NTNU
Norwegian University of
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Shell Eco Marathon

Electric Drive for World's Most Fuel Efficient Car

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Problem Description

A motor for the Shell Eco Marathon car must be redesigned to match the onboard voltage. Also consider improvements in the design, such as individually controlling each winding.

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Supervisor: Robert Nilssen, ELKRAFT

Shell Eco Marathon 2009
Electric Drive for World's Most Fuel Efficient Car

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In Cooperation with SmartMotor, Supervised by Robert Nilssen

A direct driven permanent magnet synchronous machine with concentrated windings is optimized with respect to system efficiency. The goal is to win the European Shell Eco Marathon Urban Concept group using a hydrogen fuel cell and an electric motor. Considerations such as on-board energy storage, a freewheel for coasting, winding design and connections are taken into account. The result is a machine with higher efficiency at all loads and an optimal operation point at cruising speed, obtaining 93% efficiency. Considerations for further improvements in both power electronics and motor design are presented, along with a new philosophy for making very slow PMSM CW machines with multiple phases, both yielding higher efficiency and smaller requirements to structural stiffness.

Shell Eco Marathon, FuelFighter, PMSM CW, THD, efficiency, multiphase

I. Introduction

NTNU participated their second time in the European Shell Eco Marathon hydrogen Urban Concept class, this year with ambitions of breaking 1000 km per liter[1]. Four master students started orchestrating the rebuild of the car fall 2008, then six more master students joined at new-year.

All parts of the car were gone through in search of increased efficiency, minimized resistance and decreased weight. The basic shell from last year was kept, but it went through major aerodynamic and mechanical improvements, thus reducing drag, friction and weight. Last year's fuel cell and drive train were taken out and replaced. H2logic supplied a superior fuel cell having better efficiency at the actual cells, but also not requiring a compressor to run.

Last year's electric drive consisted of a model airplane BLDC machine connected through a freewheel to a nylon gear running on the inside of the rim. It was estimated to 70% efficiency before the gear, and the gear having 97% efficiency. I was asked to enter the project in December - the race takes place in May – but in cooperation with SmartMotor, an existing machine was rewound to our voltage needs and installed in time for the race.

II. Load Model

Modelling the load correctly is the fundament for optimal motor design. This was done by Anders Gellein in the fall semester. There were some uncertainties about the track as the competition was moved from the Nogaro Circuit in France to the Eurospeedway Lausitz in Germany, and it actually turned out that the track was stickier than previously. Many competitors came short of their previous records.

The Urban Concept group uses the inner parts of the track, doing turns and slopes, but they must also make three stops lasting ten seconds each. According to Anders' model, 92% of the resistance would come from drag, (if the aerodynamics were unchanged) and the remaining 8% from rolling friction. Both are speed-sensitive, meaning that the car should drive as slowly as possible the whole time, approximately 24 km/h.

Acceleration from standstill should be quick so as to save time and lower the cruising speed, but a limit should be set so as not to blow the fuse or overloading the fuel cell. The structural integrity of the car must also be taken into account. Approximately 20 Nm on the 17" wheel gives reasonable acceleration and is more than enough to keep the speed up in the slopes. If the drive efficiency were unchanged, the mean consumption would be 130 W, peak consumption 300 W and there would be sections that the car could roll or use regenerative braking.

III. On-board Voltage

There are two separate electrical circuits on board; one using batteries to open valves and one supplying power from the fuel cell to the inverter. Only the power circuitry is taken into account in this report, regarding the fuel cell, DC rail voltage, and the inverter output voltage.

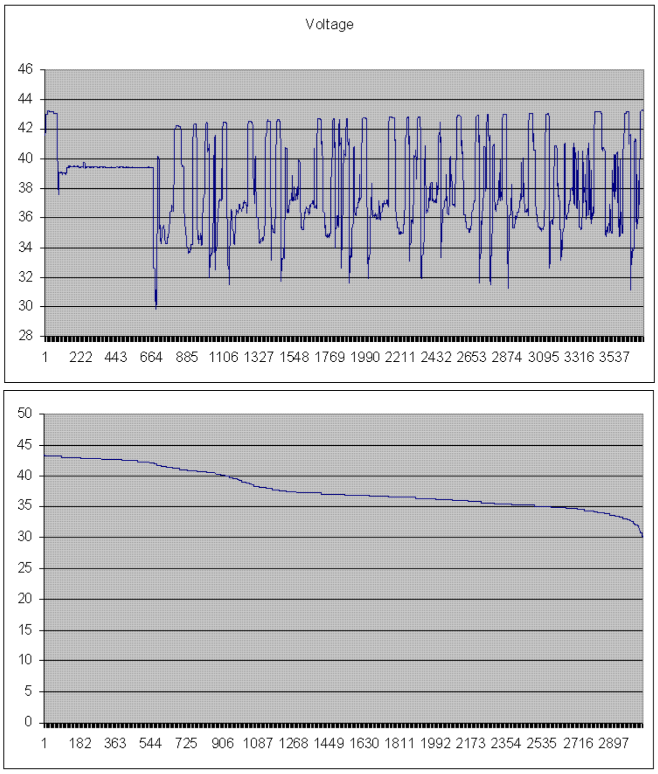
One of the main improvements for this year was avoiding a compressor, air moisturizer and extra cooling systems, leaving only two degrees of freedom: number of cells and their area, affecting the DC voltage and current capability respectively. A high voltage would be desirable to avoid resistive losses, but 48 V is the upper limit at the competition. Hydrogen can be purged through the cell, and to leave some margin in case of a control measurement at idle, the maximum voltage was set to 46 V.

Fuel cells polarize, meaning that as the output current increases, the voltage decreases. Efficiency also decreases

[1] Comparing the energy of one liter of 95 Octane gasoline to the amount of hydrogen spent, actually driving 25 km in less than 53 minutes for each race.

when current density increases, so an as-large fuel cell as possible was chosen. Operating conditions limited the capacity to 1600 W (continuous), yielding an on-board voltage of 32 V at full speed full power, 28 V at the largest acceleration, and 37 V at average running from laboratory results.**Error! Reference source not found.**

The lab results and load model proved to be quite accurate when race data was analyzed. Acceleration voltage only dropped to 29.8 V, which is explained by the capacitive effect of the fuel cell. Average running voltage was 37.9 V.



Figur 1 - DC voltage race 3

These two figures show the DC voltage at the fuel cell. The upper one is unsorted race data also showing the 10 minutes of running before race start. The lower figure uses the values only from the race in sorted order. The X-axis values show seconds – one sample is taken per second.

A DC current measurement was supposed to be installed as well as this voltage measurement, but because of difficulties in making the fuel cell control software there was simply no time to implement it – nor was it crucial to our performance at the race. The current can be roughly estimated from the polarization curves of the fuel cell, but according to the team's chemist, this would be too dependent upon loading time, temperature, humidity and other factors.

IV. Freewheel System

Running the motor at idle requires a significant amount of energy, and depending upon whether the motor is in "running state" or "stop state" this resistance is equivalent of 32 W and 14 W. Changing motor state and sending the speed word takes one second, requiring using the "flying start" mode. It was estimated that the car would be able to roll 15% of the track (the voltage profile above shows 17% rolling) thus reducing the power use while rolling was a very important task. The following options were considered:

A. *Bicycle Freewheel*

Road-bike freewheels are known for their extremely low friction. They operate by small spring-loaded teeth that glide one way and lock the other way against the hub, which has tracks for these teeth to lock against. There is a finite number of locking positions, and this presents a challenge when an electric motor is coupled to an axle through this kind of mechanism. The motor will start from standstill and increase its speed to the same speed of the wheel – but it will have to go slightly faster than the wheel in order for the teeth in the freewheel to lock. When the locking is accomplished, there will be a knock on the axle, potentially destroying the freewheel, axle and rims. (The rims are especially fragile, being made out of carbon fiber and only weighing 800 g each.)

A simulink model was developed to show the energy released to the axle at the moment of coupling so the rotor and wheel would have the same speed. If accepting 5 second spinup-times, this energy would be in the magnitude of one to two joule.

The coupling energies would get larger as the wheel speed increased. To minimize the spinup time, a solution using a speed dependent speed ramp was plotted. Variables in the motor control can be accessed from outside, so in a spinup situation, one could measure speed and set a new acceleration value many times per second. A system like this would reduce spinup times from 5 to 2 seconds, given that the same energy could be delivered to the axle at any speed. The speed and speed ramp became exponential functions.

Another approach is to measure wheel speed. Motor speed can be increased quickly up to near wheel-speed, then gently until contact is made.

Both our approaches would complicate the system a lot, thus increasing the risk of not making it to the start line. Another major factor is that the drive wheel sits on the right side of the car – mounting a bicycle freewheel would require the drive wheel to be moved to the other side. This was out of the question as last year's motor which was our backup was on that side.

B. *Locking Bearing*

A locking bearing is similar to a bicycle freewheel as they both rely on locking teeth, but the locking bearing is smooth on the inside. It has no play, and there is no risk of obtaining a speed difference between the rotor and the wheel. Ones that are made for 20 Nm are quite rare and expensive, but we had economic freedom to choose the best.

C. *Clutch*

The advantage of a clutch is that regenerative braking is possible, as well as the opportunity to roll. Several teams were seen using magnetic clutches at the competition, which require energy only to change state. This would probably be the ideal solution if the motor cannot be made to have less resistance at idle.

After these considerations, the locking bearing was chosen as the most suitable for our application. It worked very well for our application, the car rolled just as well as a bicycle if not better.

A future eco-vehicle might benefit from an iron-less motor as these have much lower losses at idle. This could possibly eliminate the whole freewheel system. For this project, the freewheel is mostly a nuisance in assembly but implies no major drawbacks in the car's functioning. The freewheel does not scale, so a commercial-size vehicle would benefit much more from an iron-less motor than us.

V. Energy Storage

There is a possibility of using a supercapacitor bank on board, smoothing out the voltage. Benefits are a more even load for the fuel cell and thus a higher efficiency and the avoidance of voltage drops for the motor thus enabling faster acceleration. It would also give the possibility for regenerative braking. Disadvantages are increased weight, more complex monitoring, and a diode must be installed to ensure no power is given to the fuel cell.

Regenerative braking has, according to Anders' model, a potential of increasing driving distance 250 meters per stop, and there are four required stops, extending range 1 km/l. The possibility of rolling 20% of the time rather than have the motor spinning all the time would extend range around 20 km/l. In addition comes the weight penalty.

A hypothesis was formulated, stating that eliminating the energy storage would make a voltage drop which would reduce the Total Harmonic Distortion between the power electronics and the motor, which could improve drive efficiency through the acceleration. This is discussed later.

VI. Motor Choice

A major improvement from last year would be the motor itself. The previous motor was a model airplane BLDC motor which was geared down 1:10 through a nylon gear directly on the wheel. Drive efficiency was approximately 70%, gear efficiency was assumed to be 97% but was never measured in full-scale. This was the best motor that was found last year, and no efforts were made to find a better motor of the same kind.

Due to the four-month time scale, designing a motor from scratch had to be ruled out. The Trondheim-based company SmartMotor was contacted, and luckily they could provide us with the existing SP300 from "Hugin" and its electronics, but we were advised to redesign the windings to suit our voltage application. The match was almost perfect:

The table column "ideal" is to compare what we might have made if we were to redesign for our specifications, running a PMSM at 50 Hz.

	SP300	Ideal
DC link voltage	18 – 48 V	26-46 V
Rated speed	176,5 RPM	256 RPM
Rated Torque	18 Nm	20 Nm
Magnetization	17 Pole-Pair Permanent Magnet	11 Pole-Pair
Phases	3, star connected	3, star connected
Windings	18 Concentrated Windings	12 Concentrated
Efficiency – drive	~88%	

The high pole count of the machine was, after considering the efficiency diagram, not going to pose any problem. The efficiency increases at higher than rated speeds for low loads.

Since a high-efficiency machine was available for direct drive, there was no reason (other than to save weight) to use a geared system. A quick and good solution had to be chosen because of the lack of time.

VII. Winding Design

Some background research was attempted, so as to quantify the importance of matching the voltage of the motor to that of the DC bus.[1-7]. Finding a relationship between switching harmonics and losses in PMSM is difficult; the best result was in [12] where the following expression was found:

$$\Delta P_{cu} = \sum_{h=2}^{\infty} (R_s + R_r) I_h^2$$

But because the resistances are extremely sensitive to frequency, and skin effect becomes significant at the switching frequencies, this expression is very difficult to evaluate.

A. *Current SP300*

Looking further into the SP300, the windings were connected 3 in series for each of the two parallel branches of each phase. The phases were connected into a single neutral, star coupling. Each of the windings had 31 turns made from 1.5 mm Ø copper wire.

Each of the stator slots measure 6 mm wide by 22.5 mm high. This gives a fill factor of 0.4058, not particularly impressive as the fill factor can reach 0.66 [14][13] using round wire.

Laboratory results from the original SP300 yielded the following values:

E_k = 0.0676 V / rpm back EMF line voltage, open loop

T_k = 1.119 A / Nm phase current at 1.55 pu speed, equivalent of 27 km/h

$P_{axle} = \sqrt{3}$*Vemf*Iph*cos(phi) - Piron = w * T

$P_{in,motor} = \sqrt{3} * V_{ll} * I_{ph} * \cos(\theta)$

R_{50} = 109.7 mohm

$R_{77.5}$ = 116.5 mohm

L = 3.1 +- 1.1 mH

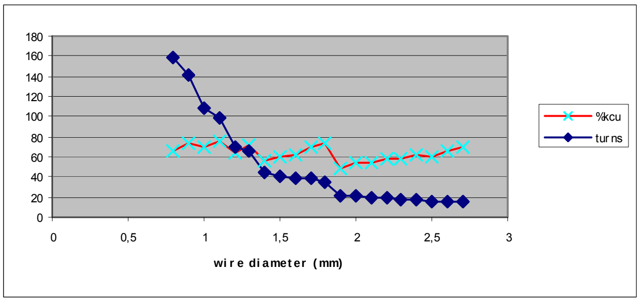
B. Rescaled version

The number of turns on each winding is modified to make the induced voltage as large as possible while maintaining the required output. The purpose of this is minimizing the ripple current at switching frequency, because high frequency ripple only turns out as loss in the machine.[1]

$$2\hat{V}_{ll} = V_{dc}$$

$$\hat{V}_{ll} = \sqrt{6} * abs(E + ZI)$$

Through scaling of the variables, we ended up at 42 turns per coil. Because of the stator slot geometry, copper fill would be larger if 38 turns were chosen - this was also more conservative as the motor would have more power at high speed because of the lower back-emf thus allowing more current to pass.



Figur 2 - wire diameter affects turn number and fill factor

The figure displays how the copper fill factor (in percent) is affected by the wire diameter and number of turns in the given geometry of the stator slots. Ideally a wire diameter 1.66 mm should be used, but this was not available in the workshop. If using the wire diameter 1.6, the winding would have 38 turns. If using 1.5, it could have 41 but a slightly lower fill factor. Both were made and the 1.6 mm wire was chosen in the end for practical reasons.

Winding two parallel wires is also a possibility, but it was not tested because of time constraints. The copper fill could potentially be raised to .7 if thinner wire were used, as opposed to .6 with a single wire.

C. Copper Fill Relation to Efficiency

One of the main goals in machine building is to pack as much copper as possible into the stator slots to reduce copper losses. Let E be the voltage drop over each wire in a particular stator slot V/m, and J be the current density for the whole slot A/m^2. Sigma is the resistivity of copper, ohm*m, A is the area of the stator slot.

$$J = \frac{NI}{Ak_{cu}}$$

$$E = \sigma J$$

$$P_{cu} = E\,J\,Vol\,k_{cu}$$

$$P_{cu} = Vol\,J^2 \sigma\,k_{cu}$$

$$J = \frac{NI}{A}$$

$$P_{cu} = \frac{Vol\,\sigma}{k_{cu}}\left[\frac{NI}{A}\right]^2$$

The losses in copper are inversely proportional to the copper fill factor given that the machine and materials otherwise are unchanged. Given that the machine has, for example, 88% efficiency and only copper losses are considered, increasing the copper fill factor from 0.4 to 0.6 can increase the efficiency to 91.7%. Increasing copper fill to .9 can increase efficiency up to 94.6% given that all other losses are ignored. If considering other losses, the potential for improvement would be smaller. These example values match the original machine, the produced machine and an ideal machine. A fill factor of 0.9 can be produced by compacting a winding made of round wire, and it is also achievable using rectangular wire.(ref: Roberts artikkel om dette)

VIII. Parameter Estimates for Motor Controller

A day's work was put into finding the motor parameters as accurately as possible, so that the estimator would have the correct information and function properly. This could possibly help keep the power factor closer to unity. Motor parameters were both calculated as a scaling of the existing parameters and measured with appropriate instruments. Scaling was considered the most accurate, as the inductance varies a lot with rotor position.

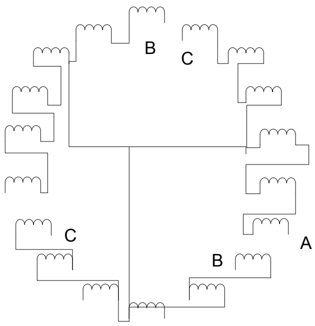
When the new parameters were loaded, some very surprising behavior occurred when running the motor: The motor would spin up normally to 1.5 pu speed, but setting the speed lower caused the machine to spin up to approximately 2 pu speed for about ten seconds, then coming to such a sudden stop that the jig jumped.

An integrator somewhere deep in the inner workings of the motor controller might have been very sensitive about some parameters. The old parameters were uploaded and the machine worked fine again – but one should make note of this phenomena when considering rescaling machines running in-house software and power electronics!

IX. Machine Connections

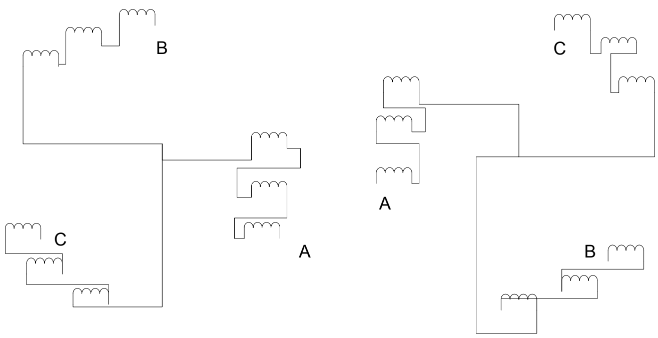
The SP300 consists of 18 windings, which are made into three phases. Three coils are placed in series, and put into parallel with the opposite side's series as shown in the upper diagram. The neutral ends are put together in a wye connection.

Circulating currents can be caused by different induced voltages in the series pairs for many reasons: The motor can be off-centre, causing higher voltages on the side with the least air gap; magnet strength can be slightly different; there can be a fault between two wires in a coil. It is an easily avoidable problem as the parallel connection can be skipped by making two neutral points.



Figur 3 - all phases connected in a single wye

The single neutral point has its benefits: there is a very short distance between the different coils, so a relatively thin wire can be used to connect the three connections thus making the fault rate low in the assembly. Splitting the machine can be done in two ways, either using three coils from the same side, or using every second coil. If rotor alignment is the problem, using coils from the same side can be just as bad as using a single neutral point. Using the method depicted in the lower drawing solves this potential problem, and was the chosen alternative for this machine.



Figur 4 - two sets of wye connections to avoid circulating current

If the machine were perfectly aligned, the dual neutral point would actually increase losses, so to defend this decision some estimates were made. Measurements show that the induced voltage could vary up to 5% in magnitude between the phases on a healthy machine with a single neutral point. This variation can be assumed to be valid for each parallel phase branch also.

Using new machine parameters, and the machine running at 1 pu speed and torque, equivalent of 50 Hz and 18 Nm, loss calculations are performed. The following calculations are only illustrative to show how little the dual neutral points matter in a *healthy* machine, assuming 5% difference in the magnitude of the parallel sets of voltage.

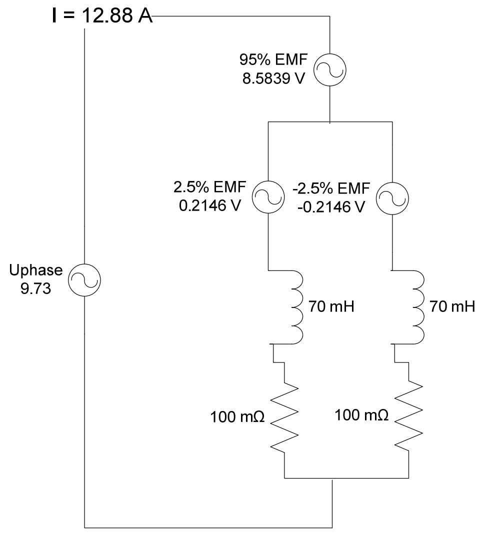
The circulating current I_circ is easily found in the following circuit.

Icirc = 0.0098 A

Pcirc = $Icirc^2$*R*2

Pcirc = 0.002 W per phase

There is a possibility that the introduction of the dual neutral points account for more loss in the wires than the circulating current losses!



Figur 5 - schematic showing the circulating current path

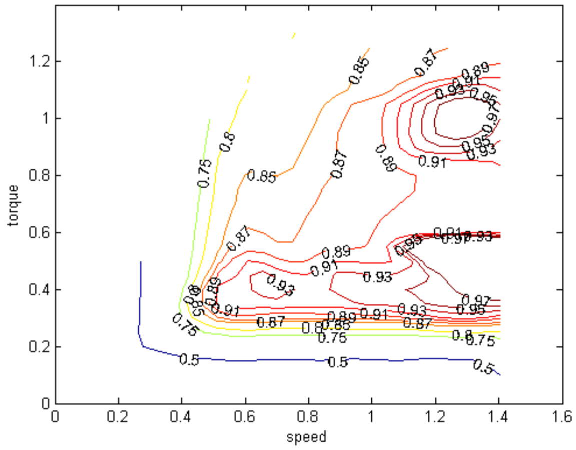
At this point, other factors came into account. While building the machine, earth faults were occurring very often. If they were to occur while in Germany, half of the machine could be disabled so it could run fault-free. It would be hard to take it apart and also hard to fix the fault – the machine would still be running more efficiently than our model flight backup motor from last year, and it would be faster to do this modification.

The whole car as a system was not test run before we had to leave, and instead of bringing another machine as a load, the dual neutral points allowed us to stress-test the car at standstill using resistors as load for half the machine and running the other half normally. This mode of operation was rather noisy and could quite possibly damage the magnets and bearings, because the field picture gets very ugly when trying to force almost twice as much flux as the machine is designed for through one sixth of the stator teeth. This stress-test was performed for an hour, and fortunately the machine did not seem to have taken any damage from this. Air circulation problems were uncovered by this stress-test; the motor control went too warm. Making two neutral points proved to be very useful for the team.

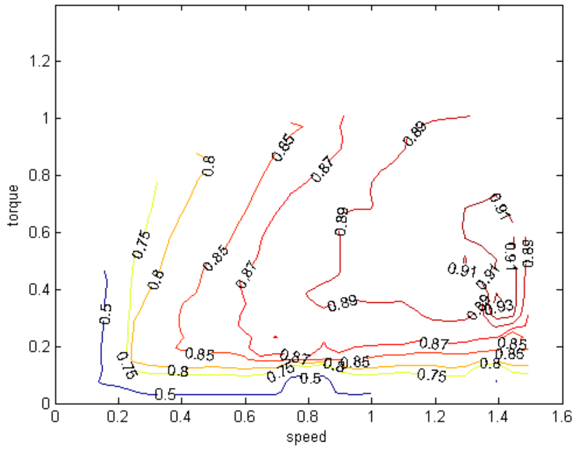
X. The Effect of Voltage Matching

To achieve the highest efficiency, the voltage of the motor was matched as closely to the DC link voltage as we dared. This was a decision more based on intuition than hard facts, as this field of knowledge is relatively undocumented for switching losses in PMSM-CW..

The number of turns was increased from 31 to 38, which in turn also increased the inductance. For lower than rated speed, the torque would increase as high as 20 Nm, increasing the current drawn from the DC link. The voltage from the fuel cell would then drop along its polarization curve, minimizing the difference between the dc voltage and motor voltage.



Figur 6 - motor efficiency when run at 48 Vdc



Figur 7 - motor efficiency when run from fuel cell (variable voltage

The hypothesis stating that motor efficiency would be higher with a variable dc voltage rather than a constant voltage held up by an energy bank is hereby confirmed. A harmonic analysis links this phenomena to the measured total harmonic distortion.

These show that the THD values decreased from 7% to 4% when voltage difference is minimized, i.e. running the motor from the fuel cell versus from the power supply at the same load conditions. This was not tested thoroughly as a clear hypothesis linking the current THD to machine efficiency never existed. It is suggested to perform further research in this area because no papers were found on this exact subject in the IEEE database.

There are many more ways to reduce switching harmonics; for instance the unipolar switching scheme can be used rather than the bipolar one. Furthermore the switching frequency can be increased, and finally a filter could be installed – these measures have traditionally been taken to increase longevity of the bearings but should also be considered for increasing machine efficiency or reduce cooling needs.

XI. Multiphase Machines

Some scenarios have been performed to analyze the benefit of adding more phases to a machine. Inverter controlled machines have no good reason to limit the number of phases to three [2] – especially not for concentrated winding machines – each winding may be controlled individually so that each of the coils sees a smaller phase angle. This would reduce the current required to produce a given amount of flux.

This short study has not taken the waveform of the induced voltages into account; these effects will probably vary given different machine design. A sinusoidal current is assumed.

A. SP300

The SP300 has, as previously stated, 18 sets of concentrated winding coils, 20° electrically separated. To make three phases, three series connected coils are put in parallel, but this implies that two of the three coils are operating at a 20° angle between current and induced voltage, given that cos(θ)=1 for all three of them. The required current to produce the same flux could be reduced, thus reducing losses in the machine itself.

“Nearly all the power dissipated in a MOSFET switch-mode power supply occurs when the device is in the on state and is given by

$Pon = Io^2 * r_{DS(on)}$. ”**Error! Reference source not found.** therefore increasing the number of phases should have no direct implication of the losses in the power switches.

The savings can thus be expressed as following:

$NI_{3phase} = N*I_{3phase} * (\cos(20°) + \cos(0°) + \cos(-20)) / 3$

$NI_{3phase} = N*I_{3phase} * 0.9598$

$NI_{9phase} = N*I_{9phase} *(\cos(0°))$

$NI_{3phase} = NI_{9phase}$

$I_{9phase} = 0.9598\ I_{3phase}$

$P_{cu} = RI^2$

Pcu

$P_{cu\ 9phase} = 0.9212\ P_{cu\ 3phase}$

For our particular machine, reducing copper losses (still assuming these dominate entirely) by 8% means an increase in efficiency from .9200 to .9258 – an increase of 2.8%. Given that the machine is large enough, this may represent a lot of energy but for the SP300 use in the FuelFighter car, the savings add up to ¾ W at 100 W output. The “60 degree philosophy” of Robert Nilssen apparently works very well for these small machines.

B. Concentrated Winding machines in General

It is interesting to see what would happen to a machine with more than three windings in series. The improvement in phase angle can be expressed generally as follows:

for odd numbers of coils per group:

$$\overline{\cos\theta} = \frac{1+\sum_{i=1}^{n}\cos\theta_i}{2n+1}$$

$$n = \frac{\frac{coils}{phase*parallel\_branch}-1}{2}$$

$$\theta_i = \frac{i*360^\circ}{coils}$$

for even numbers of coils per group:

$$\overline{\cos\theta} = \frac{\sum_{i=1}^{n}\cos\theta_i}{2n}$$

$$n = \frac{coils}{2*phase*parallel\_branch}$$

$$\theta_i = \frac{(i-\frac{1}{2})*360^\circ}{coils}$$

The reason for splitting even and odd-numbered coils per group, odd-number coil groups will have the middle coil centered, whereas even-number coil groups will have no single center coil.

C. Practical Implementation

As far as the author knows, inverters for many phases do not exist on the market, and they won't necessarily need to either. There are already generators operating on paralleled inverters, or inverters on separated neutral circuits, but they operate in phase. ScanWind and Wärtsilä have demonstrated such machines. Typically one of the inverters run on speed reference and calculate torque requirement. The rest of the inverters are controlled by torque reference.

Machines running on in-house inverters do not necessarily need several resolvers; if measurements are done on one of the three-phase connections, gate drive of the "slave" connections need only be delayed in time.

The implementation of multiple phase machines might be extremely simple in practice, but if using existing inverters it would be smart keeping to phase numbers which are multiples of three.

D. Wind Generator Scenario

The main benefits of the Multiple Phase Machine may not actually be one of efficiency alone, but of structural strength/weight savings, especially for very slow Axial Flux machines, for example for wind power. The benefit of multiple phases is much larger for these machines, as the following example will show:

Assume a machine is to be built for 22 RPM at 50 Hz, thus having 134 pole pairs in the rotor and 135 coils in the stator per flux pattern repetition. Also assume that if the machine is operating in three phase mode, its efficiency is .92. They are assumed grouped into 3, 9 and 15 phases[2]:

	3 phases	9 phases	15 phases
Average Cos(θ)	0.8271	0.9799	0.9928
Efficiency	0.9200	0.9417	0.9431
Losses (relative)	1.0000	0.7124	0.6940
Losses (relative)	1.4037	1.0000	0.9742
Losses (relative)	1.4409	1.0265	1.0000

[2] A MATLAB script has been made to compare different phase number options.

This model shows that it is most important to increase phase number when the original phase number is low, but also that there always will be a benefit in increasing the number of phases even further.

XII. Conclusion

Anders' load model from this fall semester has proved itself very useful and accurate. It has helped us focusing on the most important parameters which are efficiency first then weight – as opposed to last year. The result was a direct-driven motor weighing 12 kg but having an efficiency of up to 93%, rather than a 200 g motor with 70% efficiency. For redundancy, the last year's motor was kept compatible with the modifications and could easily be installed at any time if the new motor should fail.

The freewheel system that was chosen worked very well, but there is still uncertainty as to whether an on-board energy bank should be used for regenerative braking. Ultimately the free wheel should be eliminated through a new motor design which does not have such a high rolling resistance – but until then, the free wheel enables the car to roll approximately 15-20 per cent of the race time. If regenerative braking is wanted, a magnetic clutch should be considered instead of the free wheel – but it was observed that these mechanical parts unfortunately tend to break at the race. For a commercial sized car, an ironless stator design might be considered.

The floating on-board voltage posed no problem to the system; in fact it was a great benefit. The fuel cell was so over-rated (for efficiency purposes) that it had no problem supplying the car with enough energy during acceleration. The voltage dip seemed to have a positive effect on the motor efficiency, but likewise the high current loading has a negative effect on the fuel cell. Modelling these dynamics should be prioritized for improving the system as a whole. Choosing the optimal size energy storage and controlling power flow is a task that must be done if the team is to participate in the Urban Concept group again.

The motor might be improved by using parallel wires in the making of the coils so as to increase the fill factor and ease of construction. 1.6 Ø mm wire is very stiff and therefore makes higher coil heads requiring a larger chassis. There is also a possibility of compacting the windings in a press, deforming it further. The copper loss scales inversely with the fill factor, making this one of the most important considerations in motor design.

Splitting the paralleled coils into two neutral networks was unnecessary, and may even have degraded performance. The advantage is that half the machine could be run in case of failure, a very important feature at such a race. Paralleling connections should not be of great concern for machines of this size and mechanical tolerances.

Floating voltage directly from the fuel cell made the efficiency much higher at low loads and had no significant impact on the top load. Designers of future cars running on fuel cells or solar panels should take this feature into account, especially for city driving. The electrical drive is more efficient at low speeds when run at floating voltages. No work on this subject has been reported in the IEEE database.

Permanent Magnet Synchronous Machines with Concentrated Windings and high pole numbers should be considered split into many phases, not only three. A routine for estimating the benefit with respect to efficiency has been mathematically shown and programmed. Other benefits such as minimized forces also exist, though these have not been explored in this document. The SP300 did not have enough windings to benefit from this new design philosophy; it works well on the traditional 60° philosophy.

There was a new record set in the Shell Eco Marathon Urban Concept class. Not only did we break 1000 km/l which was our goal – we set the new record to 1246 km/l! This is 50% further than our nearest contestant in the hydrogen class. According to Shell's CO_2 footprint calculations, we even set a new world record with 2.6 g CO_2 / km. If the next year's team chooses to participate in this class, they ought to get 1500 km/l…

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I. APPENDIX

APPENDIX 1 - MOTOR ASSEMBLY

As the production of the motor was the most time consuming part of the project before the race, it is worth presenting some thoughts and findings in this text. It could save the next person building a machine of this design a lot of time.

A. Tools

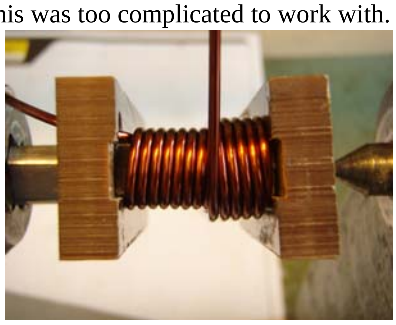
Some tools must be fabricated for the production of the windings. The winding is spun on a shape similar to that of the stator iron, mounted on an axle. This part has two pieces forming the edges. These are also mounted on the axle, and a nut is used to keep these together.

Two pieces were made to fit exactly into the form so the winding could be pressed together before removal.

When using 1.6 mm Ø wire, which is very stiff, the tools should be made entirely out of aluminum. Some tape can be used to protect the insulation. Wooden pieces are simply too weak for this size winding, and should be avoided.

B. Winding the Windings

Great care must be taken when placing the wire. Crossing of wires should only occur on one of the short sides so as to minimize winding width on the long sides which fit into the stator slots. For this particular winding, 13 turns were used in the bottom and top layer, while 12 turns were used in the layer between. Originally, 13 turns should have been used for all layers, but this was too complicated to work with.



C. Compressing

It is important to sufficiently compress the winding before removing it from the tool. This makes the long-sides flatter, the short side rounder and the wire more stable. It is important to compress as much as possible, but hammering is not advisable as it damages the insulation too much and consequently causes faults.

Before removing the winding from the form, it should be kept together with self-locking strips. This prevents the winding from getting too loose.

Approximately two out of three attempted windings were produced with success. The major problem was getting layer one and three laid out correctly, but other issues such as breaking the form also occurred. Because wood was chosen, new tools were remanufactured three times through the building process.

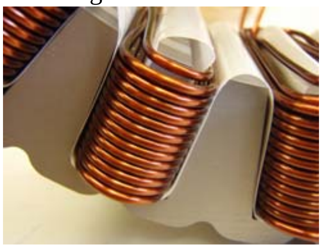
D. Mounting Windings into Stator

A stiff, thin plastic band called Mylar is placed into the stator to enable the insertion of windings. The stator is sharp and will easily take off all insulation causing earth-faults. It is important that the Mylar is sufficiently wide, 2 mm to each side of the stator is appropriate. If it is too long, it folds and exposes corners of the stator teeth, rendering itself useless. Too short, and winding movement will cause contact to steel.

On these particular windings, the thread enters in the center of the winding and exits on the opposite side. To avoid crossing problems, the winding should be placed such that the exit thread comes closest to the rotor. This ensures that the rotor won't conflict with the winding.

Getting the winding in place requires quite a lot of wiggling and perhaps also hammering. Once it's almost in place, another self tightening strip is attached to prevent the winding from moving out. Then alternate between light hammering and tightening the strips. Check if there is electric contact between the winding and the stator.

When all the windings have been placed, cut the wires equal length and remove some insulation. Measure the inductance and resistance of each winding to uncover faults between wires within each winding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As a note, 18 windings were finally used, seven had to be discarded after these checks. Of the seven replaced windings, one had to be replaced again, meaning the success rate of winding installation was 70%.

After installing the windings, the Mylar in the air gap covering stator iron should be cut loose. This can be done with a scalpel, but beware: when the blade breaks, it flies at great speed. Wear protection.

E. Gluing the windings in place

There was some discussion as to how the winding should be kept in place, and how this process was best done. The following alternatives are presented:

1) Glue-coated wire

Wire is coated with a heat-sensitive type of glue which melts and cures in the oven. This type of wire or coating was not available at our workshop, but would be the preferred method. The only potential problem is that the Mylar wouldn't attach itself to the stator iron, so some extra glue would be needed there.

2) Pre-gluing the windings

The first windings that were produced were glued and wound at the same time. It was not possible to mount these into the stator as they were not sufficiently compressed, and too stiff to place into the stator.

3) Spray lacquer

PRF 202 - Plastic Spray was recommended by Oddvar Landrø at the electrical workshop of NTNU. Each winding was sprayed, and the thin laquer worked its way through more than half the winding. Spraying from the other side then filled the winding completely. The spray seemed to work nicely, but was not hard enough and the windings started sagging out overnight.

4) Lacquer dipping and heat treatment

The normal procedure when producing stators is either to vacuumate then fill with lacquer, or simply dipping the stator. The lacquer must typically be heated to 80° for eight hours. A piece of plastic would have to be manufactured to fit the stator inner radius, and this would hold the windings in place.

The main problem was that all the vacuuming equipment was in use, making rims and body parts for the car. The dipping method was too inconvenient as we'd have to drive 20 minutes from where the stator could be dipped to get to our oven for heating it – the lacquer supplier had no ovens we could use.

5) Araldite Rapid (15 minute)

As an effort to save the stator which had been spray-glued, each winding was attempted glued with 15-minute Araldite. Glue was smeared on one winding at a time, then it was compressed with a piece of Teflon in a bench. It seemed to work nicely, but the next day it turned out the glue was too soft, and the windings were sagging again.

A large piece of Teflon was placed in the bench lathe and cut to the stator inner radius. The stator was then forced onto this piece of Teflon and placed in the oven at 80° for two hours (although rapid Araldite isn't meant to be cured). Since the main problem with the windings was where the wire entered and exited each winding, extra araldite was used to cover these areas. Unfortunately, this was made too high and thick and the stator no longer fit inside the chassis.

6) Regular Araldite

A new and improved stator was produced and mounted directly onto the Teflon mould. It was decided only to connect the series windings within the chassis, neutral point connections were to be made outside so the system could be easily reconfigurable. The stator was lifted so the mould only covered halfway up. Araldite was poured into the "bowl," which was spun around in all directions to make the glue flow into the windings. The windings were held solidly in place after curing.