



# HIGH EFFICIENCY AXIAL FLUX MACHINES

Why Axial Flux Motor and Generator Technology  
Will Drive the Next Generation of Electric Machines

- WHITE PAPER -

MAGNAX

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Why **Axial Flux** Motor and Generator Technology Will Drive the Next  
Generation of Electric Machines

**WHITE PAPER**

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## Introduction

At present, 45% of electricity consumption comes from electric motors and this figure is constantly rising, while 70% of industrial electricity usage is accounted for by industrial motors.

The impact of electrical machines' performance on all aspects of energy, from cost-effectiveness to environmental footprint, cannot be overstated.

Today, however, most motors and generators are built on a combination of induction motors and gearboxes – mature technology that has peaked at an average worldwide efficiency of 84% to 90% <sup>(1)</sup>. New generations of drive trains come with more advanced, direct-drive designs, but traditional direct-drive solutions (radial flux machines without gearboxes) suffer from problems with machine cost and size. The shortcomings of existing machines are particularly clear in mass- or volume-constrained implementations (wind turbines or wave energy converters), or in all-electric drive trains (electric vehicles).

## The Innovation

With regard to electrical motor technology, one particular type of electrical machine demonstrates superior characteristics: the **axial flux** permanent magnet machine. Axial flux permanent magnet machines perform excellently at a very broad range of rotational speeds, which makes them perfectly suitable for high-speed-low-torque as well as low-speed-high-torque applications.

Moreover, axial flux permanent magnet machines are significantly compact; the axial length of the machine is much smaller compared to radial machines, which is often crucial for built-in applications. The slim and lightweight structure results in a machine with a higher power and torque density. But also, Axial Flux Permanent Magnet (AFPM) machines can attain the highest energy efficiency of all electrical machines.



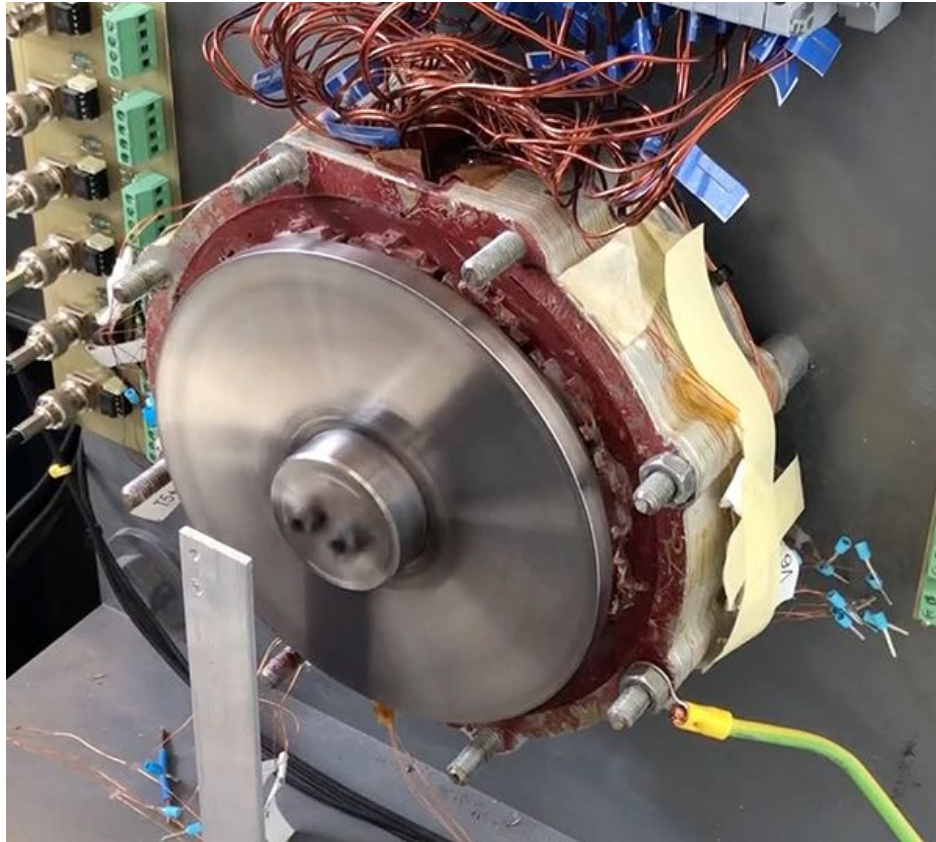


Figure 1: Early 2016 - Magnax / UGent 150 mm prototype on the test bench  
Check out the [youtube video](#)



Figure 2: Summer 2017 - Magnax 100-kW 16 kNm Prototype Generator on the test bench  
check out the [youtube video](#)

Magnax, a technology company from Belgium ([www.magnax.com](http://www.magnax.com)), has developed a unique machine concept, based on the AFPM topology. These machines have substantial advantages over other existing state-of-the-art generators or motors (figures given here are indicative for a 100kW generator machine):

- Increased efficiency (+96% efficiency vs. typical industry values of 84 to 92%).
- Reduced length (5 to 8 times shorter than traditional motors/generators).
- Reduced mass (2 to 5 times lighter than geared or traditional direct-drive machines).
- Reduced resources requirement ( $\frac{1}{2}$  to  $\frac{1}{3}$  of materials required vs. other machines, which also results in lower costs).

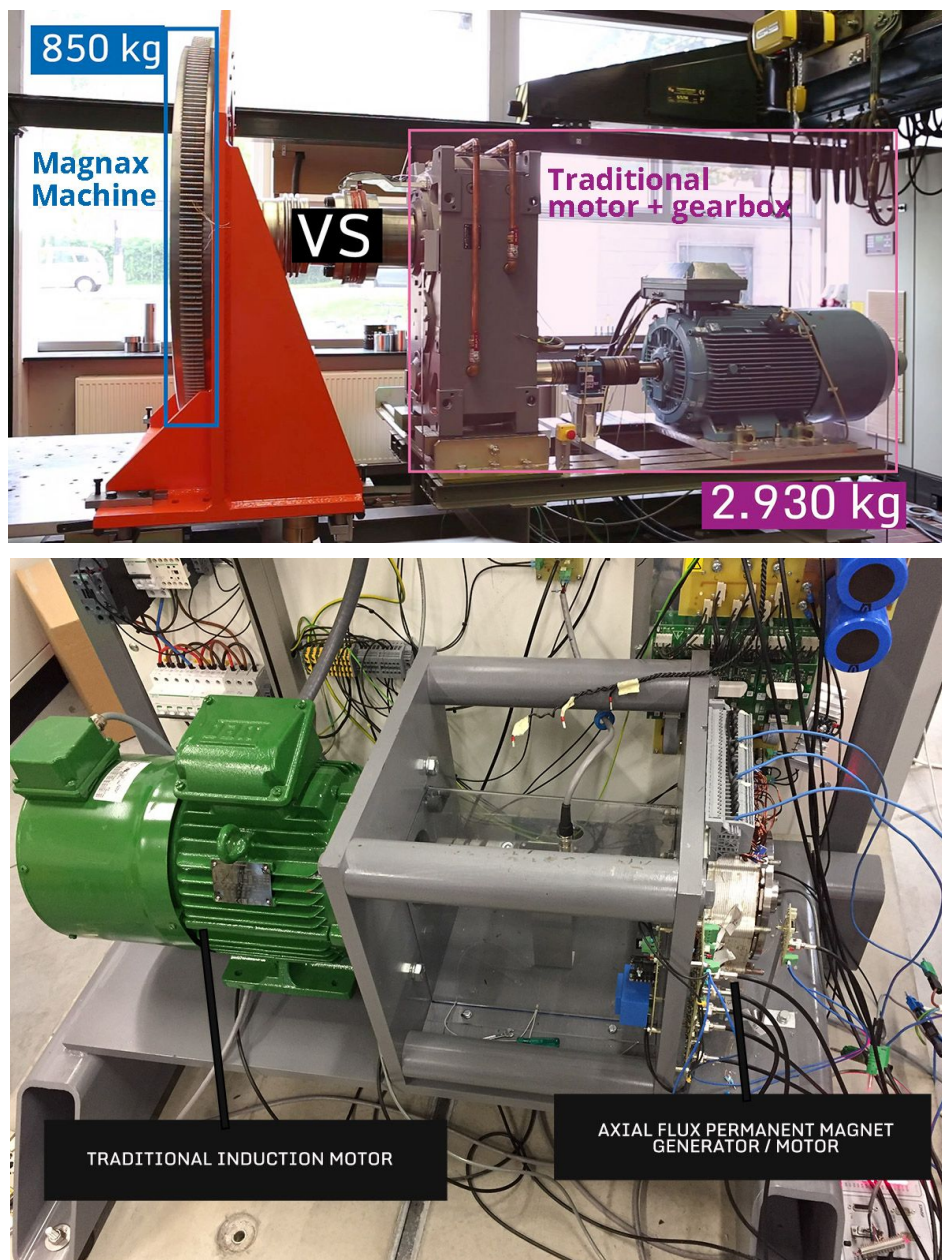
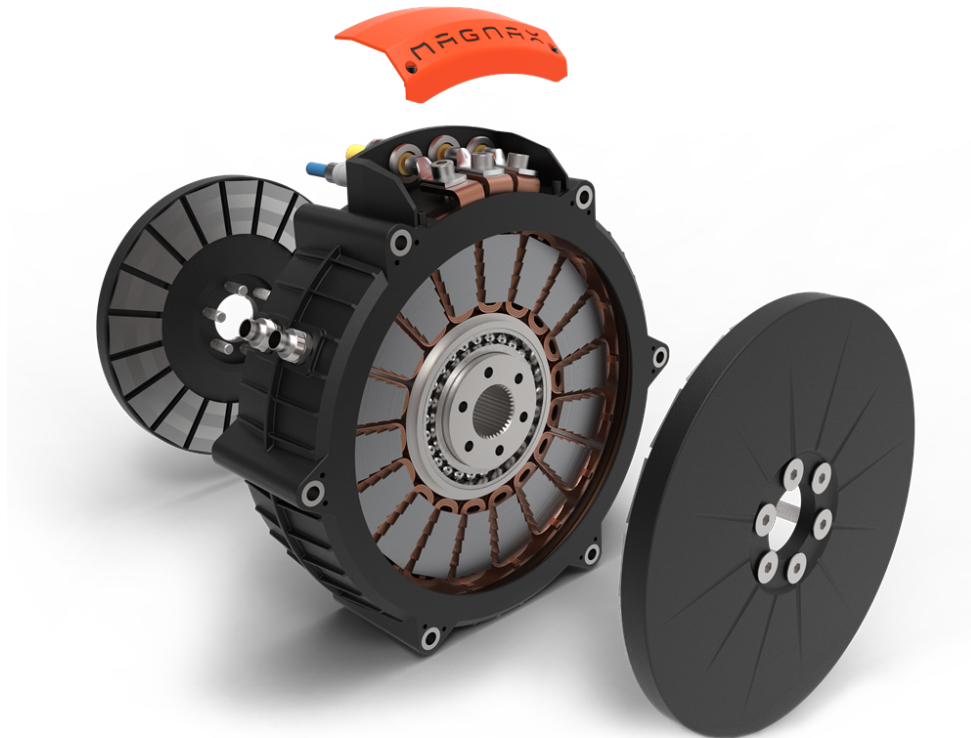


Figure 3: Prototype bench tests (AFPM vs I+G)



The Magnax axial flux machine concept attains vastly superior characteristics by **enabling the combined use of the following best-in-class practices into one machine**, a feat which has thus far been impossible using known machine concepts:



*Figure 4: The Magnax 275 mm AF motor for e-mobility applications*

- Dual permanent magnet rotors, for the highest possible torque-to-weight ratio.
- Yokeless stator, for the shortest possible flux paths.
- Rectangular section copper wire, for the highest possible copper fill factor (90%).
- Concentrated windings, for the lowest possible copper losses (no coil overhangs).
- High-performance grain-oriented electrical steel (ThyssenKrupp GOES), lowering the core losses by as much as 85%.
- A patented system for cooling the windings, for the lowest possible stator temperatures.
- The entire manufacturing chain is based on low-cost, easy-to-scale production processes.

## Scaling the machine concept

The concept is scalable from 150 mm diameter to 5400 mm diameter or more. The multi-stator “feature” where multiple machine discs are combined in parallel, adds flexibility by multiplying both torque as power.

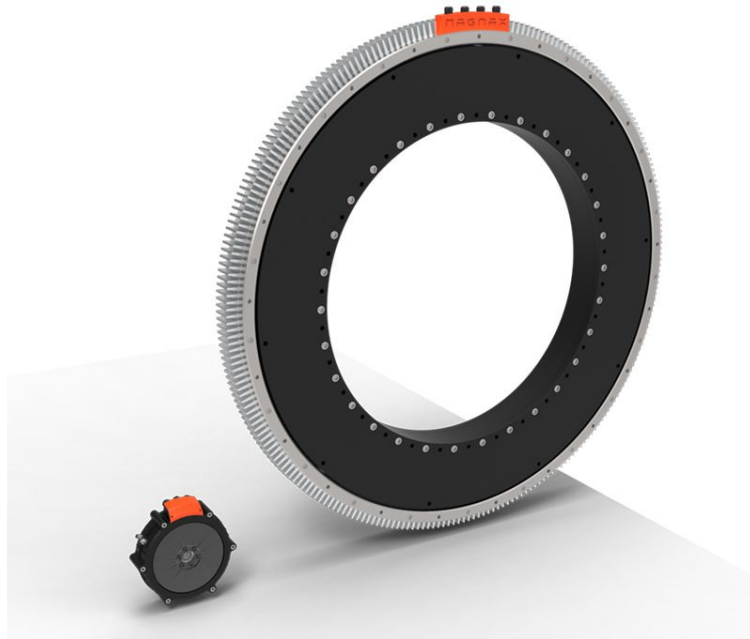


Figure 5: The Magnax concept is scalable from 150 mm to 5400 mm diameter or more



Figure 6: maximum flexibility and scalability while keeping high manufacturability

## Concepts and methodology

### The case for Direct-Drive

Electric machine solutions are currently dominated by combinations of standard induction motors and gearboxes. Figure 2 shows a typical induction motor/gearbox (I+G) combination, and the equivalent gearbox/generator combination found in a utility scale wind turbine. These solutions have a maximum efficiency typically below 90% at full load, and lower at partial loads.

They also often result in long, massive, drive trains. Although relatively inexpensive to buy (lower capital expenditure, CAPEX), these solutions always require a certain maintenance (increased operational expenditure, OPEX, and lower lifespan). For example, one study concludes that [up to 25% of an offshore wind farm's maintenance costs were related to gearbox failures](#).

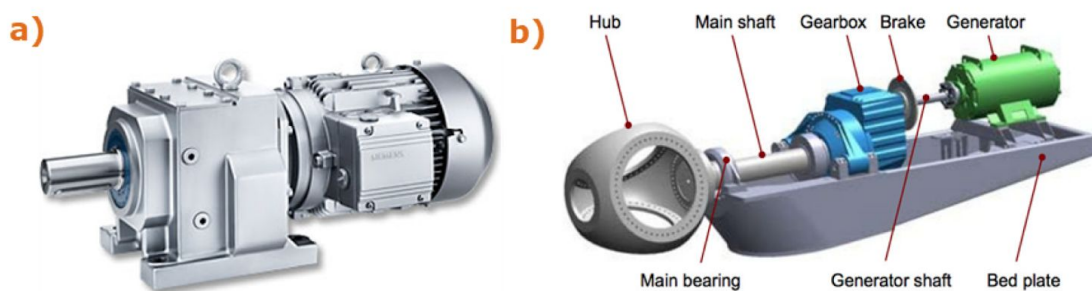


Figure 7: a) Standard induction motor with gearbox, b) typical utility wind turbine application with generator and gearbox

Since 2000, we have witnessed an evolution in the direction of motors and generators fitted with permanent magnets in the rotor (usually referred to as Permanent Magnet Synchronous Machines PMSM). In any motor, interaction of the magnetic fields of the rotor and the stator create the rotational force that drive the machine.

Permanent magnets generate a constant magnetic field and thus generate a flux by design. As a result, the power density and dynamic performance of PMSM machines is higher compared to induction machines or electrically excited machines, where this magnetic field must be created (directly or indirectly) via an electrical current.

Radial-flux (RF) direct-drive (DD) machines are an alternative solution to overcome the issues with efficiency and reliability of traditional (I+G) solutions associated primarily with gearboxes. Here, the gearbox is removed entirely, with the generator or motor coupled directly to the load. For this solution to be effective, the motor/generator needs to be able to supply the required drive torque directly, and at low speed, which requires an entirely new motor/generator design.



Figure 8: A Direct Drive Radial Flux Motor in a Washing Machine



Examples of RF DD machines can be found, for example, in some recent washing machines (e.g. Figure 3), through to the largest class of wind turbines from [Siemens](#) and [General Electric](#) (developed following heavy R&D investment since 2010).

These machines are generally more efficient and reliable than I+G combinations, to the extent that they are the only viable solution in many applications, such as offshore wind generation. However, RF DD machines are generally larger, heavier and more expensive than I+G solutions with the same power rating.

The reasons why RF DD machines are heavier and more expensive is due to the use of radial magnetic flux to transfer power. Fundamental electromagnetic and thermal constraints with this approach result in machines that are often both wide and long, compared to state-of-the-art models in I+G. Large machines require in turn a large amount of resources: rare-earth metals for strong permanent magnets and copper for the coils. It is the use of rare and valuable resources which has a huge impact on the cost and environmental footprint (life cycle analysis) of RF DD machines.

## Introduction of Axial Flux (AF) Direct Drive (DD) machines

A fundamentally different approach to direct drive is to put two sets of magnets parallel to each other, perpendicular to the axis of rotation. Figure 4 shows the basic differences in geometry. This **Axial Flux (AF)** topology allows machines that are much less wide and less heavy than RF DD machines. As well as being more compact, AF DD machines can reach higher efficiencies than RF DD machines, which has been verified in multiple experiments. <sup>(2)</sup>

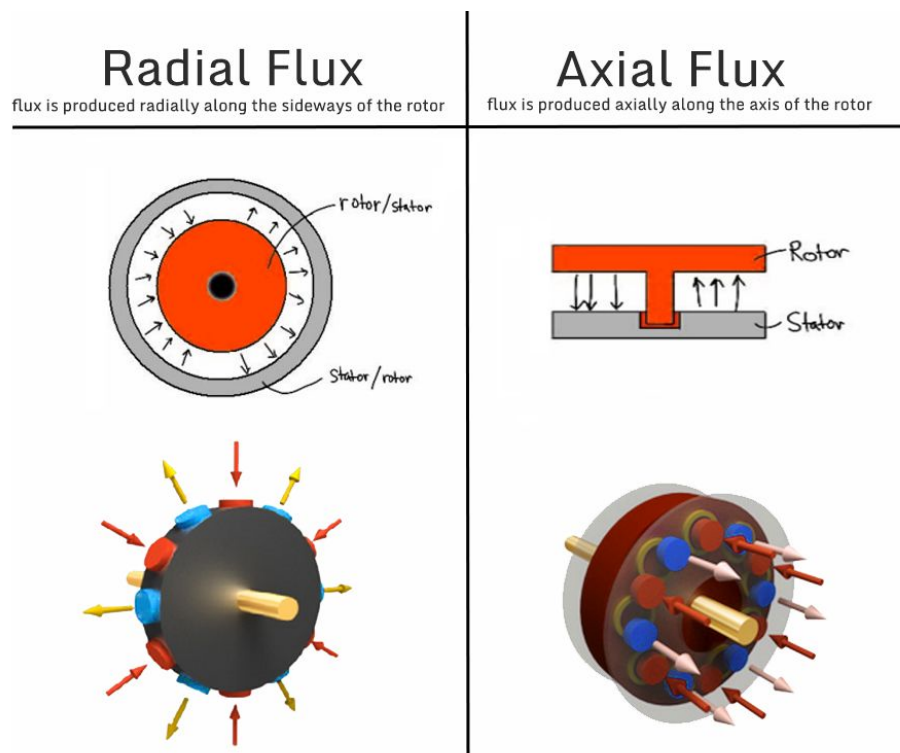


Figure 9: Radial Flux vs. Axial Flux

## Why axial flux machines have the highest power density and efficiency

As previously stated, most of the Permanent Magnet machines used today work with a radial flux topology. In this case, the flux loop starts at a first permanent magnet on the rotor, then passes through a first tooth on the stator, then flows radially along the stator, then passes through a second tooth, to finally arrive at the second magnet on the rotor.

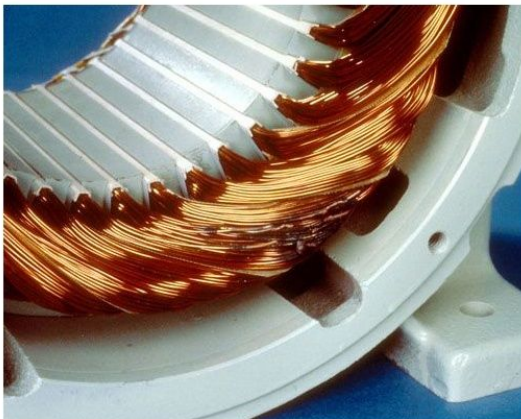
In comparison with the axial flux topology, the flux loop starts at a first magnet on the rotor, then passes axially through one stator tooth, and immediately arrives at the second magnet. So it is clear that, in axial flux machines, the flux path is much shorter compared to radial flux machines. This results in a higher power density and efficiency.

There are 4 reasons why Axial Flux machines deliver a significantly higher power density:

- 1. Lever:** For Axial Flux machines, the magnets are located further away from the central axis. This results in a larger "lever" on the central axis.
- 2. Electromagnetic:** Axial Flux machines have an inherently more efficient topology in the electromagnetic sense. For radial flux machines, the magnetic flux moves through the first tooth and then via the stator back to the next tooth to the magnets. In contrast, Axial Flux machines, the flux path is shorter: from the first magnet, through one core and straight on the other magnet. (only applicable for dual rotor topologies such as Magnax machines).

Additionally, in case of radial flux machines, the flux must make a “bend”: it must follow a 2-dimensional path. As a result, unlike axial flux machines, radial flux machines cannot use oriented electrical steel for the cores (stator). In case of axial flux machines, the flux path is one dimensional. As a result, Magnax can use grain oriented steel for its axial flux machines. This results in fewer iron losses when the flux passes the cores. Oriented steel makes it easier for the flux to pass which results in an additional efficiency gain.

**3. Windings:** in case of radial flux machines, a big part of the windings (as much as 50%) is not active (the part located at the exterior of the stator teeth which is only used to make loops (so-called “coil overhang”). The coil overhang results from additional electrical resistance (= heat dissipation) and has no function. It is what they call a “distributed winding” and results in much worse overall power/weight ratio compared with axial flux machines which have no coil overhang at all. In case of Magnax axial flux machines, “concentrated windings” are used where 100% of the winding is fully active (at least for Magnax axial flux machines).



**Winding of a radial flux concept**



**Magnax axial flux concept**

*Figure 10: The coil overhang in a traditional radial flux motor is not beneficial for its functioning (left). At the right, the concentrated windings of the Magnax axial flux motor.*

**4. Cooling.** In case of radial flux machines, the heat has to be transported through the stator to the outside of the machine. But steel is not a very good heat conductor. The “coil overhang” is also difficult to cool, because it is not directly in contact with the motor casing. In case of Magnax axial flux machines, the cooling is optimum because the windings are directly in contact with the exterior aluminium outside casing. And Aluminium conducts heat very well. As a result, the windings of Magnax axial flux machines stay cool while the resistance of the copper remains low. And this results again in a much higher efficiency.

These advantages generally result in several additional percentages of efficiency, which makes a huge difference on a global scale.



## Why are not all machines axial flux machines?

Historically, Axial Flux designs have posed some serious design and production challenges.

- **Mechanical challenges:** the high magnetic forces acting between the rotor and the stator produces an engineering and material challenge in maintaining a high-tolerance uniform air gap between these two components.
- **Thermal challenges:** windings in an axial flux machine are located deep within the stator and between the two rotor discs – which presents a greater challenge in terms of cooling than for an RF DD design.
- **Manufacturing challenges:** AF machines have thus far been very difficult to manufacture because the design of the stator iron has continued to be based on that of an RF machine, using a stator yoke to close the flux loop. This design is well-trying and tested for RF DD and is based largely on the same principles as for I+G systems, meaning it is easy to manufacture. In AF topology, however, this results in a far more complicated stator than for an RF system, making automated production and achieving volume scaling savings extremely difficult. These challenges translate to cost and very poor scaling, which is the reason most direct drive generators and motors today are based on Radial Flux. There are however a few large volume deployments of AF technology, where the high manufacturing cost and low specific power are overridden by other advantages such as size: [Kone](#), for example, uses the AF topology in their '[Ecodisc](#)' elevator motors, where the size advantage enables the elimination of a machine room.

Some alternative topologies attempt to fundamentally address these issues: one alternative, the **Coreless** AF Topology, addresses the challenges of AF machines by removing the entire stator iron. However, the lack of a stator iron requires the machine to have a much larger diameter and much more permanent magnet material. Not only does this significantly increase size and weight, it results in a prohibitively high magnet cost. This remains a popular and viable solution for very low-power applications, such as DIY wind turbines and off-the-grid solutions, but it does not scale commercially – as [Boulder Wind Power](#) (Colorado, USA), and [NGenTec](#) (Glasgow, UK), who both pursued this solution but who recently went out of business, discovered.

## Description of the solution as developed by Magnax

A second alternative is the **Yokeless AF Topology**. In this case, only the iron yoke of the stator is removed, but the iron teeth are kept. This overcomes some of the problems with AF whilst avoiding the need to scale the machine diameter and magnets. It is the only AF topology to be successfully commercialised to date by [Magnax](#) (Belgium) and [Yasa Motors](#) (UK). Removing the yoke, however, introduces new challenges: how to fix and position individual teeth without a yoke connection (mechanical) and a greater thermal challenge. YASA uses complex methods to overcome these challenges which result in expensive products that are difficult to scale in both size and production volume. Furthermore, using SMC cores (soft magnetic composite) is very difficult to subcontract and scale.

Ghent University has been working on these specific challenges since 2008 and Magnax has benefited from several years of R&D to develop a better version of yokeless axial flux machines and manufacturing methods. These machines can be manufactured on a large scale using established manufacturing techniques.

Magnax introduces a fundamentally new -patented- technology, accelerating Yokeless AF Topology beyond the current state-of-the-art model. The Magnax AF DD machines overcome mechanical, thermal and manufacturing challenges, resulting in machines which are not only relatively easy to manufacture, they also combine proprietary solutions in resource usage, modularity and suitability for highly automated manufacturing.

In the summer of 2017, Magnax showcased the first prototype of a 100-kW AF generator (as shown on page 2). This 100-kW generator is smaller, lighter and more efficient than the best I+G and radial flux direct-drive PM (RF) machines. As an example, the prototype weighs about 850 kg while I+G and RF version of the same power/torque typically weigh about 2 to 6 tons. Compared to other Yokeless AF machine concepts, this concept is also more flexible, robust and modular which offers huge possibilities in terms of production scaling and cost-effectiveness.

### Rotor and Stator

The Magnax axial flux machine consists of a stator and two rotor discs where the stator is located between the two rotor discs. So there is a small air gap between rotors and stator. The stator contains the windings and the rotors contain the magnets.

With regard to the attraction force between the two rotor discs and the stator: the two rotor discs exert an equal (but opposite) attraction force on the rotor. The discs, however, are directly connected to each other via the shaft ring, so the forces cancel each other out.

Hence, the internal bearing does not carry these forces, it only needs to keep the stator in the middle between the two rotor discs. Theoretically, when the stator is exactly in the middle, it is in equilibrium and no forces act upon the bearing (but in reality, this is not achievable; so a small force will always act upon the internal bearing).

## Flux efficiency

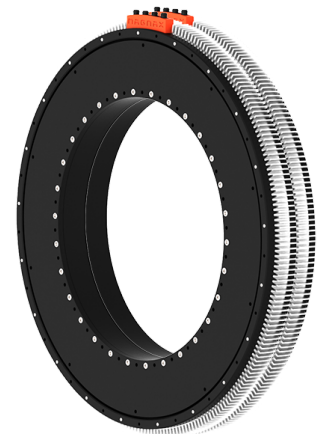
The Magnax Axial Flux machines use ThyssenKrupp's high-performance Grain-Oriented electrical steel (GOES) for its cores. Grain-oriented steel cannot be used with RF machines because the flux paths in these machines follow a non-linear 2D path. In the Magnax axial flux topology, the grains of the steel are oriented in the same direction as the flux paths. The advantageous low losses and excellent permeability of the grain oriented material in the rolling (axial) direction results in a machine with 85% reduced stator core losses and a slight increase of the electromagnetic torque.

## Modular design (multi-stator topology)

Since the length of the machines is very short (140 mm for a 100-kW @ 60 rpm model for instance), multiple machines (discs) can work in parallel. We call this the multistator topology. This is usually done when the outside diameter of the generator - or motor assembly - must be kept limited.

Combining multiple machines in one stack gives a lot of flexibility to the end-user application and allows a more "standardized" engineering approach. This configuration allows fault tolerance as the machine can keep working even if any of the stages is damaged or disconnected.


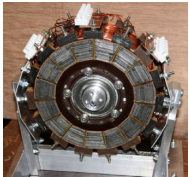
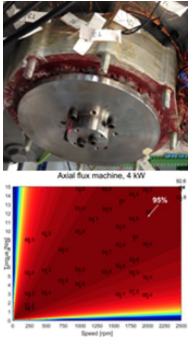

To reduce the axial length and weight even more. Back-to-back rotors can be combined into one while internal bearings can be replaced by one or two external bearings.





## Magnax Axial Flux Machines - Development History

The Magnax axial flux machine has a yokeless topology. Development of this topology goes back to 2008 when Ghent University started researching this method. A first proof of concept was created in 2009 and the concept was heavily researched by Ghent University over the following years. The first viable prototype operated successfully when Magnax added specific development and engineering skills to develop the 4-kW prototype.

Date	TRL definition	Demonstration of achieved TRL	Picture
	Basic principles observed technology concept formulated	Electromagnetic principles of axial-flux machines have been known since the early 19th century	
2009	Experimental proof of concept	First prototype built at Ghent University, as proof of concept	
2016	Technology validated in lab	Magnax axial flux technology validated via the construction of a small-scale machine by Ghent University (4kW)	
Aug 2017	Technology validated in relevant environment	100-kW prototype built and tested at Lemcko lab (Ghent University)	

## Overview of the generator technology for high torque - low rpm direct-drive applications.

Table 2 below compares Magnax AF DD machines with other technology, for a 100-kW 60 rpm generator/motor, with a constant 16 kNm of torque.

	Induction Motor + Gearbox	Radial Flux Direct Drive	Magnax Axial Flux Direct Drive
<b>Efficiency</b>	80 – 88%	92 – 95%	96% - 97%
<b>Axial length</b>	1500-3000 mm	700 – 1200 mm	140 mm
<b>Weight</b>	2000-3000 kg	2400 - 5000 kg	850 kg
<b>Investment cost</b>	€	€€	€
<b>Reliability</b>	+	+++	+++
<b>Ease of installation</b>	-	+	++
<b>Maintenance cost</b>	Very high	Low	Low
<b>Modularity</b>	Medium	Low	High
<b>Manufacturability</b>	High	Low	High

Table 1: Magnax compared with RF DD and Induction Motor + Gearbox

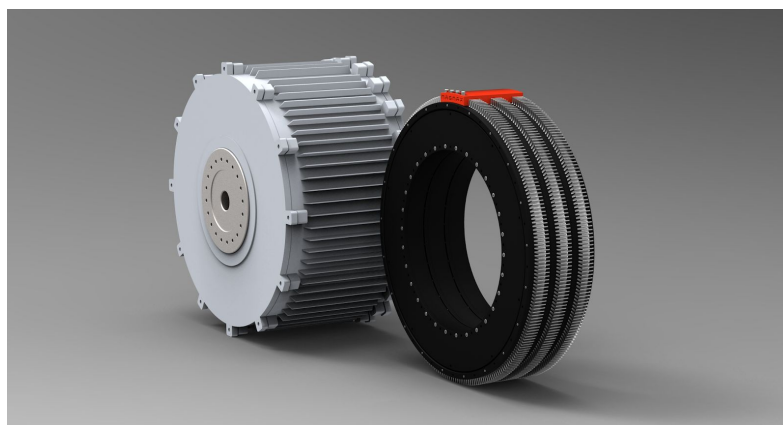


Figure 11: Comparison of a 300-kW Radial Flux Direct drive generator (left) to a 3x100-kW Magnax AF direct-drive generator (total = 300-kW).

## Overview of the motor technology for high-speed applications

Table 2 below compares Magnax AF DD machines with other technology, for a 300-kW 8000 rpm machine. Source of the numbers: online.



Figure 12: The Magnax AXF275 Axial Flux Motor

Example: AF motor in 275-300mm diameter range	Axial Flux EVO AF-130 (acquired by Avid)	Yokeless Axial Flux YASA P400 S	Magnax Yokeless Axial Flux AXF275
Efficiency at <b>nominal speed (not peak)</b>	< 90%	88-90%	91 - 92%
Diameter (mm)	<b>300 mm</b>	<b>305 mm</b>	<b>275 mm</b>
Axial length	110 mm	106,7 mm	86 mm
Weight	30,5 kg	27 kg	24 kg
Torque (peak/Nom)	350/145	370/125	520/260
Power (peak/Nom)	140/64	160/60	300/150
Max Power Density	<b>4,59</b>	<b>5,92</b>	<b>12,5</b>
Max Torque Density	<b>11,48</b>	<b>13,7</b>	<b>21,7</b>

Table 2: Comparison of Axial Flux Motor design from different vendors. Magnax uses GOES (grain oriented electrical steel) cores and a patented cooling concept which is very effective in extracting the heat to the outside.



## Typical use cases for axial flux technology

### High-Speed Motor Applications

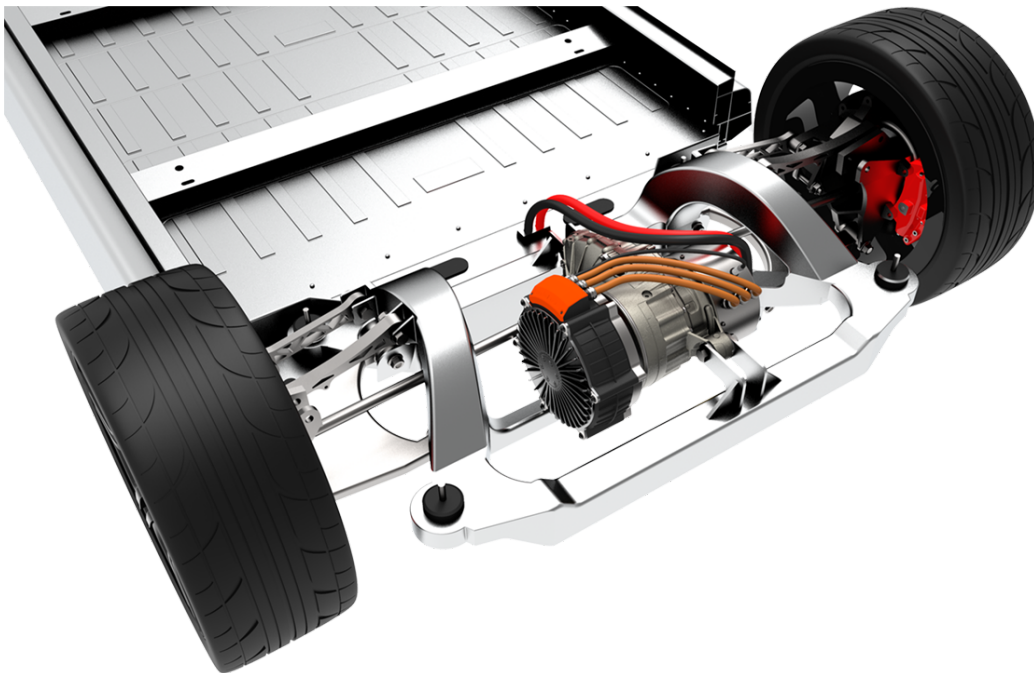
The Magnax axial flux concept is used for electric motor applications where weight and size must be kept to the absolute minimum while delivering high amount of power and torque. Since torque directly relates to diameter, we usually use the diameter as the main specification to size our machines.



*Figure 13: 4 standard Magnax motors (from left to right: 335 mm - 275 mm - 225 mm - 185 mm diameter)*

These small versions of Magnax yokeless axial flux motors are generally water cooled and reach power densities up to 15 kW / kg.

## E-mobility



*Figure 14: Magnax AXF275, which delivers 300-kW with a weight of only 24 kg, integrated in car chassis.*

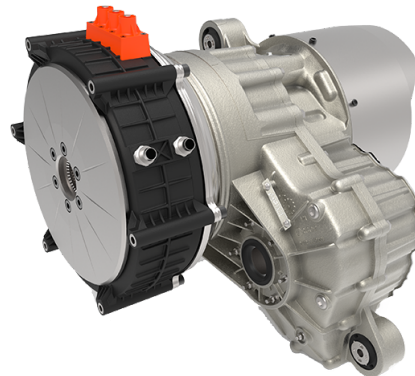
For all transportation systems, such as vehicles, weight should be avoided at all cost. Magnax Axial Flux Motors are used for drive train applications with power densities up to 15 kW/kg. The peak efficiency of these machines can reach 98% and remains very high at partial loads.



*Figure 15: Magnax AXF275 integrated in powerful e-bike*

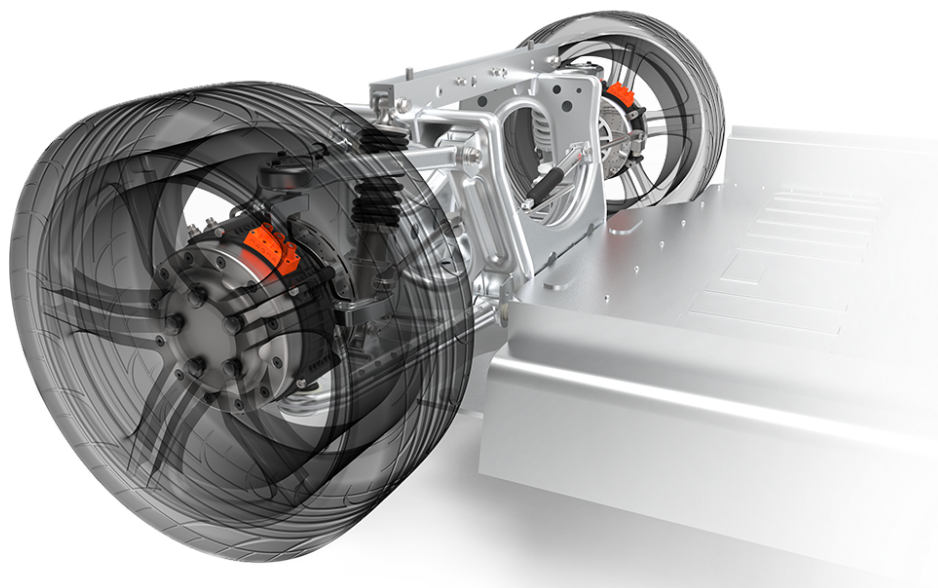
## Combining the axial flux motor with a gearbox

Magnax axial flux motors can be combined with gearboxes in different powertrain configurations. Chassis mounted or in-wheel.



## Direct Drive

Some e-mobility applications require direct-drive motor concepts. A gearless design significantly reduces complexity and maintenance requirements. Since Magnax axial flux motors already deliver the nominal torque at 0 rpm and have a very compact design, they are an ideal choice for direct-drive (in-wheel) configurations. For these applications, we make sure that the efficiency mapping is optimized for lower rpm ranges. (usually wheel speed 500-2000 rpm).



## Electric aircraft, helicopters and drones

Helicopters and drones require electric propulsion systems with extreme reliability combined with low weight. This is exactly what direct drive axial flux machines can offer.

Removing the gearbox by using the direct-drive concept of Magnax axial flux machines decreases the risk of failures significantly. Especially for aircraft, the low weight of the Magnax machines (vs. geared motors or radial flux direct-drive motors) are a huge benefit. Also here, efficiency mapping is optimized for the nominal rotor speed.





## High Torque - Low RPM Generator Applications

Wind power



Using Magnax axial flux direct-drive generators for wind turbine applications is an obvious choice when we compare its specifications with the current technologies used in wind turbines:

- Wind turbines with induction motors and gearboxes are generally less efficient (Below 90% while 96-98% Magnax axial flux generators can reach 96% or more). Also, gearboxes are considered to be more maintenance intensive and less reliable because of the higher amount of moving components.
- Traditional direct-drive generators (typically based on the radial flux topology) are 2 to 5 times heavier than Magnax axial flux generators and a few percent less efficient compared with axial flux direct drive generators. This is mainly due to the fact that Magnax generators can use grain-oriented steel in their cores and the windings have a higher copper fill factor.

## Wind turbine concepts



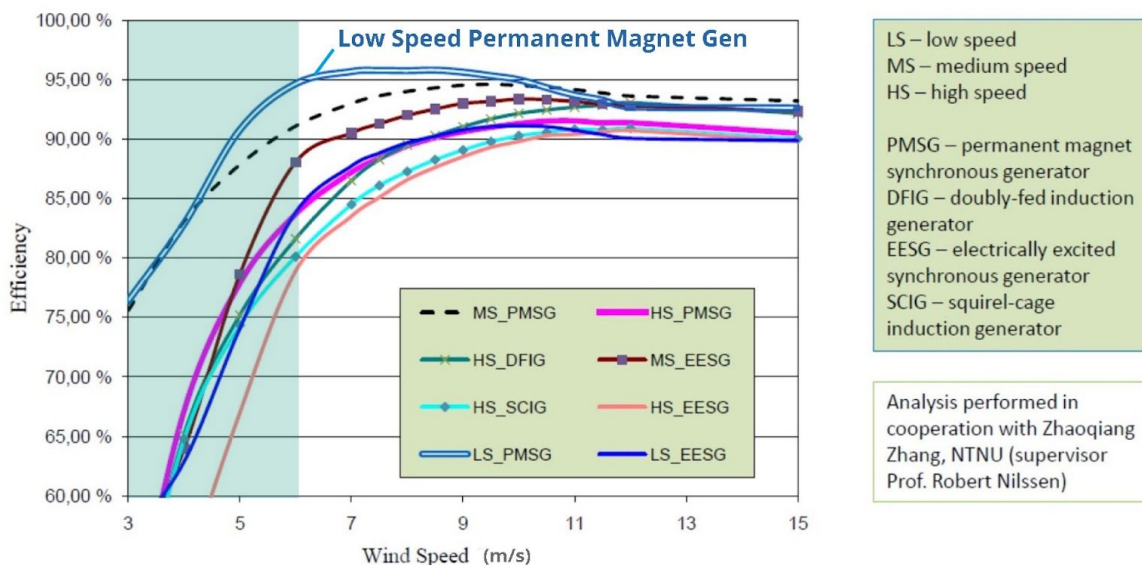
For the axial flux machines, output torque quadruples when we double the diameter of the machine. So if the outside diameter would not be a limitation, the Magnax axial flux concept can deliver direct-drive generators which are easily 5 to 6 times lower in weight compared with traditional direct-drive generators. However, the reality is that wind turbine designs cannot be changed overnight and larger diameter generators require different mechanical support systems. Wind turbine manufacturers consider initially a 1-to-1 replacement of the current generator concept to axial flux direct-drive. A huge advantage of the Magnax axial flux topology is the “**multistator**” topology where we add a number of generator

discs to reach required torque and power.

As a result, you get a very simple, modular and cost-effective design.

A stacked topology allows the use of only a single generator bearing.

## Efficiency curves



Permanent Magnet Generators have a much higher efficiency at lower and higher wind speeds. According the Weibull wind distribution chart, half of the wind speeds are below 6 m/s, therefore the overall gain in efficiency by using PM machines is significantly higher.

Magnax axial flux machines are using permanent magnets (attached on the rotor discs).

## Hydro & Wave energy applications

Hydro applications such as wave energy converters and hydro turbines benefit from the same advantages as wind turbines. An IP66 dust and water protection makes the Magnax machines a perfect choice for hydro applications. The internal parts (windings, permanent magnets, etc.) of the axial flux machine are completely sealed, making sure that short circuits and corrosion are completely avoided.

The direct-drive concepts, combined with the lower weight and size, makes axial flux generators a interesting choice for new hydro & wave concepts.

## High Torque - Low RPM **Motor** Applications

### Rotating machines

As an example, Archimedes' screw pumps are a great application for Magnax axial flux motors since the current systems (induction motor + gearbox) require maintenance while the efficiency of these geared systems are low (80-85%).

By using Magnax axial flux motors, efficiency increases by at least 10%. This makes the system extremely cost effective in terms of weight, size, reliability and cost (CapEx).

### Winches

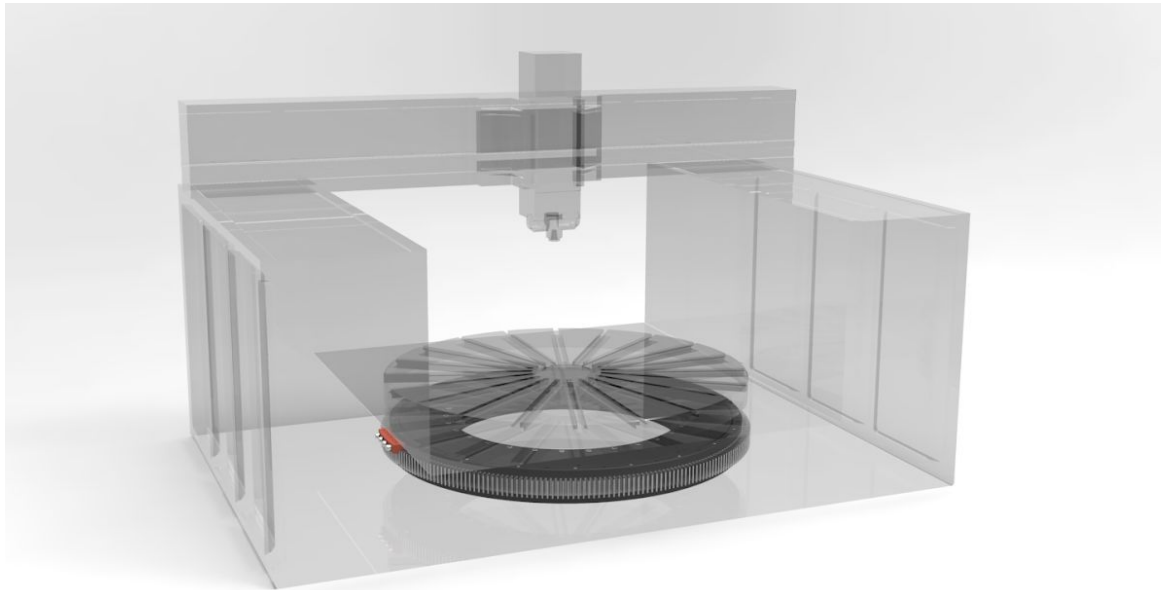
Winch systems currently use geared induction motor systems or hydraulic systems to operate. Both systems can be replaced with electric direct-drive motors based on the Magnax axial flux concept. This simplifies the general concept and adds an eco-friendly element because hydraulic systems can be completely avoided.

The Magnax axial flux motors can be easily connected to the existing water cooling systems on a ship, for instance. Since the electric motor also functions as a generator, electricity can be generated to relieve the auxiliary systems.

Also, in this case, we can combine multiple stators to create a significant combined torque while keeping the outside diameter low.

## Production machinery

Production machinery such as vertical lathes usually operate at low speed while very high torque is required. These machines can benefit from axial flux technology at different levels:



- **Maintenance and cooling requirements.** Removing the gearbox significantly simplifies the general machine concept and reduces maintenance requirements. The reliability is high, which is important since production machines are part of the total production chain.
- **Compactness.** A Magnax AF Direct-Drive motor is 3 to 5 times shorter in axial length.
- **Efficiency.** Production machines consume a lot of energy, so the higher efficiency of the axial flux machine (96% vs. typically 82 to 90%) can save a lot of energy for the end-user of the production machines and the production machine manufacturers; complies with the new energy efficiency regulations.

## References

(1)

[https://www.copper.org/environment/sustainable-energy/electric-motors/education/motor\\_text.html](https://www.copper.org/environment/sustainable-energy/electric-motors/education/motor_text.html)



# Company data



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