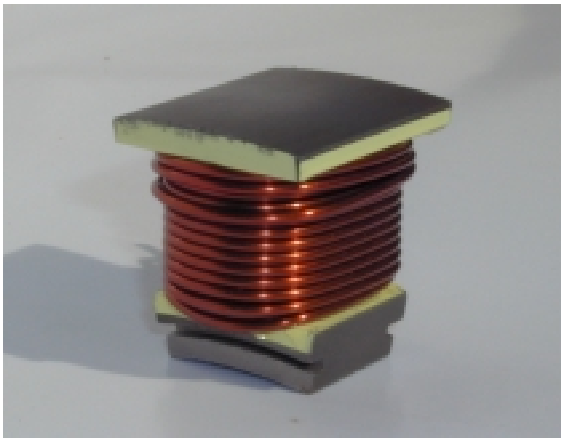

Figure 9: Tooth with winding of the new motor

would lead to an even higher ratio of copper/mass and electric loading.

As the motor is installed as a direct drive, the speed is low and iron losses are almost insignificant. Hence, the efficiency of the motor is dominated by the copper losses, and, as the back EMF does not limit the current within the allowed current range, increases with speed. Because of saturation it does not decrease linearly with load. Figure 10 shows the efficiency for 10 and 20 kph as a function of load.

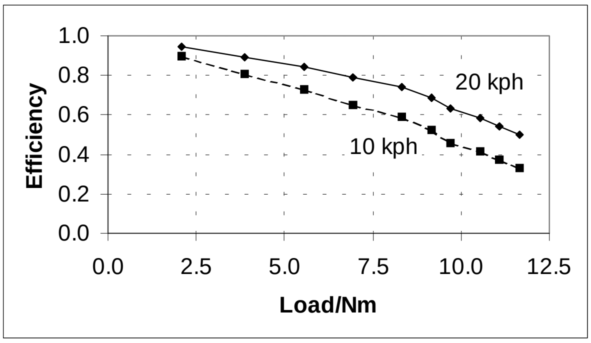

Figure 10: Load dependent efficiency of the motor

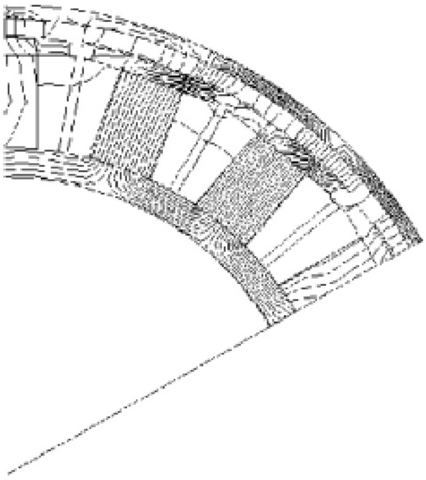

Figure 11: 3D Finite element picture of 4 poles - flux distribution for 20A two phases on

Figure 11 shows the flux distribution for 20A load with two phases on. Due to the three dimensional flux carrying capability of the soft magnetic composites, the winding overhang can be used for torque production. Hence, the tooth tips and the magnets cover the whole winding. This structure is used as form of flux concentration. Therefore, the cross-section of the core of the teeth and the thickness of the tooth tips have to be large enough to prevent saturation.

Each bobbin spans 240°. Despite the larger leakage flux, the machine with 240°-pitch is superior to a machine with the more normal tooth span of 120° for a non-overlapped winding. This may be explained by considering these two variants with the same rotor in each. In the 240° case there are half as many slots but each slot has a greater area and hence can carry more current. The flux is the same in both cases. The reduction in teeth means that the total available slot area is more in the 240° case than in the 120° and hence a gain in electric loading can be made. The disadvantage is that the magnet must withstand this extra slot current and thus needs to be more than twice the depth than would be required for a 120° design. It is common that the depth of magnet required to withstand demagnetisation is less than the practical manufacturing limit for the magnet material used. This would be true for this design if 120° pitched slots were used and hence using 240° span slots is not a disadvantage in magnet material usage. A similar concept with bobbin-shaped stator pieces that are oriented axially has been analysed. Here, magnets could be applied at one or both sides of the bobbins. In the second case the twice as many magnets have to magnetise twice as many air gaps as in the first case. The gain in flux that passes through the bobbins is not sufficient to outweigh the increase in cost. Because the bearings have to carry the magnetic load of the one-sided machine and the smaller effective radius for torque production, this axial bobbin-concept is not as good as the radial one.

The concept with air gap windings that had been used as a starting point requires a large quantity of magnetic material and is difficult to wind. Therefore, it could be eliminated early in the optimisation process.

Concepts with a slotted structure and radial and/or axial magnets were also analysed. Among these, the best type has magnets on both axial and the outer radial side. However, due to core saturation, for the same output this concept requires a much larger number of poles than the one with bobbin-like stator pieces.

Because of the flux concentration principle as described above, cheap ferrite magnets could be used instead of expensive rare earth magnets for all concepts except for the ones with air gap windings.

Due to the low weight, the ferrite magnets and the easy production process, the overall cost of the new motor is very low. As mentioned above, the bicycle context was chosen for the prototype. However, because the scaling effects are the same for the different concepts analysed, the results apply for other sizes and applications as well.

Further Developments

The prototype motor showed the viability of the new motor concept. It confirmed the strong as well as the critical points pointed out during the design process. It pointed out some areas of further development, also: The fill factor of the motor can still be increased. Therefore, a higher electric loading can be achieved. Special attention has to be given to the saturation of the core and the tooth tips. The influence of larger cross sectional areas on the overall performance of the motor should be analysed more in detail. Because of the possible increase of the fill factor an improvement is expected. Pre-pressed windings as described in [5] should also be considered.

The motor itself has a very low weight, but the batteries are heavy. Hence, the drive concept could be used for an electrically assisted bike. This bike would give the same power yet less reachable distance, but be less heavy. As for such a bike, the batteries wouldn’t provide enough energy to heat the motor up to thermal limit, the loading of the motor could still be increased.

Because of the outer-rotor structure and the adjustable speed due to the controller this motor is very suitable for drive applications in general. Hence, the concept should be analysed in the frames of performance requirements of other drive applications, e.g. scooter, push-chair or wheel chair.

However, the suitability for this kind of application should not confuse a more general view of the merits of the concept. Designing motors and improving the concept towards different applications would probably point out further fields of interest as well as limits.

Conclusions

A new electric bicycle has been designed. The motor is installed as a direct drive in the front hub, while the battery box is rear pannier mounted. This drive concept is favourable, because it leads to an even weight distribution and deletes the need for gears. Furthermore, the drag with the motor off is reduced, thus no free wheel needed. Hence, the total cost for the drive is reduced and the bike more pleasing to ride and to look at.

For this drive a new motor concept using soft magnetic powder and cheap ferrite magnets has been shown. The operating principle is the same as for a brushless-dc machine. This machine shows not only good electrical performance but has low material costs and offers methods of production and assembly suitable for mass production. Applications that favour an outer-rotor arrangement are an excellent target for this type of machine.

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