

Use of 3 kW BLDC motor for light two-wheeled electric vehicle construction

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Abstract. The article presents design and construction of the light two-wheeled vehicle powered by the brushless DC motor of 3 kW. The construction of the vehicle is based on a steel frame similar to the classical bicycle frame. The vehicle has been additionally equipped with pedals as an alternative driving source as well as with the standard motorcycle equipment, i.e. lamps, breaking light, horn, front disc brake, etc. The prime power source which is the BLDC motor has been installed in the rear wheel hub and is powered by a pack of 220 lithium-ion power cells of 2600 mAh each. The nominal parameters of the designed power pack is 72 V and 27.5 Ah of capacity. The motor controller which can be powered by the voltage from 36 V to 95 V can deliver up to 80 A of current. It enables regenerative braking which increases an overall range of the vehicle. The article discusses also the problem of classification of such construction according to the Polish law described in the Act on the Law of Road Traffic as well as in the Regulation of the Minister of Infrastructure of 31 December 2002 on the technical conditions of vehicles and the scope of their necessary equipment. Finally, the designed construction has been tested on the MAHA LPS 3000 chassis dynamometer in order to measure mechanical and electrical parameters like maximal electric power of the motor, maximal mechanical power on the wheel, motor torque, maximal rotational speed, energy consumption, windings temperature reached, etc. These quantities will serve to further development of the designed construction.

1. Introduction

Electric vehicles have been known since 19th century. In general, they can be divided into few groups: bicycles, motorcycles, cars and buses. One of the first electric car was constructed in 1834 by Thomas Davenport [1]. For comparison, the first car with combustion engine was built by Carl Benz in 1885. At that time, electrical technology was developed on a par with combustion technology. Even Ferdinand Porsche, known today as a legendary designer of the super sports cars with powerful combustion engines, in 1900 unveiled his electric front-wheel drive car. However, at the beginning of the 20th century, Ford started the mass production of the Ford T model. It was a relatively cheap car which has motorized the USA. From that moment, the combustion engines began to gain in popularity.

After all, in the recent years one can observe a return to the electrical technology. This is because of the huge progress in the field of energy storage, batteries, electrical motors, permanent magnets, frequency converters and control strategies. Second important reason for the electrical energy use in automotive applications is fast decreasing fossil fuel resources like petroleum and so the uncertain future of the combustion technology. At the same time, the cost of electrical energy in comparison to the energy from fuel is several times smaller. Moreover, nowadays the electrical energy from



renewable sources is playing the more and more important role in the global energy market because the production cost of 1 kWh of so called green energy is now much more profitable and achievable than a few decades ago. Furthermore, one can observe the growing demand for the environment protection which forces the biggest energy companies and automotive concerns to implement the newest technology achievements for continuous reduction of pollution emissions [2], especially in the cities [3]. The above mentioned arguments have encouraged authors of the article to design and to build a light two-wheeled electric vehicle similar to a bicycle.

1.1. Conception of E-bike

History of electric bikes began in 1890 but on the 31st of December 1895 Ogden Bolton was granted the first patent for the battery powered bicycle. His idea was to place the motor in the rear wheel hub of the bicycle. Even if over the next many years, the constructors have created various types of drives, from belt transmissions to planetary gears, the Bolton's idea is considered the best concept to this day. His motor was the 6-poles DC brush and commutator motor which could take up to 100 A from a 10 V battery. Today, the most widely used drives in the E-bike constructions are the BrushLess Direct Current motors (BLDC) with the high density neodymium permanent magnets and continuous powers up to 6 kW. The robust frame construction combined with the powerful electric motor make that these vehicles can compete with motorcycles and are of great interest today. Electric bikes have become popular all around the world thanks to the electric bike parts manufacturers. They design and produce all kinds of electric bike components that meet requirements of the customers. For example, nowadays one can buy a set for conversion a classic bicycle into an electric one. With the user's manual, the ready-made elements are easy to assemble and to configure. This fast growing market makes the E-bike companies compete with each other offering the more and more efficient drive solutions.

The purpose of the presented project has been to design and to build a light two-wheeled electric vehicle similar to a bicycle, i.e. E-bike and to measure its electrical and mechanical parameters on the chassis dynamometer originally dedicated for four wheel vehicles. The constructed vehicle has been used as a means of transport to benefit the low cost of transportation in comparison to the internal combustion vehicles. Cost of full charging of the battery is about 2.5 PLN and enables to drive about 80 km. Another advantage of the E-bike construction is a pleasure of driving a silent vehicle with a considerable torque which can be used on tracks as well as in terrain conditions.

The basic assumptions adopted in the project are as follows:

- Large battery capacity (~ 30 Ah)
- Fast battery charging
- Maximal discharging current of the battery (~ 150 A)
- Use of BLDC motor of 3 kW of power placed in a rear wheel hub
- Possibility of driving on tracks as well as in terrain conditions
- Possibility of driving parameters change while driving a vehicle
- Ability to immediate disconnection of the power supply

All of above mentioned assumption have been met and the light two-wheeled electric vehicle has been constructed in order to perform the further research. The described vehicle has been presented in the Fig. 1.



Fig. 1. Two-wheeled electric vehicle during tests on the chassis dynamometer

2. Classification of the vehicle according to the Polish law

2.1. *Electric bicycles*

Polish law regulations concerning electric bicycles and other vehicles still evolve. The definition of a bicycle was formulated in the Act on Road Traffic of June 20, 1997. However, only on April 1, 2011, some changes concerning vehicles equipped with an electric drive have been made. According to this act, the bicycle is "a vehicle of width not exceeding 0.9 m, moved by the strength of a person riding this vehicle; the bicycle can be equipped with an auxiliary electric drive activated by a pedal pressure, of no more than 48 V, with a nominal continuous power not exceeding 250 W, of which output power decreases gradually and falls to zero after exceeding the speed of 25 km/h" [4]. The above definition is valid to this day.

This law contains some restrictions and uncertainties that may affect the interests of sellers as well as customers. For example, an auxiliary electric drive can be activated only by the pedal pressure. The device adjusting the motor power to the speed of the bicycle is called the cadence sensor. This device measures the number of crank turns per minute. Then, basing on this information, the controller adjusts the motor power to facilitate pedalling. It means that when the cyclist stops pedalling, the bike will automatically turn off the drive, which will result in bike braking. It would be more convenient to control the motor power with the handle but this solution is forbidden.

To sum up, the constructed vehicle does not meet the conditions mentioned in the above act, especially in terms of battery voltage, motor power and cadence sensor so it cannot be called an electric bicycle. Nevertheless, for this article purpose the name of E-bike has been used.

2.2. *Electric mopeds*

Another vehicle group similar to the bicycles and included in the previously mentioned act are mopeds. Requirements that must be met by a vehicle to be specified as a moped are described in the act definition: "Moped – a two- or three-wheeled vehicle equipped with a combustion engine of a cylinder capacity not exceeding 50 cm³ or an electric motor with a power not exceeding 4 kW, whose design limits the speed of travel to 45 km/h" [4]. In addition, the moped should be equipped with appropriate running lights, dipped headlights, high beams, two front and two rear direction indicator lights, stop light and other equipment like warning signal, exhaust silencer (only for combustion engines), rear-view mirror located on the left side of the vehicle, etc. The external noise level, measured when the moped stops at a distance of 0.5 m, must not exceed 90 dB (A) what is easily achievable by electric mopeds. Also in this case, the presented in the article construction cannot be called a moped because of exceeding the maximal speed of 45 km/h and lack of some equipment like rear-view mirrors or retroreflector lights placed on each side of the vehicle.

2.3. *Electric motorcycles*

There are some slight differences between the regulations for mopeds and motorcycles. Namely, they do not precise the maximal engine capacity and power for the motorcycles as well as the top speed of the vehicle. Finally, according to the Polish law, even if the light two-wheeled electric

vehicle is based on the bicycle frame and is equipped with pedals but its auxiliary electric motor can accelerate the vehicle to a speed of more than 45 km/h it should be classified as a motorcycle and should subject to totally different law regulations than a classic electric bicycle. One driving such a vehicle must among other have a valid registration document with positive technical examination, cannot drive on sidewalks or without helmet. That is why a lot of people are hiding the real potential of their constructions by installing an electronic power and speed limiter in case of police control while driving on public roads or sidewalks. Officially, owners of such constructions admits that they use their vehicles only on closed tracks or private terrains.

3. Electric drive system

Electric drive system of the presented vehicle consists of three main elements, i.e.: battery pack of 220 lithium-ion power cells of 2600 mAh each, BLDC motor of 3 kW of output mechanical power and the Sabvoton 3-phase controller of the electric motor. They are characterised in the following chapters.

3.1. Battery pack

There are several types of batteries used in electric vehicles. Term “battery” usually refers to the pack of cells connected together in one of the specific ways – in series, in parallel or in combined series and parallel way. Lead-acid and gel batteries are rarely used as an energy storage in electric vehicles due to their significant weight and dimensions. Whereas, nickel-cadmium cells have low capacity and to low continuous discharging current for this kind of application. Lithium-ion and lithium-polymer cells have large capacity, high discharge current and high operating temperature what meets the project requirements. The only feature that differs these two products is the price. Lithium-ion cell is few times cheaper than the lithium-polymer cell. Taking into account the number of cells needed in the project, the lithium-ion cells have been chosen. Parameters of a single cell have been presented in Table 1.

Table 1. Parameters of the SONY US18650VTC5 C5 2600mAh cell

Parameter	Value
Nominal capacity	2500 mAh
Maximum voltage	4.2 V
Nominal voltage	3.6 V
Minimum voltage	2.0 V
Charging voltage	4.2 V
Maximum charging voltage	4.25 V
Charging current	2.5 A
Maximum charging current	4.0 A
Maximum continuous discharging current	10 A
Discharge current intensity at a temperature below 80 °C	30 A (<10 sec.)
Discharge current intensity at a temperature above 80 °C	20 A (<10 sec.)
Safe discharging current	10 A (> 10 sec.)
Weight	44.3 g
Charging temperature	0 ÷ + 45 °C
Discharge temperature	–20 ÷ +60 °C

During the tests on the chassis dynamometer, the temperature of the battery pack did not exceed 35°C.

3.1.1. Cell connections

The way of cell connections are closely related to the controller parameters and at the same time to the electric motor parameters. The space provided for the battery pack placement is also important. The motor Sabvoton 3-phase controller can be powered by the voltage from 36 V to 95 V and can deliver

up to 80 A of current. Therefore, 20 cells have been connected in series and 11 such sets of 20 cells have been connected in parallel. In order to gain in space, the battery pack has been additionally splitted into 2 sections: 17x11 and 3x11 what is shown in the Fig. 2. The overall maximum voltage of the designed battery pack is 84 V with the capacity of 27.5 Ah. Taking into account that the maximal continuous discharging current for one cell is equal to 10 A, the battery can deliver up to 110 A of current for about 15 minutes. As the maximum current output of the Sabvoton controller is 80 A, the cells are discharged by the maximal current of 7.27 A what is the safe level in terms of battery life. Consuming the current of 7 A, the time needed to discharge the SONY cell to a safe voltage of 2.8 V is about 22 minutes [5].



Fig. 2. Connections of cells in the battery pack

The battery pack is charged with the automatic charger via BMS system (Battery Management System), which continuously controls the charging and discharging process parameters of the battery. The purpose of this device is to prevent the cell from being charged above 4.2 V and discharged below 2.8 V. Exceeding these values causes disconnection of the power supply [6]. After charging process, the BMS performs a passive balancing of the battery cell sections which takes from 6 to 8 hours [7].

3.2. BLDC motor

Brushless direct current motors (BLDC) are a type of DC motors with an electronic commutator. Due to their numerous advantages they are more and more often used instead of classic DC motors with the mechanical commutator. The main advantages of the BLDC motors are: high durability, high efficiency, relatively low weight and small dimensions in comparison to other electric motor constructions. These features are of great importance during the construction of an electric vehicle as it has to be as light as possible [8].

In the project, the Mxus 3K-Turbo motor of the Chinese manufacturer QSMotor has been used. This is one of the most powerful motors on the market which is designed to be installed in the rear wheel hub. Its mechanical and electrical parameters have been presented in Table 2.

Table 2. Characteristics of the Mxus 3K-Turbo motor

Parameter	Value
Winding	10 x 6 (6T), 3-phase
Motor torque constant K_T	1.59 Nm/A
Motor velocity constant K_V	6.0 rpm/V
Nominal power at 60 V	3 kW
Maximum instantaneous power	7 kW (~80÷90 A)
Power supply voltage	24 - 120 V
Maximum continuous current	50 A

Wheel speed for a diameter of 26"	0.9 km/h for each 1 V of power supply
Torque	> 125 Nm
Weight	9.2 kg
Fork spacing (dropout)	145 mm (36 spokes)
Hall sensor	yes
Number of magnets	46 (23 pairs)

Fig. 3 presents the photos of disassembled rotor and stator of the motor. In the BLDC motors the windings are connected directly to the controller which switches the voltage on the corresponding winding using information from the three Hall sensors placed inside the motor every 120 of electric degrees. Despite sophisticated control strategy, the BLDC motors have stable torque characteristics as a function of rotational speed. The lack of mechanical commutator makes them more durable and silent than the classic DC motors. They can also reach higher speeds [9].



Fig. 3. Photos of the rotor and the stator respectively of the Mxus 3K-Turbo motor.

1 – stationary motor shaft, 2 – shaft and stator fixing element, 3 – windings, 4 – stationary stator, 5 – rotating neodymium magnets of the rotor

Three-phase motors are divided into two types: outrunners – where the casing rotates and inrunners – where the interior of the motor rotates. The presented Mxus 3K-Turbo motor is the outrunner type. Windings of the stator are connected in star.

One of the main problem during electric vehicle design and construction is a heat dissipation from the motor. The temperature inside the motor can reach up to 170°C what negatively affects the insulation of leads and windings and weakens the magnetic induction of the neodymium magnets. They have to be therefore assembled with a strong high-temperature adhesive. During the tests on the chassis dynamometer, the maximal temperature inside the motor has reached 150°C. This has been caused by very intensive tests with high dynamometer resistance. During normal road exploitation of the vehicle the temperature usually does not exceed 50°C. The distribution of the temperature on the motor housing has been registered by the thermal imaging camera FLIR and is shown in the Fig. 4.

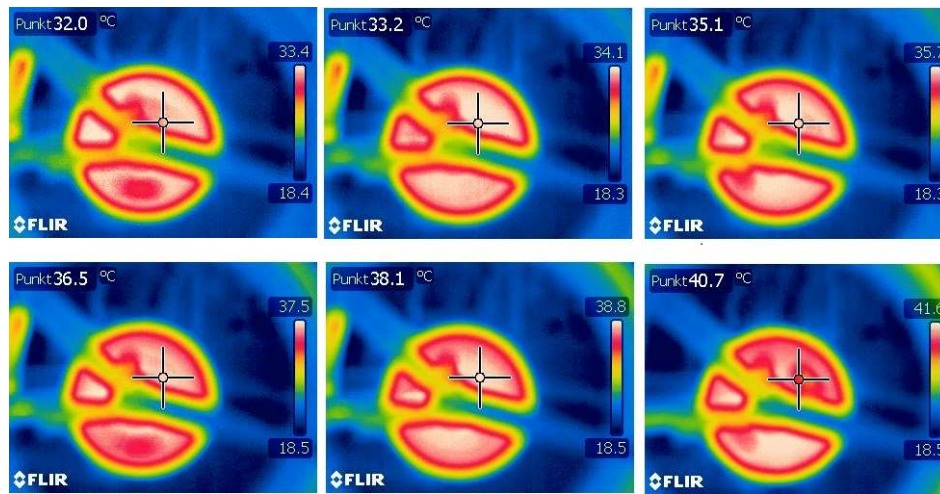


Fig. 4. Distribution of the temperature on the motor housing

3.3. Motor controller

The controller used in the project is the Sabvoton SVMC072080 from the Chinese manufacturer MQCON. It can control the BLDC motors as well as the PMSM motors (Permanent Magnet Synchronous Motors). Its characteristic has been presented in Table 3.

Table 3. Characteristics of the Sabvoton SVMC072080 controller

Parameter	Value
Power supply	36 V – 95 V
Nominal power	2500 W
Maximum power	7600 W
Maximum current	80 A
Maximum working temperature	50 °C
Weight	2.2 kg
Dimensions	243 x 146 x 62 mm
IP code	IP65

The controller enables speed and braking control by the lever based on the Hall sensor. It has also regenerative braking function which enables charging the battery during deceleration what increases an overall range of the vehicle. Furthermore, it is equipped with the extensive diagnostic system and the several protections such as: overcurrent, overload, too high temperature, too high or too low voltage or accidental handle lock. The photo of the Sabvoton controller is shown in the Fig. 5.



Fig. 5. Photo of the Sabvoton SVMC072080 controller without casing

The heart of the controller are the IRFB4410ZPbF transistors, 470 μ F 100V electrolytic capacitors and the TMS 320F28015PZA integrated circuit. Unfortunately, most of the elements do not have a catalog number or any description due to the manufacturer's protection against copying a given product. During the tests on the chassis dynamometer, the temperature of the controller did not exceed 30 °C.

4. Tests on the chassis dynamometer

The designed and constructed vehicle has been tested on the MAHA (Maschinenbau Haldenwang GmbH & Co. KG) LPS 3000 chassis dynamometer which is dedicated to investigate the power characteristics of cars, trucks and motorcycles. This dynamometer enables measurement of many parameters for predefined gasoline, gas and diesel engines. In addition, it can measure also the four-wheel drive vehicles. The traffic load simulation is realized by an eddy current brake.

The above mentioned chassis dynamometer with simple electrical measuring instruments have served to investigate the constructed E-bike parameters such as: mechanical power on the wheel, electric power of the motor, maximum torque, maximum speed, acceleration and energy consumption. The measured parameters have been gathered in Table 4.

Table 4. E-bike parameters measured on the MAHA chassis dynamometer

Parameter	Value
Maximum mechanical power	3.6 kW at 375 rpm (49.8 km/h)
Maximum electric power	6.37 kW at 375 rpm (49.8 km/h)
Maximum torque	132.2 Nm at 185 rpm (25.0 km/h)
Maximum speed achieved	79.04 km/h

Acceleration measurements have been carried out on the road conditions as the mass of the dynamometer measuring rollers and the lack of wind resistance could significantly perturb the results.

The weight of the E-bike has been equal to 78 kg and the driver has weighed 72 kg. The final results of the vehicle acceleration have been shown in Table 5.

Table 5. Acceleration results of the E-bike

Speed	Acceleration time
From 5 km/h to 30 km/h	2.1 sec.
From 5 km/h to 60 km/h	4.3 sec.
From 5 km/h to 78 km/h	6.9 sec.

4.1. Energy consumption of the E-bike

Energy consumption test of the built E-bike has been carried out on the MAHA dynamometer for three different speeds: 27.5 km/h, 40.5 km/h and 61.2 km/h. The speed has been maintained by programmable constraints applied in the Sabvoton controller. Then, the formula (1) has been used to calculate the energy consumption.

$$C = \frac{U \cdot I \cdot t / 3600}{s / 1000} \quad (1)$$

where:

C – energy consumption in [Wh/km],

U – motor voltage in [V],

I – motor current in [A],

t – time of drive in [s],

s – distance covered in [m].

The main problem with performing such a test in the laboratory condition is the lack of wind resistance but on the other hand too high minimal load produced by the dynamometer measuring rollers which are originally dedicated to the more heavy and powerful vehicles and therefore giving too much of resistance. The MAHA dynamometer has a lot of predefined parameters but for the internal combustion vehicle testing, where the parameters such as wind resistance and road conditions can be simulated automatically by the dynamometer. For the electric vehicle testing these different conditions may influence the results and will be investigated in further research by comparing the laboratory tests with the road condition tests.

Fig. 6 shows the laboratory test results for the energy consumption of the constructed electric vehicle in the above described conditions. Additionally, taking into account the bigger weight and wider tires of the studied construction they are comparable to those presented in [10] which have been obtained in the road conditions for lighter and less powerful construction. One has to take also into account that the drive's rated power influences not only vehicle's dynamics but also its energy efficiency [11].

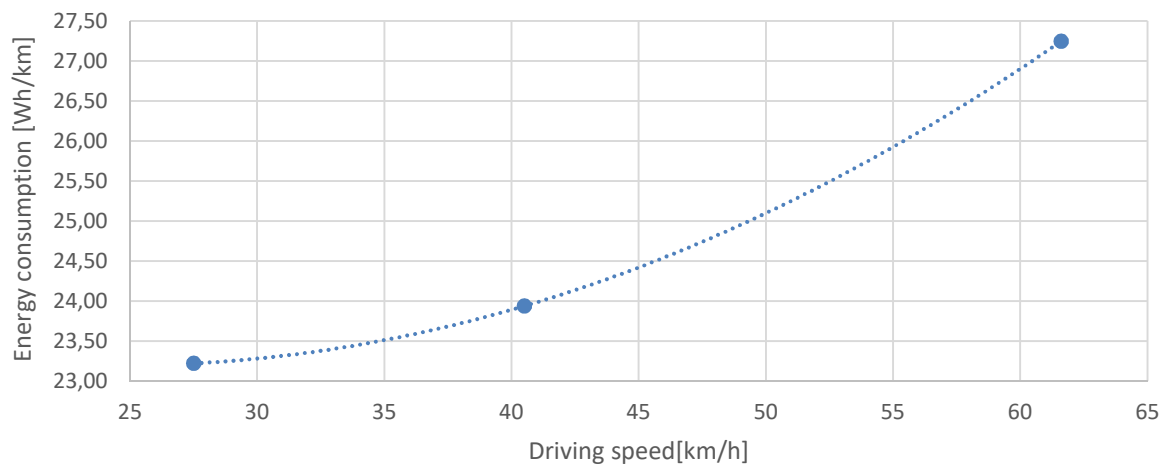


Fig. 6. Characteristic of the E-bike energy consumption

Taking into consideration the capacity of the designed battery pack which is equal to 27.5 Ah and the nominal voltage of the battery which is 72 V, the energy source can deliver up to 1.98 kWh of electric energy what enables to cover the very theoretical distance of about 85 km driving with the speed of 27.5 km/h and the distance of about 72 km driving with the speed of 61.2 km/h. Obtained results show that the higher but constant resistance of the measuring rollers does not compensate the nonlinear dependence of the wind resistance for higher speeds. Nevertheless, in everyday use in the road conditions and at variable speeds, the constructed vehicle is able to reach the average distance of about 70 km on one battery charge.

5. Conclusion

In the article the construction of the light two-wheeled electric vehicle has been presented and tested. The vehicle is powered by the brushless DC motor (BLDC) of 3 kW of nominal power which seems to be the best solution for this type of construction. The presented vehicle is based on a steel durable bicycle frame and has been additionally equipped with pedals as an alternative driving source which by the significant power of the electric motor do not contribute much to the driving dynamics. Nevertheless, according to the Polish law such a construction cannot be called an electric bicycle as its auxiliary driving source parameters considerably exceed the requirements for the electric bicycles described in the Act on Road Traffic of June 20, 1997.

The use of BLDC motor of 3 kW in such a construction makes the vehicle relatively fast and powerful as the motorcycle. During the laboratory tests performed on the MAHA chassis dynamometer the built E-bike has reached almost 80 km/h of maximum speed. The measured mechanical power and the torque on the wheel has been equal respectively to 3.6 kW and 132 Nm. The acceleration to 78 km/h is less than 7 seconds.

The last chapter of the article has been dedicated to the energy consumption of the presented vehicle. With the 27.5 Ah of battery capacity the E-bike can cover the average theoretical distance of about 80 km consuming about 25 Wh/km. The road tests confirmed the average distance of about 70 km on one battery charge. After all, if there were no legal aspects of driving such a vehicle it would be a very economic and pleasure giving means of transportation.

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