Forschung im Ingenieurwesen (2025)89:52
https://doi.org/10.1007/s10010-025-00792-4

ÜBERSICHTSARBEITEN/REVIEW ARTICLES

Identifying path ahead for tackling future challenges in direct-drive permanent magnet wind turbine generator's electro-mechanical design and manufacturing

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Received: 15 September 2024 / Accepted: 30 January 2025

Abstract

Increasing the number of offshore wind farms and installing larger wind turbines, are just two ways to meet the Net Zero targets set in both the UK and EU. The offshore environment is harsh and there are additional challenges such as accessibility, so it is important to have reliable equipment installed within these wind turbines. Geared drivetrains have been observed to lack the sufficient level of reliability required in an offshore environment, so the direct-drive generator designs without any gearbox, aim to increase the reliability. Due to the increased level of torque the direct-drive generators tend to be larger and heavier, they require more permanent magnets and accordingly more rare earth material, as well as more demanding mechanical structures for the generator and drives and these all cause issues with design, supply chain, manufacturing and installation for original equipment manufacturers (OEMs). This paper has reviewed the state-of-the-art design, manufacturing and assembly of direct-drive permanent magnet generators. The key OEMs that supply the current state-of-the-art direct-drive turbines have been identified and some interviews with experts from industry have been conducted. These efforts aimed to understand the challenges with direct-drive turbines, that is a significant contribution to the growth of offshore wind, to address Net Zero's growing demand. These challenges are found to be primarily imposed on the manufacturing side, to the scaling up in numbers and size to catch up with the market demands. Finally, this work proposes recommendations to overcome these challenges, with regards to the design and manufacturing respectively, which includes, reducing the amount of permanent magnet material, optimizing the design to reduce the structural mass, automating as many of the manufacturing/assembly processes as possible and practicable, and using alternative processing such as additive manufacturing.

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Published online: 11 March 2025

Identifizierung eines Wegs zur Bewältigung zukünftiger Herausforderungen im Bereich der elektromechanischen Konstruktion und Fertigung von Windturbinengeneratoren mit Direktantrieb Permanentmagnet

Zusammenfassung
Die Erhöhung der Zahl der Offshore-Windparks und die Installation größerer Windturbinen sind nur zwei Möglichkeiten, um die in Großbritannien und der EU festgelegten Netto-Null-Ziele zu erreichen. Die Offshore-Umgebung ist rau und es gibt zusätzliche Herausforderungen wie die Zugänglichkeit, daher ist es wichtig, in diesen Windturbinen zuverlässige Geräte zu installieren. Es wurde festgestellt, dass Getriebeantriebe nicht über das erforderliche Maß an Zuverlässigkeit in einer Offshore-Umgebung verfügen, daher zielen die Direktantriebsgeneratorkonstruktionen ohne Getriebe darauf ab, die Zuverlässigkeit zu erhöhen. Aufgrund des erhöhten Drehmoments sind die Direktantriebsgeneratoren tendenziell größer und schwerer, sie benötigen mehr Permanentmagnete und dementsprechend mehr Seltenerdmaterial sowie anspruchsvollere mechanische Strukturen für den Generator und die Antriebe, und all dies verursacht Probleme bei Design, Lieferkette, Herstellung und Installation für Erstausrüster (OEMs). In diesem Dokument werden das Design, die Herstellung und die Montage von Direktantriebs-Permanentmagnetgeneratoren auf dem neuesten Stand der Technik untersucht. Die wichtigsten OEMs, die die aktuellen hochmodernen Direktantriebsturbinen liefern, wurden identifiziert und einige Interviews mit Experten aus der Industrie durchgeführt. Ziel dieser Bemühungen war es, die Herausforderungen bei direkt angetriebenen Turbinen zu verstehen, die einen wesentlichen Beitrag zum Wachstum der Offshore-Windenergie leisten, um der wachsenden Nachfrage nach Netto-Nullenergie gerecht zu werden. Diese Herausforderungen bestehen vor allem auf der Fertigungsseite, nämlich bei der Steigerung von Stückzahl und Größe, um den Marktanforderungen gerecht zu werden. Abschließend werden in dieser Arbeit Empfehlungen zur Überwindung dieser Herausforderungen in Bezug auf Design und Fertigung vorgeschlagen, darunter die Reduzierung der Menge an Permanentmagnetmaterial, die Optimierung des Designs zur Reduzierung der Strukturmasse, die Automatisierung möglichst vieler Fertigungs-/Montageprozesse und der Einsatz alternativer Verfahren wie der additiven Fertigung.

1 Introduction

Due to the recent energy crisis, the urgent need to invest in more alternative energy sources [1] has been highlighted, to ensure energy security. This crisis, along with the multiple targets i.e. net zero set by many countries worldwide, have heightened the spotlight on renewable energy, with the increase in wind energy playing a major role.

The wind energy sector covers both onshore and offshore wind, with the Global Wind Energy Council's (GWEC) latest report showing that during 2023, 117 GW of wind capacity was added, which now takes the total wind capacity to over 1 TW [2]. This was an increase of 50% from the previous year, with the total onshore wind installations increasing by almost 54% compared with 2022 and the total offshore wind installations increasing by 24%. GWEC

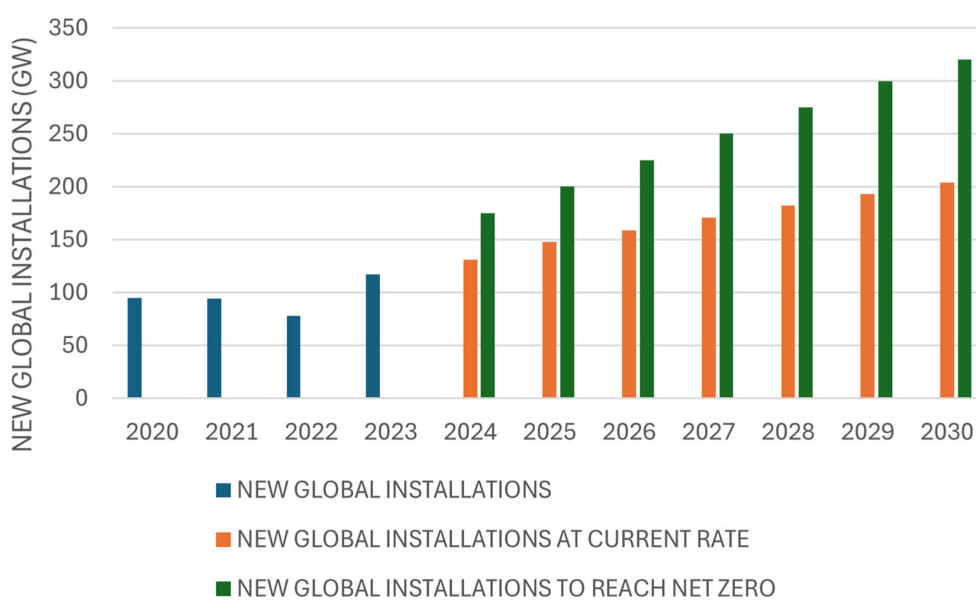


Fig. 1 Required Wind Energy Capacity Growth in Order to Reach Net Zero by 2050. Diagram Courtesy of [4]

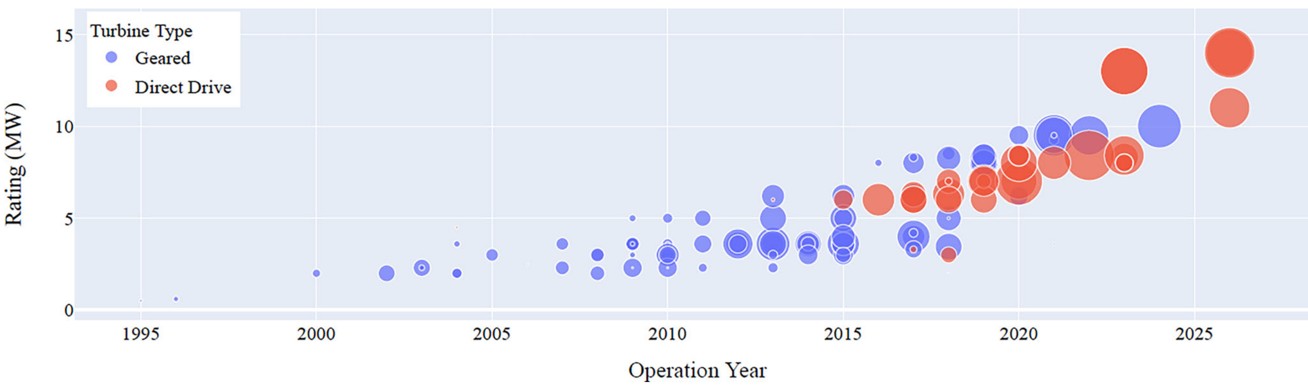


Fig. 2 Graph shows both Geared and Direct-Drive Offshore Wind Turbines Installed in Europe, [9]

also states that in order to meet the net zero commitments, wind installations need to triple to around 320 GW by 2030, which is only 6 years away, as shown in Fig. 1. In the UK, the National Grid estimate that wind generation in the UK needs to go from 6%, which is it's current share of energy supply, to 41% in 2050, [3].

Offshore wind installations are increasing because there is much more space offshore to install larger wind farms, the planning process is quicker and lower risk and the conditions (i.e. stronger and more steady winds) are more ideal to use higher power producing turbines. Because the offshore Balance of Plant (BoP) incurs greater capital expenditure, and because this is a strong function of the number of turbines in a farm, then offshore developers prefer fewer, but larger wind turbines. As a result, the size and power rating of offshore wind turbines are significantly greater (than for onshore wind). For example, the current offshore wind turbine size is about 15 MW, which would mean that for a project like Scotwind which is due to supply approximately 30 GW of wind capacity [5], then 2000 wind turbines would need to be installed.

Whilst there are many advantages with installing wind turbines offshore, one disadvantage is that it is much more expensive to carry out any repairs and/or maintenance. One reason is that vessels are needed to visit the turbines, which increases both downtime (in the case of repairs) and cost.

Many failures occur within the wind turbine's powertrain—the sub-system that converts mechanical power into electrical power [6]. The powertrain is located within the nacelle, on top of the turbine tower. The implication of any failure here can be severe, as large components need to be replaced using heavy lift vessels [7]. Therefore, ways to increase the reliability and reduce failures within the powertrain are continually being investigated. In early offshore wind farms, a large number of gearboxes had to be replaced, [8]. This industry experience has encouraged some turbine OEMs (e.g. Siemens Gamesa and General Electric) to pursue designs with direct-drive electrical generators. Most offshore wind turbine manufacturers also opt for permanent magnet synchronous generators, as they are more efficient, lighter and need less servicing than their electrically-excited counterparts. Fig. 2 shows the increasing shift towards direct-drive generators in Europe.

Eliminating the gearbox means that the wind turbine rotor is directly coupled to the generator, so the rotational speed of the generator is relatively low, in the order of 10 rpm or less. This implies that for the turbine to convert the turbine mechanical power, the rated generator torque needs to be very large indeed, as per Eq. 1. The torque can be calculated from Eq. 2, where 'R' is the radius, 'σ' is the electromagnetic shear stress and 'l' is the axial length of the machine.

$$P = T\omega \tag{1}$$

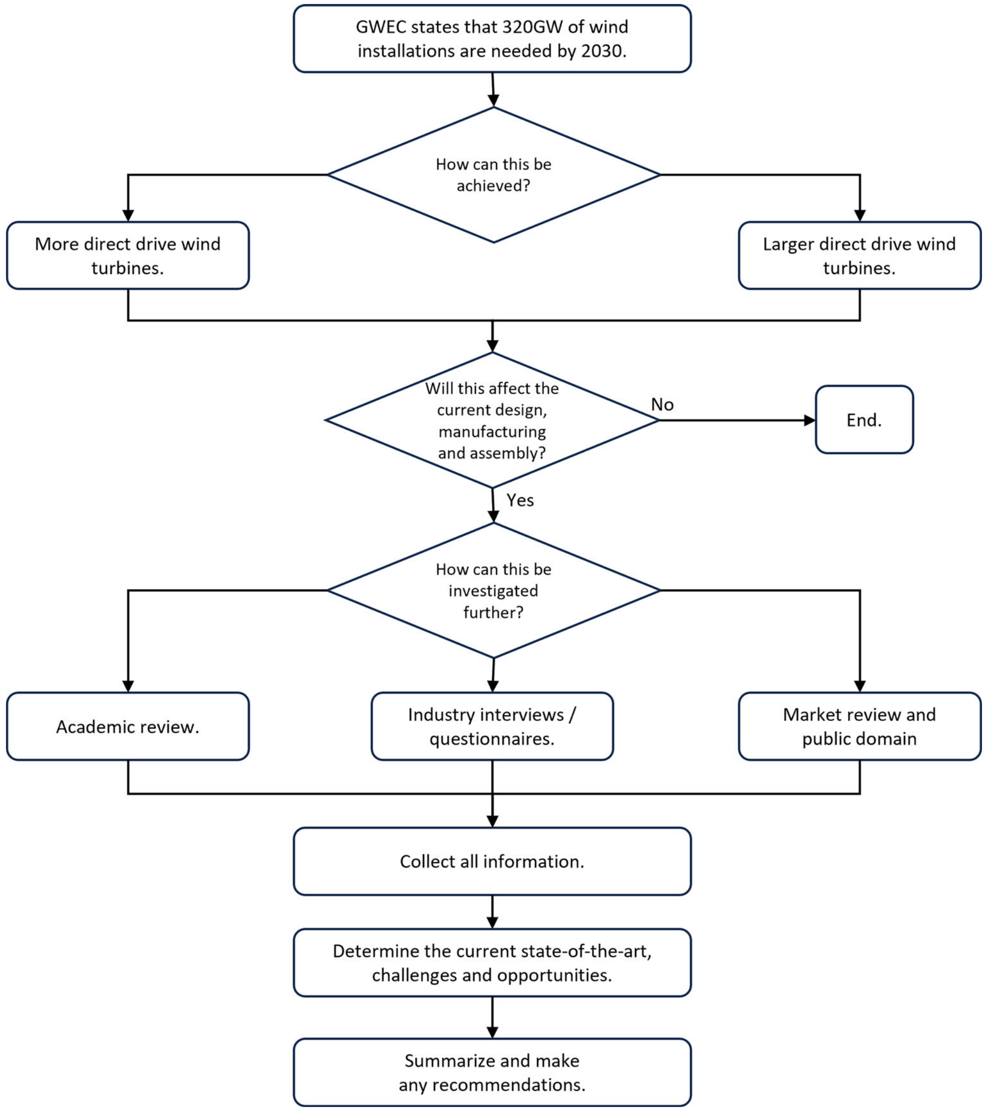
$$T = 2\pi R^2 \sigma l \tag{2}$$

Typical figures for these generators are 40 kPa for air-cooled machines [10] to 60 kPa for liquid cooled machines [11]. From this equation, it can be seen that if more torque is required, either the radius and/or length needs to increase. These direct drive generators are very large indeed; the 15 MW NREL benchmark generator design has an outer diameter of around 11 m [11].

Because of their size, and also because of the significant forces acting on and in the generator (such as the normal stress in the airgap, which tends to pull the rotor and stator towards one another) these generators need to have significant structural stiffness. The structural material that provides this stiffness means that these large generators are heavy, [12].

The weight and size of these generators can cause issues, especially with regards to manufacturing and installation. Therefore, research has been carried out and continues to be carried out, looking into ways to reduce the weight of these generators, i.e. light-weighting, [13, 14].

Fig. 3 Flowchart Summarising the Method Used to Perform this Work



If we refer to changing technology for light-weighting, this would be possible through superconducting generators, [15], which based on the principles of Eqs. 1 and 2, can generate higher magnetic shear stress, thus higher power density. For instance, a 15 MW permanent magnet synchronous generator has a stator diameter of 9 m, axial length of 2.5 m and weight of 314 T but by using a low-temperature superconducting generator, the stator diameter remains the same but the axial length reduces to 1 m, meaning the weight reduces to 192 T, [16]. Advances in superconducting machines means that they have a high shear stress, so for the same torque value, the radius or length can be reduced, resulting in lighter weight machines. However, the scope of this work is limited to permanent magnet direct-drive generators.

As offshore wind turbine designs continue to grow, the torque rating and volume of the direct-drive electrical generators have to grow even quicker (as maximum tip speeds have reached their limits, so larger wind turbine rotors lead to lower rated rotational speeds). As such, the industry is facing challenges of scaling up in terms of unit sizes and scaling up in terms of throughput. There are also challenges for generator designers and manufacturers because these wind turbines (and their generators) are now being installed on floating platforms, subject to additional loading and which are more challenging to access for maintenance.

With this in mind, this paper looks at the design and manufacturing challenges and opportunities for offshore wind turbine permanent magnet generators. Where possible it will try to identify research and development routes aligned with those challenges and opportunities.

The rest of this paper is structured as follows: Sect. 2 explains the methodology used, Sect. 3 describes the current state of the art, Sect. 4 discusses the challenges, Sect. 5 describes the opportunities and Sect. 6 explains the conclusion and any future work.

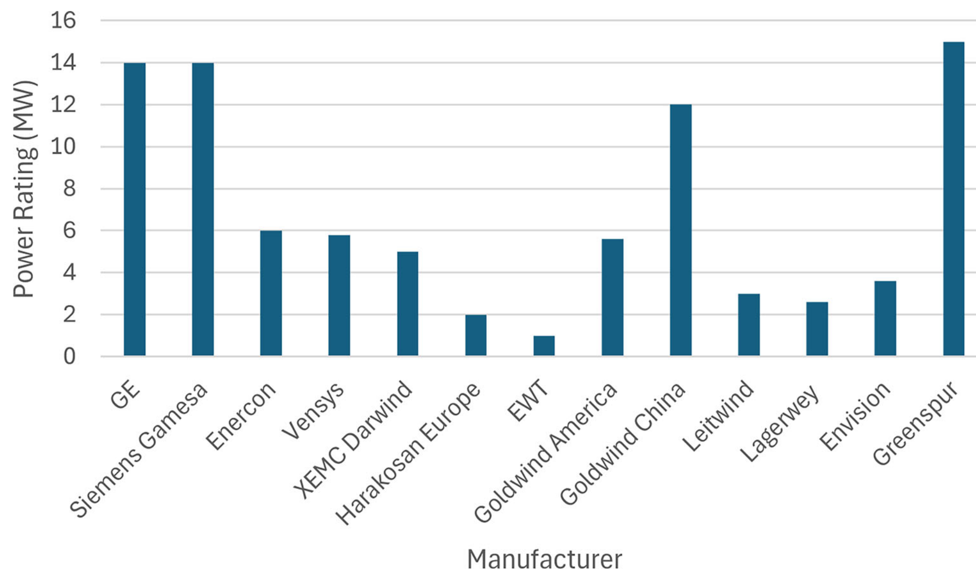


Fig. 4 Graph showing the Manufacturers vs. Maximum Power Ratings of their Direct-Drive Generators

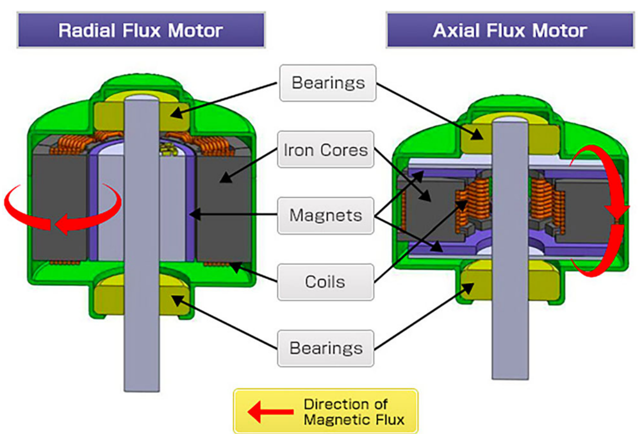


Fig. 5 Diagram showing the difference between Axial and Radial Flux Topology. Diagram Courtesy of [19]

2 Methodology

A flowchart showing the process from the motivation of this work, through to the methodology used and finishing with the desired outcomes, is shown in Fig. 3. Initially, the main ways of increasing the wind installation capacity over the next 6 years are determined, these are: increasing the number of wind turbines and/or increasing the size of wind turbines, specifically direct-drive. Then obviously, these developments will affect the design, manufacturing and assembly, so research is carried out using a number of sources. The first being academic review, so a large volume of papers, books, articles, etc. are reviewed and the key points noted. The second source is market analysis and any information available in the public domain, such as, wind turbine specifications, manufacturer information etc. The final source is interviews with industry, in order to obtain first hand information of challenges and opportunities they both currently face and what they predict they may face, when turbines are either scaled up in size or number. Nearly twenty companies were contacted to either complete a questionnaire that has been prepared, or have a face-to-face interview but unfortunately the majority declined, due to non-disclosure of sensitive information, only a few people were willing to be interviewed.

3 State of the art

3.1 Key players and turbines

Many wind turbine and generator manufacturers are now producing direct-drive generators for both onshore and offshore wind turbines. As part of this contribution, a comprehensive search in the public domain was carried out to identify the wind turbines with a direct-drive generator. It should be noted that due to the dynamic nature of the market, this information could change to some extent even during this project, more likely the turbine model and power rating. These are shown in Tables 1 and 2, with the direct-drive generators used onshore marked with an asterisk, and a hashtag for both onshore and offshore turbines. In most cases, these generators are of a 'radial flux' type, with different manufacturers choosing between permanent magnet rotor excitation and DC electrical excitation, [17]. Fig. 4 illustrates the various manufacturers alongside the maximum power ratings of their direct-drive generators.

The existing direct-drive generators below MW power rating such as GenesYs mbH's 600 kW, [18], are not included in the tables.

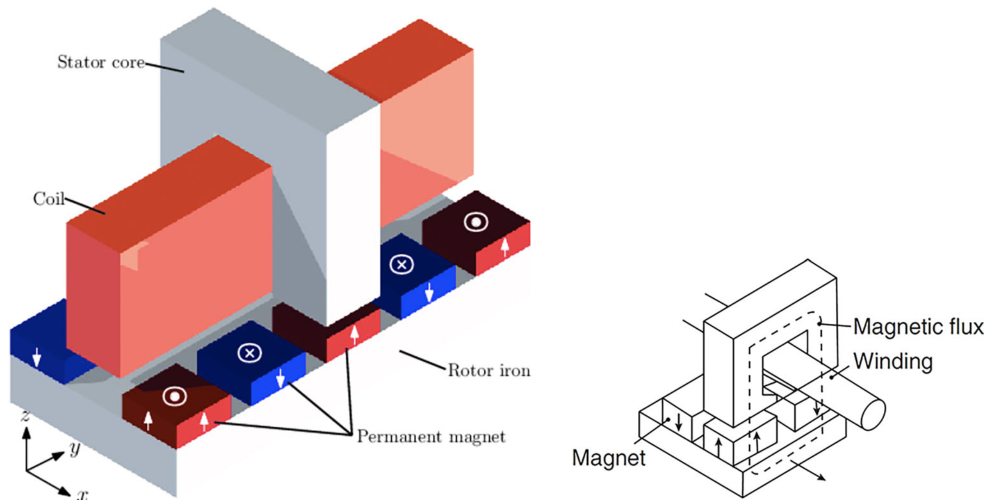


Fig. 6 Cross Section of Transverse Flux Generator [20] (LEFT) Cross-Sectional Drawing of Transverse Flux Generator Showing Flux Flow (RIGHT). Diagram Courtesy of [21]

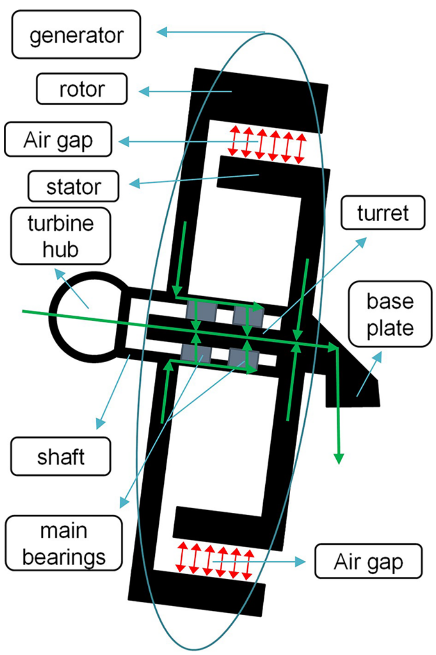


Fig. 7 IEA's outer rotor 15 MW direct-drive generator, authors' illustration inspired by [11]

3.2 Design

3.2.1 Generator topologies

The various generator topologies depend upon the preferred flow of magnetic flux as it crosses the air gap, with respect to the axis of rotation, which are: axial flux, radial flux and transverse flux.

Radial flux means that the magnetic field runs perpendicularly to the rotor shaft as it crosses the air gap, as shown in Fig. 5. This is the most common machine configuration in electrical machines, and the same is true for wind turbine generators. Different generator designers prefer 'inner rotor-outer stator' or 'inner stator-outer rotor' configurations. The former allows for easier cooling of the stator (where most losses and hence heat are produced); the latter can allow for larger torque for the same outer diameter.

Axial flux means that the magnetic field runs in parallel with the rotor shaft. These machines are sometimes referred to as 'pancake' machines as they are relatively thin in the axial direction. One potential area of development is the use of stacks of these pancakes, [22].

Finally, transverse flux machines are a mixture of both, as the magnetic field runs three dimensionally, for example, the flux runs parallel through the stator, perpendicular through the air gap and around the rotor [23], as shown in Fig. 6. These types of machines allow for very large electromagnetic shear stresses, but have not yet been widely used because of other performance issues such as that with power factor, [24].

3.2.2 Overall principles

The main role of the direct-drive generator structure is to sustain the minimum airgap of the generator. Direct-drive electrical generators can be categorised from different standpoints. From the electromagnetic point of view, the generator components can be categorised into active and non-active parts. The non-active parts of the generator's rotor and stator should primarily provide adequate mechanical strength, in terms of the required stiffness for carrying the loads imposed by the active parts. As such, one can also consider active and non-active sub-structures for categorising the generator components. The active parts of the generator—mainly those in the stator—are embedded into the active sub-structures such as laminated stacks, windings and rotor cores.

The direct-drive electrical generator depending on the rotor-stator position is divided into inner and outer rotor.

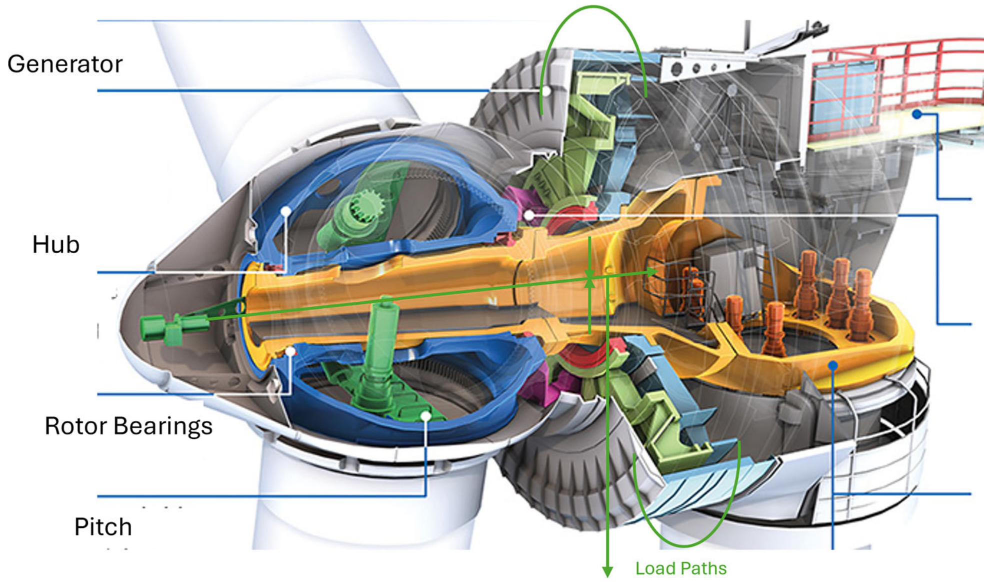


Fig. 8 GE's Haliade 150 (6 MW) direct-drive generator originally designed by Alstom [25]

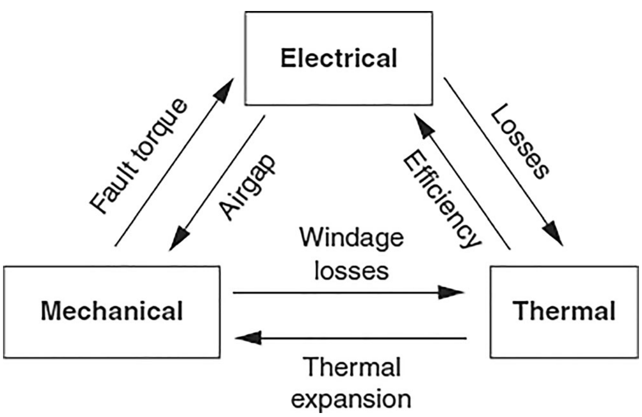


Fig. 9 Diagram showing the interactions between electromagnetic, structural and thermal design elements. Diagram Courtesy of [26]

Depending on the number of bearings, the direct-drive generators may have single, double or triple-bearing layouts. The single bearing allows for a more compact configuration of the generator, at the cost of higher structural requirements of the drivetrain and generator. The double or triple bearing configuration can have a less complex design of the mechanical structure but requires a higher mass, as the length of the shaft/axle has to be increased. In a triple bearing arrangement, part of the drivetrain's axle usually penetrates into the wind turbine rotor hub. According to the current figures in industry, radial flux direct-drive electrical generators are more common and more favourable in the design of multi-MW offshore wind turbines. The loads that affect the airgap of these machines include the magnetic-induced stresses in both the radial and tangential directions between rotor-stator and—depending on the drivetrain layout—the turbine hub loads due to rotor aerodynamic interactions can also be present. The drivetrain with the direct-drive generator is located within the load path of the wind turbine, from the rotor hub to the support structure. As such, direct-drive generators unlike its geared counterpart undergoes a more complex combination of loads, which makes the design more difficult. Therefore, the selection of the layout or additional components such as devices for taking the non-torque loads, require adequate consideration.

Figs. 7 and 8 show examples of direct-drive generators. Fig. 7 presents a schematic sketch of the concept IEA 15 MW wind turbine direct-drive and Fig. 8 depicts the GE's 6 MW Haliade 150 with the so-called pure torque design by Alstom.

3.2.3 Loads acting on generators

When designing an electrical generator, it is critical that the airgap clearance between the rotor and stator is maintained. It should be noted that as the size of the generator increases, so does the size of the forces, [26].

Some of the forces that are present within the generator include, [26] and [27]:

- Normal Stress—A large force of attraction between the rotating and stationary parts caused by magnets on the rotor.
- Shear Stress—Area where mechanical energy is converted to electrical energy. Mechanical torque from the rotor is transmitted to the airgap and the same torque must be resisted by the stator.
- Wind Turbine Loading—From the rotor blades, wind shear, yaw error and inertial effects.
- Gravity—Weight of the generator.

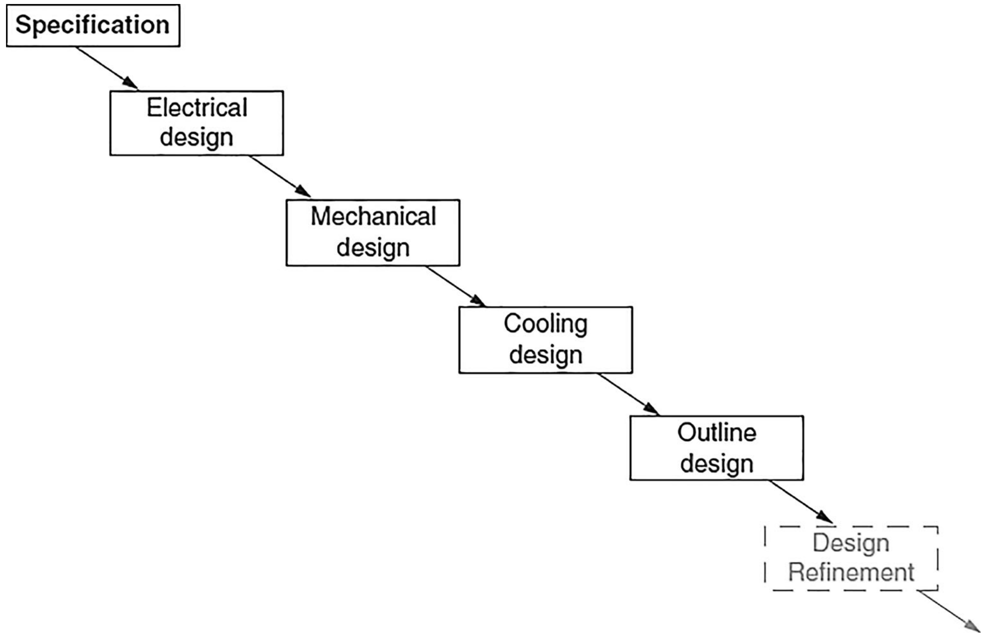


Fig. 10 Diagram showing the traditional early stage design approach. Diagram Courtesy of [26]

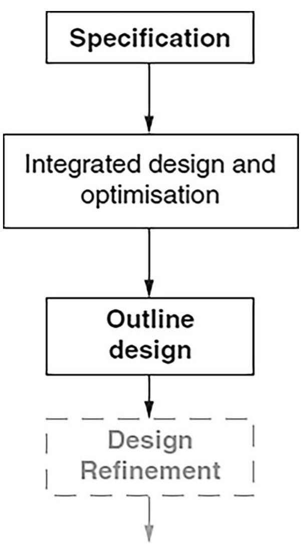


Fig. 11 Diagram showing the integrated early stage design approach. Diagram Courtesy of [26]

- Thermal Strains—Temperature increases, decreases and rates of change cause differential thermal expansion and contraction, which can produce changes in flux density.
- Centripetal Forces.

As opposed to simpler layout of the drivetrain compared with the geared systems, the combination of several loads listed above, indicates the complex nature of loading that the structure of the direct-drive turbine undergoes, in addition to the dynamic interactions and coupling between turbine and generators' structural and electrical sub-systems.

3.2.4 Electrical design of DD generators

With regards to the electrical design of a direct-drive permanent magnet generator, it typically accounts for approximately 52% of the total cost of the generator and the main aim is to obtain maximum power output or efficiency, using the least amount of material, [26]. The electrical insulation and cooling is also extremely important, [27].

The generator is required to convert an input force i.e. rotational torque or linear motion, from a prime mover, along with speed into electrical power, [28]. Therefore, the torque and speed are the most important requirements. Followed by the cogging torque, which should be low to enable start-up at low power levels. Another requirement is high efficiency, as well as a high part-load efficiency which may increase energy yield.

The main design choices are: materials i.e. laminated electrical steel, copper, magnets and machine topology i.e. radial-flux or axial-flux, electrical or permanent magnetic excitation, stators with slots, air-gap winding or air cored machines, open slots, semi-closed slots or slots with magnetic wedges, distributed windings or concentrated fractional pitch windings, skew or not, buried magnets with flux concentration or surface-mounted magnets, voltage level selection, power factor and cooling method (air vs. liquid cooling).

3.2.5 Electromagnetic, structural and thermal management

When designing a generator, in order for it to be successful, the links between electromagnetic, structural and ther-

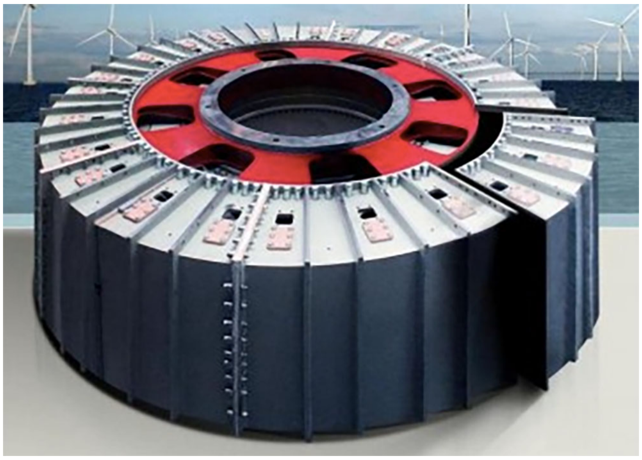


Fig. 12 Picture showing the Segmented Stator. Diagram Courtesy of Siemens Gamesa [30]

mal elements need to be understood, [26]. Fig. 9 shows an example of the interactions between these three elements.

Traditionally, electrical design dominated in the early design stages, as shown in Fig. 10, but this is not an optimal method, as it constrains the thermal management, mechanical and structural design, which are also critical aspects in designing a generator.

Simplification of design can reduce cost of manufacture and assembly. This can include modularisation or less strict manufacturing and assemblage tolerances. For instance, higher tolerances can be achieved by increasing the air gap height. However, this leads to use of more permanent magnet material, which is unfavorable. There is also a similar dependency between the air gap height and the structural stiffness of rotor assembly, including the rotor structure, shafts and bearings. In order to reduce the air gap increasing the flux density, the stiffness of the rotor assembly needs to be increased, which means increasing the generator's rotor weight. If more innovative approaches are taken such as, topology optimisation of the rotor structure or use of composite structures, higher stiffness with reduced mass may be achieved but at the cost of more challenging manufacturing processes, tighter tolerances and higher energy usage, [29]. These are the examples, where an integrated approach to design (Fig. 11) is essential, to obtain a global optimal design and manufacturing where there are several contradicting multi-objectives.

3.3 Manufacturing and assembly

Manufacturing and assemblage of direct-drive generators and the entire drivetrain is indeed complex. Due to the large size of this type of drivetrain and complex combination of loads, the manufacturing and assemblage tolerances must be carefully taken into account to ensure the air gap clearance during turbine operation and to avoid excessive unbalanced magnetic forces, that can cause further electrical and mechanical issues, along with efficiency reduction. In order to figure out the industrial practice and scarcity of the contents in the literature and public domain, this part of the contribution primarily relies on the insights obtained from industry through interviews.

The non-active structural parts of the rotor, stator, shaft/axle of the directly driven drivetrains are made of large thin-walled parts that are usually segmented or modularised. Therefore, the interfaces for a proper connection between the segments must be adequately designed and manufactured to deliver the integrity of the entire unit statically (in terms of stiffness) and dynamically (in terms of components vibration and resonance of any modes). An additional challenge in the manufacture of the rotor is attaching the magnets to a drum like structure, which may also be segmented, where symmetricity of the magnets layout and mounting mechanism for protection against the offshore harsh salty environment are essential. According to common practice the rotor structure is usually manufactured/free issued by the turbine OEM and delivered to the generator manufacturer for assembling the generator. The insitu activation of the magnet assemblies would be far safer. However, the equipment for this purpose could be far too bulky and costly—further thoughts to overcome this are required—for instance, could the Halbach arrays be used to help with magnet insertion force reduction.

The manufacture of the stator is slightly more complicated than the rotor. The major part of the stator including the production of winding and insulation wrapping for its conductors and installation of the lamination stacks are carried out by the generator manufacturer, often in a laborious manual process. As a matter of fact, more automation or mechanical assistance is beneficial to reduce the cost of quality (CoQ) and TAKT time/Standard Minutes.

Similar to the rotor, the stator is also made up of segments, as shown in Fig. 12, which are made from laminations. These laminations are stamped from steel, which have enamel coated on one side. This stamping process is typically monitored using vibration testing to ensure there is a clean break. Once all the laminations have been produced, they are then stacked and measured. Some larger machines may have as many as 72,000 laminations. Other stator components include compression plates, compression bars, finger plates and coils. With regards to coil manufacture, copper rectangular bars are typically pre-formed. Turn-to-turn insulation is then applied by hand. Over-taping is a semi-automated process, which is hand manipulated over the bars. The coils are then tested for continuity. Assembly is then carried out using jigs. The compression plate is placed first. Stacking starts at the bottom and builds up in a staggered pattern so there usually is some overlap. A 3D

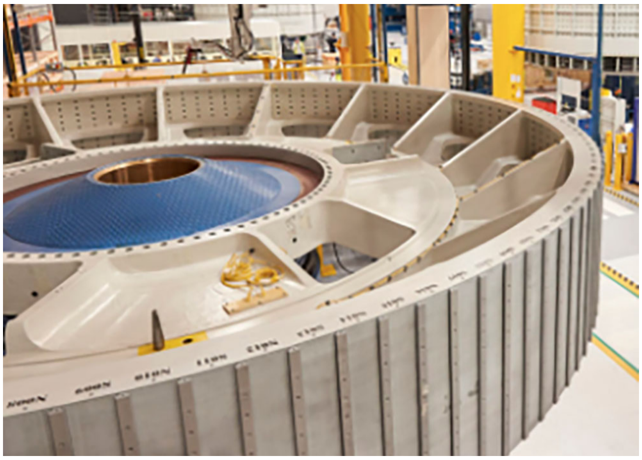


Fig. 13 Photo of GE's Haliade 6 MW Rotor [32]

Fig. 14 Photo of GE's Haliade 6 MW Generator Assembly Process [32]

visual scanner is used to check alignment against the jig. The laminations are then stacked and the compression bar applied to the back of the back iron. The top compression plate is then fitted. Consolidation of the lamination pack is then performed, where it is pressed in the axial direction. Both compression pressure and deflection are monitored. Each segment is then stamped with a serial number to ensure full traceability. Next step is assembly of the coils in the slots, installation of slot wedges, end windings and bracings, connection to the bus-bars and tapings made. Then comes the vacuum pressure impregnation (VPI) process, where the stack segment is placed in a vacuum full of resin, followed by being rotated in an external oven. For larger segments, this curing process may take several days. After the curing process, it is tested again. Once all the stator segments are ready, they are afterwards assembled together. They are assembled on a consolidation plate, which holds the drive end and bearing together. This consolidation plate is critical to alignment. So the segments are placed, aligned and doweled in place. The cooling system is then mounted and it is connected electrically.

Regarding coil winding and assembly to the stator, most machines have distributed windings although some are tooth-wound—like the GE-Alstom Haliade Machine. The stator coils are long and as a design aim, that need to be a tight fit into the slot. Manufacturing is part manual and part mechanically assisted—the overtaping is assisted by a taping machine which is hand operated. If this could be fully automated, then CoQ goes down and time improves. In terms of future opportunities, some radical thoughts on the slot fill and fitting can be considered. This could be realised by using an Auxetic material to hold the coils tightly in place that solidify during VPI (vacuum pressure impregnation).

There are various components within a directly driven drivetrain, which require a precise assembly process. In this section, the assembly concerns the assembly of components and that of the sub-components, lamination stacks, winding slots, magnets, etc. are disregarded. One major challenge in the assembly of the units is related to rotor-stator placement. There are typically two methods of assembling the stator with the rotor, which can be referred to as either hot or cold marriage. One method of assembly also known as cold marriage, is that once the stator is complete, the rotor drum is placed either on the outside or inside of the stator, depending upon the design, and the magnets fitted. This is quite a dangerous process and requires good, strong equipment. In some cases nylon sheet is placed within the air gap during the magnet installation process. The second method, referred to as hot marriage, is where the magnets are attached to the rotor drum using jigs and fixtures, prior to placing it either inside or outside of the stator. This method uses a hydraulic control system and is a little safer. The rotor drum is held, then rotated round as each magnet is attached. Once all the magnets are attached, the rotor is then dropped over the stator assembly, which as mentioned earlier, is held by the consolidation plate. The final stage after all the tests are performed, is painting and addition of all the safety stickers. Rotor assembly is generally a difficult and precision process, but perhaps a better way to assemble the machines would be to assemble up to the rotor (using the rotor as a "fixed point" datum). This would need to be made safe, and the tolerance stack made good enough to allow or require fine alignment only. In this regards, there are thoughts that cast resin like "Chockfast" could be used to good effect to do this—borrowing the materials from marine diesel engine making [31]. (Figs. 13 and 14).

Afterwards, mounting the generator onto the shaft/straddle or axle (depending on the drive's configuration) and placement of the bearings matter. Preserving the eccentricities within the allowable tolerances that do not excessively impact on the air gap variation must be taken into account. The bearings are either bolted or press-fit, where the smaller diameter bearings are more favourable from cost of the production and assembly view point.

4 Challenges

4.1 Current manufacturing processes

The main challenges in the manufacturing of direct-drive generators and its corresponding entire drivetrain, arise from the inherent differences between this type of drivetrain and its geared counterpart. Some major examples of these differences are as follows: a) physical size of generator and weight (amount of material), b) supply chain of active and non-active components, c) logistics and manufacturing space that requires bespoke investment by manufacturer, d) cost of assembly and required bespoke machinery and e) testing, verification and quality control methods and cost.

Moreover, the conventional tools and methods are not applicable in the manufacture of sub-components such as coil manufacturing and winding assembly, where e.g., double layer overlapping and use of VPI tank is needed. Maintaining the quality throughout the manufacturing process to avoid any flaws is crucial, as any post-installation repair in a remote offshore environment can be highly costly [33]. In comparison with the high-speed generators, there are additional challenges with the placement of rotor magnets. Due to the large number and size of the magnets in direct-drive generators, care has to be taken when installing the magnets on the rotor drum as this is a dangerous activity.

Ensuring tolerances and the air gap uniformity are maintained, as well as controlling shrinkage during the welding process used on compression bars and plates, are other challenges currently faced.

4.2 Scaling up in size and number

From an electrical point of view, the generator size may not reach its limit even beyond 15 MW. However, the interaction between the mechanical and electromagnetic field will be challenging. The harmonic electromagnetic forces applied on the mechanical structure of the rotor has a different nature in comparison with that of high-speed machines. In addition to the demanded stiffness for the structural subcomponents of the rotor and stator, the dynamic response and vibration of these structural components should be carefully taken into account. It is noted that in the high-speed machines these vibrations are primarily emitted in terms of noise, whereas in direct-drive machines these structural vibrations can cause asymmetric deformations of the air gap and in ultimate cases an interaction with the turbine rotor loads and the electromagnetic field can cause air gap collapse. As such, ensuring the design structural strength of the generator components and control of tolerances through the manufacturing and assembly process matters significantly.

With regards to the damping. many geared drivetrains include dampers, damping mechanisms and devices, allowing for adjustments to mitigate noise and vibration, [34]. However, in contrast, the direct-drive systems still require further research to identify the challenges [35] with vibration, noise and the mechanisms and methods to address them.

The number of manufactured direct-drive generators at the moment is dictated by the number of personnel, equipment, workshop area and space, as well as sub-component suppliers and supply chain. Any decision for up-scaling the production number by the manufacturer will require more investment by the manufacturer, as such is business model driven and depends on the security to obtain the revenue. Examples where investment may be needed includes, larger facilities, employing more personnel and also training them, especially with regards to the wrapping and buying more equipment, such as VPI pots and ovens for curing. Production standardisation is another factor that influences the manufacturing speed. But the configuration production line is usually driven by the orders placed by the turbine OEMs, which can be generators of different design, size and power rating.

For scaling up in size, larger equipment may also need to be purchased to accommodate the larger components. Along with the larger equipment, ensuring the workshop structure can handle lifting heavier components may also need to be checked. Further challenges, for example, through life management, end of design life and life extension such as those similar to the geared counterpart drivetrain is outside the scope of this work, [36, 37].

4.3 Floating turbines

Due to the fact that more and/or larger turbines will need to be installed in order to meet the wind installation targets and the availability of shallow offshore sites becoming more limited, the demand for floating wind turbines will most likely increase, especially in deeper waters and areas further from shore but then these come with their own issues. The heavy nacelle will require higher buoyant force and resisting bending moment, to react to the turbine weight and overturning bending moment, due to increased inertial loads. This will lead to floating systems with increased dimensions and more demanding mooring, depending on the specific floating system. However, according to [16] for power ratings beyond 22 MW, this issue appears to be more challenging for medium speed permanent magnet geared

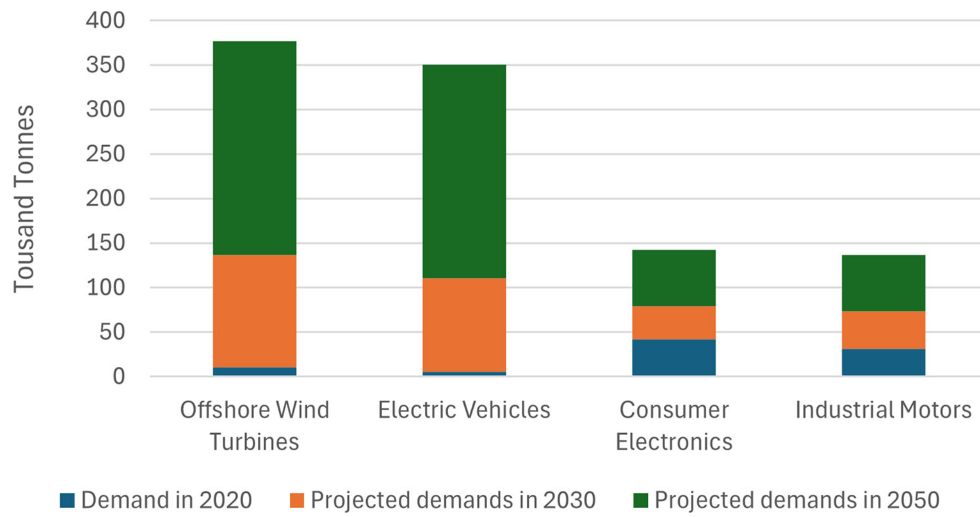


Fig. 15 Graph showing the global projected demand for NdFeB Magnets [41]

drivetrains. Further more, the other key issue being the additional platform or floater motions i.e. pitch, roll, surge etc. causing larger inertial loading of the rotor nacelle assembly and in turn the mechanical responses within the drivetrain, [34]. This can potentially lead to an increased dynamic coupling between the turbine support structure and the drivetrain in the presence of wind and wave excitation and generators electrical end. Increased motion on the pitch and surge can threaten the air gap stability, causing unbalanced magnetic pull or even collapse of the generator air gap, [38]. As mentioned previously, maintaining a stable and uniform air-gap is important, due to a non-uniform air-gap causing "fatigue loads on the generator". Sethuraman et al. [38] investigated whether a direct-drive radial flux permanent magnet generator would be suitable. They looked at two designs, with the aim of preventing closure of the air-gap. The first design made the structures stiffer to limit radial deflection to 10% and the second increased the air-gap, as well as increasing the magnetic material. There are several interesting studies focusing on the mutual impact and interactions between the drivetrain and support structure. However, much more research particularly on turbines with directly driven generators is still necessary, [17].

4.4 Supply chain

The main material/products that need to be procured for the manufacture and assembly of generators are: laminated electrical steel for magnetic purposes inside the generator, copper for the windings, permanent magnets and carbon steel for the structure supports, [28].

The challenge with procurement of the above materials, aside from the permanent magnets, appears to be more related to project management aspects than the materials themselves. However, the main challenges within the supply chain are related to the neodymium iron boron (NdFeB) magnets, as they have a long supply chain and more recently there has been a shortage. This recent shortage is due to the enormous demands rising across industries from electrification in transportation, to the wind turbine generators and the fact that the main production of rare earth elements are controlled by just a few countries (see Fig. 15), as well as dependency on dysprosium and terbium, which are also mined in the same country, [39]. NdFeB are classed as a rare-earth magnet, which are widely used. A typical production sequence of manufacturing [40] include:

- Extraction of the raw material. Neodymium is sourced from bastnasite and monazite. This is a challenging mining process.
- Separation and Refining. This is important because the purity directly impacts the quality.
- Production of the Alloy. Neodymium is combined with iron and boron.
- Manufacturing the Magnet. The key steps include: powder production, pressing, sintering and machining and coating.
- Quality Control.
- Distribution.

Sourcing magnets from ethically sourced/politically stable companies/countries is important for the vast majority of manufacturers so this can limit the number of suppliers. Innovate UK have researched the supply chain opportunities with regards to permanent magnets, [42]. Due to the weight of the magnets, they are typically shipped from wherever they are purchased. This factor has to be taken into account, as shipping delays may effect the completion date.

Another challenge which will affect the supply chain if production of generators increase worldwide, is the availability of material in general because as the demand increases, availability may reduce (i.e. there will be a shortage) which may result in longer lead times and also push up prices. This may also be a problem if additional equipment is required for manufacturing of the generators.

5 Opportunities

5.1 Design

With regards to design, researching other materials that are more readily available may be an opportunity, as well as redesigning the components so that less active and non-active material may be required. One example is Greenspur's 15 MW generator [43], where aluminium coils replace copper coils and a spoked design is proposed. Low density materials i.e. composites, have been proposed by [13] and is another example of researching alternative materials to reduce the weight. Another example of researching other designs could be to use a distributed drivetrain, where the drive path from the rotor is split, so it drives several generators in parallel, that are inspired by older ideas [44]. A third example is by using generative design techniques, where a 4% reduction in structural mass was obtained, [45]. A final example consists of using a parametric approach, specifically a conical design, [29, 46].

As the generator size grows the interactions between electromagnetic forces and mechanical stress and dynamic deformation of structural load carrying components increases. Therefore, a more holistic approach to the coupled aero-electro-mechanical analysis and design versus a separate conventional method can prevent or reduce later design iterations. This leads to more complex multi-physics and dynamic multi-body analysis, to be implemented either analytically or computationally that will require the development of newer analysis tools. Furthermore, as highlighted in the design challenges, an integrated multi-objective design optimisation aimed at reducing overall costs and material usage is considered essential.

Ideally during the design phase, ease of maintenance is also taken into account. One example is by using a modular design. Whilst we aren't aware of the extent in which it is possible to repair the generator on-site, whether modules can be exchanged on-site and if disassembly of the rotor is necessary in all cases, we assume that by using a modular design, repair and exchange of modules on-site is a possibility. However, due to the commercial sensitivity of the data, getting hold of information from the owner/operators in this context, seems to be extremely difficult.

5.2 Manufacture and assembly

One opportunity could be for the manufacturers to try and automate as many of the manufacturing/assembly processes as possible and practicable. This may not only speed up the process but by replacing manual processes, may remove some risks employees face when performing the tasks manually i.e. improve safety and may also reduce the possibility of human error, especially, when maintaining a small air gap will become even more critical.

Design for manufacturing seems to be essential for direct-drive machines and this has been obviously exercised to-date at least at high-level drivetrain layout design. Nevertheless, clear vision of the manufacturing routes of subcomponents, as well as manufacturing and assembly process of the entire drivetrain at early design stages can help realise many improvements, such as increased automation and mechanical aid. Furthermore, the manufacturing/assembly induced impact on structural components such as local stress/strain arising from machining, welding, bolting, interference fit and change in mechanical behaviour of material e.g., due to specific forming and casting method, should be further integrated into the design phase, which can have favorable or detrimental impacts on stiffness, dynamics and light-weighing of mechanical structures.

Using alternative processes may also be another opportunity, for example additive manufacturing, which has been researched previously to determine if this process can help reduce the structural mass of the generators, [47, 48]. Hayes et al. [47] found a weight saving of up to 39%, when using an "additive manufactured optimised rotor and stator". Additive manufacturing can be defined as "a process of fabricating three-dimensional objects by depositing materials layer-by-layer directly from computational geometry model", by [49]. They go on to explain the main advantages of using additive manufacturing which include: design flexibility, the ability to fabricate complex geometries, as well as consolidate multipart assemblies into a single component and the potential to increase the supply chain efficiency. The disadvantages include: accuracy of dimensions, structural integrity and issues with monitoring and controlling the process. A review has been conducted by [50], who found that printed WAAM mild steel parts had a similar tensile strength to wrought material and [51] found that additive manufactured steel has a much higher endurance limit than cast iron. However, further research is required to investigate the feasibility of this technique in the wind energy sector.

Testing and verification of generator operation can be a time consuming and accordingly highly costly process, both during and after the manufacturing and assembly processes, so a way of streamlining this may be beneficial, especially in the case of scaling up production. In this regard, some radical thoughts on the development of downscaled testing methods that can preserve the ratio between the required mechanical stress/deformation and the electromagnetic forces of larger machine at smaller scale can be significantly promising.

Some opportunities at component level can also be mentioned. For instance, alternatives for the mechanical bearings that are one of the weak links in a directly driven drivetrain. There are a number of bearing systems/design as an alternative to the classical mechanical bearings to enhance the reliability of direct-drive generators, such as magnetic bearing (passive and active) and hydro static bearing.

6 Conclusion and future work

This work aimed to shed light on the challenges the wind industry faces in meeting the demands for Net Zero, particularly in designing larger and more efficient direct-drive wind turbines. It included a comprehensive review of literature, public data, market trends, and industry interviews. The investigation focused on the challenges in designing and manufacturing future direct-drive generators. Additionally, it highlighted the need for more advanced analytical methods and tools to address the complex physics, loading conditions, and dynamics of direct-drive generators.

Next, the challenges in the manufacturing process of the direct-drive generators was studied. Details on the current manufacturing and assembly processes for direct-drive generators in the public domain is limited. Therefore, as well as reviewing all the literature already published, interviews were held with a few industry personnel to assist with understanding the current processes, including any challenges currently experienced and predicting any future challenges and opportunities (if any) as the generators are scaled up in size and numbers produced. It should be noted that obtaining the agreement for elicitation in terms of the interviews is not straightforward, due to the sensitivity and confidentiality of the industrial information.

Current manufacturing challenges can include: material handling i.e. installing the magnets, ensuring tolerances are met, controlling shrinkage during welding and distortion and maintaining quality and safety, to name a few.

Challenges with regards to scaling up production, may include: ensuring there are sufficiently trained personnel, workshop space, equipment and material, as well as ensuring that quality and safety are maintained. Similar challenges exist with regards to scaling up in size but additional challenges may include: ensuring the workshop structure can handle lifting heavier components, avoiding introducing new mode shapes in segmented structures and maintaining a uniform air-gap between the rotor and stator. This is crucial, so increasing size may make this more of a challenge.

As mentioned earlier, it is inevitable that generator size and production is going to increase, in order to meet the net zero targets set by multiple countries worldwide. Therefore, reviewing the manufacturing, assembly and installation challenges that are faced currently, can only assist going forward. These challenges can be addressed and taken into account when designing and manufacturing generators for the future.

This work attempted to present opportunities to address the aforementioned design and manufacturing challenges for future direct-drive generators. From both design and manufacturing perspectives, an integrated approach to electrical and mechanical design and a multi-objective optimisation approach, aligned with manufacturing requirements, is considered essential to achieve a globally optimal solution, especially when dealing with multiple conflicting objectives. Additionally, opportunities to overcome current challenges in the manufacturing and assembly of direct-drive systems were presented, primarily based on industry elicitations gathered through interviews.

Future work can include discussions with more companies from part suppliers to wind turbine OEMs to capture the views of different parties involved in design and manufacture of the wind turbine direct-drive systems. Further investigation into through-life management of direct-drive generator systems and failure analyses (repair and maintenance), end-of-service life considerations (lifetime extension, decommissioning, disassembly, recycling and circular economy aspects), all in relation to manufacturing materials, process and assembly and installation methods are also of high importance.

7 Appendix

7.1 List of direct-drive manufacturers and turbines

Table 1 Table showing Current Direct-Drive Wind Turbines (Onshore and Offshore)

Manufacturer	Model	Power Rating	Reference
GE	Haliade X	12 MW/13 MW/14 MW	[52]
(Designed by Alstom)	Haliade-150	6 MW	[53]
Siemens Gamesa	SWT-DD-120*	3.9–4.3 MW	[54]
	SWT-DD-130*	3.55–4.3 MW	[54]
	SWT-6.0-154	6 MW	[55]
	SWT-7.0-154	7 MW	[56]
	SG 8.0-167 DD	8 MW	[57]
	SG 11.0-200 DD	11 MW	[58]
	SG 14-222 DD	14 MW	[59]
	SG 14-236 DD	14 MW	[60]
Enercon	E-175 EP5*	6 MW	[61]
	E-160 EP5 E2*	5.5 MW	[62]
	E-160 EP5 E3*	5.56 MW	[62]
	E-138 EP3 E2*	4.2 MW	[63]
	E-138 EP3 E3*	4.26 MW	[63]
	E-115 EP3*	2.99 MW/4.2 MW	[64]
	E-115 EP3 E4*	4.26 MW	[64]
	E-92*	2 MW/2.35 MW	[65]
	E-82 E2*	2 MW/2.3 MW	[66]
	E-82 E4*	2.35 MW/3 MW	[66]
	E-70 E4*	2.3 MW	[67]
Vensys	Vensys 62*	1.5 MW	[68]
	Vensys 70*	2.1 MW	[69]
	Vensys 82*	1.5 MW	[70]
	Vensys 126*	3.8 MW	[71]
	Vensys 136*	3.5 MW	[72]
	Vensys 115*	4.1 MW	[73]
	Vensys 170*	5.8 MW	[74]
XEMC Darwind	XD115	5 MW	[75]
	XE128	5 MW	[76]
	XD140*	4 MW	[77]
	XE93*	2 MW	[78]
	XV90*	2 MW	[79]
Harakosan Europe	Zephyros Z72	2 MW	[80]
EWT	DW52*	500 kW/900 kW	[81]
	DW58*	500 kW/1 MW	[82]
	DW54*	500 kW/900 kW	[83]
	DW61*	500 kW–1 MW	[84]
Goldwind America	GW 82/1500*	1.5 MW	[85]
	GW 87/1500*	1.5 MW	[85]
	GW 109*	2.5 MW	[86]
	GW 121*	2.5 MW	[86]
	GW 140–3.4 MW*	3.4 MW	[87]
	GW 140–3.57 MW*	3.57 MW	[88]
	GW 136–4.8 MW*	4.8 MW	[89]
	GW 155–4.5 MW*	4.5 MW	[90]
	GW 165-5.2/5.6 MW*	5.2 MW/5.6 MW	[91]

Table 2 Table showing Current Direct-Drive Wind Turbines (Onshore and Offshore)

Manufacturer	Model	Power Rating	Reference
Goldwind China	GW 82–1.1 MW*	850 kW–1.1 MW	[92]
	GW 136–4.2 MW#	4.2 MW	[93]
	GW 136–4.8 MW#	4.8 MW	[94]
	GW 150–3.0 MW*	3 MW	[95]
	GW 155–3.3 MW#	3.3 MW	[96, 97]
	GW 155–4.5 MW#	4.5 MW	[98]
	GW 165-3.6/4.0 MW#	3.6 MW/4 MW	[99]
	GW 165-5.2/5.6/6.0 MW#	5.2 MW/5.6 MW/6 MW	[100]
	GW 168–6.45 MW	6.45 MW	[97]
	GW 168–8.0 MW	8 MW	[97]
	GW 175–8.0 MW	8 MW	[101, 102]
	GW 184–6.45 MW	6.45 MW	[103]
	GWH 242–12 MW	12 MW	[96]
Leitwind	LTW42*	250 kW/500 kW	[104]
	LTW80*	800 kW/850 kW/1 MW	[105]
	LTW90*	1.5 MW/2 MW	[106]
	LTW 80*	1.5 MW/1.65 MW/1.8 MW	[107]
	LTW 90*	900 kW/950 kW/1 MW	[108]
	LTW101*	2 MW/2.5 MW/3 MW	[109]
Lagerwey	L100–2.5 MW*	2.5 MW	[110]
(subsidiary of Enercon)	L93–2.6 MW*	2.6 MW	[110]
	LW72–2000 kW*	2 MW	[110]
	LW50–750 kW*	750 kW	[110]
Envision	E128	3.6 MW	[111]
Greenspur	–	15 MW	[43]
ABB	–	Per customer request	[112]

7.2 An example of interview questions

Fig. 16 Example of Some of the Interview Questions

Credentials:

1. *Can you tell us a little bit about where you have worked and how it relates to big electrical machines?*
2. *Career to date? / how many years? / what position now? / what position in past?*
3. *What companies? / what is/was the business of the company? Who were the customers?*

Manufacturing today:

1. *Could you describe briefly how a direct drive generator is manufactured and assembled?*
2. *What / where are the biggest challenges? Processes or parts?*

Now moving onto the future…

3. *If you were in charge of designing and manufacturing electrical generators in the offshore wind industry, what do you think are the biggest challenges? …In 10 years time?*

Scale up (size):

1. *What size of generators did you work on?*
2. *What is/was the biggest generator that you were involved in designing and/or building?*
3. *What are the current limits in terms of manufacturing sizes?*
4. *As the size of generators increases, what other additional challenges do you see occurring with regards to the generators and their design/manufacture/assembly?*
5. *What role do you see for modularity?*
6. *What are the current limits in terms of wind turbine sizes?*
7. *If not current generator technology, then what?*

Scale up (numbers):

1. *What are the challenges faced in manufacturing* ***more*** *direct drive generators?*
2. *What are the challenges faced in manufacturing direct drive generators* ***more quickly****?*
3. *Do you see any issues within the supply chain if the number of direct drive generators manufactured need to increase?*
4. *What industries and/or techniques should we be learning from (and adopting)?*

Other challenges?

1. *What are the expected failure mechanisms of direct drive generators (i.e. entire drive train)?*
2. *What role, if any do you see for manufacture and assembly, to reduce failures?*
3. *What issues of end of service life have you considered? E.g. repair, life extension, disassembly?*
4. *How should recycling and sustainability be incorporated into design and manufacture?*
5. *If you could spend £1m of research money in this area, how would you spend it?*

Is there anything else you would like to add?

Are there other questions we should be asking?

Who else should we be talking to?

Acknowledgements We would like to sincerely thank both Stuart Bradley, Ricardo, and Raimo Sakki, ABB, for taking the time to discuss the current manufacturing processes regarding direct-drive generators.

Thanks also goes to the Engineering and Physical Sciences Research Council (EPSRC) for supporting this work through the EPSRC Centre for Doctoral Training in Wind and Marine Energy Systems and Structures (Grant Number EP/S023801/1). Finally, we would like to acknowledge and thank the UK's EPSRC Future Electrical Machines Manufacturing (FEMM) Hub for their contribution to funding this research.

Conflict of interest A. M. Kazemi Amiri, K. Tartt and A. McDonald declare that they have no competing interests.

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