Design and Development of a Modular Motor-Gearbox-Unit for an Electric Light Vehicle

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ABSTRACT: This project focuses on the development of a modular Motor-Gearbox-Unit (MGU) for an experimental vehicle, aimed at validating diverse research findings in the field of electric mobility. The vehicle, a small and cost-effective electric light vehicle in the L6e-B class, aims to support to climate-friendly transportation. The contribution includes adapting a variable flux machine without rare earth elements and designing a modular gearbox compatible with different electric motors. Emphasis is placed on effortless switching of transmission ratios to facilitate motor validation. The authors aim to advance cost-effective and sustainable mobility solutions, supporting the transition towards a greener transportation system.

KEY WORDS: variable flux machine, e-mobility, L6e-B, experimental vehicle

1. Introduction

Small and cost-effective electric light vehicles of the L6e-B class [1] or similar can make a significant contribution to the traffic transition towards climate friendly mobility. Within the scope of a research project, such a vehicle is being built as an experimental vehicle. The experimental vehicle will serve as a platform to validate the results obtained from various research projects in the context of the Innovation Campus Future Mobility (ICM), ensuring their real-world applicability. These ICM projects encompass a broad spectrum of research findings, ranging from manufacturing systems, software-system-architecture to mobility technologies. This contribution to the experimental vehicle has a dual focus. Firstly, it aims to adapt a variable flux machine to the vehicle, eliminating the need for rare earth elements. This involves scaling down the machine from a previous design and simplifying the manufacturing process. The motor will serve as a baseline for the design of the gearbox and as the primary motor of the vehicle. Once additional motors have been developed within the framework of the ICM, they will also be tested in the vehicle. Secondly, the project involves the design and construction of a modular gearbox, engineered to be compatible not only with the baseline motor but also with a wide range of diverse electric motors from further research projects. The gearbox's transmission ratio needs to be tailored to the specific requirements of each individual motor being used. To facilitate a quick and straightforward validation process for different motors, it is essential to ensure effortless switching of transmission ratios.

For the development of the modular motor and gearbox combination, the first step was a situation analysis and problem delimitation. For this purpose, the performance data of other vehicles in the L6e-B class, such as a Renault Twizy [2], were analyzed. Furthermore, a comprehensive simulation model of the vehicle was constructed, placing particular emphasis on the drive system. To accomplish this, CarMaker from IPG Automotive GmbH [3] was utilized. To ascertain the necessary specifications for the drivetrain, including power and torque, the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) [4] driving cycle was simulated using the established toolchain. Because of the low power to weight ratio and the limited top speed of 45 km/h the WLTC Class 1 with a low speed profile instead of a medium speed profile is used. Subsequently, the design of the electric motor and gearbox could be tailored accordingly to meet these requirements. In the next step, alternative technical solution concepts were developed for the transmission, which were then compared based on evaluation factors such as availability, costs and required design space. Following the evaluation, the synchronous belt transmission proved to be the most favorable concept, which is why it was designed and manufactured.

2. Design of the variable flux machine

2.1 Working principle of variable flux machines

The machine developed for the lightweight vehicle discussed in this work was derived from a variable flux machine using a design process presented in [5]. The advantage of variable flux machines compared to conventional permanent magnet synchronous machines, which are widely used in electric vehicles, is the avoidance of rare earth magnet materials. Instead, AlNiCo magnets are used. These magnets have similar remanence flux densities compared to NdFeB magnets. However, their coercive field is lower by a factor 5-10, meaning they are more easily demagnetized

than rare earth magnets. This property is used to an advantage in variable flux machines, as it allows a "permanent" reduction of the machine's rotor flux, which is beneficial for the efficiency especially in the field weakening range, i.e. at high motor speeds.

The principle of variable flux machines is presented in Figure 1. Once the external field H_{ext} reaches a value beyond the flexion point, the magnet's working point will change from WP_1 to WP_2, meaning the magnet outputs less flux. The same principle can be applied to enhance the magnet flux. To do so, a positive external

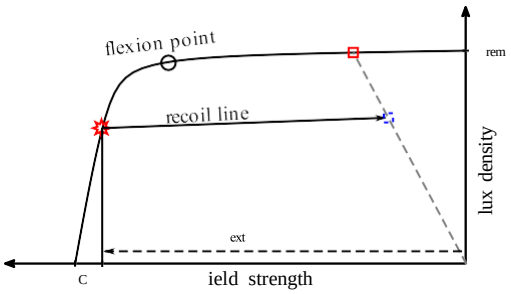


Figure 1 Working principle of variable flux machines

field H_{ext} needs be applied. For further reading on the working principle and advantages of the variable flux machine [6], [7] and [8] are recommended.

2.2 Stator design

The vehicle's on-board voltage level is 48 V, which sets the frame for the DC link voltage of the machine. Two machines drive the two rear wheels of the vehicle, the total peak output power is 6 kW in total, meaning 3 kW per machine. With the voltage level given through the system's grid and the required output power, the winding of the machine is designed analytically. The boundary conditions for the winding design are the maximum machine speed, for which an estimated gear ratio of $i_{\text{est}} = 6$ is taken as a basis, the required output power $P_{\text{mech}} = 3$ kW, the machine's dimensions, with a specified active length of $l_{\text{Fe}} = 70$ mm and the inverter's current rating, which is $I_{\text{inv}} = 70$ A.

Based upon this data, the winding configuration is chosen as presented in Table 1.

Table 1 Machine's winding parameters

Parameter	Value	Unit
Number of slots N	36	-
Pole pairs p	3	-
Number of turns per coil w_{co}	4	-
Parallel coils a	1	-
Stator outer diameter D_{s}	150	mm
Stator bore diameter D_{b}	90	mm

The stator outer and bore diameters are selected to match IEC's standard motor sizes allowing for cost and time efficient acquisition of stators.

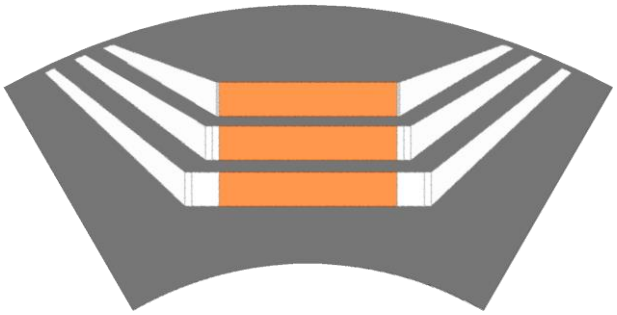


Figure 2 Parameterized geometry for the rotor design

2.3 Rotor design

Based on the data derived from the stator design, the rotor geometry is developed using a design of experiment (DOE) and multi-objective optimization. A parameterized model of a high reluctance torque base geometry as presented in Figure 2 is varied using Latin hypercube sampling (LHS). This sampling technique allows for the generation of a number of near-random samples in multi-dimensional problems. For further reading, [9] is recommended.

In total, 11 parameters are varied, including the width and thickness of the magnets, the thickness of the rotor yoke and the form of the flux barriers, as listed in Table 2.

Table 2 Parameters and respective limits for the LHS design

Parameter	Limits	Unit
magnets' thickness	[1.5, 4.0]	mm
magnets' width	[10.0, 17.5]	mm
outermost magnet's depth	[4.0 7.5]	mm
middle magnet's depth	[8.0, 11.0]	mm
inner magnet's depth	[12.0, 14.0]	mm
pole cap width	[4.0 8.0]	mm
outermost flux barrier's opening angle	[1.0, 2.0]	°
innermost flux barrier's opening angle	[1.0, 2.0]	°
middle flux barrier's opening angle	[1.0, 2.0]	°
angle between middle and outer magnet	[1.0, 3.0]	°
angle between inner and middle magnet	[1.0, 3.0]	°

A total of 2500 rotor designs are quasi-randomly generated using LHS. Electromagnetic FEA calculations of these designs are then carried out using Ansys Electronics. The simulation results are imported to MATLAB and the machines' characteristics are calculated using a post processor. Of the 2500 designs generated using LHS a total of 1240 were simulated successfully. This discrepancy is due to the nature of the design generation: The LHS will select the values for each parameter quasi-randomized, leading

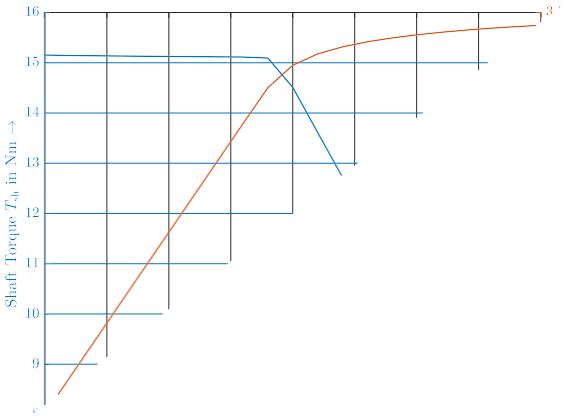


Figure 3 Torque envelope of the developed machine

to parameter combinations which turn out to be invalid once applied to the machine model in the FEA tool.

With these simulation results as sample, the optimization is carried out. A multi-objective genetic algorithm provided in MATLAB's global optimization toolbox is applied. Using Gaussian process regression, functional relations between the rotor's geometric parameters and the machine characteristics of interest are formulated, which are then used as the target functions and the nonlinear constraints, respectively.

The optimization goals are the machine's base speed torque T_{base}, the maximum efficiency η_{max}, the torque ripple and the difference between the external fields ΔH_{ext} acting on each of the three magnets. The constraints applied are the nominal power at maximum base speed $P_{\text{base}} > 3$ kW (just before entering the field weakening range) and the power at maximum speed $P_{\text{nmax}} > 3$ kW as well as the number of points in the FEA data, for which the external fields on each magnet are larger than the value corresponding to the flexion point, $H_{\text{PM}} < 1$.

With the target function and constraints in place, the optimization is carried out. In total, 70 machine designs result from the optimization. These designs are then simulated using FEA and the design most applicable is selected. The torque envelope and the efficiency map of the resulting design are presented in Figure 3 and

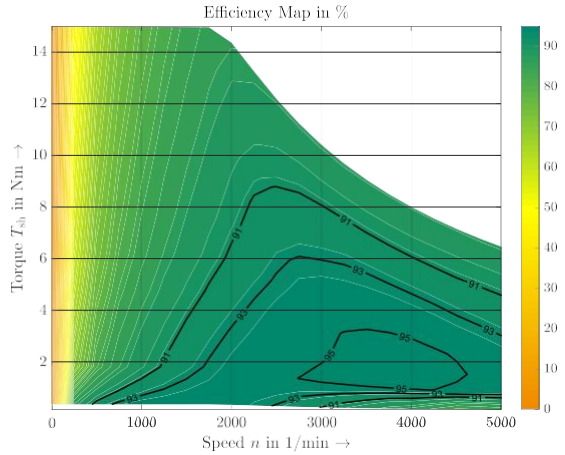


Figure 4 Efficiency map of the developed machine



Figure 5 Cross-section of the optimized machine

Figure 4, respectively, the cross-section of the resulting machine is presented in Figure 5.

Since the machine's stator is dimensioned in accordance with the IEC's standard machine sizes, a standard housing for air-cooled machines is used.

3. Design of the modular gearbox

As previously described, the transmission is modular in design so that different electric machines can be evaluated in the test carrier vehicle. The variable flux machine described in the previous section is used as a baseline for the design.

3.1. Requirements

The objective of this project is to achieve drivability in the test carrier vehicle by integrating a modular transmission into the drive system. To serve as a validation platform, the project must meet various requirements. One essential requirement is the incorporation of a changeable gear ratio to accommodate the experimental use of different electric machines within the test vehicle. Additionally, the independent driving of the two rear wheels, without a differential, necessitates the implementation of two separate gearboxes on the rear axle. To optimize cost-effectiveness, the utilization of numerous standardized components is favored. Furthermore, it is imperative to design the transmission system in a manner that allows for clear visibility of its operation from the exterior. This design consideration is driven by the vehicle's intended use at trade fairs and events, aimed at effectively showcasing the underlying technology to a diverse audience.

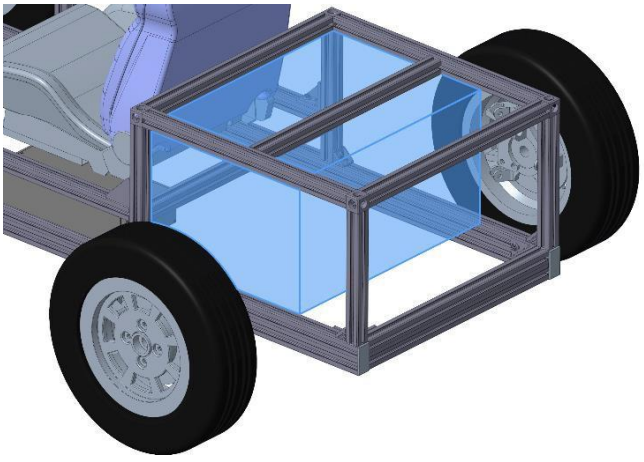


Figure 6 Design space for the placement of motor and gearbox

3.2 Conceptualization

In the first step of the conceptualization of the gearbox, the necessary transmission ratio for the baseline motor is calculated. From the characteristic diagram shown in Figure 3, the maximum driving speed of 45 km/h and the dynamic wheel radius, a transmission ratio of $i_{SRM} = 8$ is obtained. In another ICM project a Transverse Flux Machine (TFM) has been successfully developed, which will also be used for evaluation purposes in the vehicle. In contrast to the baseline motor, this does not offer enough power to reach the maximum speed. For this reason a target speed of 15 km/h is chosen, which can be reached with a gear ratio of around $i_{TFM} = 4$. All other motors to be potentially used have torque speed characteristics between the two machines. Therefore, gear ratios between $i_{TFM} = 4$ and $i_{SRM} = 8$ should also be configurable. Subsequently, the analysis focuses on the available space for the motor and gearbox. Given the presence of diverse chassis components and a fuel cell system situated at the rear of the vehicle, the area marked in blue within Figure 6 is allocated for this purpose. Multiple gear unit types are viable within the available installation space, including spur gears, planetary gears, or belt drives. After careful consideration, a synchronous belt drive was selected based on two primary decision factors. Firstly, different gear ratios can be easily achieved by modifying the toothed pulleys and adjusting the belt lengths. Secondly, an appropriate housing design allows for clear visualization of the gearbox's operation. Additionally, this kind of gearbox has a very high efficiency. According to [10] a efficiency of 99 % has been assumed per stage. However, it should be noted that compared to gear drives, a belt drive has a lower power density.

There exists a tension between the belt width and the minimum size of toothed pulleys, creating a delicate balance in their selection. A wider belt width allows for the use of smaller pulleys as fewer teeth need to engage to maintain acceptable surface pressure. However, it is important to consider that a wider belt width also contributes to increased weight and requires more installation space for the gear unit. In this specific application, a belt width ranging between 20 and 30 mm is deemed appropriate, striking a compromise between installation space or weight constraints and pulley size optimization. To allow for these narrow belts, an 8M High Load (HL) belt is used. A minimum pulley size of 59,75 mm is specified for this particular belt width and design. With the maximum required transmission ratio of $i_{SRM} = 8$, this leads to a diameter of 478 mm for the output pulley. Since this diameter is similar to that of the tire, it is impractical for vehicle application. Consequently, a two-stage gearbox is devised. For the conceptualization and the design of the synchronous belt drive [10] has been used.

3.3 Selection of the gear ratios

The two-stage concept raises the question of which ratio factors are realized in the first and second stage. Since the ratios of the two stages are multiplied, significantly lower ratios per stage are possible if the ratios are chosen wisely. In addition, as few pulleys as possible should be required for the highest possible number of possible ratios. Furthermore, the ratios in the first stage are chosen so that a narrow 20 mm belt can be used. Table 3 shows four different ratios for each of the first and second stages with the respective toothed pulleys. In total, 16 different gear ratios between 3.98 and 8.0 can be achieved. The required spacing of the gear is thus possible with the use of only eight different pulleys.

Table 3 Gearbox ratios (i_1, i_2) and pulleys (p_1 - p_4) of the first and second stage with resulting total ratio for the Transversal Flux Machine (TFM) and Variable Flux Machine (VFM)

		p_3	26	24	26	24
		p_4	48	48	72	72
p_1	**p_2**	**$i_1 \backslash i_2$**	**1.85**	**2.00**	**2.77**	**3.00**
26	56	**2.15**	3.98	4.31	5.96	6.46
24	56	**2.33**	4.31	4.67	6.46	7.00
26	64	**2.46**	4.54	4.92	6.82	7.38
24	64	**2.67**	4.92	5.33	7.38	8.00
			TFM		**VFM**	

Figure 7 shows the gearbox ratios with an exemplary combination of toothed pulleys. For better utilization of the installation space, the two stages are arranged at an angle to each other.

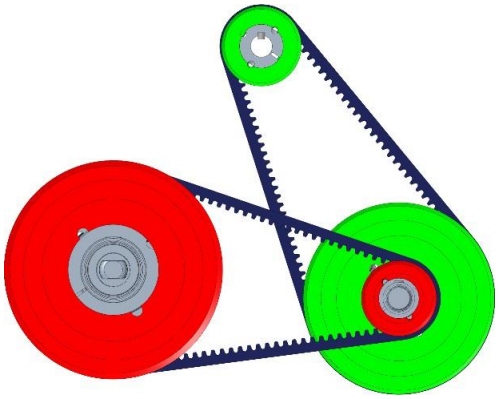


Figure 7 Arrangement of the two gearbox stages

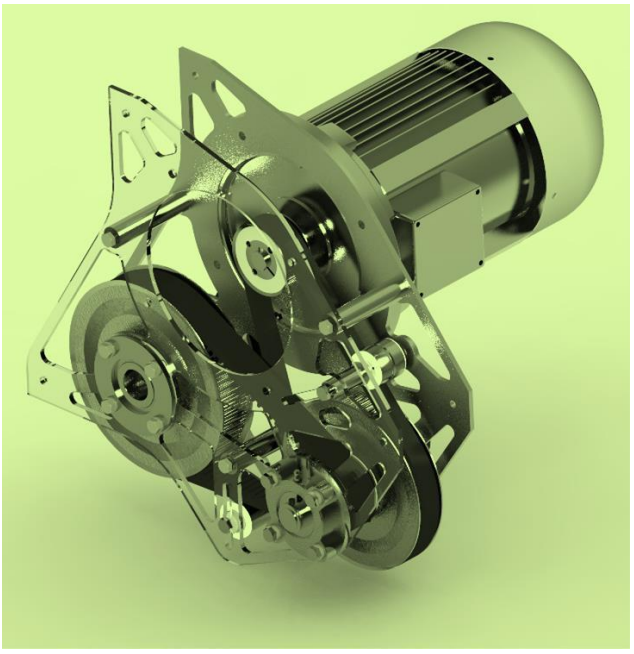


Figure 8 Gearbox housing. One plate is shown transparent for illustration

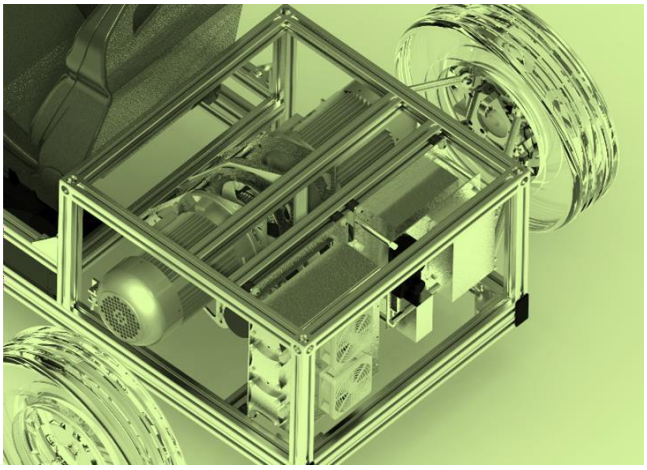


Figure 9 Rear of the vehicle with the two symmetrical motor-gearbox-units

3.4 Gearbox housing

As depicted in Figure 7, the gearbox features two parallel transmission stages stacked on top of each other. To optimize production efficiency, the gearbox housing is designed with two parallel aluminum plates. These plates can be manufactured cost-effectively using methods such as waterjet cutting. The housing design, shown in Figure 8, includes connecting posts to secure the plates together, aside from the gear shafts. The use of two parallel plates offers the advantage of direct attachment of the electric machines to one of the plates. Furthermore, the plates are equipped with mounting brackets at their edges, allowing for direct mounting to Bosch-Rexroth aluminum profiles on the test vehicle.

3.5 Belt tensioner

The utilization of different pulley combinations gives rise to varying belt lengths and shaft distances to achieve the desired transmission ratios. Additionally, the installation of the belt is impeded by fixed shaft distances, primarily due to the presence of flanged pulleys. Consequently, the incorporation of belt tensioners becomes essential. However, standard commercially available belt

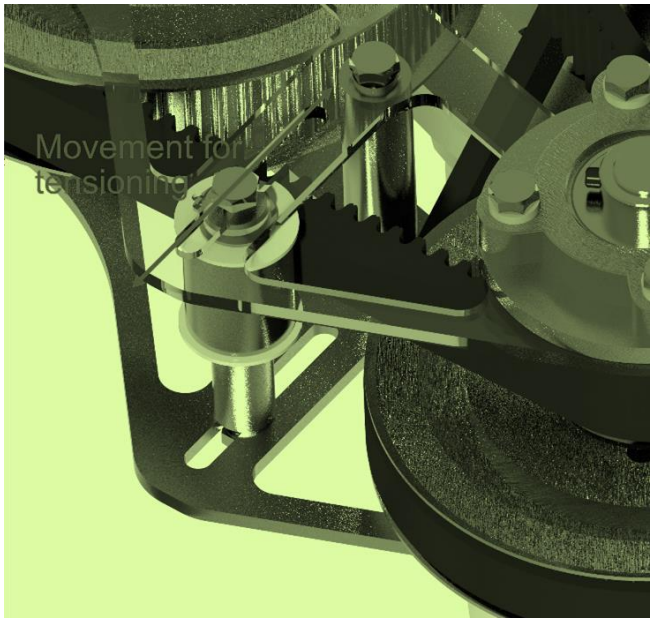


Figure 10 Belt tensioner

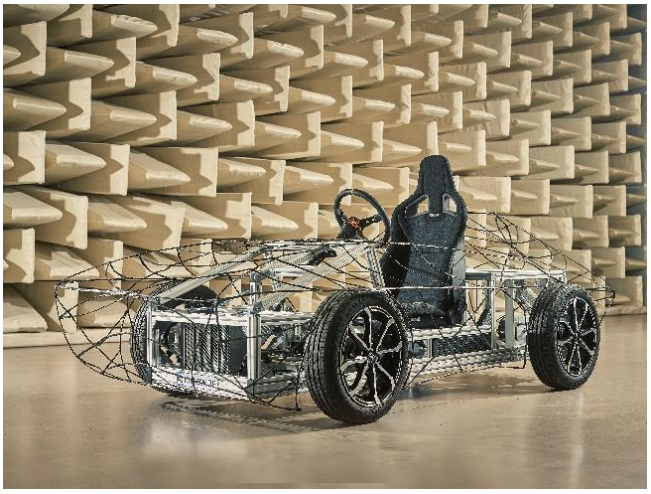


Figure 11 Test vehicle

tensioners typically facilitate power flow in only one direction, limiting their suitability for this application. To address this limitation, a bespoke belt tensioner, as depicted in Figure 10, was designed and manufactured. The belt tensioner comprises a shaft that fits into slotted holes located between the two housing plates. These slotted holes enable adjustable movement of the tensioner, ensuring precise belt tension adjustment. The shaft incorporates a needle bearing accompanied by two thrust washers, promoting efficient belt tensioning with minimal energy losses.

Figure 11 shows the test vehicle at the end of the research project.

4. Discussion

The motor-gearbox-unit developed in this project offers a well-suited solution for the specific application, characterized by its simplicity and utilization of readily available components. In the context of a test carrier vehicle intended for the evaluation of different electric motors, a synchronous belt transmission emerges as a favorable choice for a straightforward transmission system. It enables efficient testing and validation of various motor configurations. However, when considering series applications, the limitations of belt transmissions become apparent, primarily due to their substantial installation space requirements. Consequently, alternative transmission technologies are typically preferred in series production scenarios, emphasizing the significance of compactness and optimal space utilization. Future research could focus on optimizing space efficiency and exploring alternative transmission options to address these limitations and expand their potential utilization in specific series production contexts.

The integration of variable flux machine technology holds potential for further transferability to series applications, providing the advantage of reducing reliance on rare earth materials. This aspect is particularly significant considering the importance of sustainable resource management. The additional degree of freedom in motor control given through the variable flux machine is promising especially for lightweight vehicles, since the total power of these vehicles is limited by the L6e-B class standards. This limitation makes the power requirements for the vehicles more reasonable than is the case in “classic” traction applications, where the output

power is often very high compared to the requirements and application of the vehicle.

5. Conclusion

As part of this project, a modular motor-gearbox-unit (MGU) was designed and developed for use in an electric light vehicle of the L6e-B class. The aim was to develop a transmission that allows a variable and easy to change gear ratio and can thus be used in combination with different electric motors. As a baseline motor a variable flux machine is adapted for this application. Throughout the development process, comprehensive simulations, analyses, and design optimizations were conducted to ensure the efficient and reliable performance of the motor and gearbox combination. The synchronous belt transmission emerged as the most favorable concept, addressing the requirements of the vehicle while maintaining high efficiency and cost-effectiveness. A two-stage gearbox design was adopted to accommodate the necessary transmission ratios effectively.

Overall, this project contributes significantly to the advancement of eco-friendly mobility solutions. It offers insights into the development and validation of electric light vehicles and showcases the potential of the variable flux machines in contributing to climate-friendly transportation. The successful integration of the modular motor-gearbox-unit positions the vehicle as an effective validation platform for a wide range of research projects in electric mobility.

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