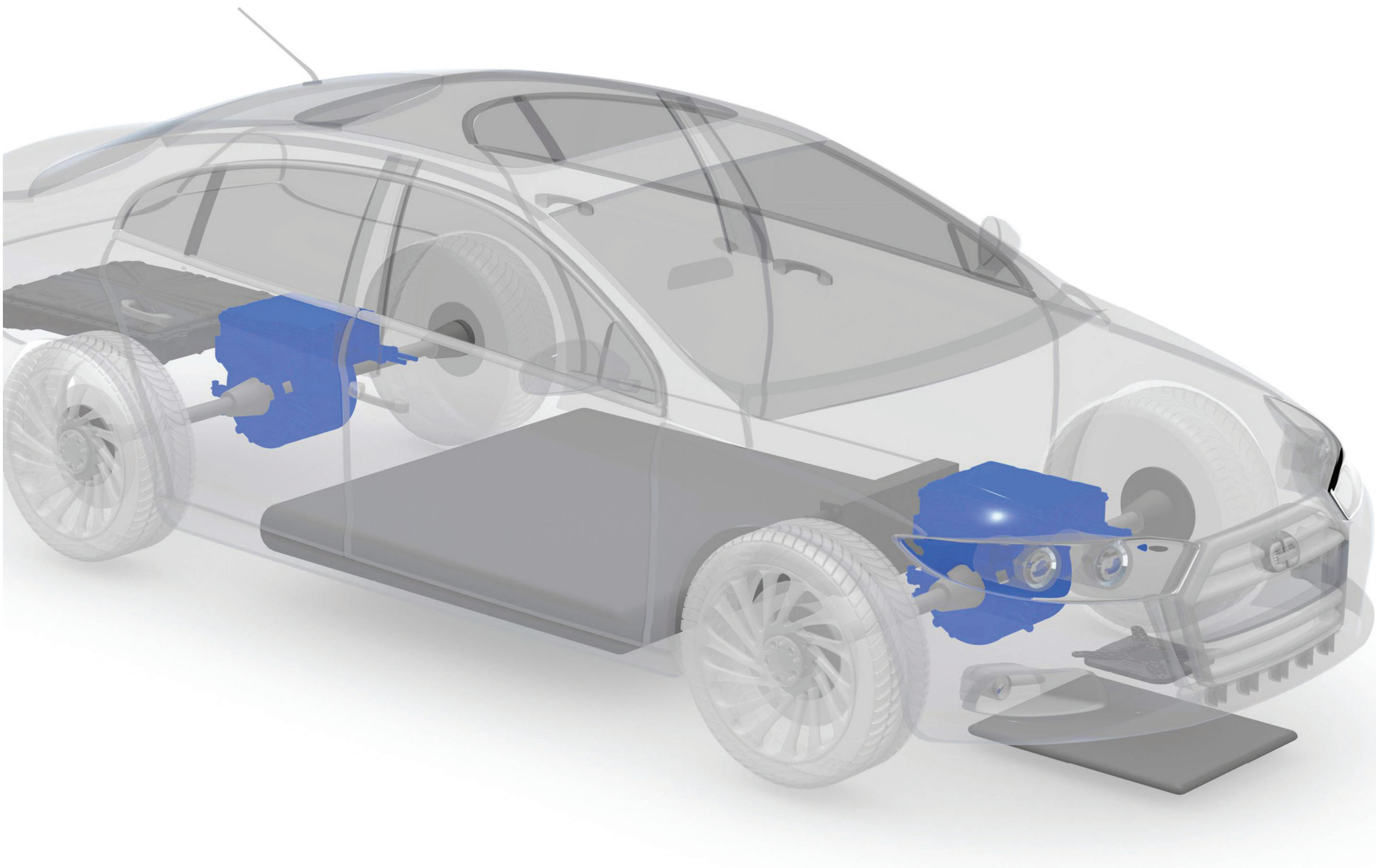
ELECTRIC POWER PACKAGE WITH HIGH EFFICIENCY

Electric cars no longer have to shy away from comparisons with petrol and diesel vehicles. Nevertheless, work continues on electric motors to make them more compact and more efficient. BRUSA Elektronik AG (Sennwald/SG) has now achieved further progress in a project supported by the Swiss Federal Office for Energy: an electric motor with a continuous power density that was unknown until now. If the engineers' ambitious goals become reality, the motor for particularly powerful electric vehicles could be mass-produced in a few years.



BRUSA Elektronik AG is a specialist for high-performance electric drives. Illustration: BRUSA

A technical report about the results of a research project in the field of mobility, which was financially supported by the Swiss Federal Office of Energy. The report has been published in the Handelszeitung (issue of December 6th 2018).

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Electric cars are fast on the move today: a Renault Zoe is moves with a continuous output of 43 kW. In a BMWi3, the continuous output is 75 kw—the peak output 125 kW. The 2017 version of the eGolf has also been upgraded and now has a peak output of 100 kW. In commercial vehicles that rely on electric drives, the engines are all the more powerful: the electric truck developed in Switzerland with the name E-Force-One is driven by two electric motors with a (peak) output of 150 kW each. These figures make it clear that electric vehicles can easily compete with gasoline and diesel vehicles in terms of performance and are far superior to them in terms of efficiency.

Inside the E-Force-One, the eGolf and the BMWi3 is Swiss know-how: BRUSA Elektronik AG was involved in the development of the respective electric motors. Josef Brusa founded the company in 1985 in Sennwald in the St. Gallen Rhine Valley to manufacture components for solar and electric vehicles. Today the company has 200 employees. Car manufacturers like to revert back to the company's expertise in electric motors. Be it motor design, DC converters or contactless charging stations - the know-how of this development service provider, which is little known to the general public, is in demand throughout Europe.

The BRUSA development engineers Daniel Oeschger (left) and Marko Cvorak. Photo: B. Vogel

High Performance with Low Weight

It is hard not to miss company headquarters on the main street of Sennwald. The journalist is given a friendly welcome at the reception desk. However, the doors to the development laboratories remain closed to the visitor. "For reasons of patent protection, we would rather not show the details," says Daniel Oeschger when he greeted the journalist. Oe-

FORMED-LITZ-WIRE TECHNOLOGY

Strands - electrical conductors made of thin, twisted copper wires - are widely used in electrical engineering because they are more flexible than single copper wires and have a large diameter. BRUSA uses strands to build electric motors. These are so-called high-frequency strands (see photo 04). In these strands, the thin individual wires are insulated from each other by a layer of varnish. This 'trick' achieves the so-called skin effect and thus the (heat) loss at high speeds can be reduced.

There is a lot of know-how in the manufacture of high-frequency strands. The high-frequency strands used by BRUSA for the manufacture of electric motors are pressed together by a special roller so that the individual wires have a hexagonal cross-section (see photo 06). The result is a compact strand with a high fill factor that produces a particularly strong magnetic force field. Because of the mechanical deformation caused by pressing, the high-frequency strands are referred to as 'shaped strands.' These shaped strands are then used to produce winding coils for very efficient electric motors. Depending on the type of coil winding, a distinction is made between pull-in winding and formed litz wires .

Instead of formed litz wires, copper wires can also be used for the production of coil windings as long as they are not composed of thin individual wires. Such windings are called 'hairpin.' Hairpin windings are very common. They are used for example in the electric motors of Toyota Prius or Opel Ampera. BV schger is a trained automotive engineer and, as deputy manager, supervised a project in which his company developed a particularly powerful electric motor between 2015 and 2018.

The aim was to achieve a high continuous power density, i.e. high engine output with the lowest possible motor weight. Motors with high power density are crucial for the success of

HSM1-10.18.11-FLW-C01, 400V, 450A

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	90.6	93.1	95.2	95.3	95.4	95.6	95.5	95.4	95.4	95.2	95.1	94.9	94.7	94.5	94.2	94.0	93.8	93.5	93.2	92.9	92.6	92.3	92.0	91.7	91.3	90.9	90.7
4000	90.8	94.0	95.0	95.6	95.9	95.9	96.0	96.1	96.2	96.2	96.2	96.1	96.0	95.9	95.8	95.7	95.5	95.4	95.3	95.0	94.9	94.7	94.5	94.4	94.1	93.9	93.8
6000	89.7	93.3	94.8	95.3	95.5	95.8	96.0	96.1	96.3	96.3	96.3	96.3	96.3	96.3	96.2	96.1	96.0	95.9	95.7	95.4	94.9	94.5	94.4				
8000	88.7	92.8	94.2	94.9	95.5	95.8	96.0	96.3	96.3	96.2	96.1	96.0	95.8	95.3	94.8												
10000	87.9	92.3	94.0	94.8	95.2	95.6	95.6	95.7	95.5	95.0	94.2																
12000	84.7	91.3	93.4	93.7	94.9	94.3	94.7	94.0	93.6																		

HSM1-10.18.11-FLK-B01, 400V, 450A

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	86.4	92.2	93.8	94.3	94.3	94.6	94.4	94.5	94.2	94.2	94.0	93.6	93.4	93.2	92.8	92.5	92.1	91.7	91.5	91.1	90.9	90.7	90.5	90.2	89.8	89.3	89.1
4000	87.3	91.4	93.0	93.7	94.2	94.7	94.7	94.9	95.0	95.0	94.9	94.9	94.8	94.7	94.6	94.4	94.3	94.1	94.0	93.8	93.7	93.6	93.5	93.4	93.1	92.9	92.8
6000	85.0	90.3	92.2	93.2	93.8	94.2	94.5	94.8	95.1	95.4	95.4	95.5	95.5	95.4	95.4	95.3	95.1	94.9	94.5	93.9							
8000	82.7	88.6	91.3	92.6	93.8	94.2	94.4	94.7	94.7	94.7	94.6	94.3	93.7	93.1	93.2	93.1											
10000	81.1	88.9	91.4	92.7	93.3	93.4	93.5	93.6	93.3	92.1	92.1	91.9	92.0														
12000	81.4	87.0	90.2	91.1	91.5	92.4	91.7	89.0	89.3	91.1																	

HSM1-10.18.11-A01, 352V, 450A

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	87.0	92.0	95.0	95.5	95.4	95.5	95.4	94.8	94.8	94.8	94.2	94.6	94.4	94.2	93.6	93.4	93.0	92.8	92.7	92.5	92.0	91.5	91.3	90.9	90.5	90.1	89.6
4000	85.8	91.7	93.3	94.4	94.9	95.1	95.4	95.6	95.5	95.6	95.5	95.5	95.5	95.4	95.2	95.1	95.0	95.1	94.6	94.5	94.2	94.1	93.8	93.6	93.3	93.1	92.8
6000	86.9	91.6	93.3	94.2	94.9	95.3	95.4	95.6	95.6	95.6	95.5	95.4	95.3	95.1	94.6	94.4	93.8	93.1									
8000	86.0	91.0	91.5	93.0	93.8	94.3	94.1	94.1	94.1	93.8	93.2	92.5															
10000	84.7	90.1	91.8	92.0	92.7	92.7	92.2	91.7																			
12000	81.5	89.2	89.4	90.9	91.1	90.5																					

Efficiency as a function of revolution speed and load point for the electric motor with plug-in winding (latest version/top or earlier version/middle) and the electric motor with pull-in winding (bottom). The table shows that the new motor achieves very good values of 96 and more percent in the partial load range of a vehicle weighing 3.5 to 7.5 t (70-120 Nm at 4000-8000 rpm).

Differenz (FLK-EZW)

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	-0.60	0.14	-1.23	-1.19	-1.07	-0.92	-1.02	-0.34	-0.51	-0.59	-0.25	-0.98	-0.99	-1.06	-0.80	-0.90	-0.95	-1.11	-1.20	-1.35	-1.03	-0.79	-0.81	-0.78	-0.77	-0.75	-0.46
4000	1.55	-0.33	-0.30	-0.67	-0.73	-0.40	-0.71	-0.70	-0.51	-0.59	-0.61	-0.68	-0.66	-0.67	-0.63	-0.68	-0.72	-0.93	-0.66	-0.65	-0.50	-0.47	-0.33	-0.22	-0.21	-0.15	0.05
6000	-1.94	-1.24	-1.07	-1.02	-1.08	-1.08	-0.87	-0.81	-0.43	-0.25	-0.10	0.02	0.17	0.33	0.74	0.85	1.25	1.81									
8000	-3.27	-2.39	-0.23	-0.42	-0.05	-0.08	0.25	0.63	0.59	0.95	1.41	1.80															
10000	-3.61	-1.15	-0.46	0.73	0.57	0.69	1.30	1.92																			
12000	-0.12	-2.12	0.75	0.23	0.38	1.87																					
Mittelwert	-0.4																										

Differenz (FLW-EZW)

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	3.63	1.08	0.22	-0.25	0.02	0.07	0.01	0.61	0.60	0.38	0.85	0.25	0.29	0.24	0.62	0.66	0.72	0.67	0.51	0.41	0.63	0.78	0.69	0.75	0.76	0.84	1.08
4000	4.98	2.27	1.71	1.21	0.98	0.77	0.59	0.51	0.65	0.61	0.61	0.53	0.58	0.54	0.56	0.59	0.53	0.32	0.62	0.57	0.67	0.67	0.73	0.78	0.80	0.83	1.02
6000	2.82	1.75	1.46	1.07	0.66	0.53	0.66	0.53	0.71	0.70	0.77	0.87	0.99	1.18	1.61	1.71	2.17	2.87									
8000	2.74	1.77	2.71	1.91	1.71	1.54	1.84	2.14	2.18	2.45	2.94	3.53															
10000	3.23	2.20	2.13	2.77	2.48	2.90	3.43	3.99																			
12000	3.19	2.12	4.00	2.82	3.82	3.77																					
Mittelwert	1.38																										

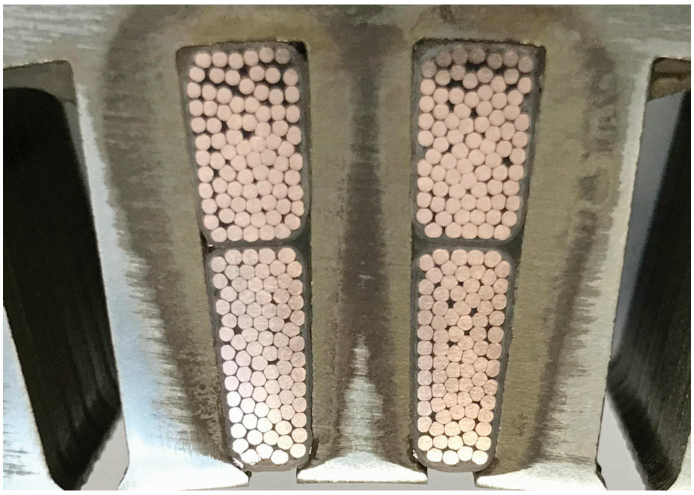
Differenz (FLW-FLK)

Q1 – Torque [Nm]; speed [rpm]

0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270
2000	4.23	0.95	1.45	0.94	1.09	0.99	1.03	0.95	1.11	0.96	1.10	1.23	1.29	1.30	1.42	1.56	1.67	1.78	1.71	1.76	1.66	1.57	1.50	1.52	1.53	1.58	1.54
4000	3.43	2.60	2.01	1.88	1.71	1.17	1.30	1.21	1.17	1.21	1.23	1.21	1.24	1.21	1.18	1.26	1.24	1.25	1.28	1.22	1.17	1.14	1.06	0.99	1.02	0.98	0.97
6000	4.75	2.99	2.53	2.09	1.73	1.60	1.53	1.34	1.14	0.95	0.88	0.84	0.83	0.86	0.87	0.86	0.93	1.06	1.23	1.52							
8000	6.01	4.15	2.93	2.33	1.75	1.62	1.58	1.51	1.59	1.51	1.54	1.73	2.09	2.17	1.66												
10000	6.84	3.35	2.59	2.04	1.91	2.21	2.14	2.07	2.13	2.94	2.15																
12000	3.30	4.24	3.25	2.59	3.43	1.90	2.97	4.94	4.30																		
Mittelwert	1.86																										

The three tables show the improvements in efficiency. Above: Electric motor with plug-in winding (older version) compared to electric motor with pull-in winding. Middle: Electric motor with plug-in winding (new version) compared to the electric motor with insert winding. Below: Electric motor with plug-in winding (new version) compared to the electric motor with pull-in winding (older version).

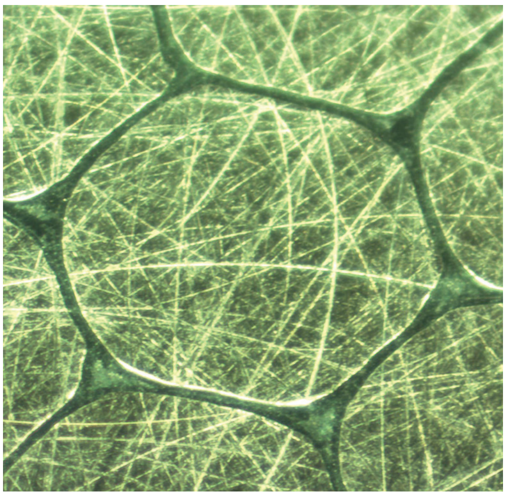

Earlier generation of a shaped strand coil-winding installed in the stator of an electric motor (photos: two different grooves of the same stator in cross-section). The winding is realized as a pull in winding and achieves a fill factor of approx. 40%. Photo: BRUSA



Modern shaped strand coil winding for the stator of an electric motor, designed as a plug-in winding. The winding is extremely compact and thus achieves a high fill factor of 56%. Photo: BRUSA

electric mobility. The lighter a motor is, the less energy required to accelerate the vehicle. Ideally, lighter motors not only enable space saving designs, but are also cheaper to build.

In the conference room Daniel Oeschger reports on progress over the past decades. “The engines have made a leap forward in power density,” says the developer. He refers to the 114 kW electric motor developed in the above-mentioned project (30-minute continuous output according to the ECE R85 measurement standard). The motor is designed to drive a small truck attached to a trailer with a total weight of 6.5 t. Today this engine weighs only 41 kg, it achieves 2.5 kW per kilogram of its own weight—this is five times more than was possible 30 years ago.

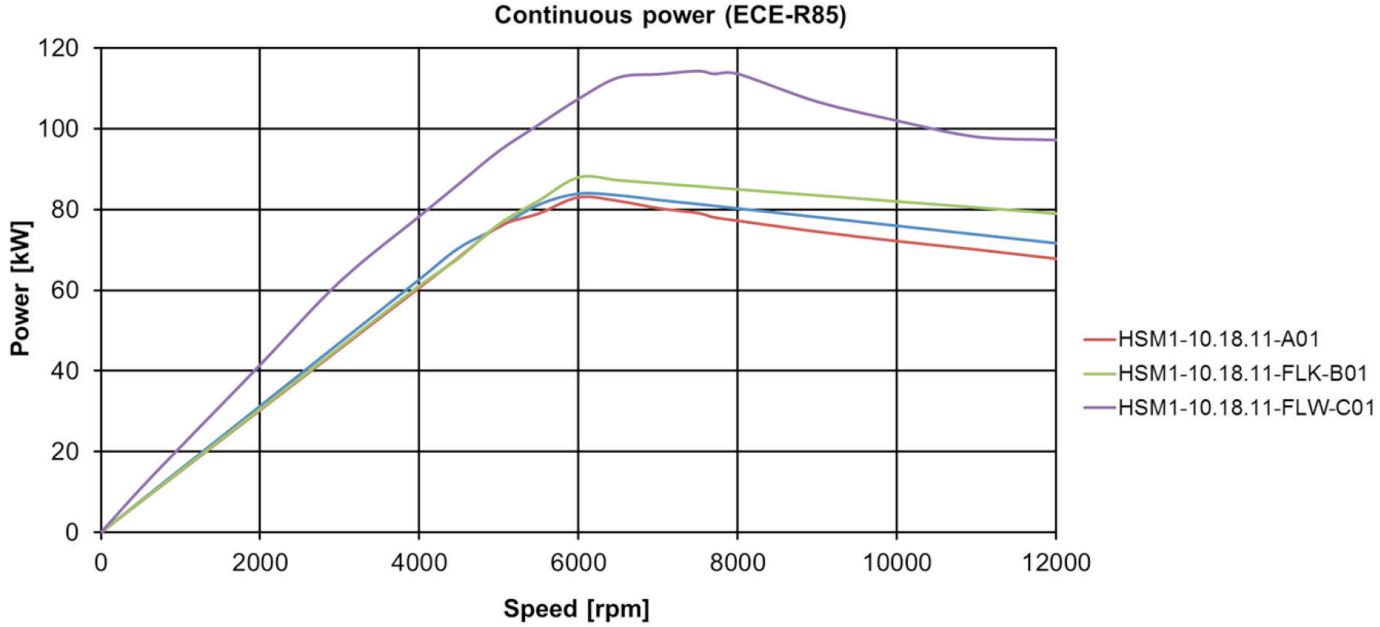


The microscopic image shows the cross-section of a single strand of a stator winding: The strand takes on a hexagonal shape because of mechanical shaping. Photo: BRUSA

Continuous output improved by 20%

In the most recent project, Oeschger and his development colleagues were able to increase the continuous torque and thus the continuous output of an electric motor (with almost no change in weight) by around 20% (see Figure p.5). Remarkably, this performance increase can be observed over the entire speed range. In everyday life, engines are only rarely fully stressed, which is why it is crucial to assess how an engine behaves in the partial load range. This behavior can be described by the efficiency with which the motor converts the supplied electrical energy into mechanical power (measured at the shaft). In the typical partial load range of a vehicle weighing 3.5 to 7.5 t (70-120 Nm at 4,000-8,000 rpm), the innovative motor achieves very good efficiencies of 96% and more (Figure 02). The improvement in efficiency at high revolutions is particularly high at 2% and more (Graph 03).

The example of a commercial vehicle travelling at high speed (10,000 rpm) is intended to illustrate the efficiency gains achieved: With the former electric motor (pull-in winding), the vehicle was running at a torque of 70 Nm with an efficiency of 92.2%, with the new electric motor (formed litz wires) it is now 95.6%. This improvement is significant, as Oeschger points out: “Commercial vehicles travel almost exclusively on the motorway, which means that start-up losses can be almost neglected. In this case battery size can be reduced by more than 3.4%, if one takes into account that the efficiency is also better in recuperation.” Oeschger illustrates the advantage with the example of a battery with 100 kWh storage



The new electric motor with plug-in winding (violet) has around 20% more continuous power (and this over the entire speed range) than existing electric motors (green: older version of the plug-in winding; red: insert winding; blue: similar motor without plug-in winding). The new electric motor achieves the highest continuous output (114 kW or 155 PS) at 7500 rpm. The continuous output according to the ECE-R85 measurement standard is the 30-minute continuous output normally used for evaluating motors in the automotive sector. Graphic: Final project report 2018

capacity that weighs 600kg and costs 100 francs/kWh. In this case, a 3% improvement in efficiency already corresponds to a cost advantage of 3 kWh times CHF 100/kWh, or CHF 300. "This is about half the price of a large-scale production engine of this kind and the battery is also about 20 kg lighter," says Oeschger.

High efficiency with shaped strand technology

To understand how development engineers have improved power density, it is necessary to remember the design of electric motors: A stator containing a rotor with each consisting of coils of electrical conductors (copper wires insulated from each other) that generate magnetic fields under current and produce kinetic drive energy. The following applies: The more compact the copper coil winding, the stronger the generated magnetic field. On this point, thanks to several years of development work, the engineers have achieved the latest step forward: By implementing the stator winding as a ' formed litz wires' using modern shaped strand technology called Formlitzen (see Textbox p.2), they achieved a particularly compact coil winding, which - as the technicians put it - has a high fill factor and thus generates a particularly strong magnetic field. The new plug-in winding (see graph 05) is not only more compact than that previously used in pull in winding (see graph 07) or windings based on hairpin wires, it also improves the thermal conductivity between the copper winding and the iron core on which it is applied. This reduces (heat) losses and additionally increases efficiency. Thanks to magnetic optimizations, the heat losses in the rotor are now so low that active cooling of the rotor is no longer necessary, although the continuous output has increased significantly. Active rotor cooling always leads to additional losses, which is why these should be avoided if possible.

The motor with plug-in winding is a prototype. If such motors are to be produced in series, suitable processes are required for the industrial production of formed litz wires. "Our prototype has a unique power density thanks to the formed litz wires. BRUSA has set itself the goal of industrializing the associated Formlitzen technology and mass-producing the powerful electric motors together with a partner from the manufacturing plant engineering sector," says Dr. Holger Fink, CTO at BRUSA. This is a big step for the company from the St. Gallen Rhine Valley, because until now it has limited itself to prototype applications and small series production. And it is demanding for the partners, because they first have to design the production machines for the formed litz wires. “Our goal,” says Holger Fink, “is to be on the market in five years with an industrialized product that will then be available for applications with particularly high performance requirements.”

- Further **information** on the project can be obtained from Martin Pulfer (martin.pulfer[at]bfe.admin.ch), head of the SFOE research program “Mobility.”

- Further **technical articles** on research, pilot, demonstration and flagship projects in the field of mobility can be found at www.bfe.admin.ch/CT/verkehr.

A POWERFUL ELECTRIC MOTOR - ADAPTED FOR A WIND POWER PLANT

An electric motor converts electric current into kinetic energy. An electric motor - equipped with a suitable converter - can be transformed with little effort into a generator that produces electric current from kinetic energy. Against this background, it is not surprising that BRUSA’s expertise was in demand on a Swiss project on wind power generation: In this project, Urs Giger, an engineer and wind power enthusiast from Aargau, designed a wind turbine (‘Altanus’) that does not produce electricity with one large generator but with twelve small generators and that has a high degree of efficiency in partial load operation. The idea behind the approach: when using a large number of generators, each generator has less weight; it can be replaced more easily (without a crane). This could reduce maintenance costs, especially in locations that are difficult to access. It would also be possible to continue operating the wind turbine in the event of a generator failure.

“Within the scope of this project, compact and powerful generators with a continuous output of 140 kW were required,” reports Marko Cvorak, who was one of BRUSA’s supervisors of the research project supported by the BFE at the FHNW University of Applied Sciences and Arts Northwestern Switzerland. In order to provide the desired performance, he and his colleagues proposed an extended (and thus somewhat heavier) generator at the time. With today’s knowledge, it would be possible to build a short motor with Formlitzen technology, says Cvorak. So the generator would be lighter and cheaper. However, BRUSA does not want to venture into this business segment, as Cvorak emphasizes: “ Due to our workload, our focus is currently on optimizing applications for the automotive industry.” BV

- Final report of the research project available at: www.aramis.admin.ch/Grunddaten/?ProjectID=36954

Author: Dr. Benedikt Vogel, on behalf of the Swiss Federal Office of Energy (SFOE)
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