Design and Optimization of an Axial and Solid Double-Inner-Rotor Configuration in PM Flux Switching Generators

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***Abstract*—Permanent Magnet Flux Switching Generators have gained interest over the course of the last years due to their robustness, simplicity and high power density. The permanent magnets are exclusively placed in the stator where they are safer from high rotation speeds and risk of demagnetization. These machines are however, not absent of drawbacks, seeing that they have increased torque ripple when compared to more commonly used generators.**

This dissertation is aimed at reducing torque ripple by optimizing the design of a double rotor permanent magnet machine where both rotors are similar but are phase shifted so that each rotor's force acts as a counteracting measure. Through theoretical analysis with complementary finite element method simulations, a series of machine topologies are tested in order to judge the most advantageous features, with emphasis on the subjects of torque ripple and generated electromotive force.

In order to make the most out of a double rotor configuration, a non linear contact rotor/stator combination is proposed as it enables for a better torque waveform combination and therefore a better cancellation.

The machine is to be coupled to a Boeing 767's engine, while functioning as a generator for its electrical load with a rectifier/inverter module serving as an intermediate for a stable output. The torque waveforms are then further analysed in load conditions as the imposed currents from the load have a significant impact on magnetic flux. The results show the possibility of having a reduction of up to 96% of torque values when compared to a single rotor topology, although the torque waveform suffers some distortion when a load is applied.

***Index Terms*—Electric Machine, Flux Switching, PM Generator, Double Rotor, Torque Ripple.**

I. INTRODUCTION

The use of permanent magnet (PM) electric machines has intensified over the last decades as they are high in performance ratings [1] [2], power electronics are greatly more developed and they can be built without commutator brushes or slip-rings attached to the rotor. Placing permanent magnets (PM) in the rotor however has its drawbacks such as altering the PM magnetic characteristic since they are subjected to forces created by high rotation speeds and may suffer from demagnetization [3]. The most common type of attempt on reducing it has been by injecting controlled currents in the windings [4], but these involve complex electronics or chamfering/filleting the rotor and stator's saliences [5] [6] in order to smoothen the change in reluctance throughout each turn.

Permanent magnet flux switching generators have received significant attention and have triggered new research topics for diverse applications. The simplicity of the rotor is what makes this type of machine so interesting since the rotor is absent from, and thus not dependent of, permanent magnets or excitation windings with regards to their vulnerabilities associated with fast rotation speeds, geometric complications and centripetal forces. In this type of machine the permanent magnets are located in the stator where they are protected from mechanical stresses.

Despite protecting the PMs, the machine is still vulnerable to cogging torque [7] as it is responsible for undesirable torque fluctuations, specially at high speeds where these fluctuations translate to vibrations and can have a significant impact on the machine's integrity. To solve this, a double rotor machine topology is studied, in order to improve the machine's performance based on a theoretical analysis as well as resorting to finite element method simulations. This ripple causes unwanted vibrations that could compromise not only the machine itself but also its surroundings, specially if the frequency of the torque is close to the resonant frequency of the structure holding the machine in place.

Various topologies are analysed, where different arrangements of the machine's components are tested to see which one possesses characteristics that enable performance that is closest to being optimal. In each topology, the electromotive force and cogging torque are the two main attributes being scrutinized and serve as references for the evaluative chain.

The torque however, is the main focus as allowing for significant fluctuations coupled with high rotor speeds can result in crippling performance and serious damage rendering the machine and all its other features useless. So for safety and preservation reasons, the torque ripple must be minimized to its best extent, while keeping the machine operational and capable of delivering power.

By incorporating two rotors in the same axis, but at different stages of their rotational period, it is possible to significantly reduce the torque ripple without compromising the electromotive force as they will simply counteract each other.

II. DOUBLE ROTOR FLUX SWITCHING PM GENERATOR

Depicted in figure 1 is a topology featuring 2 rotors magnetically coupled trough 2 stator pieces, each one incorporating a permanent magnet in the middle section. Between the top and bottom parts of the stator pieces are ferromagnetic material slots placed to increase the separating distance between the rotors as the permanent magnet itself is not thick enough to create space to prevent flux leakages. The final stage of the machine will have a cylindrical shape on the outside therefore each stator piece is shaped as a cylindrical sector. The position of the coils is also shown in figure 1 and this figure shows that the flux linkage is to be measured along each stator salience.

By displacing the rotors by half a period, each one will counteract the force that the other one is subjected to as they will be in opposite stages when in comes to reluctance variation, i.e. the reluctance of a path crossing the top rotor rises when the reluctance on the bottom rotor falls.

However, this topology has a problem similar to a machine whose number of rotor poles is not a multiple of the number of stator poles, in the sense that when the top rotor is fully aligned with the stator poles, the bottom one is completely misaligned meaning that the full amplitude of magnetic flux is not seized implicating a reduction in EMF. Furthermore, the magnetic flux has now 4 air-gaps to cross as it passes through both rotors. For this reason, the actual path of the magnetic flux will depend strongly on leakages.

That being said, the torque characteristic for each rotor will not depend solely on the magnetic field that is common to both (although they would if the ferromagnetic material's permeability were to be infinite), nor could they be because for a torque free operation to be possible in said conditions there would have to be no magnetic reluctance variation along the magnetic circuit which would imply no magnetic flux variation which results in no electromotive force.

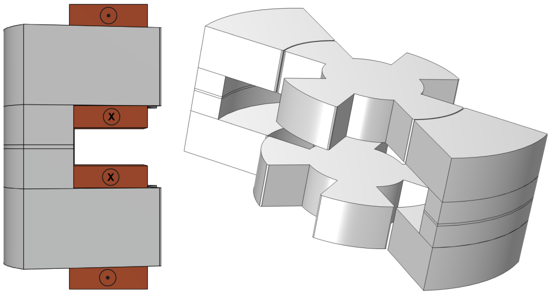

Figure 1: 2 Rotor Common Stator Base Model

III. SHAFT COUPLED 2 ROTOR TOPOLOGY

A machine with magnetically linked rotors does offer some disadvantages, mainly the average path length of the flux and the fact that the potential of each half of the machine (taken as separate machines) is not put to its best use.

To solve this, a new topology is tested, one where two individual machines are only mechanically coupled as presented in figure 2. Highlighted in blue are the permanent magnets.

The permanent magnets are now placed facing the center of the machine with alternated magnetic pole directions so that the magnetic flux travels strictly in a radial fashion rather than having to cross the stator pieces vertically. This represents a much shorter path when compared to a common stator topology which translates to a greater amplitude of magnetic flux.

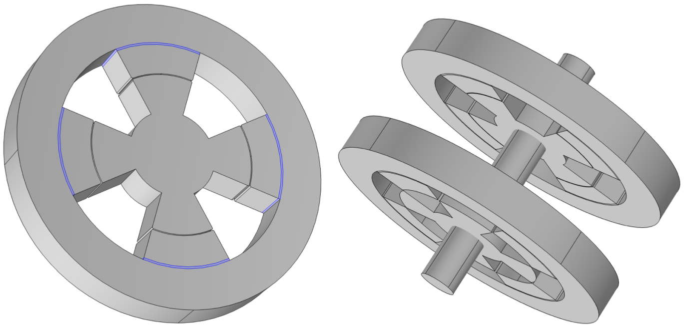

Figure 2: Shaft Coupled Topology

Additionally, a common stator machine should guarantee minimal flux leakage through the rotors, i.e. minimal passage of magnetic flux directly from one rotor to another as this would cripple the magnitude of magnetic flux through the coils and that is why each stator piece has ferromagnetic material slots between the permanent magnets and the stator poles. The same does not happen with radially placed magnets as the magnetic flux will not cross to the opposing machine because any machine-crossing path would imply a substantially higher value of magnetic reluctance, specially considering the fact that if the top stator poles and bottom stator poles are aligned, the north and south poles of each magnet for each machine will sit next to each other, which means that the two machines can be as close as a possible friction between them will allow.

Much like the previous topologies, the coils are placed along the stator poles as shown in figure 3 together with the path of magnetic flux.

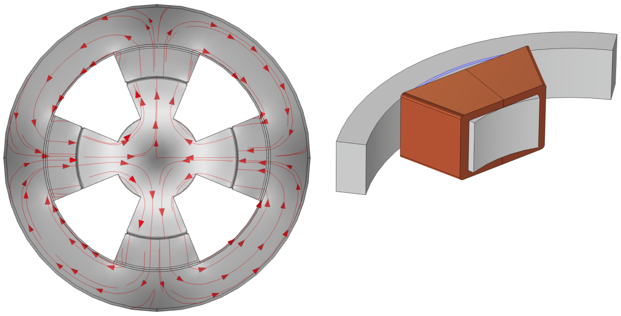

Figure 3: Flux path and coil positioning

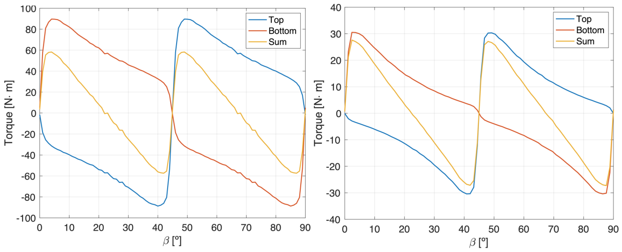

Figure 4: Torque Comparison between common (left) and separate (right) stator

By looking at figure 4 one can see that, as expected, the torque characteristic for the shaft only coupled machine yields

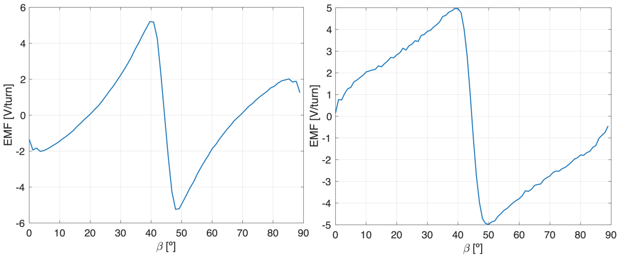

Figure 5: EMF Comparison between common (left) and separate (right) stator

a much greater amplitude but also has a greater reduction of amplitude in relative terms seeing that even though it has nearly 3 times the amplitude when compared to the other machine, the combined torque amplitude is only 2.1 times greater, resulting in a 26% further decrease in relative terms.

Although the peak values of electromotive force are similar, figure 5 shows a greater sustained value for a separate stator topology throughout its period because the magnetic flux path is not interrupted by the opposing rotor which results in a greater RMS value for the EMF.

IV. NON LINEAR CONTACT TOPOLOGY

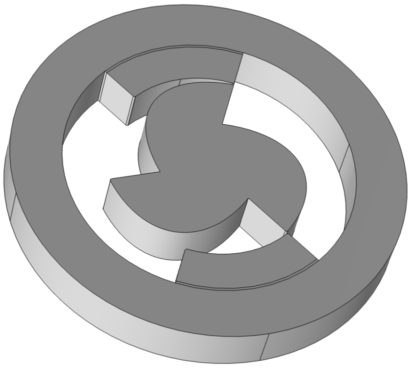

Figure 6: Non-Linear Contact Rotor Topology

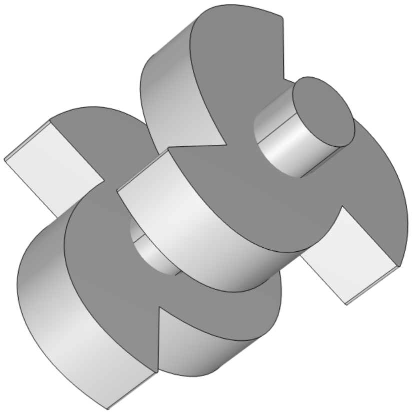

Figure 7: Rotor Coupling

In figure 6, a 2 pole single stator and 3 pole rotor machine is depicted. By taking the derivative of the torque, one can see that it is very similar to the torque itself from a theoretical analysis even.

Another machine is then coupled, but the rotor is now mirrored as shown in figure 6.

A simulation is then made for the opposing machine. In figure 9, the bottom rotor torque appears to have a waveform that is symmetric to that of the top rotor, however, due to the shape of the rotor its phase is not ideal just by a mirroring, having to be adjusted post simulation because even if the perfect phase were to be calculated, flux leakages would have a great impact and cause a shift. In figure 9 the rotors have a correct alignment and so the combined torque curves virtually cancel each other with the exception of the zone surrounding half period.

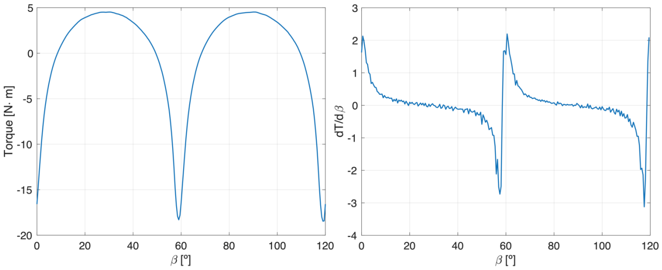

Figure 8: Non-Linear Contact Rotor Torque and Derivative

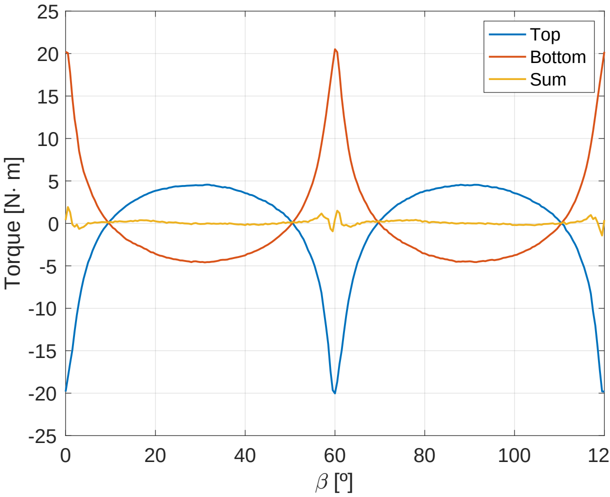

Figure 9: Combined Torque Action for a Non-Linear Contact rotor/stator combination

Despite being possible to calculatedly relate both waveforms, there is, unfortunately, no further geometric transformation that allows for this mirroring (for this type of rotor at least), which implicates a mandatory symmetry for each waveform.

In figure 10 half of a 5 pole rotor and 4 pole stator machine is depicted alongside its EMF characteristic which is a great improvement when compared to its 3 pole rotor equivalent. The opposing machine simply has its rotor mirrored.

As the number of poles increases the more complex the task of obtaining symmetry gets because as they increase, the arc upon each pole spans decreases, leaving less margin for error when it comes to finding the ideal shape, which leads to higher torque values.

In figure 11 one can see that the torque is still significantly low even though it contains small fluctuations.

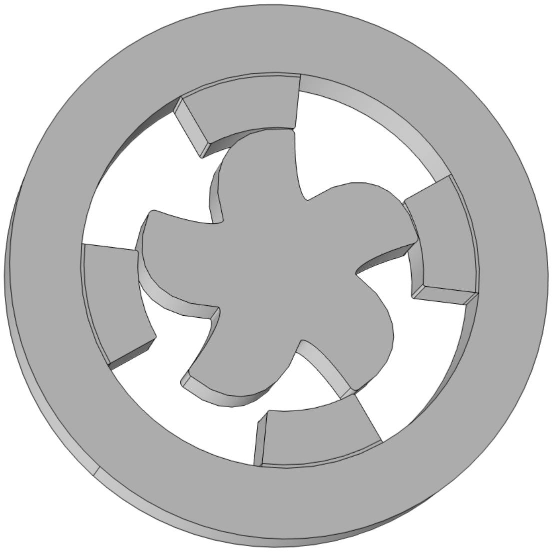

Figure 10: 5 Pole Rotor 4 Pole Stator Non Linear Contact Machine (Half)

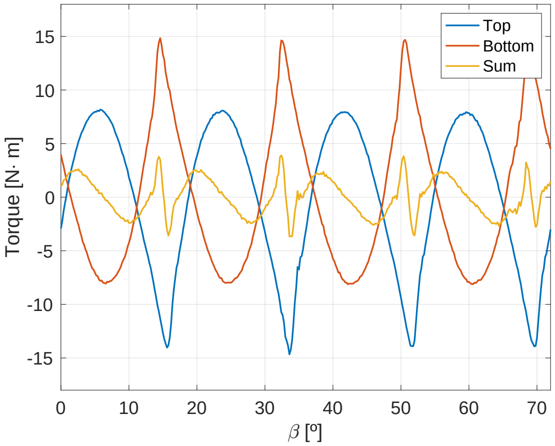

Figure 11: 5 Pole Rotor 4 Pole Stator Machine Torque

V. LOAD OPERATION

The final stage of the machine should fit the engine casing of a Boeing 767, which has a maximum of allocated dimensions for a generator of 132 mm for its depth and 400 mm for its diameter. The machine is to be coupled to the high pressure spool of the engine (although not inline with such), as it cannot be connected to the faster rotating, low pressure spool, because the two compressors are loosely coupled so at startup and during stationary operation, the power is mostly transmitted to the high pressure section, so for simplicity reasons, a rotational speed of 3000 rpm is assumed.

Having met the outer dimensions the focus must be directed to the optimization of the machine's parameters within the imposed constraints.

The ferromagnetic material is made of 35JN200 silicon steel. The stator is laminated while the rotor is solid. The neodymium permanent magnets are simulated as sintered N48 NdFeB with a remanent flux density of 1.4 T and one can infer that if the cross-sectional area of the path where the flux is taken does not change then the ferromagnetic material will not incur saturation as it only occurs at a much higher value.

Figure 12 shows how the coils are numbered and following its reference, figure 14 shows the electromotive force generated for a series connection between coils 1 and 3. The best possible connection would be that of a series connection between facing coils, because even though their EMF waveforms are not equal, they have similar zero-crossing points which is enough to not have cancellation. The same procedure is then repeated for the opposing half of the machine which by doing so, comprises an arrangement of 4 phases in total.

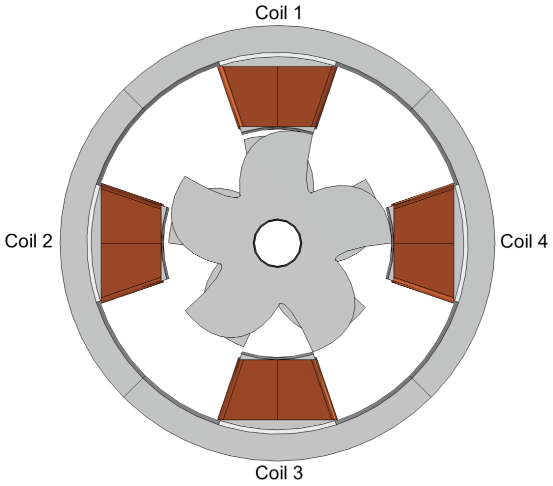

Figure 12: Machine with coils top view

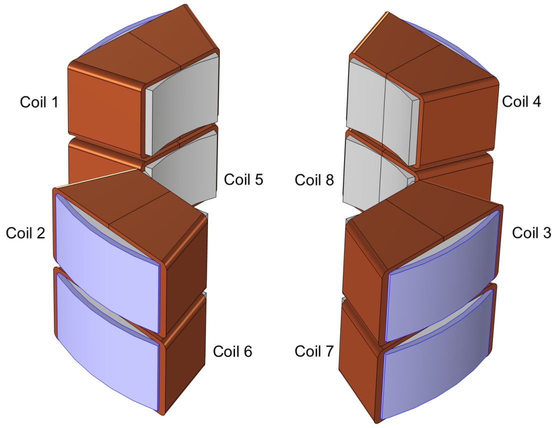

Figure 13: Coil Numbering

Under a load the machine must be tested as the currents demanded by the load have a significant impact on the magnetic flux, affecting the torque.

The maximum output that the machine can bear will be dependent on the value of total impedance. This depends not only on the load but also on the inductance of the coils themselves which also depends on their dimensions and

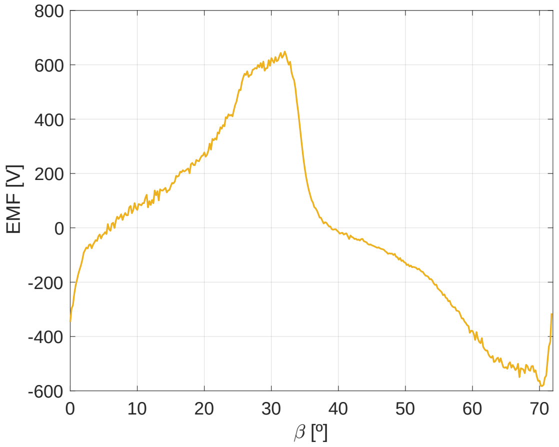

Figure 14: Series Connection Between Coils 1 and 3

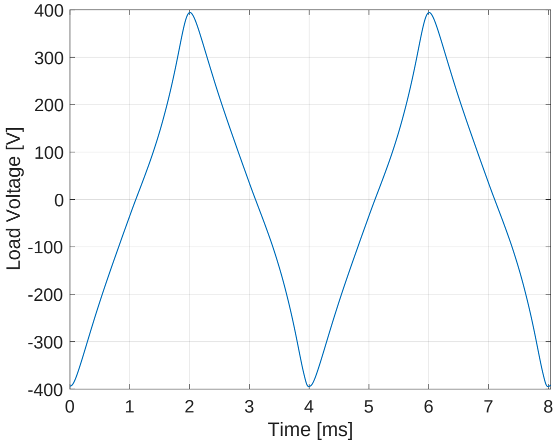

Figure 15: Load Voltage per Phase

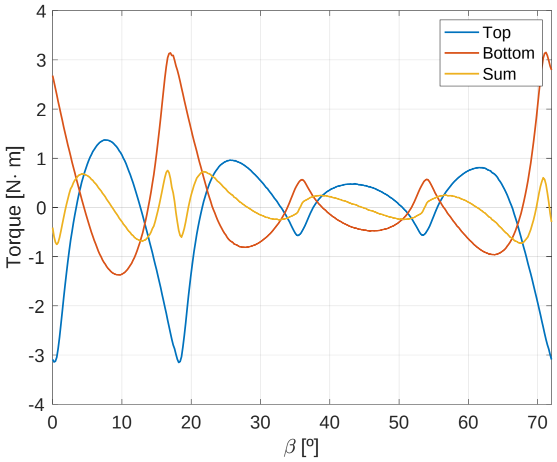

Figure 16: Torque Under Load Conditions

number of turns. Beyond that, there is an optimal resistive load value for maximum power output.

The generator is to be connected to a rectifier/inverter module, whose efficiency depends greatly on the amount of time during an ”on” state of the semiconductors which increases proportionally with the disparity between input and output voltage. This means that the output voltage of the generator should be the closest possible to the output voltage of the inverter module (400 V) in order to maximize efficiency, while guaranteeing that the current does not exceed its upper boundary. The torque waveforms are significantly deformed when compared to no load conditions, this is because the period of the cogging torque is different from the period of the magnetic flux, which means that when a current (with the same period as the magnetic flux) is present, it does not affect the torque in a uniform manner, leaving it distorted. The torque ripple is still, however, significantly low.

Table I: Mechanical specifications for the final stage of the machine

Rotor outer radius, r	105 mm
Rotor inner radius	43 mm
Stator Inner Radius	175 mm
Magnet Length, l_m	4 mm
Stator Outer Radius	200 mm
Rotor Depth	60 mm
Minimum Air gap length, g	1.6 mm
Number of turns per coil	50
Wire Cross-Section	1.04 mm^2
Rotor angular speed, ω	3000 rpm.

Table II: Electrical specifications for the final stage of the machine

Phase Current	Phase Voltage	Output Power	EMF frequency
20.41 A	218.4 V	18.29 kW	250 Hz

The individual rotor torque is now reduced due to the effect of the currents. The RMS value of the combined action torque is still effective and is also further reduced, down to a point where it is 0.63% of the average load induced torque.

Efficiency wise, regarding the coils resistance, the Joule effect losses are in total approximately 630 W which equates to 3.44 % of the total output power. The core losses are not taken into account as an accurate simulation of the machine under load to compute all losses that includes all the correct properties of the materials and surroundings, requires a very taxing, time dependent study for multiple scenarios.

VI. CONCLUSIONS

A non-linear contact rotor/stator combination is promising with regards to its cogging torque canceling properties when used in a multiple rotor arrangement, although not without its drawbacks as increasing the number of rotor poles makes the task of achieving torque symmetry increasingly harder. So the most important aspect to be retained is the fundamental idea behind the final machine’s build as it may be applicable to other, possibly better, models.

The 3D geometry can also be improved as 18.3 kW for such a scale, although not a reduced value of power output, can be improved as it is important to keep in mind that variable reluctance machines hold great potential.

In conclusion, the solution relies not only in the optimization of its geometry, but also in the scale of the machine because, as the size increases the inductance and the maximum supported current also increase at a greater rate than the losses due to longer coil wiring, meaning that the machine can have a greater efficiency.

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