NTNU – Trondheim
Norwegian University of
Science and Technology

Electric Motor Development for Shell Eco-Marathon

Manufacturing an ironless axial flux permanent magnet Motor with Hallbach array and Development of existing Motor for the Shell Eco-Marathon Competition

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Problem description:

Providing the best possible electric motor for the Shell Eco-Marathon Europe 2012.

Based on a series of studies by students at NTNU, the student is expected to implement and verify a series of suggested improvements.

An optimized design, proposed by Lubna Nasrin, is going to be built and compared with earlier version. The new motor will hopefully be used in this year's race, but more important is it to get knowledge of building strategies for a compact ironless axial flux motor.

Since very few measurements have been performed on the older version, it is expected to be implemented a new test rig/regime that can be the basis for future verification of design.

If time limitations make it difficult to finish/verify the latest version of the motor, a description of all experiences from the building process and from the lab must be documented.

It is important to make the report a good basis for eventual later students/contributors in the project.

Robert Nilssen 18 Juni 2012
Veileder
NTNU Elkraft.

Abstract:

This thesis describes the process of making a new engine for the car DNV Fuel Fighter 2 that participated in the Shell Eco-Marathon Europe 2012 in Rotterdam. The decision was made to construct a new engine based on an optimized design by Lubna Nasrin. The engine is an ironless axial flux permanent magnet machine with Hallbach array. As a contingency plan there was the possibility to modify the engine used in 2010 and 2011 built by André Dahl-Jacobsen. The result of the process is that the new engine is operational and it has displayed an efficiency of 68 %. However the old engine has displayed an efficiency of 86 %. Because of this, the car raced with the old engine and had an energy consumption of 163 km/kWh. It is still believed that the new engine can be a very successful engine given that it is modified. The new engine has room for improvement especially with regards to stator production and wiring connections. Suggestions are made for how to achieve a higher efficiency. This thesis describes some of the practical engineering challenges that arise when constructing a novel motor. The construction of the Hallbach array is well described here.

This work has been a part of a larger project where the end goal was to participate in and win the Shell Eco Marathon Europe. This means that the engine must not only perform well on its own. The engine must also function well with the other components technically and it must be possible to make it with the time and resources available. The development of new technology is expensive and it has therefore been a priority to find funding for this project. This will also be described.

Sammendrag:

Denne rapporten beskriver prosessen med å lage en ny motor til bilen DNV Fuel Fighter 2 som deltok i Shell Eco-Marathon Europe 2012 i Rotterdam. Det ble tatt en avgjørelse om å bygge en ny motor basert på en optimaliseringsanalyse utført av Lubna Nasrin. Denne motoren er en jernløs, permanentmagnet aksialfluksmotor med Hallbach array. Som en alternativ løsning kunne motoren brukt i 2010 og 2011 bli modifisert. Resultatet av prosjektet er at den nye motoren er operativ og har en virkningsgrad på 68 %. Den gamle motoren har imidlertid vist en virkningsgrad på 86 %. På grunn av dette kjørte bilen med den gamle motoren og hadde et energibruk tilsvarende 136 km/kWh. Kandidaten mener at den nye motoren kan gi gode resultater gitt at den blir modifisert. Den nye motoren har rom for forbedringer spesielt i forbindelse med statorproduksjon og kobling av viklinger. Forslag er gitt for hvordan å oppnå høyere virkningsgrad. Denne rapporten beskriver flere av de praktiske utfordringene som er knyttet til konstruksjon av en uvanlig motor. Produksjonen av Hallbach array er et eksempel på dette som er beskrevet her.

Dette arbeidet har vært en del av et større prosjekt der målet har vært å delta i og vinne Shell Eco-Marathon Europe. Dette medfører at motoren ikke bare er nødt til å prestere godt isolert sett. Motoren må også fungere godt med de andre komponentene i systemet og være mulig å bygge med den tid og de ressurser som er tilgjengelig. Utvikling av ny teknologi er kostbart og det har derfor vært en prioritet å finne finansiering. Dette blir også beskrevet i denne rapporten.

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Introduction

Shell Eco-Marathon

The Shell Eco Marathon is a competition that challenges students to build, test and race vehicles with the goal of creating the most fuel efficient vehicle. There are two main categories; Prototype and Urban Concept. In prototype there are few limitations concerning design and features. The vehicles are often small three-wheeled compartments where the driver is lying flat on her/his back. For Urban Concept there are more regulations. The cars must have four wheels, a minimum height, headlights rear lights, windshield wiper et cetera. The cars must complete ten laps, each 1617 meter, within 39 minutes. For the urban concept class the cars must come to a complete stop in between each lap.

The legacy:

NTNU has participated in Shell Eco-Marathon Europe every year since 2008. In 2009 NTNU set a world record in the urban concept hydrogen class with an energy consumption equivalent to 1246 km per liter of petrol[1]. In 2011 the team had a great deal of problems related to the drive train and came in second place with a energy consumption of 900 km per liter. In all previous years the teams from NTNU have participated with the car built in 2008 in with a hydrogen fuel cell[i]. Every year there has been an entirely new team from NTNU. This has led to an unfortunate knowledge loss in between each team. With regards to the engine this meant that this project began with an existing engine but little measurement data, mostly stories of what had been done. As a result of this there was no knowledge about the efficiency of the machine except that it was not as good as it should have been.

The work with the engine development is based on the work by André Dahl-Jacobsen[ii] and Lubna Nasrin[iii]. André Dahl-Jacobsen was the designer of the engine built in 2009 and Lubna Nasrin performed an optimization for the new engine with Hallbach array. Both engines were designed for a nominal torque of 3,5 Nm. The candidate has not been able to find the reason why this was chosen as the nominal torque.

Theory:

Both engines are axial flux, permanent magnet machines with no iron in the stators. The principal differences from an electromagnetic point of view is that the old engine uses a iron ring behind the magnets to lead the magnetic field while the new engine uses a magnet arrangement called Hallbach array. A benefit of Hallbach array is that the flux lines are more concentrated giving a higher flux density[iv]. Also the first engine has a stator with single layer distributed windings made of enameled copper wire. The new engine has a double layer wave winding made with litz wire. The litz wire consists of 380 separately insulated strands. This reduces the eddy currents that will arise at alternating current. This is why litz wire was preferred for this design. There is however a great difference in weight. The original engine has a weight of 17 kg while the new has a weight of 7 kg. The heaviest part in the original engine is the iron ring leading the magnetic field. This ring is located far away from the center of rotation and thereby gives a high moment of inertia.

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[1] Shell FuelSave 95 has 32’010 kJ/l given a fuel density of 0,74616 kg/l

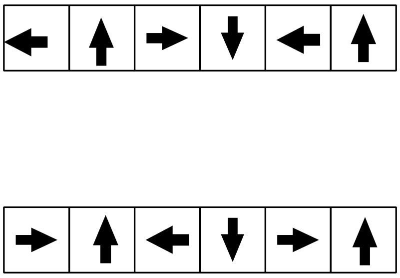


Figure 1 Magnets in a Hallbach array, arrows showing direction of magnetization

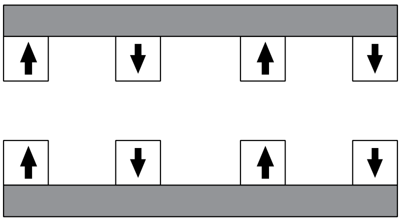


Figure 2 Magnets and iron ring, arrows showing direction of magnetization

Figure 3 Single phase single layer wave winding

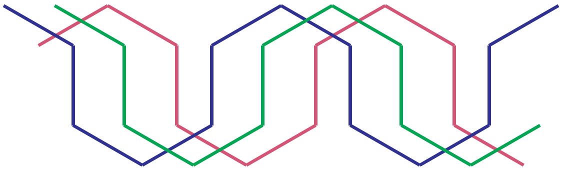


Figure 4 Three phase single layer wave winding

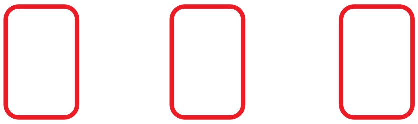


Figure 5 Single phase distributed winding

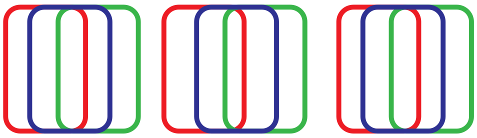


Figure 6 Three phase distributed winding

Production:

Assembly of rotor:

The rotor consists of carbon fiber plates and NdFeB permanent magnets. The magnets were glued on with a two component epoxy, Araldite 2021. The epoxy was recommended by one of our major sponsors with a wide experience within composites. Before the magnets were glued, the epoxy was tested on a stretch bench. The needed strength of the glue was found by first calculating the force that between the magnets with axial magnetization. This was done with the following formula:

$$F = \frac{B^2 * A}{2 * \mu_0}$$

and found to be 87,6 N per pole. In its natural state the magnetic forces in a Hallbach array will seek to displace every other magnet. As the tangentially magnetized magnets would attract the outer end of the axially magnetized magnets, these forces needed to be added to the calculation. These forces were found by assembling the Hallbach array and pressing them in an industrial press with force measurement.

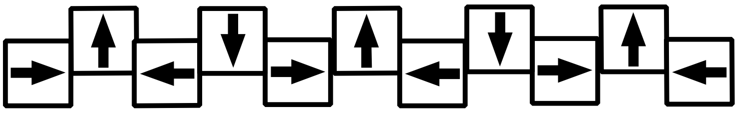


Figure 7 Hallbach array at natural state

Four tests were performed. Three of these showed acceptable results, the last showed insufficient glue in the contact area. The successful tests showed that the carbon fiber delaminated before the glue failed. This makes the carbon fiber the limiting factor. The results from these measurements have however been lost.

Figure 8 Testing epoxy and carbon fiber

The magnets used were NdFeB N42 magnets. These were selected because of their magnetic strength and their thermal abilities. The magnets were assembled in a Hallbach array before they were attached to the rotor plates. Several attempts were made in order to find the right technique for doing this. The first attempt was to use a circular wooden plate with another wooden plate of a smaller diameter centered on top of the first. This way it was possible to control the shape and diameter of the array. This procedure was however unsuccessful as the magnetic field caused the magnets to turn out of position. This problem was fixed by adding a third circular wooden plate on top of the center plate to keep the magnets down. The plates were made of wood since wood is quick to work with and not magnetically conductive. When the magnets were arranged in the Hallbach array they kept themselves in position. This is however very unstable and sensitive to disturbances. An important challenge here was to keep all ferromagnetic material in a safe distance.

Figure 9 Assembly of Hallbach array

The rotor plates were made of carbon fiber. These were milled out from a solid plate to the correct thickness and with the proper flange to support the spacer ring and magnets. The necessary thickness was found by multiplying the force per pole with the number of poles. These were found to be 87,6 N per pole and thereby 4,2 kN in total. When these were found an expert from Smart Motor with a wide experience with carbon fiber suggested a thickness of 2 mm. It was then decided to use a thickness of 4 mm as an extra safety. Since carbon fiber dust is especially hazardous to human health, the dust created during milling needed to be collected safely. This was achieved by disconnecting the milling machines cooling fluid and spraying a mist of cooling fluid on the material during milling by hand. This led to a thick pulp which was then gathered and disposed.

Before the magnets were to be attached to the rotor plates, both the plates and the magnets needed to be cleaned with aceton. Since the Hallbach array is a highly unstable arrangement they should not be exposed for longer periods of time and should definitely not be handled while they are exposed. Therefore a circular wooden plate with a slot for four magnets was designed. This made it possible to only expose the magnets being cleaned while providing support for the rest of the Hallbach array. This gave extra stability and worked well.

In order to assemble the rotor properly, special equipment had to be constructed. This was particularly important when gluing the magnets as the forces here would be especially high. When the magnets were assembled in the Hallbach array, Araldite 2021 glue was put on the carbon fiber plates. The plates were then lowered onto the Hallbach arrays. In order to get the magnets centered on the rotor plates, wide shafts were designed to exactly match the attachment holes in the rotor plates. These shafts were then put on the bolts in the center of the wooden plates used for the magnet assembly. This ensured the right position of the magnets and also forced us to keep the carbon fiber plates horizontal while lowering. This led to a successful distribution of glue. The shafts were made of brass in order to avoid ferromagnetic disturbance.

At a later stage in the production process three magnets came loose. These three magnets were then removed, the glue was scraped off and they were then reglued. Clamps were used to apply the needed pressure. Special aluminum pieces with magnet sized rails were designed to prevent the magnets from sticking to the clamps.

Stator production:

The stator consists of litz wire and two component epoxy of 17110 Araldite and Ren Hy956 mp.

Windings:

The wire was wound on a wooden board. To ensure a clear layout of the wires a technical drawing was printed and stapled onto the wooden board. Nails were used to keep the wires in place. With three phases and 24 pole pairs, 288 nails were needed. Another wooden board was used to make an outer radius guideline. This was necessary to ensure the correct size of the coils and the wooden guideline had a diameter of 329 mm while the stator mold had a diameter of 330 mm. This provided a margin of 1 mm. 6 wires were then wound in a double layer wave winding. The winding was then tied up with 288 knots to replace the nails. Cotton string was used to tie the winding as this is not magnetically conductive. Steel wire was also considered as this would have an easier assembly but this was discarded as it would lead to a higher leakage flux. The nails were then removed.

After the wires had been wound, tied and properly fitted in the circumference ring, the wires were placed in the mold. For the vacuum casted stator the wires were Y-connected as shown in figure 20 before casting. Only three wires came out of the cast.

Figure 10 Winding production

Mold *production:*

For the different stators two different molds were made. The first mold was made for vacuum casting. This was a four piece mold made of steel. This mold consisted of a plane bottom plate with an entry hole for the epoxy, two semi-circle shaped side plates and a plane top lid with exit hole for air, epoxy and wires.

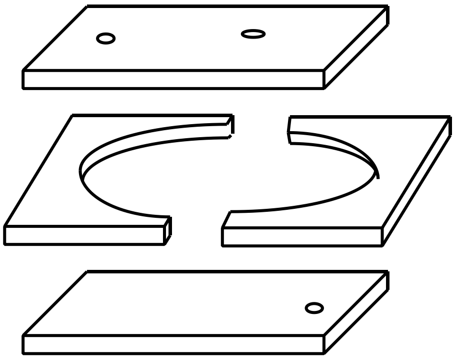


Figure 11 Stator mold for vacuum casting

In the bottom plate, four bolts were attached. These ran through holes in the remaining pieces. These bolts were intended for tightening the plates together during the vacuum process. In order to get the cast out of the mold after casting the mold needed to be covered with release agent. This was smeared on the pieces which were then baked at curing temperature for 10 minutes. This was done 3 times. The pieces were baked so the release agent would set properly to the steel and to prevent it from reacting with the epoxy.

The other mold was of a simpler design. This was ebaboard with a stator sized hole milled out. This was then covered with spray paint and wax. The spray paint was used to fill the pores in the material and the wax was a release agent suitable for low temperatures. The same lid was used for both molds to compress the wires in the axial direction.

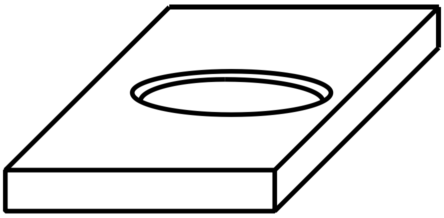


Figure 12 Stator mold for open casting

Open casting:

The open casting technique using the ebaboard mold is an easier process than vacuum casting. The winding is placed in the mold with wire ends coming out of the top lid. Epoxy is poured in and the lid is pressed down. This causes some of the epoxy to overflow the mold. Afterwards the stator would cure at 70 degrees Celsius for four hours. When this open casting was performed the casting was somewhat unsuccessful due to a lack of epoxy. The resin to hardener ratio was 3,92:1 instead of the desired 5:1 and the total amount was too little. Still, this stator had many of the desired properties.

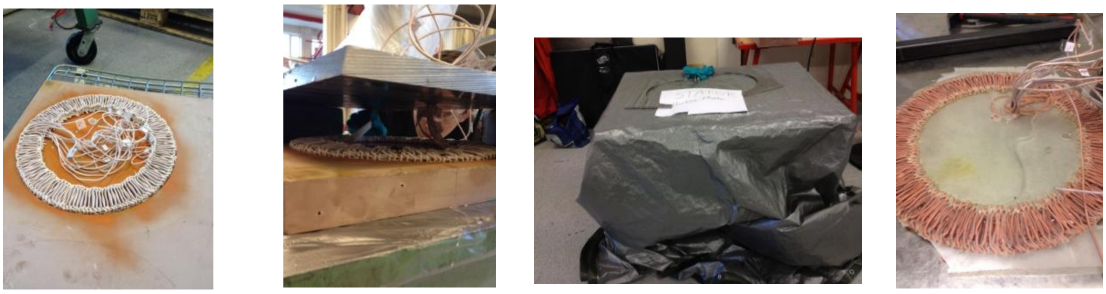


Figure 13 Stator production, open casting

Vacuum casting*:*

The method of vacuum casting was recommended, by a professor with experience with epoxy, as a casting method suitable for electrical equipment. This method will, if performed successfully, give great dielectric properties and prevent partial discharges. In this design partial discharges is not an issue due to low voltage and we would therefore be able to accept minor imperfections in the cast. However, casting the stator was challenging.

As seen in figure 14, a vacuum pump was used to generate the vacuum (left). This pump was then connected with tubes to two safety chambers (green and grey cylinder) in series, before it was connected to the topside of the mold. On the first safety chamber there was a gauge showing the pressure difference between the internal and atmospheric pressure. The mold was slanted so the outlet tube was the highest point in the mold. From the other end of the mold, at the lowest point, an inlet tube went to a bucket of epoxy (right).

Figure 14 Setup for vacuum casting

This configuration enabled the mold to be filled with epoxy in a controlled manner. The epoxy would flow into the mold and it was easy to see when the epoxy would come out of the topside. When this happened the outlet tube was blocked and the epoxy would continue to fill the mold until the pressure inside the mold was equal to the atmospheric pressure. One major challenge here was to keep all interfaces airtight. All connections were covered with sealing tape, but the mold was particularly challenging to seal. This might have been due to the weld created when making the mold as this may have created an air canal from the side of the mold. Also the distance between the pressure bolts was too long for supplying the right pressure in between the bolts. This problem was solved using clamps along the circumference of the mold. In order to check the cast procedure several test stators were made. When the first test stator was made it included three wires coming out of the mold for simulating the power cables and a bundle of litz wire was also tied tightly and put in the mold. This was done in order to examine how the epoxy would surround the litz wire.

Figure 15 First test stator

Figure 16 Second test stator

Figure 17 Final vacuum casted stator

Spacer ring:

To keep the rotor discs at a desired distance, a spacer ring was constructed. The ring was supported by a flange in the rotor discs. In order to achieve the mechanical strength to withstand 4,2 kN, polyoxymethylene (POM) was selected as material. The ring was milled out from a solid plate. The flanges in the rotor discs were highly necessary as there was a very small margin for misplacement. This was due to the fact that the stator had a diameter greater than the outer diameter of the rotor magnets. Any misplacement of the spacer ring would therefore lead to rubbing between the spacer ring and the stator.

Assembly of the engine:

The stator was to be fitted on an aluminum axle made for especially for this project. The necessary holes needed for fitting and securing the stator on the axle were milled out in the center of the stator. In order to find the center of the stator, the mill was slowly brought closer to the stator until first contact in order to find position of the four points needed for finding the center. This was done with a numerical accuracy of 1 micrometer but with visual inspection of when the contact occurred. This might have lead to some inaccuracy.

The stator was then mounted on the axle and the three power wires were lead through the hollow axle. The wires would then come out on the inner side of the engine, the side facing the car. The rotor plates were fitted with ball bearings in the center holes. The axle was then put through the ball bearing in the outer plate, with the stator still attached. The spacer ring was then put on, surrounding the stator. At last, the inner rotor plate was to be lowered onto the remaining parts. Since the magnetic forces are very strong, this process needed special tools. Five holes were made in the inner rotor plate. These holes were then fitted with threaded inserts of aluminum. These inserts would allow us to use threaded rods to lower the plate down in a controlled and level manner. The threaded inserts also distributed the forces on the carbon fiber, reducing the mechanical shear stress. The rods went through holes in the stator and down to the outer rotor plate. To reduce the wear on the outer plate, an aluminum ring was glued to the outer plate were the rods would come in contact. As the machine has 24 pole pairs, the inner plate had 24 possible positions relative to the outer plate. With all this equipment in place the inner plate could be lowered onto the rest of the engine.

Figure 18 Rotor plate with threaded inserts

Figure 19 Assembly of the new engine

Testing and modifications:

When the engine was assembled we tried to spin the axle. We then experienced a clear cogging force, similar to that one may find in iron based machines. Since this machine is completely ironless, this indicated a short circuit in the stator. The machine was then brought to Smart Motor for testing. The engine was first spun as a generator using a separate engine to spin it and the torque was measured. Even with open wires the machine still needed 7 Nm just to spin at rated speed. To check if this could be due to mechanical issues we first tried to listen for any scrubbing. There was however no scrubbing. The engine was therefore dissembled, the stator was removed and the engine was spun again. The torque now was insignificant. This proved that the problem was indeed stator related. The stator therefore examined, first by visual inspection. The second test was to measure the dc resistance in between the three phases. A potential bias here is the resistance in the ohm-meters connection wires. In order to achieve an acceptable accuracy two sets of probes were used in parallel.

Phases	Resistance (Ohm)
Brown-Red	0,185
Brown-Orange	0,185
Orange-Red	0,175

Table 1 Resistance between phases

As table 1 shows there is no severe difference between the resistive values that would indicate a short circuit. The last test was to load it with a high current while examining it with a thermal camera. Still the problem was not fund as no isolated area showed any severe heat dissipation.

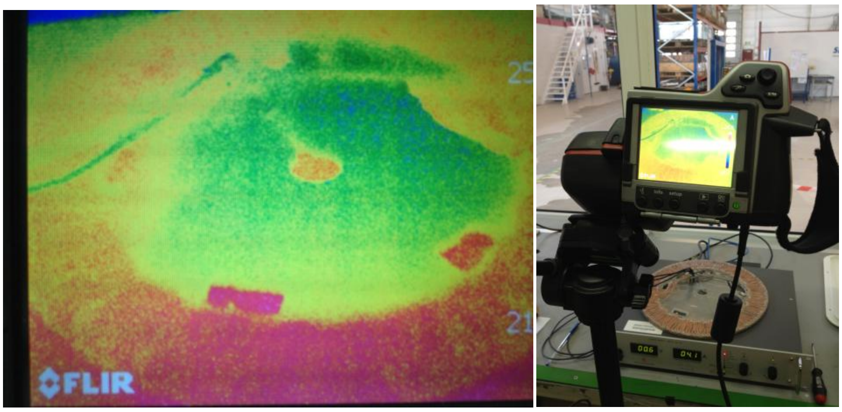


Figure 20 Thermal photo of first stator exposed to high current

After this, a new stator was constructed. Due to the problems with the first stator it was a high priority to keep all connection points of the wires out of the epoxy.

Since the outer shielding of the different litz wire was made of silk and nylon, it was not airtight. It would therefore be impossible to use vacuum casting and get the wire ends out of the mold. The open casting does not require vacuum. This is why the open casting method was selected. When the new stator was casted it was assembled and tested. The test showed an induced voltage much lower than anticipated. The connections were then opened and each wire end was connected to thinner wires which were all lead out through the axle. Thereby it was possible to monitor the voltage induced in each winding. All the induced voltages were as expected. This led to the conclusion that the wires had originally been connected so the induced voltages counteracted each other.

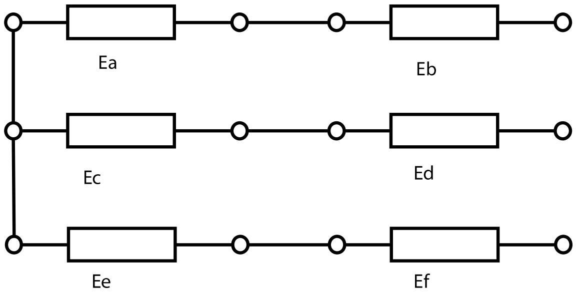


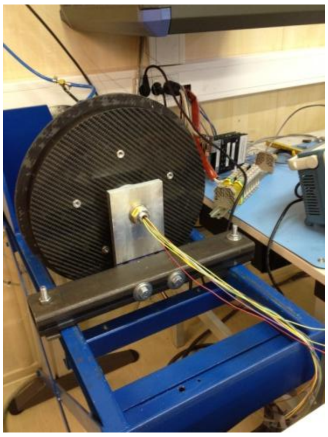
Figure 21 Winding connection with induced voltages

Induced voltage	Angle
Ea	0
Eb	180
Ec	120
Ed	300
Ee	240
Ef	60

Table 2 Induced voltages at first measurement

Since the induced voltages that are connected in series are 180 degrees apart they counteract each other. The small voltages that were measured were due to an error during production of the winding. The total span of windings A, C and E are 95 poles while windings B, D and F span 96 poles. This makes Eb, Ed and Ef approximately 1% higher than Ea, Eb and Ed.

After the measurements the windings were reconnected in the correct order.



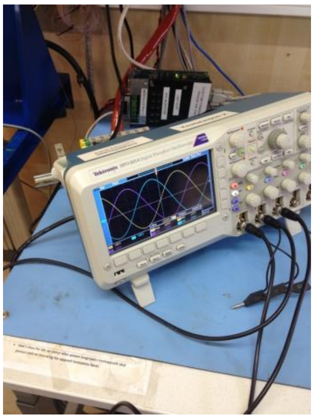


Figure 22 Engine with all wire ends accesable

Figure 23 Induced voltages in the new engines final winding setup

One severe problem with this stator was that since all twelve wire ends needed to come out of the cast, the wires needed a lot of space in the axial direction. This led to a longer air gap than what the engine was designed for. Since the torque is $\tau = B \times I$ we needed more current to achieve the same torque when the flux density decreased due to a bigger air gap. Since the loss is dependent on the current $P_{loss}=R\times I^2$ this lowered the engines efficiency severely. Attempts were made to separate the wires. The most successful approach to this was to use a heated soldering iron to scrape of the epoxy. However, this was difficult and the wires got damaged during the process.

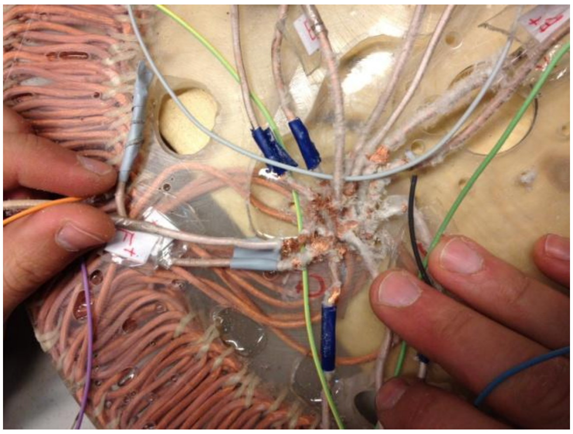


Figure 24 Damaged litz wire

Measurements

The engines were designed for a nominal torque of 3,5 Nm and a speed of 25 km/h. However calculations based on air resistance, tire friction and bearing losses showed that the engine needed to supply a much higher torque.

Testing rotating equipment can be dangerous. See appendix 1 for safety precautions.

Both engines were tested at Smart Motor. More tests were performed on the old engine as it was available for testing earlier and early showed a higher potential than the new. The tests were performed using the battery intended on board the car. In order to burn off the power supplied by the engine from the battery, three resistors were connected in a delta-connection. These were then connected to the terminals of a load engine. This was done because the electronics normally used to drive the test engine were not able to receive the generated power. In between our engine and the test motor a torque meter was connected. Thereby it was possible to control the torque by adjusting the resistors. This solution supplied constant torque for all steady states, but changed whenever the speed changed. This is due to the fact that the induced voltage is proportional to the speed, while the counter torque is proportional to the current. The current is a function of voltage and resistance. Therefore we were unable to check the transition between operating points.

$$V \sim \omega \quad I = \frac{V}{R}$$

$$\tau \sim I \qquad \tau \sim \frac{\omega}{R}$$

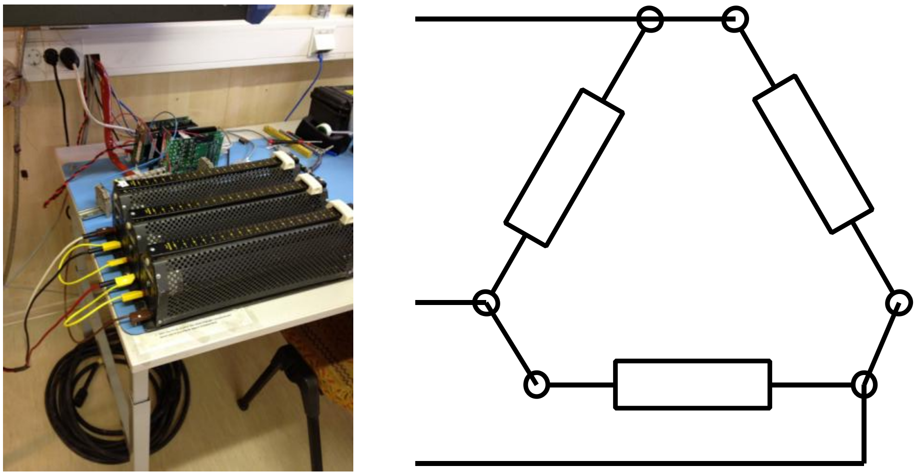


Figure 25 Resistor setup

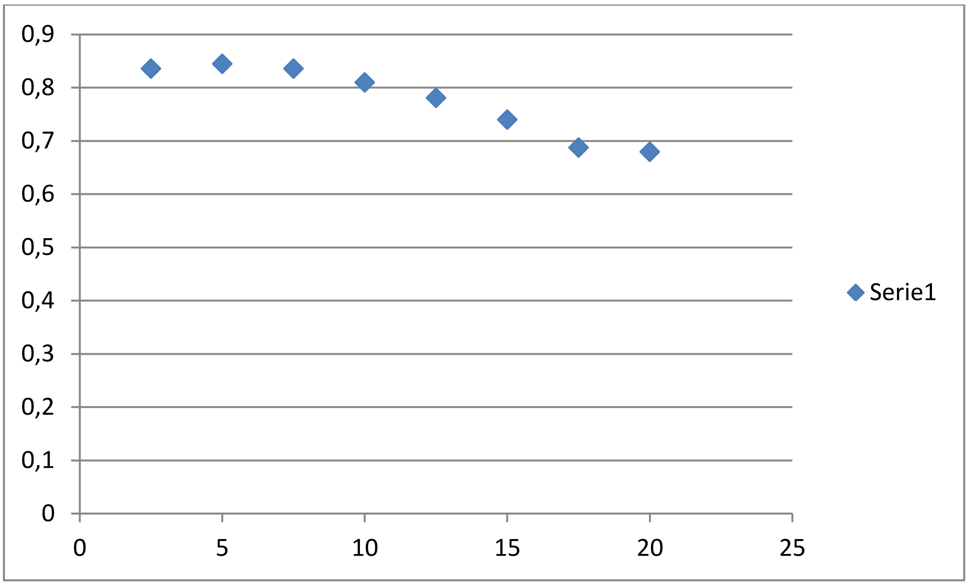


Figure 26 Efficiency as a function of torque of the old engine at 300 rpm, 31,55 km/h as it was in2011

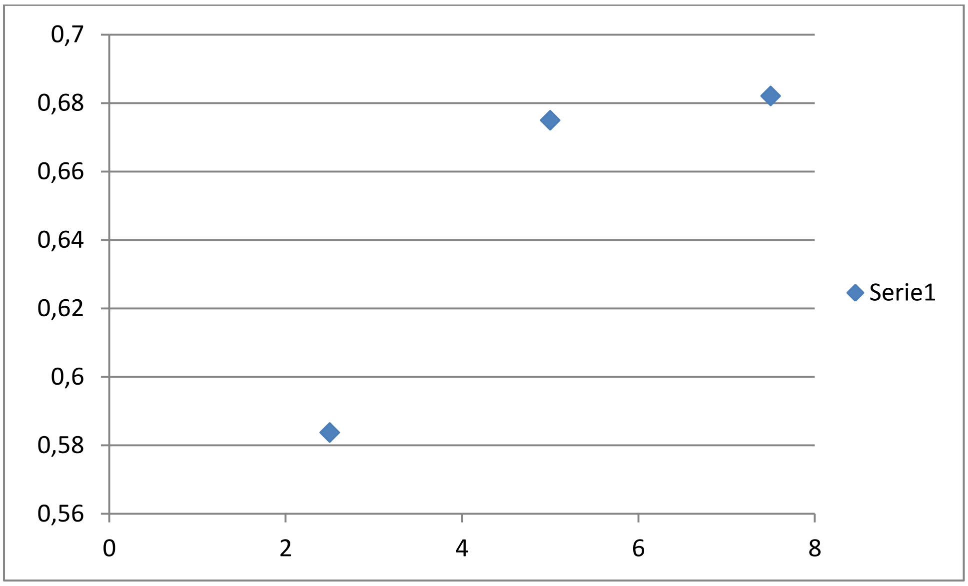


Figure 27 Efficiency as a function of torque of the new engine at 257,5 rpm, 26 km/h with the smallest obtainable air gap

As shown in figure 27 and figure 28, the efficiency of the new engine was not as high as the old engine. The measurement is not performed at the same speed due to lack of time. However there was no reason to assume that the new engine would be more efficient than the old engine at the necessary torque and speed without a new stator being constructed. The new engine was designed for an efficiency of 97,2 % so there is a great potential in further development. Due to limited time, the decision was made to race with the old engine.

The efficiency of the drive train is limited by two factors. First, $\tau = B \times I$. This can be used to increase the efficiency of the engine by reducing the air gap. Also, the back induced voltage of the machine is $e_{ind}=n\times B\times l\times v$[v] and that the maximum permitted voltage on board the car is 48 volts[vi]. The engine controller also needs a difference of a few volts in order to run the control algorithms[vii]. This means that lowering the top speed would increase the engines efficiency. This would not necessarily be a wise choice as the necessary top speed was unknown.

Modifying the old engine

As suggested in the report from the specialization project[viii] the back-up plan in case the new motor failed was to use the existing engine with a decreased air gap. The old engine was therefore modified. The spacer ring used in 2011 had been prolonged in the axial direction due to the voltage drop from the fuel cell which was used then. It was therefore believed that a battery should have been able to supply a more load independent voltage. The project had been sponsored by two suppliers of with different batteries. It turned out that the battery pack with the highest number of Ampere hours had a significant voltage drop. This did not occur at high load as with the fuel cell but somewhat in correlation with the energy delivered. To this problem one could either accept that it is not be possible to obtain higher speeds towards the end of the race or one could increase the air gap hoping that the reduction in back induced voltage would counteract the increased copper losses in order to maintain the necessary speed. It was chosen to increase the air gap and this withstood simple testing.

Figure 28 Battery used during racing

It was later discovered that the other battery pack had a much lower voltage drop. Unfortunately this battery pack had a lower energy capacity than the first battery. A third battery pack was therefore ordered, which had twice the capacity of the second. This was done shortly before the race and there was a great deal of uncertainty of whether it would be delivered in time. This battery was delivered to the team members transporting the DNV Fuel Fighter 2 down to Rotterdam when they passed through Oslo.

Race performance

Figure 29 DNV Fuel Fighter 2 during racing

The race took place on city streets in Rotterdam. There were five turns, a bumpy road and at times there was a lot of traffic. A total of 30 participants were allowed on track at any time. Also the ten laps, each 1617 meters, had to be completed in 39 minutes with a complete stop in between each lap. This means that a lower top speed would require a higher acceleration in order to make the race within the time constraint.

The first two test runs failed. The car had not been tested under windy conditions so when the car was accelerating facing the wind, this required more current than the battery was able to deliver. The battery management system therefore shut down and the car stopped. This was solved by rewriting the code in the acceleration program to have a lower acceleration.

As a result of this, the DNV Fuel Fighter 2 had the lowest acceleration of all the urban concept cars. This made it very difficult for the driver to have an optimal position relative to the other cars. The DNV Fuel Fighter 2 was overtaken by the other cars after the stop due to the low acceleration, but it had better suspension than the competitors. This allowed a higher speed while cornering and the DNV FF2 was therefore much faster than the other cars after cornering and would overtake them then.

At the necessary cruising speed of 36 km/h the necessary torque was 7,5 Nm. The maximum torque for acceleration was 18 Nm.

In the competition we had 4 attempts and only the best result mattered. The first attempt had to be aborted due to a door failure. The second attempt was valid with a result of 136 km/kWh. This attempt was however very unsuccessful as the driver, due to poor communication and confusion concerning responsibility within the team, drove eleven laps instead of ten. Before the third attempt, the car was stripped down to the absolute minimum of equipment to save weight.

Also the engine was modified. Since the engine had an air gap adjusted for the first battery pack with a high voltage drop, the air gap was reduced to better match the second battery pack with a more stiff voltage. This was done by first reducing the air gap, then using a drill to spin the engine at nominal speed, measure the back induced voltage and implement the new parameters in the engine controller.

The third attempt went without any problems and the energy consumption was equivalent to 163 km/kWh. No changes were made to the engine nor rest of the car before the fourth and final attempt. The fourth attempt did however fail as the steering broke in the middle of the race causing the car to crash. Nobody was injured in the crash.

The final result of 163 km/kWh held to a fifth place in this category.

Suggestions for further work:

The new motor is operational but it is not as energy efficient as it should. This could be greatly improved by making a new stator. Experience shows that the stator width can be reduced. A rough estimate would be from 8,7 mm to about 6 mm. Also the wires should not be taken out of the stator cast. Instead the wires should be soldered onto connection rings that are casted into the mold. When the cast has cured, one can drill away the epoxy to free these rings and thereby connect the windings without using too much space in the axial direction. It is also recommended to keep all twelve wire ends available for connections as this makes it easier to make changes if mistakes are made. Another advantage of this is that the windings can be connected in parallel instead of series as they are now. This would allow a higher current and thereby a higher torque. This could be useful during acceleration.

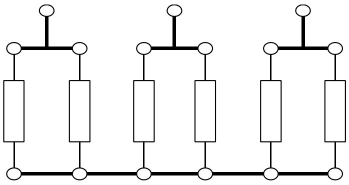


Figure 30 Possible winding arrangement

Soldering the wires to connection rings also makes it easier to perform tests on the windings. One test that is interesting is the Megger test. Here we apply a high voltage across two windings that are not connected and measure if there is any current flowing. This is interesting when working with litz wire since one may here have a partial short circuit. For this project it was impossible to perform this test as the insulation of litz wire was removed in the process of soldering the wires together.

The open casting method is recommended. When designing the mold for open casting the mold edge setting the circumference of the cast should not be perpendicular as in this project. The mold opening should be wider at the top allowing the cast to come out of the mold without breaking it. This mold design will be harder to make but has the benefit of being reusable.

One severe issue with the existing drive train is the moment of inertia of the motor. The old motor consists of big magnets and a heavy iron ring placed for away from the axle. This makes is easy for the engine to create a high torque but it also gives a high moment of inertia. The new engine has a lower total mass with smaller magnets and no iron. The problem with having a high moment of inertia is that it requires a lot of energy during acceleration. In 2012 the competition had a shorter track than before and the driver had to do more laps with a complete stop in between in each lap. This made it more necessary than ever to reduce the needed energy for the acceleration process. Ith is therefore highly recommended to make use of the new engine. Another problem is that the engine controller at low speeds, typically less than 0,2 per unit, controller draws a large current. The engine controller should therefore be investigated.

Finding funding

The most important testimony from the team manager of 2011 was "Sponsors are the crucial basis of the Shell Eco-marathon project. They have to be convinced to join through a professional approach and by creating value for them."[ix] With regards to the engine development this became especially clear. The reason for this is that the project started out with an operational motor. The first budget estimated a cost of 200'000 NOK for the development of the new engine. This was a development which would have been cut had there not been proper funding. It was therefore a high priority for the engine designer to find the funding for the project.

Det Norske Veritas (DNV) originally contacted the team stating that they wanted to be main sponsor for the project. They presented a list of demands and suggested an amount of money that they would sponsor the project with. The amount was the same as they had sponsored the earlier teams with the past three years. The team could not accept this as a new car was to be built. The project was considered to be more costly but also more valuable than previous years. The candidate was by the team selected to handle negotiations with DNV in order to increase the funding. Through negotiations and with a longer list of criteria DNV accepted the new amount and became the teams main sponsor. The team obligated themselves to get knowledge of the DNV methods for qualification of new technology and to take part in several events for DNV.

Figure 31 DNV Fuel Fighter 2 with all sponsor logos

The team also searched for support from other institutions. A lot of companies were contacted and several showed interest. Major technological companies often had some similar projects but in an industrial scale. A typical approach was to find the part of the company working with mobility through the company's website and then call them by phone asking for this department. The project was then presented. It was emphasized that it was a master project with a team consisting of 14 members. The point of this was to show the company that the project had a good starting point. Next, a specific problem was presented. This could be lack of knowledge about engine control, the need for electronic equipment or simply a motivational speech by one of the companies experienced engineers. At the end financial support was mentioned. The theory behind this was to create a sense of interest and ownership for the companies. The candidate believed that there would be a higher chance of getting financial support if one asked for something practical within the company's product range. Due to lack of time and personnel no theory was studied before making these sponsor calls. Every call was followed up by an e-mail containing a well designed presentation of the project and a short summary of the call.

However the calls were often unsuccessful. This was mostly due to the fact that companies budgets are made a long time in advance and there was not enough flexibility to sponsor a student project with hundreds of thousands of NOK with only months to realization.

With Transnova this was quite different. Transnova is a project under the Ministry of Transportation working with the goal to reduce emissions from the transport sector. They have for the recent years been given an amount of money to distribute every year. When Transnova was contacted they had recently been granted funds for the 2012. Their websites states that they will work for the development of cleaner transport technology, testing of this technology and the increased use of environmentally friendly means of transportation. The project therefore had three major selling points: First, this was a research project to make a new fuel efficient car without any emissions. Second, DNV who specializes in verification was all ready main partner. Third, there was a student working to get this out to the media which would then show the public the potential of electric vehicles. As result of this the project was granted a large amount of money by Transnova with the criteria that Transnova would get proper profiling on the car and that the team would appear at a specific event for zero emission vehicles.

Discussion

The new engine was designed for an efficiency of 97,2%. The limited amount of measurements makes it difficult to say how successful the engine really is. The motors efficiency of 68% at 7,5 Nm and a speed of 247,5 rpm is not really comparable. Since the car needed a cruising torque of 7,5 Nm at 36 km/h it is actually irrelevant what the efficiency would be at 3,5 Nm and 25 km/h.

The results from the race do however show that the overall performance of the car works very well. The decision to race with the old engine was necessary since the car needed to be tested as a complete system. This is evident as the troubles with the door, steering and wind needed to be discovered. Any more development on the car would have led to a shorter testing period and could thereby have led to even more problems. Had there not been sufficient testing time it is doubtful whether the car would have achieved a valid result.

It can be difficult to find optimized parameters for the engine. This is due to the problem mentioned with balancing efficiency and top speed. There is a great deal of uncertainty related to on track issues such as wind, rain, competing cars on the track itself.

In regards to the production, much can be learned from this project. Among the most important is the assembly of the Hallbach array. Since there is no iron in the new engine the magnets will only be attracted to each other. It therefore important to know that the naturals state of a Hallbach array is not in a single plane as this thesis shows. A plane Hallbach array needs extra forces that must be accounted for when designing these types of machines. The solution chosen here with magnets glued directly on the carbon fiber rotor plates works well. It is very likely that the thickness of these plates can be reduced. That was not done in this project as reliability was an important aspect.

Conclusion

From this project one can learn a lot about practical engineering. Concerning the Hallach array it is evident that it is not difficult to assemble given that one has thought of the necessary equipment beforehand. When handling the array it should not be exposed more than what is necessary. All ferromagnetic material must be kept in a safe distance.

From the stator production it is clear that a simple casting method is preferable. The vacuum mold was kept as simple as possible but it still had several potential vacuum leaks. Connection points should be easily accessible for testing and modifications. This will also make the production easier if planned properly.

Finally the new motor has a much lower weight and moment of inertia than the old motor. When the correct air gap distance is achieved it is likely that the new engine will contribute to great results for this type of project.

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Appendices

Appendix 1 – Safety precautions while working at Smart Motor

Appendix 2 – Magnet properties for different magnet grades

Safety rules concerning student activities at Smart Motor related to Shell Eco-Marathon

The work related to engine development includes risks. These risk will in this document be identified, evaluated and safety measures will be determined.

Risk	Consequence	Likelihood	Safety measures
Engine parts detaching from engine	Flying pieces, damage to personnel and equipment	Medium	Engine will be placed in protective box, out of reach from personnel during testing
Battery short circuit	Heat, sparks and explosion	Very low	The battery will be placed away from the personnel. It will also have a fuse and the personnel will have an emergency shutdown button
Engine starting during mounting	Personnel injury	Low	The engines power cables shall not be connected when engine is being mounted
Other hazards	Unknown	Low	The personnel shall have clear access to emergency exit at all time and be familiar with fire extinguishing equipment.

NEODYMIUM SINTERED

Grade	MAGNETIC PROPERTIES											
	Corrosion stable option*1	Remanence Br (mT)		Normal coercivity HcB (kA/m)		Intrinsic coercivity HcJ (kA/m)	Max. energy product BHmax (kJ/m³)		Br temp. coefficient*2 (%/°C)	HcJ temp. coefficient*2 (%/°C)	Max. operating temp.*3 (°C)
		min.	typ.	min.	typ.	min.	min.	typ.			
N 35		1170	1220	836	891	955	263	279	-0,12	-0,6	80
N 38		1220	1260	836	891	955	279	303	-0,12	-0,6	80
N 40		1260	1300	836	891	955	303	318	-0,12	-0,6	80
N 42		1300	1330	836	891	955	318	334	-0,12	-0,6	80
N 45		1330	1370	836	891	955	334	358	-0,12	-0,6	80
N 48		1370	1410	812	859	875	358	382	-0,12	-0,6	70
N 50		1410	1440	812	859	875	382	398	-0,12	-0,6	70
N 52*		1440*	1470*	812*	859*	875*	398*	414*	-0,12*	-0,6*	70*
N 33 M		1140	1170	812	859	1114	239	263	-0,12	-0,6	100
N 35 M		1170	1220	836	891	1114	263	279	-0,12	-0,6	100
N 38 M		1220	1260	859	915	1114	279	303	-0,12	-0,6	100
N 40 M		1260	1300	859	915	1114	303	318	-0,12	-0,6	100
N 42 M		1300	1330	859	915	1114	318	334	-0,12	-0,6	100
N 45 M		1330	1370	859	915	1114	334	358	-0,12	-0,6	100
N 48 M		1370	1410	859	980	1114	358	382	-0,12	-0,6	90
N 50 M		1410	1440	859	980	1114	382	398	-0,12	-0,6	90
N 30 H		1080	1140	780	812	1353	223	239	-0,12	-0,6	120
N 33 H		1140	1170	812	875	1353	239	263	-0,12	-0,6	120
N 35 H		1170	1220	836	891	1353	263	279	-0,12	-0,6	120
N 38 H	N 38 H/S	1220	1260	859	915	1353	279	303	-0,12	-0,6	120
N 40 H	N 40 H/S	1260	1300	859	915	1353	303	318	-0,12	-0,6	120
N 42 H	N 42 H/S	1300	1330	859	915	1353	318	334	-0,12	-0,6	120
N 44 H	N 44 H/S	1330	1360	859	980	1353	334	350	-0,12	-0,6	120
N 46 H	N 46 H/S	1360	1380	859	980	1353	350	366	-0,12	-0,6	120
N 48 H	N 48 H/S	1380	1410	859	980	1353	366	382	-0,12	-0,6	120
N 30 SH		1080	1140	780	812	1592	223	239	-0,11	-0,55	150
N 33 SH		1140	1170	812	875	1592	239	263	-0,11	-0,55	150
N 35 SH	N 35 SH/S	1170	1220	836	891	1592	263	279	-0,11	-0,55	150
N 38 SH	N 38 SH/S	1220	1260	859	915	1592	279	303	-0,11	-0,55	150
N 40 SH	N 40 SH/S	1260	1300	859	915	1592	303	318	-0,11	-0,55	150
N 42 SH	N 42 SH/S	1300	1330	859	915	1592	318	334	-0,11	-0,55	150
N 44 SH	N 44 SH/S	1330	1360	869	915	1592	334	350	-0,11	-0,55	150
N 46 SH*	N 46 SH/S*	1360*	1380*	869*	915*	1592*	350*	366*	-0,11*	-0,55*	150*
N 28 UH		1040	1080	780	812	1989	199	223	-0,11	-0,55	160
N 30 UH	N 30 UH/S	1080	1140	796	844	1989	223	239	-0,11	-0,55	160
N 33 UH	N 33 UH/S	1140	1170	812	875	1989	239	263	-0,11	-0,55	160
N 35 UH	N 35 UH/S	1170	1220	836	891	1989	263	279	-0,11	-0,55	160
N 38 UH	N 38 UH/S	1220	1260	836	915	1989	279	303	-0,11	-0,55	160
N 40 UH*	N 40 UH/S*	1260*	1300*	859*	915*	1989*	303*	318*	-0,11*	-0,55*	160*
N 28 EH		1040	1080	780	812	2387	199	223	-0,11	-0,55	180
N 30 EH	N 30 EH/S	1080	1140	796	844	2387	223	239	-0,11	-0,55	180
N 33 EH	N 33 EH/S	1140	1170	812	875	2387	239	263	-0,11	-0,55	180
N 35 EH	N 35 EH/S	1170	1220	836	915	2387	263	279	-0,11	-0,55	180
N 38 EH	N 38 EH/S	1220	1260	836	915	2387	279	303	-0,11	-0,55	180
N 28 AH*	N 28 AH/S*	1040*	1080*	780*	812*	2787*	203*	218*	-0,11*	-0,55*	220*

*Under development, not in mass production

*2 Indicative values assuming linear relation; for real temperature behaviour ask for our typical hysteresis curves
*3 Reference value for $\frac{L}{D}$=0,7; real values depend on magnetic circuit design

***1 Corrosion stable grades:**	
Standard	PCT test: P=2,0 atm, RH=100%, 120°C, after 7 x 24 hours, weight loss < 5mg/cm²
Alternative	HAST test: P=2,6 atm, RH=95%, 130°C, after 4 x 24 hours, weight loss < 3mg/cm²