ANALYSIS AND OPTIMIZATION OF DRIVE SYSTEM USED IN ELECTRIC BIKE

W. CHLEBOSZ G. OMBACH
Brose Fahrzeugteile GmbH & Co. Kommanditgesellschaft, Wuerzburg, Germany
Email: wojciech.chlebosz@brose.com, grzegorz.ombach@brose.com

J. JUNAK
Brose Fahrzeugteile GmbH & Co. Kommanditgesellschaft, Wuerzburg, Germany
Email: jacek.junak@brose.com

Abstract: *This paper presents the analysis and optimization of a drive system used in an electric bike. The analysed e-bike was equipped with the permanent brushless synchronous motor with mechanical output power in range of 250W. The electric motor together with a planetary gear was mounted in a hub of 26 inch bike wheel. This kind of e-bike can reach maximum speed up to 25km/h. The aim of this paper is to investigate e-drive system used in the commercial e-bike and to optimise the e-motor in order to keep efficiency of the motor and reduce its price. As a result of work the optimized motor topology is presented.*

Key words*: e-bike, brushless motor, electric transport, co2, mass production*

1. Introduction

First effort to make an e-bike was done at the beginning of the 20th century, but due to poor battery quality and electric motor technology, this kind of drive was replaced with combustion motors. Nowadays when oil price is still on high level, people are looking for less expensive way of transport. Electric bikes are good alternative to cars and still growing up traffic in cities.

Electric motors for electric bikes can be divided into three groups [2] : 1) motors up to 250W used in e-bikes [1], 2) motors from 250W to 750W used in electric mopeds 3) motors over 750W used in electric scooters.

Electric drive applied in e-bikes can be divided into groups in regard of position where motor is mounted 1) front wheel 2) rear wheel 3) in middle of bike frame also known as mid-drive system. All those combinations are depicted on Fig. 1.

Most easier in realisation are systems with front and back wheel hub motor. Such solution has influence on costs of drive system, and also it is easier in implementation in comparison to mid-drive system. Front and back wheel system can also offer energy recovery at breaking. Weakness of those two systems is limited space for stator length with the gear in hub. In case of short circuit in motor winding, wheel is blocked by breaking torque. Mid-system drive doesn't have this failure in case of short circuit in the motor winding and it is possible to continue ride without additional breaking torque on pedals. Mid-system drive allow all of a bike's gear range to be used in motor , in that it's possible to get better performance by up hill riding, or by riding on flat area with optimized gear transmission.

This paper describes an e-bike with a front wheel drive motor, which is most popular in e-bikes and also in conversion kits for a standard no-electric bike.

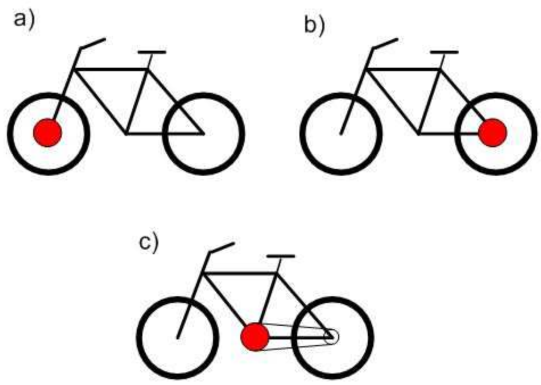


Fig. 1. Three systems of motor position in e-bikes: a) Front wheel hub motor b) Back wheel hub motor c) Mid-drive motor

2. System description

The analysis is based on the electromechanical system mounted in the e-bike in the front wheel. This system contains permanent magnet brushless electric motor- Fig. 1, mounted in a hub of 26 inch inch wheel. The e-bike with a fully charged lead-acid battery 36V can reach up to 25km/h without additional rider assistance. Electronic control unit use a square wave drive control strategy [3, 4].

3. Electric motor description

The e-motor used in a serial e-bike is a brushless synchronous motor (BLDC) with outer permanent magnet rotor shown in Fig. 2. The motor is embedded into the hub with built-in planetary gear, presented in Fig. 2. The gear ratio is 4.4:1. There are 93 teeth on outer ring wheel, 31 teeth on each planetary gear-wheel (there are 3 gear-wheels) and 21 teeth on sun wheel. The rotor is able to rotate in the housing around stationary shaft and is coupled with sun gear where planet carrier is coupled with shaft – Fig 3.

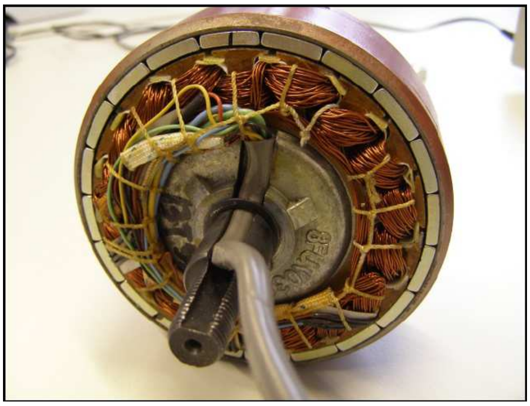


Fig. 2. Electric bike motor

Fig. 3. Planetary gear.

The winding – In one phase are six coils wounded in series with five strands-in-hand. Number of turns per coil is 13. The BLDC motor of e-bike is powered with 36V battery. The power controller limits the output power to 250W and also bicycle's speed to ca. 25km/h. The motor reaches up to 10Nm torque which on the low speed side of planetary reduction side is 4.4 times higher

5. Electronic control unit - ECU description

The E-Bike is equipped with PWM power electronics controller based on 16F72 PIC processor. The Power controller obtains rotor position by means of three Hall's sensors located on the stator. Main processor controls 3-phase inverter by drivers based on MMBT5551 npn and MMBT5401 pnp transistors. The Inverter Bridge embraces IRF1010 HEXFET power MOSFET transistors. The maximum current of transistor is 84A. The motor is driven by square wave current.

6. System examination

Test equipment provides power measurement at various load conditions, by mechanical load emulating uphill elevation on front wheel of electric bike. Obtained results are summarized in Table 1. and also depicted as power and torque versus speed chart in Fig.4. Above 160rpm measured torque instantly goes down, because generated EMF almost reaches ECU voltage.

The motor without planetary gear was also examinated. The measurements were done with original ECU. The results are shown in Fig 5. The phases current were measured at speeds 150rpm, 300rpm and 600rpm. Phase currents decrease with speed what can be seen on Fig. 6, 7, 8 by speed 150rpm were peak value of Current was 29.5A. By 300rpm - 24A and for 600rpm reach 20A. Currents were measured with LEM probe 10mV=1A – Fig 6, 7, 8. Applied planetary gear increases output torque value and also reduce motor speed, which is enough to develop by bike ca. 21km/h – Table 1. Generated Back-EMF was also measured at 1000 rpm and depicted on Fig. 9, Amplitude of back-EMF reaches value 33.6V.

Table 1

Measurements of motor performance done with electric bike

Uphill grade[%]	Moving speed[km/h]	Output power[W]	Rotary speed[rpm]	Torque[Nm]
0	21.5	56	175.7	3.04
1	21.0	93	171.6	5.18
2	21.0	124	171.6	6.90
3	20.8	177	169.9	9.95
4	20.4	200	166.7	11.46
5	20.2	245	165.0	14.18
6	19.7	279	160.9	16.55
7	18.8	300	153.6	18.65
8	16.5	295	134.8	20.90
9	13.3	260	108.7	22.85
10	11.0	230	89.9	24.44
11	10.1	220	82.5	25.46
12	8.8	196	71.9	26.03
13	8.5	185	69.4	25.44
14	8.1	178	66.2	25.69
15	7.7	163	62.9	24.74
16	7.2	150	58.8	24.35
17	6.8	128	55.6	22.00
18	5.3	133	43.3	29.33
19	4.5	109	36.8	28.31
20	3.9	79	31.9	23.68

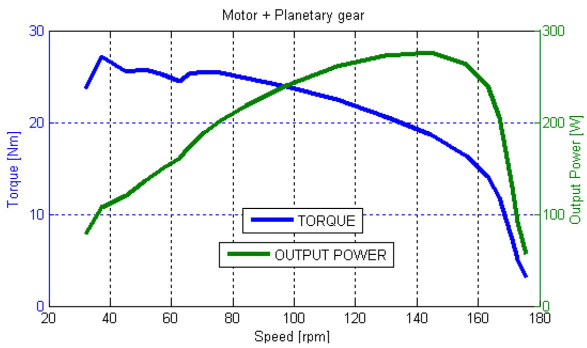


Fig. 4. Measured torque and power vs. speed for motor with planetary gear, built in front wheel of bike

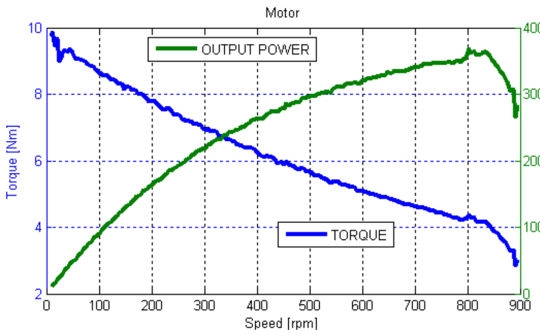


Fig. 5. Measured torque and power vs. speed for motor without planetary gear on test-bench.

7. System simulation.

Motor model with control electronic was built with parameters shown in Table 2. The results of simulations were compared with measurements, and depicted on Fig 6, 7, 8 as comparison of phase currents. Simulated and measured Back-EMF at 1000rpm is depicted on Fig. 9.

Table 2
Measurements of motor performance done with electric bike

Parameter	Value
Lamination Dimensions	
Rotor outer diameter	90 mm
Rotor stack length	25 mm
Stator outer diameter	89 mm
Stator inner diameter	27.1 mm
Stator stack length	25 mm
Air gap	1 mm
Stator Winding	
Number of stator slots	18
Stator turns per coil	13
Coils in series per phase	6
Number of wires in paralel	5 Strands-in-hand in one conductor
Wire diameter	0.56 mm
Phase resistance at 21°C	0.117 Ohm
Magnets	
Magnet Poles	20
Magnet dimensions, (one magnet)	25x14x3.3 mm
Total mass of magnets	0.170 kg

At the beginning were compared three work points measured on torque speed curve for motor without planetary gear: 150 rpm, 300rpm and 600prm. Measured Back-EMF at 1000rpm, was also compared with simulated Back-EMF.

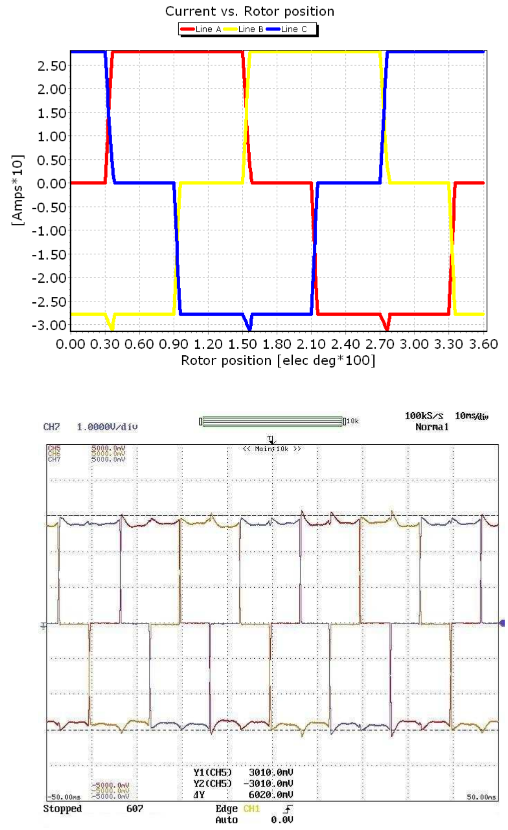


Fig. 6. Simulated and measured phase currents at 150 rpm

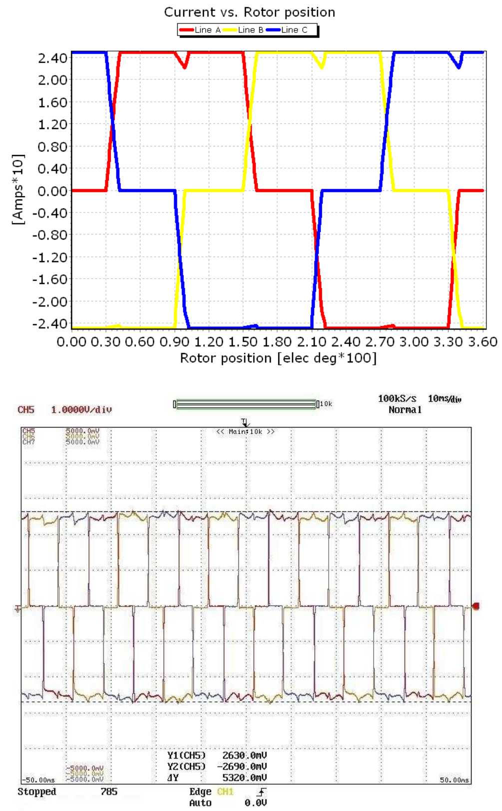


Fig. 7. Simulated and measured phase currents at 300 rpm

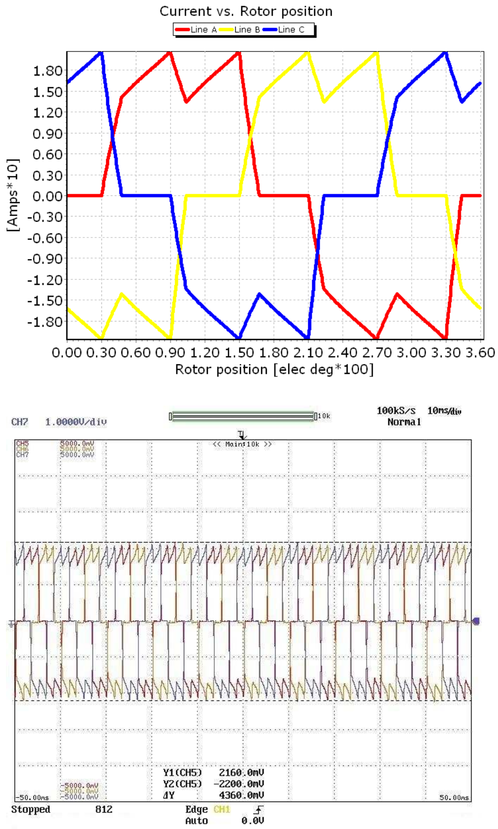


Fig. 8. Simulated and measured phase currents at 600 rpm

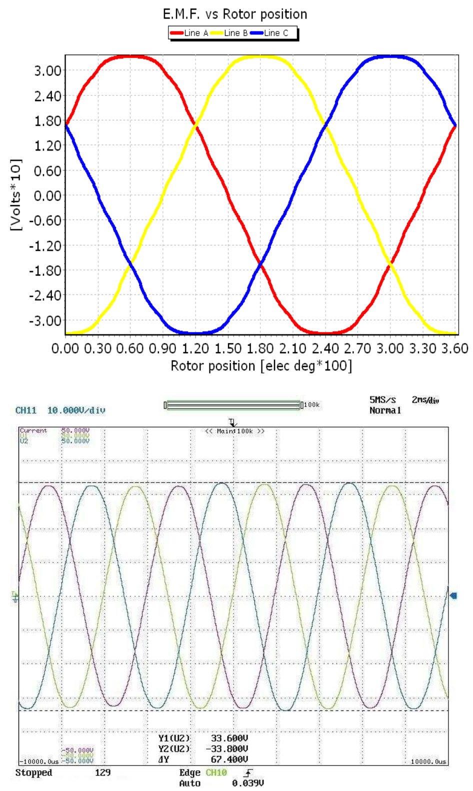
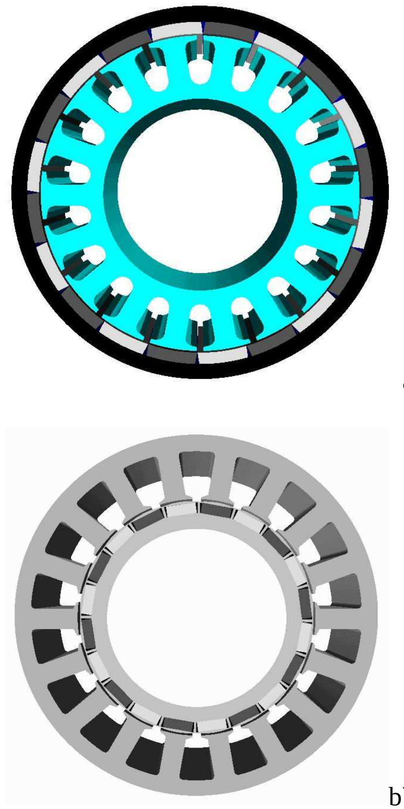


Fig. 9. Simulated and measured no-load voltage (Back-EMF) at 1000rpm

5. Optimization System.

The aim of optimization is to redesign the motor through reducing its weight and price. Proposed new construction of the motor has a reduced weight of steel and magnets, in comparison to increased weight of copper. Total weight of motor was reduced from 1.85kg to 1.52kg – table 3, and finally price of the motor due to applied materials was also reduced to 27%. In this case vary important was reduction of magnet weight and to replace arc shape magnets with cheaper rectangular shape magnets. In primary structure (Fig. 10a), rotor has an outer construction and stator is inside with build in planetary gear. This construction was replaced by opposite construction were rotor is inside, and stator is mounted outside (Fig. 10b). Such construction gives possibilities to use rectangular shape magnets and IPM rotor assembly. Inside part of the rotor has enough space for planetary gear. Main dimensions of motor were unchanged, so proposed motor can work with original housing with necessary mechanical changes. Very important in optimized motor construction was not to increase measured resistance of motor before optimization, because it will be not possible to achieve this same or better motor efficiency which was depicted on Fig. 12. [5]



a)

b)

Fig. 10. a) Primary motor construction b) New proposed motor construction

Table 3
Weight of motor material before and after optimization.

Weight:	Befor optimization	After optimization	Price
Cupper	0.32kg	0.56kg	~2.5€/1kg
Steel	1.36kg	0.85kg	~1000€/1 t
Magnets	0.17kg	0.11kg	~50€/1kg
Summary	1.85kg	1.52kg	-
Price :	~10.66€	~7.75€	-

Battery current up to 400 rpm is kept on the same level after and before optimization. Above 400 rpm battery current reduces – Fig. 11, as motor toque depicted on Fig. 13. The Motor efficiency in all speed range is still kept on this same level after and before optimization – Fig 12.

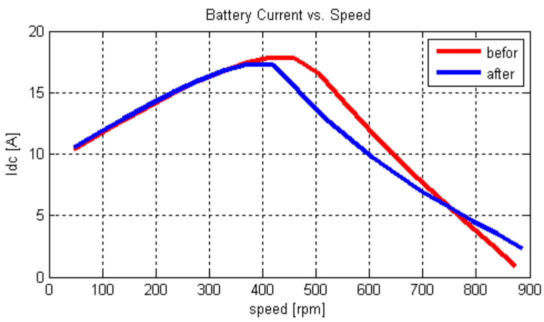


Fig. 11. Simulated DC link current vs. speed, before and after motor optimization, at 30A peak value phase current

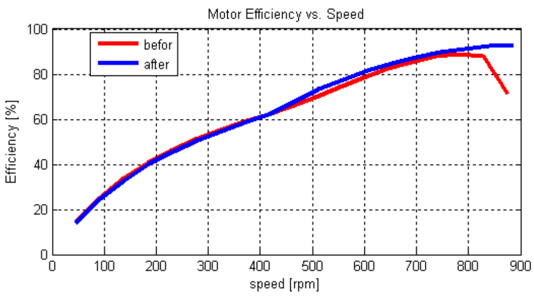


Fig. 12. Simulated motor efficiency vs. speed, after and before motor optimization at 30A peak value phase current.

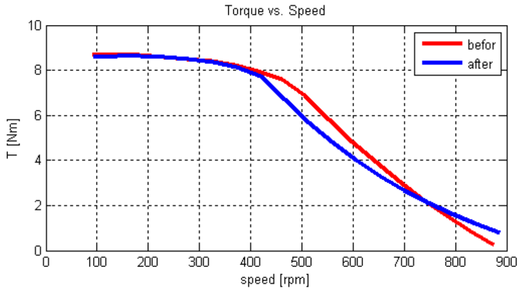


Fig. 13. Simulated Torque, vs. speed after and before motor optimization by 30A peak value phase current.

9. Conclusions

The paper describes the theoretical and the experimental analysis of drive system used for the e-bike. The most important electrical and magnetic properties like: torque/speed characteristic and motor parameters are compared. The aim of the optimization of electric motor was to minimize the weight and to reduce motor's price.

Acknowledgment

Authors would like to thank Brose Fahrzeugteile GmbH & Co. KG, Wuerzburg, Germany, for the support during preparation of this paper.

References

3. E. Jammerson, E. Benjamin *"Electric Bikes Worldwide Reports"*, march 2009 www.ebwr.com.
4. Fairley, P:;" *China's cyclists take charge: electric bicycles are selling by the millions despite efforts to ban them"* Volume 42, Issue 6, June 2005 Page(s):54 – 59
5. Boe-Shong Hong; Tsu-Yu Lin; Wen-Jui Su; *"Electric bikes energy management-game-theoretic synthesis and implementation"* Industrial Electronics, 2009. ISIE 2009. IEEE International Symposium on 5-8 July 2009 Page(s):2131 – 2136
6. Cheng-Hu Chen; Ming-Yang Cheng *"Implementation of a Highly Reliable Hybrid Electric Scooter Drive"* Industrial Electronics, IEEE Transactions on Volume 54, Issue 5, Oct. 2007 Page(s):2462 – 2473
7. Grzegorz Ombach *"Comparison of of electric power steering systems with PM machine used in hybrid vehicle with two different on-board voltage levels"* Monaco Ever 2009, March 25-29