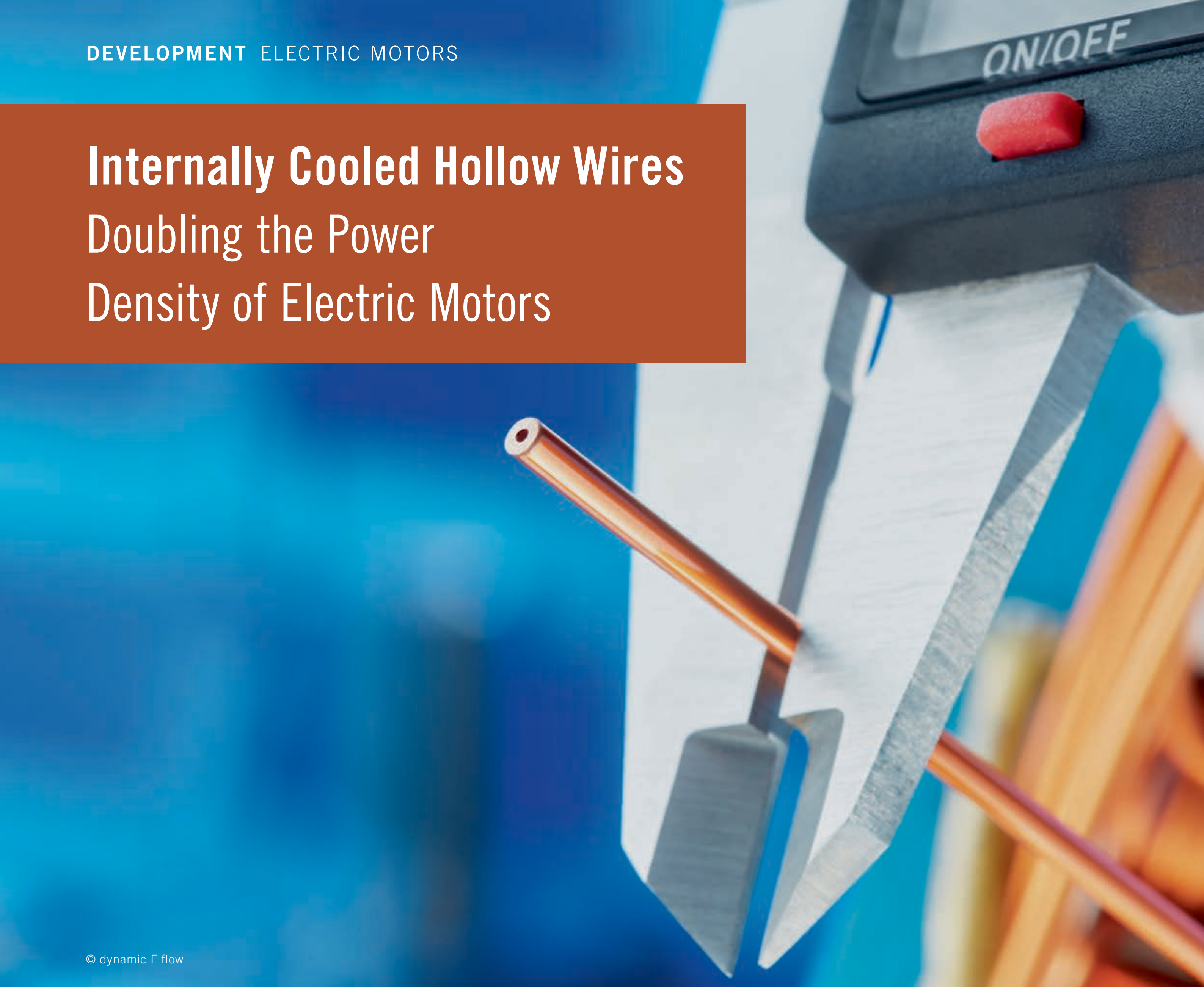
Internally Cooled Hollow Wires

Doubling the Power Density of Electric Motors



AUTHORS

Prof. Dr. Dipl.-Ing. Edmund Nitsche
is independant Consultant of the dynamic E flow GmbH in Kaubeuren (Germany).

Mag. Michael Naderer
is Product Manager and CEO of dynamic E flow GmbH in Kaubeuren (Germany).

With the conversion to hollow wire technology, the company dynamic E flow has doubled the torque density of an existing traction motor from the large automotive series in continuous operation and peak performance. This works as the hollow coils are cooled from inside. Measurements at the test rigs of the Federal Armed Forces University in Munich provide proof. It is confirmed that electric machines can be build up to 50% smaller – synchronous as well as asynchronous and reluctance machines.

INNOVATION

Hollow conductors (waveguides) have been state-of-the-art in limit power turbo-generators in power plants for a lot more than 50 years already. The development went from air cooling via water jacket cooling and indirect oil cooling up to direct hollow conductor cooling. This development has now come into its own in the construction of smaller electrical machines.

With these measurements, the use of hollow wires (capcooltech) for the conventional wind-ings of electromagnetic coils establishes new dimensions in the industrial electrical engineer-ing. The significantly higher material utilisation makes significant cost savings possible. New performance dimensions can be achieved.

STATE-OF-THE-ART

The cooling plays an important role in all drive units, in combustion engines or electric motors, for the power density and material utilisation. Up to now in small electrical machine construction, indirect cooling has been predominant. Here, the heat is dissipated on the periphery of the power unit (water jacket, air fins) as close as possible to the grooves, and also in the rotor (oil through-flow). With direct cooling, the critical heat can be lead away directly from where it arises.

With the capillary cooling technology (capcooltech) electromagnetic coils are cooled from the inside. This means that the heat can be carried away effectively, which causes positive effects on the thermal loading of all the components of an electromagnetic system. Current densities of up to more than 50 A/mm² and corresponding powers are achievable here. The reason lies in the outstanding thermal conductivity factor of the copper (400 W/ (m*K), **FIGURE 1**, and an excellent transfer of heat to liquids. With indirect cooling, the barrier of the insulation (04 W/ (m*K) and the considerably poorer heat transfer to the ambient air must be borne in mind.

The capcooltech is a comprehensive technology and can be used regardless of the chosen machine topology. It consists of two components. Of the hollow wire with diameters between 1mm and up to over 3mm, and of the connection box (alias Capcooltech-Box). These two components are freely adaptable and determine the problem-free functioning of the technology. The losses occurring in the copper can be lead away up to 100%. The size of the potential peak and continuous power densities is significantly increased by this. Depending on the heat to be dissipated, the appropriate cooling medium supply (medium, pressure, flow rate) can be set. The combination with indirect cooling for the iron losses is possible, and, depending on the application, makes sense.

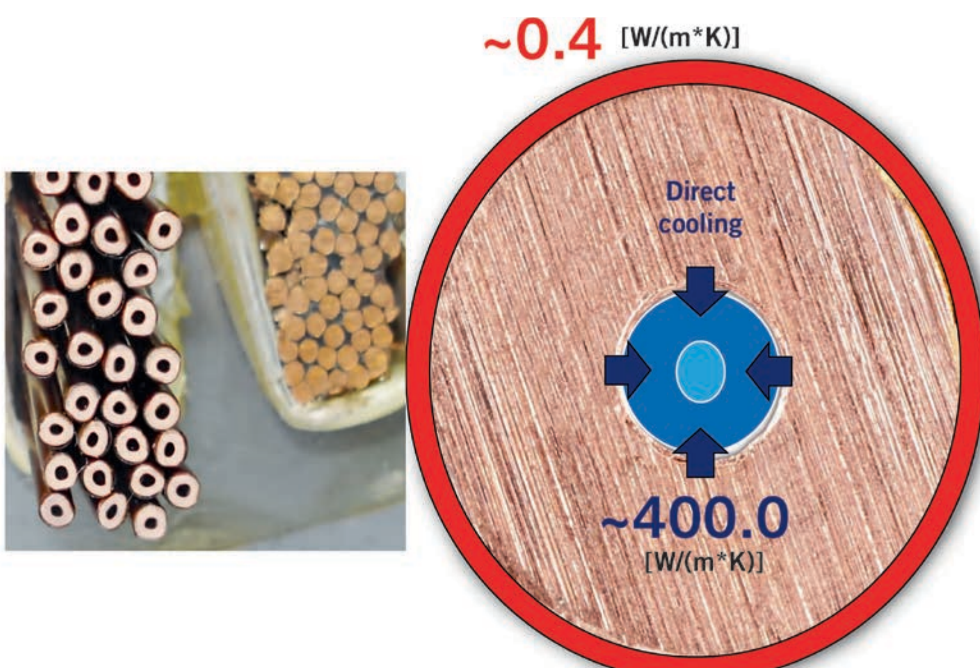


FIGURE 1 Groove comparison and cross section of the conductor with thermal conductivity factor (© dynamic E flow)

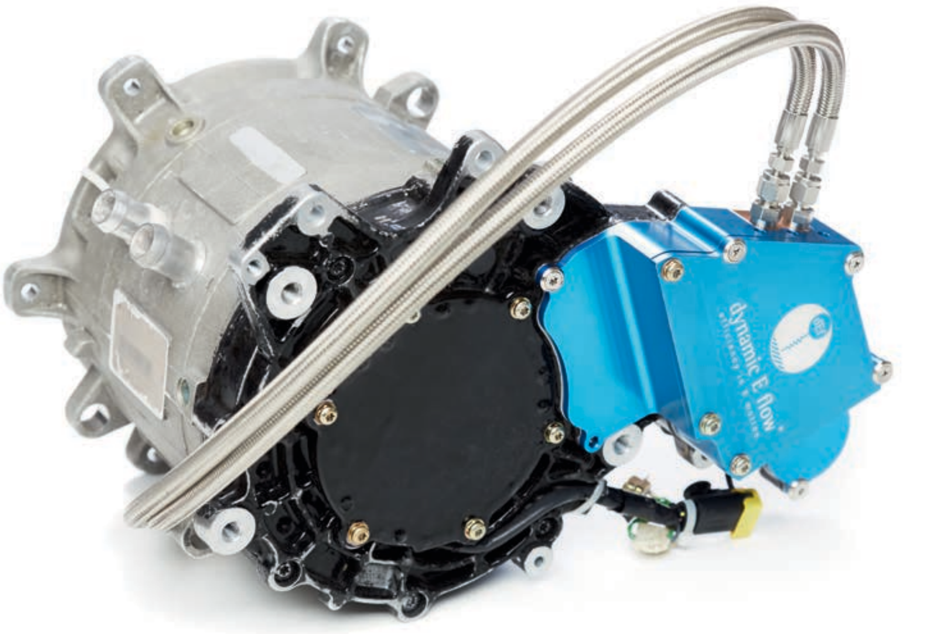


FIGURE 2 Modified electric motor, alias B1, the built-on capcooltech-Box (in Blue) (© dynamic E flow)

Direct cooling has been successfully used in limit power turbo-generators and is state-of-the-art [2, 3]. It makes it possible to realise powers of up to over 1.5 GW from one unit. Each par-tial winding is individually connected to a cooling medium supply. With the capcooltech, the entire winding length is flooded with cooling medium. The electrical utilisation of a direct cooled limit power turbo-generator is approx. ten times that of an air-cooled power unit. Despite higher current densities, thanks to appropriate designs the efficiency levels of these machines have not suffered. Efficiency levels of large machines are at 99 %.

The current density goes into the losses squared, but the reduction of the copper volume at higher utilisation means that in the end the losses only grow proportionally with the current density. In addition, the direct cooling reduces the winding temperature considerably which in turn reduces the resistance. It is cooled where decisive losses occur: namely at the winding of the pole surface next to the air gap, the magnets and the adjacent teeth.

CONVERSION OF AN EXISTING HIGH VOLUME PRODUCTION TRACTION MOTOR

For the evaluation of the potential of hollow wire technology, a high-quality and widely used series production traction power unit, very well matched in terms of magnetic circuit, material utilization and subcomponent selection, was rewound. The power unit was purchased in the marketplace and dismantled. The winding was removed and then the laminated core was newly wound. The connection box was adapted to the shape of the machine infrastructure. After assembling, the original motor and the adapted motor, alias B1, **FIGURE 2**, were measured and compared.

The original motor is a permanent magnet excited synchronous motor [1] or a traction motor (400 V, DC) with a rated speed of 4,500 rpm and a measured torque of 78 Nm at approx. 120° winding

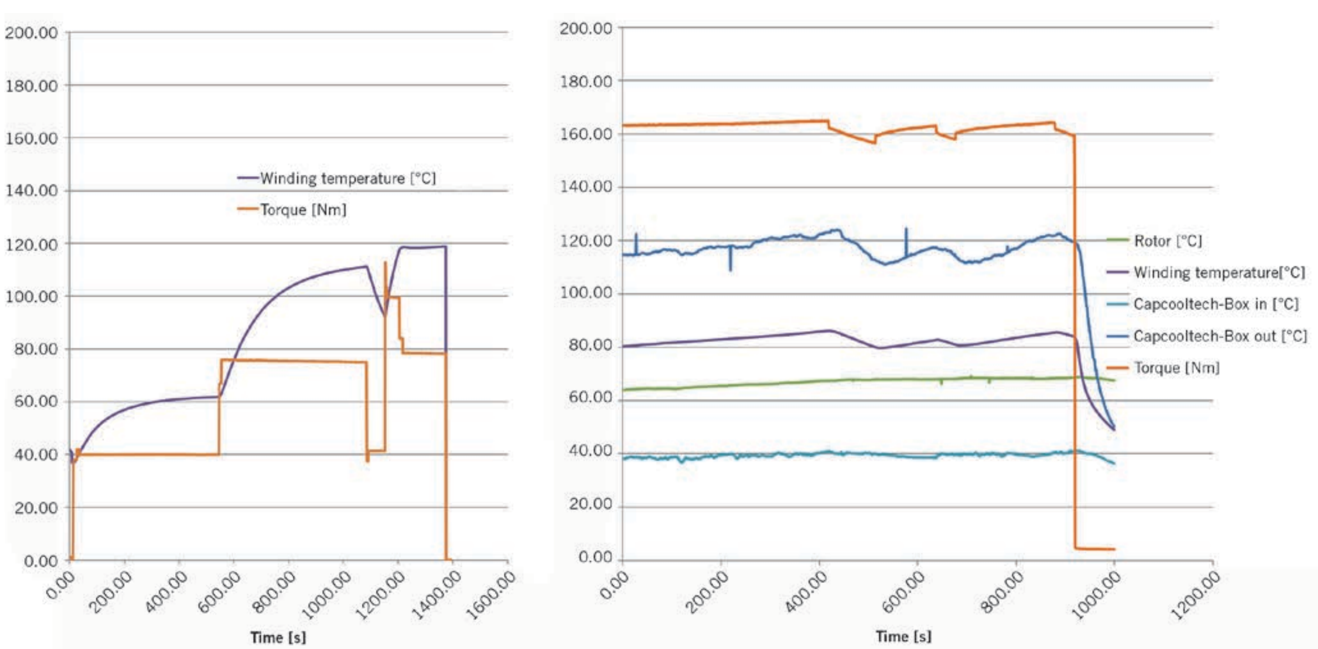


FIGURE 3 Comparison between the original motor at approx. 80 Nm (left) and the B1 (right) at 165 Nm, each at 4500 rpm (© dynamic E flow)

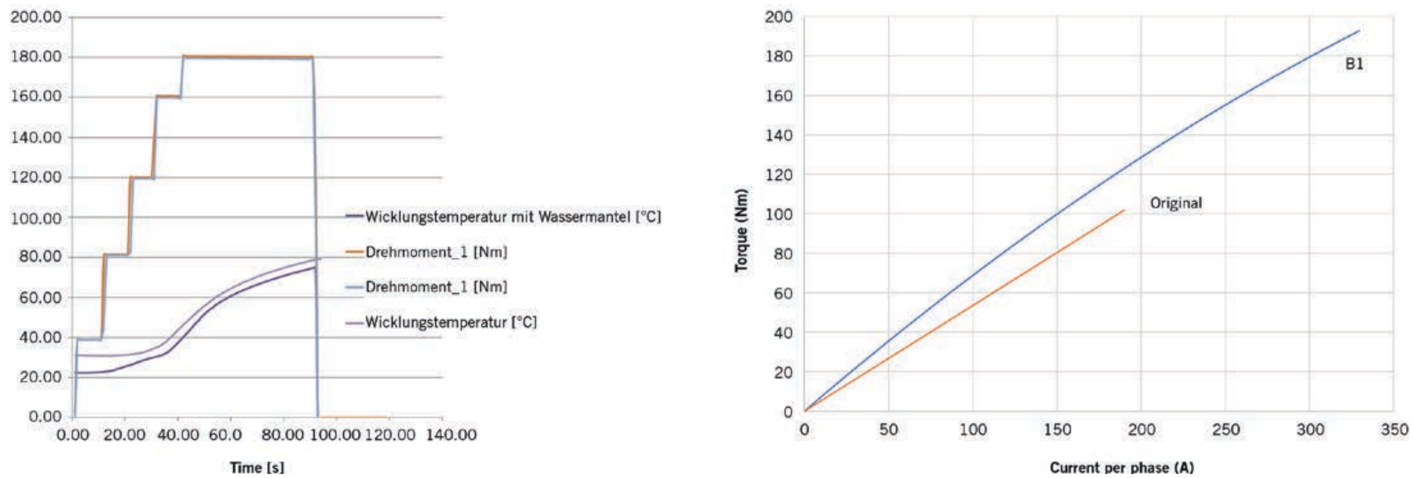


FIGURE 4 Torque Increase at 500 rpm (left) and the torque over the current per phase (right) (© dynamic E flow)

temperature. The specified peak torque is 200 Nm. The power unit is water jacket cooled and weighs 30kg, it has according to this 78 Nm/30 kg = ~2.6 Nm kg – in contrast the B1 as shown has approx. 165 Nm/32 kg = ~5.2 Nm/kg.

For the cooling medium supply, a hydraulic unit, not optimised for mobile applications, used in the industry for higher pressures and lower flow rates was used. The hollow wire technology occasionally requires relatively high pressures of up to over 100bar, but in return very low flow rates, these are specified in ml / min. With low conductor lengths – such as in 48V applications – pressures of up to 5 bar are sufficient for significant increases in performance.

The appropriate connection techniques (higher currents, higher temperature differences, higher pressure differences, coupling and decoupling of electric and hydraulic currents) represent a technical challenge for the use of the hollow wire technology.

A series of approx. 80 measurements, no load measurements, inertia measurements and peak load measurements were carried out on the original and on the modified power unit. The main focus was on the performance increase of the B1 and the determination of the differences to the original.

CONTINUOUS LOAD MEASUREMENTS

The original motor shows at a speed of 4,500 rpm and 78 Nm a winding temperature of 118 °C, **FIGURE 3**. In contrast the B1 delivers a torque of 165 Nm at a winding temperature of 85 °C. This measurement was repeated several times for 90 minutes. The cooling medium input temperature lies at 40 °C and the cooling medium output temperature at 120 °C (delta T 80 K). **FIGURE 3**.

The winding temperature sensors correspond to the sensors used as standard on the windings.

This result was achieved at 70 bar and with 2,200 ml/min with heat-transfer oil. The pump theoretically required approx. 260 , 430 W (without CPU) was measured, whereby with this a power of 78 kW was run. The measured pump power in this case corresponds to 0.55% of the power. Thereby, here approx. 5.5 kW were continuously taken from the winding.

A control-oriented optimisation for the cycle can minimise the losses; Measurements with pump powers of approx. 10 W likewise already show considerable effects. Also, the rotor remained cold at this load, which in particular must be due to the relevant heat flows to the pole surface.

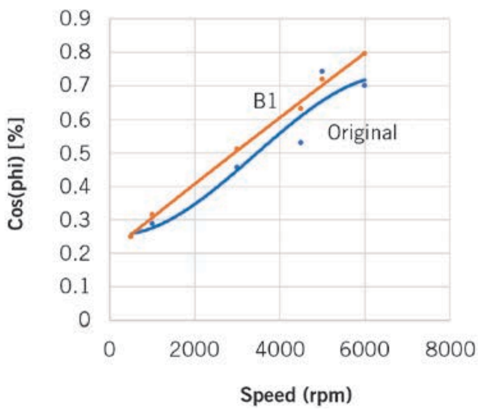
The cooling system carries away all the heat, in no load tests it could also be measured that a very small part of the iron losses can be carried away. The peak measurements at 500 rpm show that for certain short load cycles, with an appropriate design, the water jacket cooling can be dispensed with.

The peak torque specified in the original motor turns to continuous peak with the B1. The potential new peak torques based on an appropriate machine design lie correspondingly far higher. For the present measurements, the torque was increased step-by-step at different rotational speeds to 180 Nm, **FIGURE 4**. There is a measurement series at 500 rpm, a set pres-sure of 50 bar and approx. 1,800 ml/min on average, with a measured pump power of 250 W, or 360 W including CPU. Once with direct cooling and water jacket (approx. 14 l/min), once with direct cooling only. The result shows that the load dynamic gains a long-term component, the water jacket makes only a marginal difference.

COMPARISON OF THE POWER FACTOR

The diagram shows the comparison of the power factors between the original motor and the directly cooled machine at 80 Nm, **FIGURE 5**. The advantage with B1 can be explained by the fact that the hollow wire made a higher number of windings possible. Although the pre-existing groove geometry was not ideally fitted. The magnetic circuits of both machines are completely identical.
The best-fit curves show that the power factor at lower rotational speeds is more or less the same for both machines because the magnets hardly contribute to the necessary internal voltage. This improves at higher rotational speeds.
In the field weakening range, new conditions are applicable again, because the field is additionally adjusted via the longitudinal current.

The range of the current on B1 goes up to 330 A, on the original motor, due to the reached limit temperature,



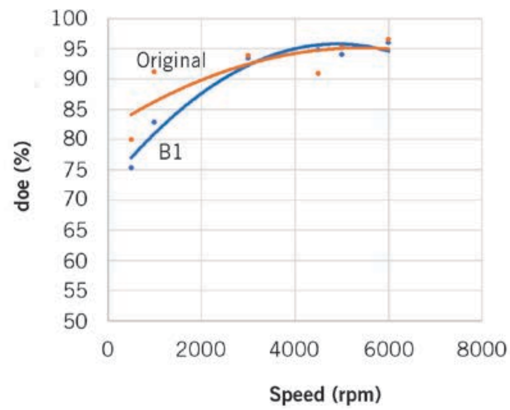


FIGURE 5 View of the power factor (left) and the efficiency (right) (© dynamic E flow)

up to 190 A. Higher loads, as is normal with synchronous machines, lead to increased magnetisation requirements and, thereby, a reduction of the power factor. It is shown that an accurate winding design with adapted magnetic utilisation favourably influ-ences the magnetisation requirement and, therefore, the cos (phi) and the overall utilisation of a PSM.

With low electrical utilisation, the achievable torque is proportional to the current. The vector control tries to satisfy this principle from a control viewpoint, which is actually already known from the direct current machine, whereby the transverse components of the current coverage are optimally aligned with the field. We now know from the direct current machine, that higher load currents can lead to adverse effects on the field and to the torque no longer increasing linearly with the current. This is shown in **FIGURE 4** (torque comparison), where the B1 goes up to 330 A. The two curves show the respective correlation between current and torque determined from the measured values for the B1 and the original. The higher torque for the B1 results once again from the higher number of windings per phase, actually in some instances in a better relationship, because the higher number of windings not only makes a greater armature current coverage with the same current, but also because the magnetic field is correspondingly better supported by the stator.

COMPARISON OF EFFICIENCY

The evaluation of the efficiency on the basis of an existing motor allows indirect conclusions to be drawn, as existing laminations were wound into and this approach was not intended for the optimisation of efficiency. A multiple of torque was obtained from B1, the corresponding efficiency changes, therefore, cannot be directly metrologically compared with the original power unit.

Naturally, the groove fill factor with direct cooling is smaller, as a part of the conducting sur-face is lost for the cooling medium. In contrast, cooler windings result in a significantly lower resistance. The thicker conductors can be considered as an argument for the additional losses, which is not unjustified, at least at higher frequencies. On the other hand, the problems of fine-wired parallel routed conductors whose loop currents likewise cause losses cannot be disregarded, either [1]. With a lot of partial conductors in the groove we have partial conductor insulation, which can no longer be made thinner as a consideration for the reduction of the groove fill factor. And with directly non-coolable plug systems there are similar challenges with the insulation and the additional losses at higher rpm.

With a metrological comparison of the efficiency, in our case, comparisons may not be made on the basis of the current as the different numbers of phase windings play a role with the resistance and the generation of torque. The definition of the efficiency permits an adequate comparison only via the powers and torques. Because the efficiency is defined by the output power at the drive shaft and the electrical input power at the terminals. Through the higher torque, the efficiency of the B1 is perfectly presentable in comparison with the original motor. At 1000 rpm, the throughput of the power compared with the losses is even lower. Therefore, too, the moderate efficiency of the two machines. At 4,500 rpm, according to the measurements, we actually have advantages with the B1. At 4,500 rpm and 80Nm the B1 has an efficiency of 94.4 % and the original 94.1%, the efficiency diagram results after polynomial averaging, **FIGURE 5**. At 165 Nm the B1 still shows an efficiency of 90 %. These advantages adjust again at higher input temperatures and currents and at higher speeds and therefore higher frequencies. An objective-oriented machine design definitely permits very positive efficiencies.

FREQUENCY AND LOAD-DEPENDENT ADDITIONAL LOSSES

Additional losses with regard to the frequency and load-dependent additional losses (groove stray field, pole surfaces), these losses increase more sharply in the high speed ranges with the B1, as expected. However they can be controlled via the cooling. In the present machine, the wires have an external diameter of 1.6mm. The loss in the copper filling of the groove due to the cooling channel, the lower winding temperature and the arranged winding nevertheless show, for example, at 1000 rpm lower additional losses than on the original. An appropriate dimension between partial load operation and maximum load, with an appropriate design will be bring about corresponding success.

The pump power required for the use of the hollow wire technology is low. In the tests, three pressure levels were operated: 70, 50 and 30 bar. The flow rates were at 70 bar with approx. 2.200 ml/min, at 50 bar approx.

1.800 ml/min and at 30 bar approx. 1.400 ml/min. The power demands of the pump were respectively 43, 250 and 120 W (without CPU).

It should be mentioned that the waste heat in the vehicle can be used as effective useful heat. Within a few seconds it is possible to return the oil at appropriate temperatures, whereby the design of the complete vehicle with respect to heating, ventilation and climate can be taken into account. Heat pump systems could also be used. In the given case, as already said, at 165 Nm constant torque and 4,500 rpm, with an approx. 450 W pump power, approx. 5.5 kW of heat can be taken directly out of the winding.

OUTLOOK

The technical realisation of the hollow wire technology leads to new possibilities for automo-tive engineering. The significant material and cost savings and the simple adaption of the industrial winding technology are decisive. The machines can be built up to 50% smaller. With it, the electric motor design has a new degree of freedom within the sense of total optimisation – in the all-electric field, too, the capcooltech can already justify up to a few percent additional battery capacity. Especially when the utilisation of the heat is taken into account.

The essential development step has been taken, further incremental optimisation and innovations, in particular for the cooling medium supply will be implemented in the next few years. Electric motors (for example: main drives, auxiliary drives, auxiliary power units), actuators (for example: chassis stabilisation) and also transformers (for example: inductive charging) and the entire electro-mobility all profit.

Higher torques and higher power densities can be achieved directly, without having to go via rotational speed and gearboxes. This means savings. Water jacket cooling can be saved through suitable design. Hybrid drives can bring profit through downsizing with higher con-stant power and fuel savings, especially in the commercial vehicle sector. The waste heat can be used as effective useful heat. Safer low voltage power units achieve completely new per-formance ranges. Direct drives will become significantly compacter and simpler.

All machine types, even separately excited machines and asynchronous motors and reluctance machines profit. The optimisation of the systems and the provision thereby of coordinated system components allow a wide range of applications. It is reasonable to assume that the capcooltech will impose itself long-term in the automotive sector as a widespread technology.

REFERENCES

[1] Bauer, D.; Nolle, E.; Reuss, H.-C.: Einfluss von Stromverdrängung bei elektrischen Maschinen für Hybrid- und Elektrofahrzeuge. Tag des kooperativen Promotionskolleg Hybrid, 11.11.2014, Stuttgart, Deutschland. Online: http://www.ivk.uni-stuttgart.de/IVK/fileadmin/media/dokumente_pdf/aktuelles/veranstaltungen/Paper_TdPKH/1.1_TdPKH_2014_Bauer.pdf, called up on 20.03.2017

[2] Fischer, F.: Thermische Fehlerdiagnose der wassergekühlten Statorwicklung von Grenzleistungs-Turbogeneratoren, Fachbereich Elektrotechnik und Informationstechnik der Bergischen Universität-Gesamthochschule Wuppertal,Diss. 1999. Online: http://elpub.bib.uni-wuppertal.de/edocs/dokumente/fb13/diss1999/fischer/d139906.pdf), called up on 20.03.2017

[3] Online:https://de.wikipedia.org/wiki/Turbogenerator#/media/File:BalakovoNPP_tb.jpg, called up on 20.03.2017