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MEASUREMENTS OF THE CHARACTERISTICS OF AN ELECTRIC MOTOR FOR AN ELECTRIC VEHICLE`S DRIVE

MERITVE KARAKTERISTIK ELEKTROMOTORJA ZA POGON ELEKTRIČNEGA VOZILA

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Keywords: electric vehicles, electric motor, brushless DC motor, solar-powered vehicle

Abstract

This paper aims to present the performance and measurement results of a load test performed on a brushless DC motor built into the wheel of a solar-powered vehicle. A brushless DC motor's theoretical background and operation are presented at the beginning of the paper. The article covers the technical specification of the solar-powered vehicle and the inbuilt brushless DC motor. The measurements were performed with the described equipment at the Institute of Energy Technology, Faculty of Energy Technology, University of Maribor. Due to the unique design of the measured electric motor, it was also necessary to make a special housing, which was intended for connecting the electric motor to the test bench. The article concludes with an analysis of the measurement results in comparison with the data provided by the electric motor manufacturer.

Povzetek

Cilj prispevka je predstaviti izvedbo in rezultate meritve obremenitvenega testa enosmernega brezkrtačnega motorja, ki je vgrajen v kolo solarnega vozila. V začetku prispevka je najprej predstavljeno

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teoretično ozadje zgradbe in delovanja enosmernega brezkrtačnega motorja. Prispevek zajema tehnične specifikacije solarnega vozila in vgrajenega električnega motorja. Meritve so bile opravljene s predstavljeno opremo na Inštitutu za energetiko, Fakultete za energetiko Univerze v Mariboru. Zaradi posebne izvedbe merjenega motorja je bilo potrebno izdelati tudi posebno ohišje, ki je namenjeno priklopu motorja na merilno mesto. V zaključku je podana tudi analiza rezultatov meritev v primerjavi s podatki, ki so bili podani s strani proizvajalca motorja.

1 INTRODUCTION

Electric vehicles are an old idea, which has become more and more popular in recent times, since they embody our green-oriented mentality. Their development started more than a century ago in France and England, which were the first countries that started developing electric propulsion systems. Since then, electric cars have gone through their ups and downs. They had some advantages over petrol cars, such as, they were quieter, did not spread a stench, they were not causing vibrations when functioning and there was no need to shift gears. However, in the 1920s electric vehicles lost their dominance over internal combustion engine vehicles. The main reasons were the construction of long roads between cities that required a longer reach of vehicles and the reduction of the oil price, which reduced the cost of the use of vehicles with internal combustion engines. [1-3]

Since then, electric vehicles have been used mainly for specific purposes, such as small transport vehicles with short-range, golf carts, etc. However, the oil crisis in the seventies has awakened the interest in electric vehicles, and environmental agencies instructed car manufacturers to invest in the development of vehicles with low emission levels. Therefore, the main objective was to develop electric vehicles with zero emissions. [1], [4]

The most significant breakthrough was the EV1 model produced by General Motors, which represented the only car that met all the objectives of the Office for Energy of the United States of America. It was offered to customers through a Lease Agreement between 1996 and 2002. Since then, many car companies have started developing different types of electric cars, namely, plug-in hybrids, extended-range electric vehicles, battery electric vehicles and solar-powered electric vehicles. [1], [4]

A solar-powered electric vehicle was also developed by high school students and their teachers in the Krško-Sevnica School Centre. This School Centre participates in custom-made solar-powered electric vehicle races actively and successfully. The Faculty of Energy Technology and Krško-Sevnica School Centre implemented a common project founded by the Student innovative projects for social benefit (ŠIPK) programme. The project's main goal was the measurement of the load characteristics of the electric brushless DC motor (BLDC), which will also be the main topic of this article. Based on the performed measurements, data were obtained on the performance characteristics of the BLDC motor, which will make it possible to optimise the performance of the solar-powered car further. In addition, the project described the theoretical foundations of electric motors, control of electric drives, and the legislation related to electric mobility, which will provide the students of Krško-Sevnica with materials to help them continue their work on the solar-powered car.

As already mentioned, this article will focus on the BLDC motor of the solar-powered car and the measurement of its load characteristics. The BLDC motor and the custom-made solar-powered vehicle will be described in Chapters 2 and 3. Chapter 4 will present the test site and measurement system, including the measurement devices at the Institute of Energy Technology in the Laboratory for Electric Machines and Drives. The load characteristic measurements and measurement results will be shown in the last Chapter.

2 ELECTRIC MOTOR

An electric motor is a device that converts electric energy into mechanical energy. They are divided into DC and AC motors in the most general aspect. This is a basic distribution, based on the supply voltage source fed to the electric motor. Other electric motors can be divided into subcategories. Under AC motors, we understand the terms induction and synchronous motors. The latter can be divided further into permanent magnet motors, stepper motors, reluctance motors, etc. Under the category DC motors there are roughly two main groups, namely, brushed and brushless DC motors. [5]

A rough distribution of the types of electric motors is shown in Figure 1.

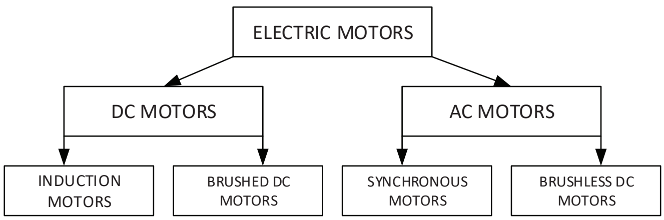


Figure 1: *Rough distribution of electric motors into categories*

2.1 Brushless DC motor (BLDC)

BLDC motors are used widely in electric vehicle drives as in-wheel motors. As the name suggests, in-wheel motors are built into the wheel of a vehicle, which improves the whole system's efficiency. Among the most important features of BLDC motors are low torque ripple, high efficiency, reliable operation and long life span. Due to the absence of brushes, there is no sparking during their operation, so they can also be used in hazardous areas. The positive properties of this type of electric motor can meet the needs of various applications. BLDC motors are used in robotics, household appliances, computer equipment and the automotive industry. [5], [6]

BLDC motors are similar to synchronous motors, with permanent magnets in their structure. However, their operation is similar to that of a brushed DC motor. From the basic version, they differ mainly in the magnetic field distribution. Due to its structure, this type of motor has a lower mass and moment of inertia, which, in practice, means better dynamics as a response to control signals. Compared to the brushed DC motor this type is better, even when it comes to efficiency, size and maintenance, as it does not need brushes for its operation. Brushes tend to wear down and require replacement for the motor to function properly. There are two basic versions of a BLDC motor. In the first, the stator is connected to the motor housing, and in the second, the motor housing is a rotor. We call the first version an "inrunner" and the second an "outrunner" motor. [5-8]

The stator core of a BLDC is made of steel, and is laminated to reduce the occurrence of eddy currents. Stators have different variations of stator winding grooves that can also be skewed. In addition to stators with grooves, there are also stator designs without grooves. We need a larger air gap between the rotor and the stator when using such stators. This, consequently, reduces the field of magnetic excitation of the permanent magnet. The problem can be solved by increasing the height of the permanent magnets, which also increases the motor's price. Such designs are used mainly when we need high speeds and performances. [5]

The rotor of BLDC motors is made of low carbon solid steel or of the same material as the stator. The magnets can be surface mounted on the rotor or located inside the rotor. Materials such as aluminium-nickel-cobalt, samarium-cobalt, and neodymium-iron-boron are used most commonly for magnets. Neodymium magnets currently allow the highest magnetic energies to be achieved, but have problems with temperature stability. Another downside is their price, which is also slightly higher compared to the price of ferrite magnets. [5], [7]

Instead of a commutator and brushes, BLDC motors use a controller or an electronic converter circuit connected to the stator winding. The electronic converter circuit detects the motor's position due to the built-in Hall sensors. Based on the rotor position information, it switches the current on and off through the appropriate windings on the stator. The rotational speed of the motor depends on the switching frequency of the switching device. Electronically commutating machines typically have three or more windings. [5], [8]

Figure 2 presents a simple cross-section view of a BLDC motor.

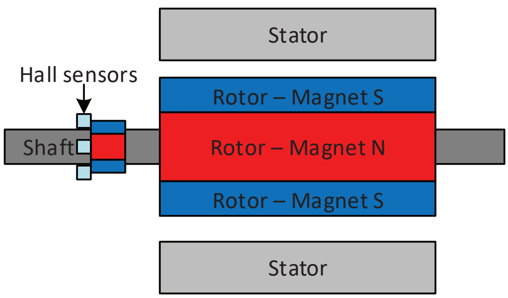


Figure 2: *A simple cross-section view of a BLDC motor*

3 ELECTRIC SOLAR-POWERED VEHICLE

The custom-made solar-powered vehicle shown in Figure 3 is a product of the students and teachers from the Krško-Sevnica School Centre. It was made with the goal to participate in a race of solar-powered electric vehicles in the city of Sisak. The vehicle was designed to meet all the required characteristics prescribed for the race. The project involved students of Mechanical and Electrical Engineering the high school, who constructed a solar-powered car with their mentors. When manufacturing, it was necessary to consider that the power of the motors should not exceed 1500 W, the minimum area of solar cells should be 3 m^2, and the mass of batteries should not be less than 80 kg. The vehicle must also be equipped with brakes on all wheels.

The technical data of the solar vehicle are given in Table 1.

Figure 3: *Custom made solar-powered electric vehicle*

Table 1: *Technical data of the solar-powered electric vehicle*

Length	2,85 m	
Width	1,75 m	
Height	1,4 m	
Total mass	260 kg	
Mass of batteries	84 kg	
Motor type	BLDC 1500 W / 48 V	
Solar modules	Type	PERLIGHT PLM-020M-36
	Module area	3,5 m^2
	Number of modules	20
	Current	1,13 A
	Voltage	17,3 V
	Power	20 W
Battery type	55 AGM 12 V / 70Ah	
Construction material	Aluminium	
Brakes	HYDRAULIC BRAKES	
Additional equipment	Speedometer and LED speed display Control and display of driving direction Battery voltage control Charging control Rear view camera Driving recording Display of controller, ambient and module temperatures	

All the wheels of the solar-powered electric vehicle have an in-built BDLC Hub Motor type QSMOTOR 205 V2 with a rated power of 1500 W and a rated voltage of 48 V. The considered motor is shown in Figure 4, and detailed motor specifications are given in Table 2.

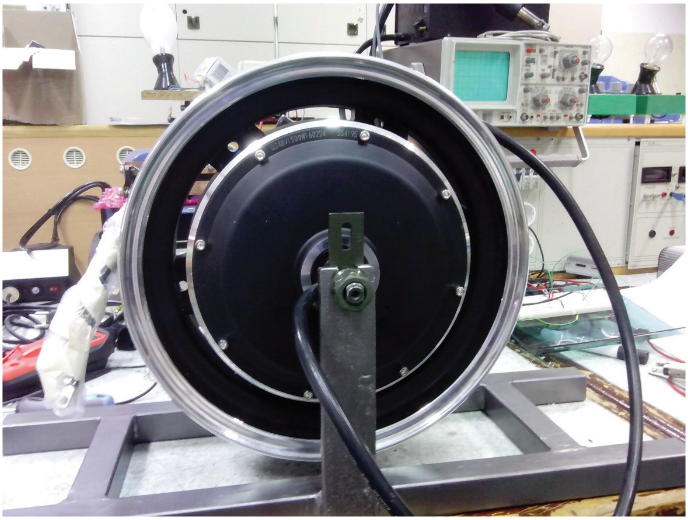


Figure 4: *BDLC Hub Motor type QSMOTOR 205 V2*

Table 2: *BDLC Hub Motor type QSMOTOR 205 V2 specifications*

Motor dimensions	**Motor diameter**	332 mm
	Wheel size	30,48 x 8,89 cm
	Wheel material	Aluminium
	Tyre	120/70-12, 90/90-12
Motor data	**Number of phases**	3
	Cable cross-section	8 mm^2
	Rated power	1500 W
	Max power	2000 W
	Rated voltage	48 V
	Rated current	31 A
	Max current	47 A
	Max torque	110 Nm
	Efficiency	89 %
	Rotational speed	400-690 rpm
	Top speed	55 km/h
	Protection level	IP54
	Max permitted temperature	70 °C
	Colour	Black

4 MEASUREMENTS

The measurements of the aforementioned motor were performed at the Institute of Energy Technology in Vrbina, Krško, in the Laboratory for Electrical Machines and Drives. The test site and the used measurement equipment will be described in the following subchapters. Also presented will be the motor mounting process and load test protocol .

4.1 Test site

In the Laboratory for Applied Electrical Engineering (LAE) and the Laboratory for Electrical Machines and Drives (LESP) at the Institute of Energy Technology, in addition to other activities, measurements of electrical machines are also performed as part of the research work. The basis for performing the measurements of electric motors are three test benches (Figure 5). All three test benches are 3D adjustable, and all have active brakes that are water-cooled. They also enable water cooling of the tested electric machine, if necessary. The largest of the benches also has a hydraulic lift with a capacity of up to 1000 kg, which allows movement and adjustment of the subjects of even larger dimensions or masses.

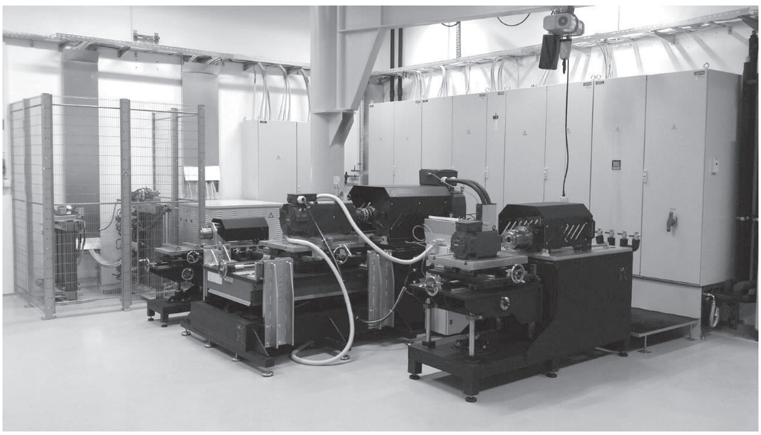


Figure 5: *Test site at the Institute of Energy Technology*

The measurements were performed on the middle-sized test bench, which allows measurements up to a power of 72 kW and a rotational speed of up to 15,000 rpm. The test bench enables the measurement of tested electrical machines with axial heights from 160 mm to 380 mm. An active brake is a synchronous machine with permanent magnets. This test bench was chosen mainly because of the appropriate axial height of the tested BLDC motor.

In order to connect the solar-powered vehicle drive to the active brake, it was necessary to construct a special mount due to the design of the measured BLDC motor. The construction of the attachment will be presented in the following subsection. The BLDC motor is connected to the active brake via a Lorenz DR-2643 speed and torque sensor (Figure 6), which enables speed measurements of up to 15,000 rpm and torque measurements of up to 100 Nm. The measured motor and active brake must be centred precisely to avoid unnecessary vibrations transmitted to the speed and torque sensor, and thus affect the measurement accuracy. A Prüftechnik Optalign Smart Ex centring device (Figure 7), which enables laser position adjustment, was used to align the subject under test and the active brake accurately.

Figure 6: *Lorenz DR-2643 speed and torque sensor*

Figure 7: *Prüftechnik Optalign Smart Ex cantring device*

The measured mechanical and electrical quantities were captured with a Yokogawa WT 1806 (Figure 8) power analyser, which is a reliable, high-performance analyser. It has the option to measure electrical quantities on six input channels, and ensures a measurement accuracy of 0,05 %. The power analyser was connected to a computer via the WT Viewer measurement program. The program is intended for managing power analyser settings, and capturing and analysing all measured data from the analyser. The program also allows data to be stored in .dat format, so the measured data were analysed in the Matlab software environment. [9]

Figure 8: *Power analyser Yokogawa WT1806*

A SCADA system (Figure 9), which was used for control of the power supply of the tested machine, cooling, operation of the external power plant, and active brakes, was used to control the active brake. When controlling individual test benches, it also allows us to set the speed and torque limit to prevent damage to the measurement equipment or electric motors in case of human error.

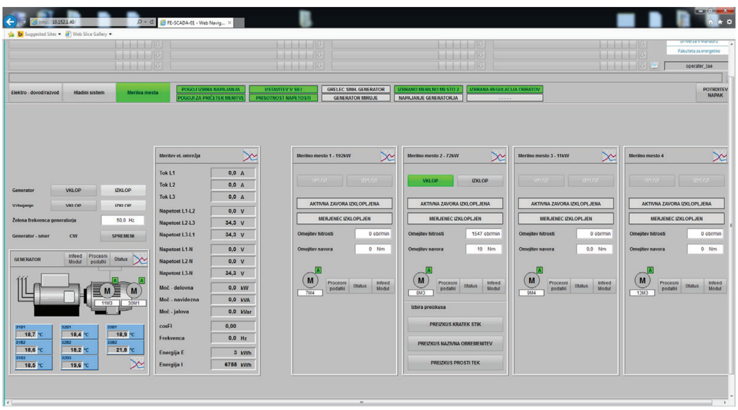


Figure 9: *SCADA system*

4.2 Electric motor mounting

The test benches in LAE and LESP are intended for testing of standard electric motor designs. In this case, the measurements had to be performed on a BLDC motor built into the wheel of a solar-powered vehicle. For this reason, it was necessary to make a housing to mount the electric motor which clamps to the test bench and keeps the electric motor in balance and prevents rotational movement of the wheel. It was also necessary to construct a part supported by bearings, which was intended to be connected to the shaft of the active brake. 3D models of individual components of the BLDC motor mount, drawn with the software package SolidWorks, are presented below.

The mount is made from one piece. There are two holes in the housing; the smaller hole is intended for rigid mounting of the electric motor, and the bearing part will be supported on the larger one. There is also a circlip in the larger hole to prevent axial movement. Figures 10 and Figure 11 show the isometric view and cross-section of the motor mount model.

The bearing part, which rotates together with the electric motor, is intended for connection to the active brake shaft. It is attached to the electric motor using three screws. The cross-section also shows the indentation in which the shaft of the electric motor is installed. There is also a dowel groove on the shaft to prevent the clutch from slipping. Figures 12 and 13 show the isometric view and cross-section of the bearing model.

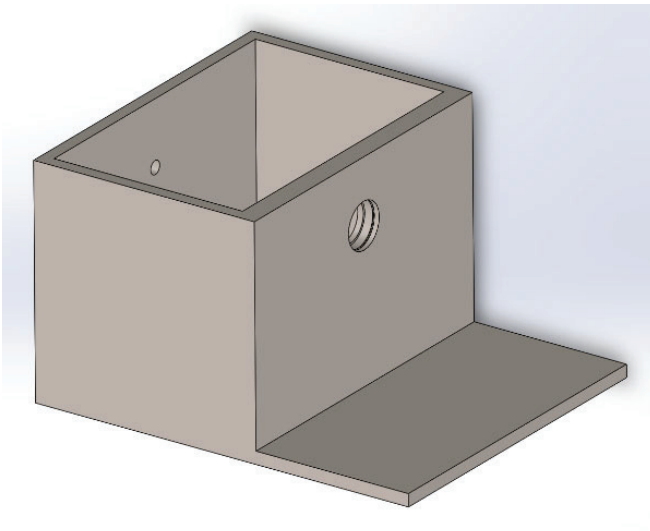


Figure 10: *Isometric view of the motor mount model*

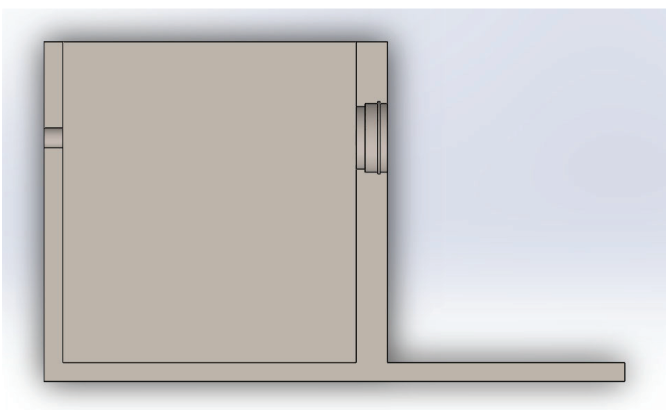


Figure 11: *Cross-section of the motor mount model*

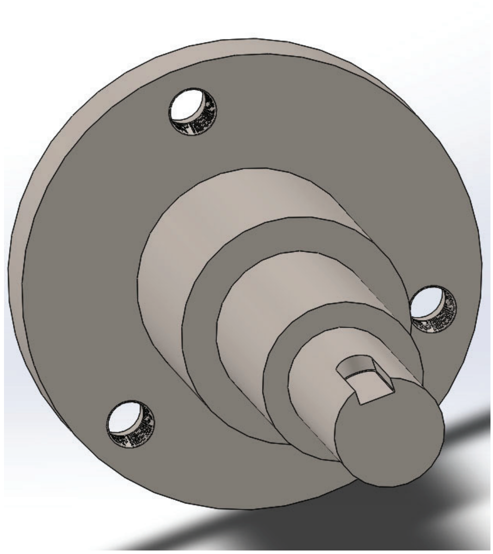


Figure 12: *Isometric view of the bearing part*

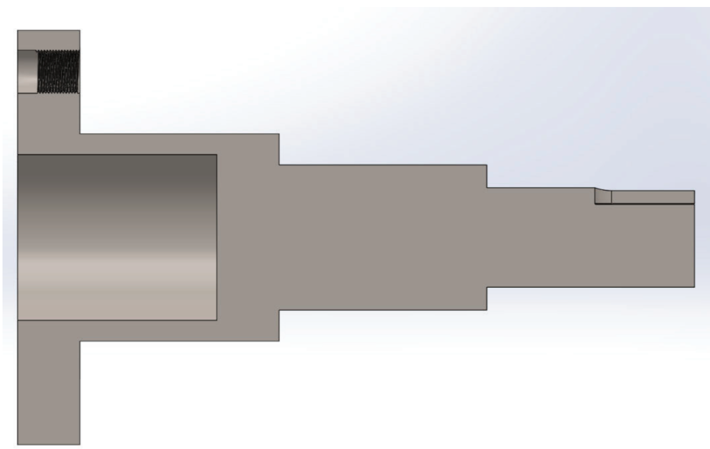


Figure 13: *Cross-section of the bearing part*

Figure 14 shows the common assembly of the constructed motor mount and the tested BLDC motor.

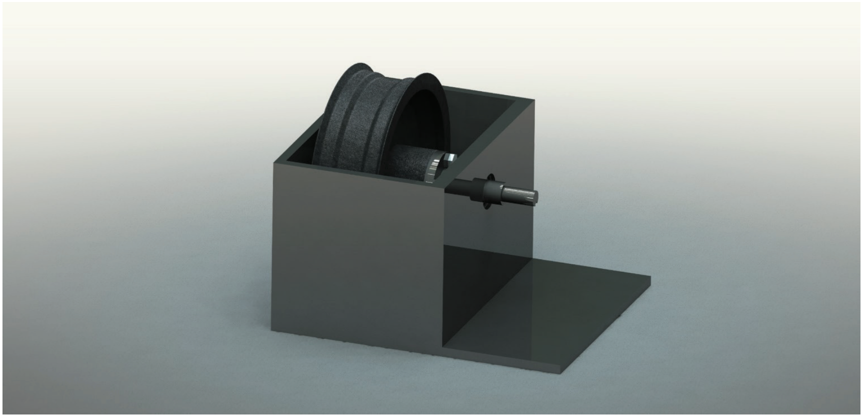


Figure 14: *Assembly of the motor mount and BLDC motor*

4.3 Load test measurement

The load measurement of the tested BLDC motor is performed by supplying the motor with a nominal voltage of 48 V via the controller and starting to load it. The BLDC motor is loaded by increasing the torque of the active brake, which acts as a load on the measured motor. The active brake is controlled via the SCADA system. All electrical quantities were measured with the Yokogawa WT1806 power analyser, and mechanical quantities were measured with a Lorenz DR-2643 torque and speed sensor. All the measured quantities were captured with the Yokogawa WT1806 and transferred to a PC for further processing.

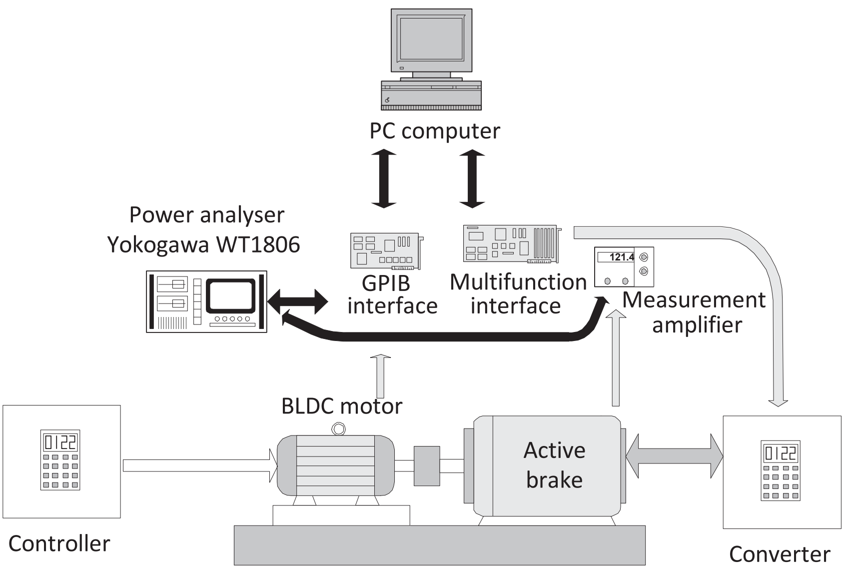
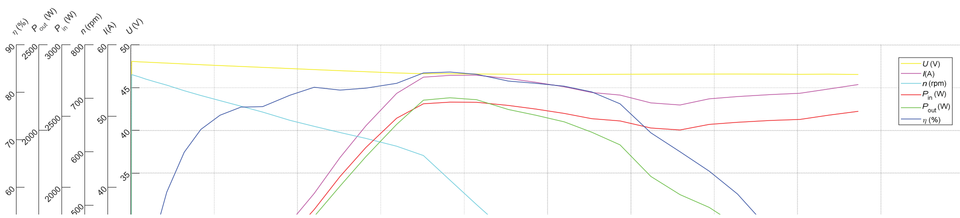


Figure 15: *Schematic of the test site at the Institute of Energy Technology*

5 RESULTS

The torque was increased incrementally during the measurement. As the torque (*M*) increased, the electric current (*I*) also began to increase, and the rotational speed (*n*) began to decrease, as can be seen from the plotted graph in Figure 16. Electric voltage (*U*) was constant throughout the measurement and had a value of 48 V. From the chart in Figure 15, we can see that, as the electric current increases the input electric power (P_{in}) also increases, and the losses in the windings also increase, growing with the square of the current. When the torque is below approximately 35 Nm, it can be seen that, despite the decrease in rotational speed, the mechanical power increases, which, later, begins to decrease when the rotational speed drops sharply. Finally, the efficiency curve reaches a maximum value at 84,3%.

The data obtained with the load measurements were compared with the data provided by the manufacturer of the BLDC motor. During the comparison, quite a few discrepancies were noted between the measured and manufacturer`s data. The manufacturer states a maximum torque of 110 Nm, which we did not meet with the measured values. At 87 Nm, the measurement was finished, as the maximum current specified by the manufacturer had already been exceeded by 10 A.



Nomenclature

(Symbols)	(Symbol meaning)
A	the area of the outer envelope of a building
a_H	dimensionless parameter
A_u	usable area of building
A_{window}	window area
B_h	direct solar irradiation on horizontal surface
d	layer thickness of the building structure
D_h	diffuse solar irradiation on horizontal surface
d_w	the number of days of hot water supply in a given period
E_{HP}	required electricity for the operation of the heat pump
F_c	blinds factor
F_f	frame factor

measured efficiency was 84,3 %. Thus, the maximum mechanical power given by the manufacturer (2000 W) was exceeded. Still, the efficiency given by the manufacturer (89 %) was not reached. The rotational speed was in the range specified by the manufacturer. The most significant deviation is shown in the electric current value, as it can be seen that the measured values greatly exceeded the nominal value of the electric current.

Table 3: *Measurement results and manufacturer's data*

	Measured values at nominal output power	Measured values at maximum efficiency	Manufacturer`s data
Torque *M* [Nm]	22	38,3	/
Voltage *U* [V]	47,12	46,63	48
Current *I* [A]	39,14	55,72	31
Rotational speed *n* [rpm]	647,5	546,6	400 – 690
Electric power P_{in} [W]	1844	2598	/
Mechanical power P_{out} [W]	1496	2191	1500
Efficiency [%]	81,1	84,3	89

6 CONCLUSION

Due to their properties, BLDC motors are used most commonly in applications for electric vehicles. The custom-made solar-powered vehicle also has the aforementioned type of electric motor, which is built into the wheel of the vehicle. Because of the in-wheel build of the BLDC motor, a special housing was made for the purpose of mounting the electric motor to the test bench. It was necessary that the housing kept the electric motor in balance and prevented the wheel's rotational movement.

The load measurement of the tested BLDC motor was performed by supplying the motor with a nominal voltage of 48 V, and the torque was increased incrementally during the measurement. The aim was to compare the results of the measurements with the data provided by the manufacturer of the BLDC motor. The comparison indicated quite a few differences between the two sets of data. More measurements would be needed for a more accurate analysis of the results and the given technical specifications of the BLDC motor. Nevertheless, the obtained data on the performance characteristics of the electric motor were helpful for optimising the performance of the solar-powered vehicle.

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Nomenclature

(Symbols)	(Symbol meaning)
A	ampere
Ah	ampere-hour
AC	alternating current
BLDC motor	brushless direct current motor
cm	centimetre
°C	degrees Celsius
DC	direct current
I	electric current
kg	kilogram

km/h	kilometres per hour
kW	kilowatt
m	metre
m²	square metre
mm	millimetre
mm²	square millimetre
M	torque
Nm	newton metre
n	rotational speed
P_{in}	input electric power
P_{out}	output mechanical power
rpm	revolutions per minute
U	voltage
V	volt
W	watt