A Highly Integrated and Modular High Speed Electric Drive for Lightweight Electric Mountain Bikes

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Abstract

In this work the application of a high-speed electric machine combined with a high gear ratio is investigated for a lightweight electric mountain bike. The proposed drive utilizes the high power density of high rotational speeds of electric machines to reach low system mass. The system integration and their components are described and compared to commercially available products. First experimental results of the proposed electric drive are presented.

Introduction

In the last years, the high annual sales figures of electric powered assisted cycles (EPAC), also known as pedelecs (max. speed 25kph, 250W continuous power, 600W peak power), confirm the increasing demand on emission free light electric vehicles (LEV), e.g. 1.2 million e-bikes were sold during the first half-year 2021 in Germany, which is nearly a +10% annual increase [1]. Several reasons like the environmental friendliness, higher urban mobility attractiveness by avoiding traffic jams, higher driving range, increased personal health awareness or even semiprofessional sports activities are well known.

Depending on the scope of the e-bike (city bike, trekking bike, all terrain bike, race bike, mountain bike) the requirements of an electric drivetrain differ in a very wide range. Electric drives can be located at several places at the bicycle frame and have different motor topologies [2]. Direct drive in-wheel motor topologies are often used for conversion kits of conventional bikes and use an outer rotor machine topology [1], but due to a high motor mass and especially a high unsprung mass at the wheels such topologies are not applicable for sportive bike applications. At mountain bikes the electric drivetrain has to fulfill very strong requirements defined by the sportive application. The electric drive shall be fully integrated into the bike frame for handling reasons and protection in the terrain, very powerful for long distance uphill driving, very compact, have a low mass and good bike balance. These targets are exactly the main focus of the electric drivetrain proposed in this paper.

Today, bike manufacturers often use a family of electric drive units which mainly differ in power, size and driving range to serve the complete range of commercial pedelecs. Therefore, in most cases hub motor topologies arranged at the bike treadle are used. Such concepts are modular and useable in a wide range but the bike integration capability is limited. Although frame integrated electric drive solutions are available (e.g. from supplier Fazua) they have limited performance. The proposed e-mountain bike shall feel and look like a conventional mountain bike by using a high integration of the electric drive. Finally, the overall e-bike performance depends on an interdisciplinary design approach with respect to system design, component design, control and testing [3],[4].

In Table I an overview of widespread available e-bike motors in 2021 is presented [5]. The mass of the e-bike motors (including treadle, gear box, control unit, but without battery) varies from 1,92 – 3,9kg and provide a peak power from 340W to 580W. Although these values differ in a wide range, the specific torque is approximately 30Nm/kg for each e-bike motor. It is well known that the size of electric machines is directly linked to the machine torque. This characteristic is specified by the so called Esson number C [6]. The torque density is mainly related to the machine type and the machine cooling which is similar at all e-bike motors. Therefore, the application of a high gear ratio combined with high rotational electric machine speeds is a possibility to reduce size and weight of electric drivetrains. According to Table I the commercial e-bike motors use a total gear ratio in the range of approximately 12 to 44. The Yamaha PW-X2 motor has the highest gear ratio of 44,1 although the overall specific torque is the lowest in Table I. Thus, the fundamental structural benefit of high gear ratios is not realized in existing products. In this paper the long-term goal is to reduce the weight of the electric drivetrain for e-mountain bikes by application of high-speed electric machines combined with a high gear ratio. In the first step, the competitiveness shall be shown and finally, by optimization a significant improvement shall be realized.

Table I: Available e-bike motors in 2021 [5]

Supplier	Type	Peak-Torque in Nm	Peak-Power in W	Motor-Weight in kg	Total Gear Ratio	Torque density in Nm/kg
Bosch	Perfomance Line CX	85	580	2,79	12,2	30,5
Brose	Drive S Mag	90	340	2,98	25,6	30,2
Fazua	Evation Ride 50	60	400	1,92 *)	24,7	31,25
Shimano	EP 8	85	*unknown*	2,57	40	33
TQ	HPR 120 S	120	*unknown*	3,9	37	30,7
Yamaha	PW-X2	80	480	3,06	44,1	26,1

*) only motor unit without treadle axle and treadle sensor (+1,3kg)

The Proposed Electric Drive System

In this work a modular and lightweight electric drive system for a full integration in the mountain bike frame is investigated. Due to legal restrictions a peak power of 600W is selected and limited by software. The first prototype concept to evaluate technological aspects has the target requirements of peak torque of 80 Nm, peak power of 600W and motor weight of max. 2,5kg. The electric motor unit consists of an inverter, an electric machine, a planetary gear stage and a bevel gear stage including treadle with torque and speed sensor. The complete drive pack as well as the battery is integrated in the bike frame. The drive pack can be inserted from the bottom of the frame, as shown in Fig. 1. The proposed drive concept is completely located in the lower tube of the bike frame and the components use a common outer diameter of 72mm as shown in Fig. 2. The drive pack is designed modular and scalable by length adjustment of the electric machine. The battery pack including the battery management system (BMS) is modular as well and fully integrated in the bike frame. Thus, several power ratings combined with variable driving ranges by battery variation can be realized to serve different bike applications.

The bike's chain drive is setup with one fixed gear on the treadle and a conventional switchgear on the rear wheel. The electric drive support works up to a treadle cadence of 122rpm, which is equal to an electric machine rotational speed of 11.000rpm combined with a total gear ratio of 1:90. This high ratio is reached with a planetary stage and a bevel gear topology. This concept shows a significantly higher gear ratio and significantly higher electric machine speeds compared to existing commercial e-bike motors. By a high geometric integration of the gear stages, the electric machine and the inverter a compact drive pack can be realized which is inserted into the frame according to Fig. 1. Finally, after system optimization in a subsequent project step a higher torque and power density compared to current available e-bike motors is proposed. The target is to reach a specific torque of 40Nm/kg after optimization.

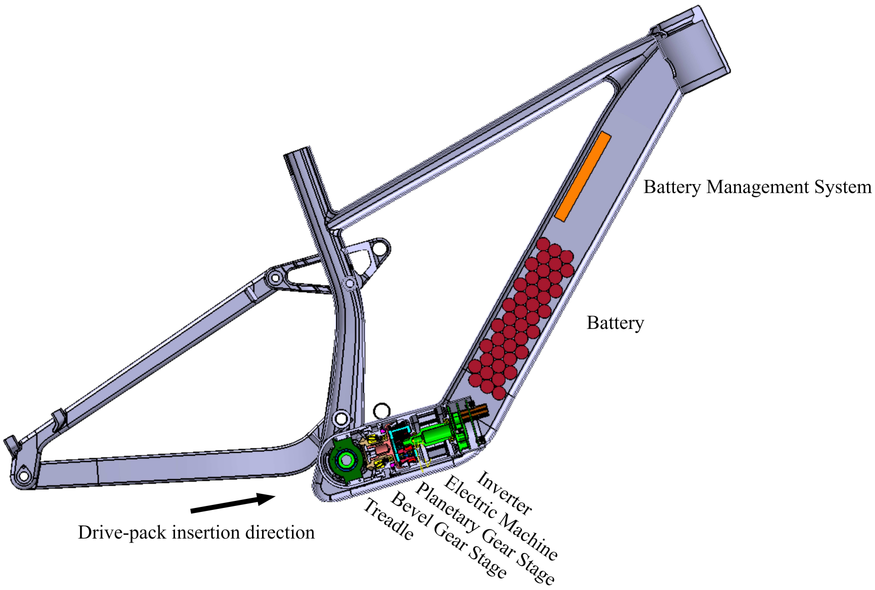

Fig. 1: Proposed frame setup including electric drive components

The e-Bike Components

The e-bike drive pack is designed modular with common interfaces and consists of several sub-components. The mass break down of the propsed design is presented in Tab. II. The total mass of the electric drive pack without battery is designed with 2,48kg with a peak torque of >81Nm.

Table II: Mass break down of the proposed E-bike drive

	Volume in cm^3	Mass in g
Bevel Gear with Treadle and Freewheel	392	995
Planetary Gear Stage	193	568
Electric Machine	211	736
Inverter	143	175
Battery (without BMS)	950	2200

The Inverter

The inverter is located directly on the electric machine and currently consists of three boards, a power board, a controller board and an interface board as shown in Fig. 3. To communicate with a display and the battery management system a CAN-interface and a wireless Ant+ interface is available. A classic three phase voltage source inverter with MOSFET power transistors is implemented. The hardware is prepared for sensorless field oriented control of the electric machine, which allows the operation without any rotor angular position sensor. In contrast to the work [7] a sensorless control method without additional injection is proposed [8]. A full integration of the 3 boards into a single inverter and a common housing is planned in the next project step.

The Gear Stages

The gear stage consists of two planetary gear stages combined with a bevel gear stage to turn the rotational axis to the treadle axle. Further, a torque sensor and a freewheel, which separates the gearbox and the motor from the treadle shaft in thrust mode, are integrated. The gearbox has a total gear ratio of 1:90 while the planetary stages reach a transmission ratio of 1:60. This high transmission ratio in a small installation space with a high output torque is made possible by an unconventional kinematic coupling of the degrees of freedom of the two planetary stages. This would enable transmission ratios of up to 1:600 in the same installation space.

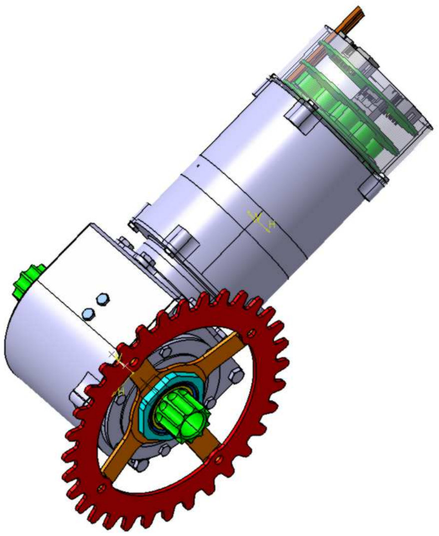

Fig. 2: CAD model of the treadle axle with gearbox, electric machine and inverter

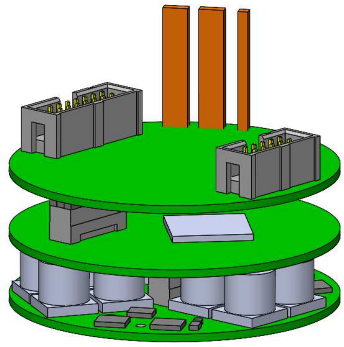

Fig. 3: Inverter concept

The Electric Machine

For a high efficient electric drivetrain a permanent magnet synchronous machine is proposed. The electric machine is designed for high rotational speeds up to 11.000rpm at compact physical dimensions. The machine provides an inductance difference in L_d and L_q to ensure sufficient sensorless control at standstill and low speeds. For simple production a fractional slot winding with concentrated coils (Fig. 4) was chosen. The proposed stator design allows the implementation of flat-wire windings for reaching higher copper fill factors and a higher machine efficiency. The simulated electromagnetic peak performance (>0.9Nm and 700W) at a phase current of 17Arms is presented in Fig. 5. For a sufficient high speed operation with low harmonics the rotor is skewed by discrete skewing. The machines active electrical components are currently designed to a simple and low cost production even at small production volumes using common materials.

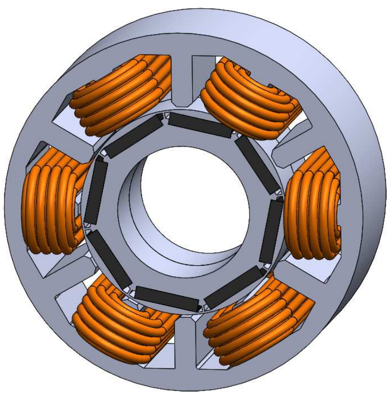

Fig. 4: CAD model of the active electrical machine components

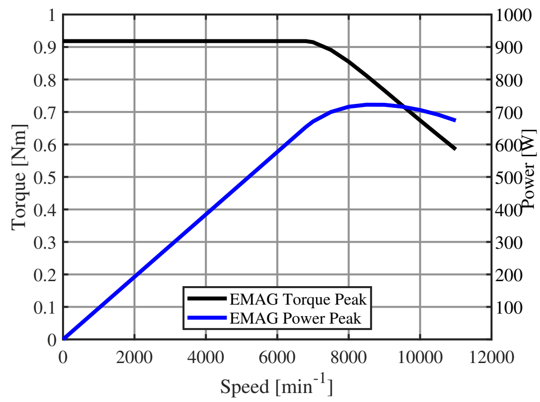

Fig. 5: Simulated electric machine characteristics

The Battery

In contrast to conventional battery packs with a nominal voltage of 36V this e-bike proposes a 48V nominal voltage. In general, the battery space within the bike frame can be equipped with several battery configurations. The proposed work considers a battery, which provides 500Wh usable energy at an operating voltage range from 46,2 to 58,8V. Thus, 42 Li-Ion round cells, type 18650 (14 in series and 3 parallel) and a battery management system (BMS) are installed, which communicates with the inverter during operation.

Experimental Results

For experimental verification of the proposed electric drive concept the electric machine and inverter prototypes are built according the design, see Fig. 6. The power board is directly mounted on the electric machine, the controller board and the interface board can be connected by board-to-board connectors.

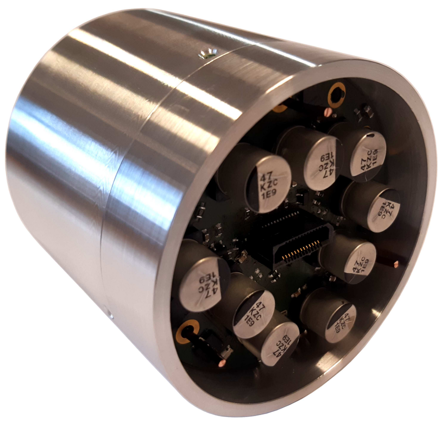

Fig. 6: Prototypes of the electric machine and the inverter's power board

A field oriented control with maximum torque per ampere (MTPA) at lower speeds and maximum torque per volt (MTPV) for flux weakening is implemented in the inverter control. The rated direct axis and quadrature axis inductances of the machine are measured (Fig. 7). The inductances show a sufficient difference to apply sensorless control methods. Further, the electromagnetic performance of the electric machine prototype at 25°C rotor temperature for several voltage levels is depicted in Fig. 8. As expected, for higher voltage levels a peak power up to 800W can be reached. By these tests the target performance of the proposed electric machine and the inverter is confirmed.

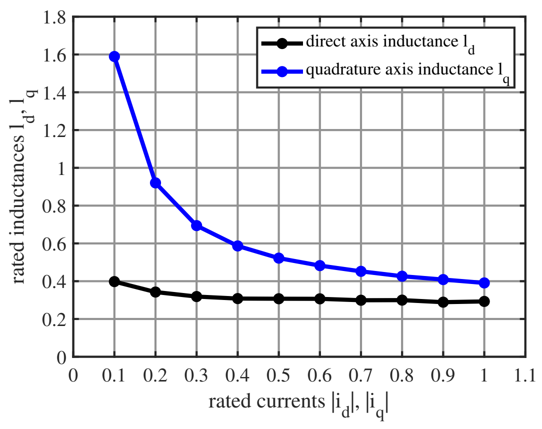

Fig. 7: Measured inductance characteristic of the electric machine

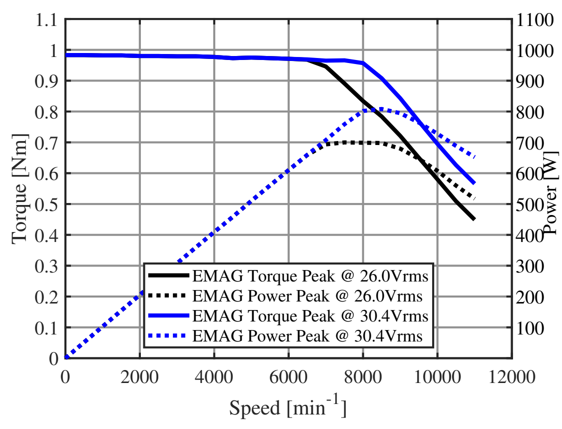

Fig. 8: Measured power and torque characteristic of the electric machine

Further Optimization

In the current project phase the complete proposed electric drive system according to Fig. 1 is investigated on a system test rig for a final confirmation of the competitiveness. After an experimental performance analysis of the complete drivetrain an optimization phase will be continued. The overall performance will be optimized by an interdisciplinary approach using several system parameters to reach a high efficiency at a low mass. First, the total gear ratio can be adjusted in a wide range without changing the installation space. The electric machine can be adjusted by changing electrical steel and permanent magnet materials. Thus, a mass and size reduction of the electric machine up to 10% at same torque and power is expected by optimization. Based on the inverter prototype design the inverter will be redesigned in collaboration with an industrial electronic manufacturer to reach a compact design and an effective high volume production capability.

Conclusion

In this paper an electric bicycle drivetrain with a high-speed electric machine and a gearbox with a very high gear ratio is investigated. By an innovative and compact gearbox design and an integrated inverter, the electric drivetrain is able to be fully integrated in the bike frame. Further, a modular concept is reached to adjust the drivetrain to several bike configurations and types. The prototype concept realizes significantly higher gear ratios as currently available e-bike motors. First components of the proposed e-bike drivetrain were successfully tested. The experimental results confirm the competitiveness to currently offered e-bike drivetrains. The proposed design represents the basis for further system improvements to point out the structural benefit of high power densities at high-speed electrical drives.

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