WIND ENERGY
Wind Energ. 2012; **15**:459–472
Published online 31 July 2011 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/we.484

RESEARCH ARTICLE

Review of direct-drive radial flux wind turbine generator mechanical design

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ABSTRACT

The direct-drive radial flux synchronous generator is considered as the modern wind turbine drive train. Both the electrically (e.g., Enercon) and permanent magnet (PM; e.g., Siemens) excited direct-drive generators are gaining popularity on the market today. Compared with the matured geared counterpart, the electrically excited direct-drive generator is heavier and more expensive but more reliable per unit capacity. The PM-excited generator is expensive, is simpler in electromechanical design, has a high power-to-weight ratio, and yields a higher energy conversion efficiency than its electrically excited equivalent. The PM generator technology has the potential to yield the highest energy-to-cost ratio. However, standardization of this direct-drive generator parts/subassemblies may overcome the existing cost barrier. Most current literature focuses on PM generator wind turbine technology, specifically on generator energy conversion optimization, and the scalability of technologies to capacities in access of 5 MW. Strangely, PM generator's mass and cost reductions through optimized structural design incorporating manufacturing, transportation, and installation constraints are less studied. This paper solely focuses on the mechanical and structural design aspects of large radial flux synchronous PM generators specific to direct-drive wind turbines. Generator topologies such as the common iron-cored and unconventional air-cored generator are discussed. However, design considerations specific to the iron-cored generator topology are studied. The design considerations investigated involve the geometries and the configurations of rotor/stator active and inactive structures, the interfaces, and the conductor/PM mounting methods. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
generator; radial flux; mechanical structure; design

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Received 16 December 2010; Revised 7 April 2011; Accepted 9 April 2011

1. INTRODUCTION

The main aim of the direct-driven generator structural design and rotor/stator/component configuration is to obtain and sustain the minimum air-gap clearance (e.g., $0.001D_{\text{airgap}}$). Secondary design considerations such as the integration of ancillary components, e.g., braking system, manufacturing, and assembling of structures; transportation; generator installation; and serviceability further limit design configuration options.[1] However, such design configuration options are numerous, and measures to compare are complex. Structurally, a generator is an assembly of modular, welded, or casted active (electrical) and inactive (structural) substructures of which the material selection, geometries, and interface tolerances influence cost, mass, and energy conversion efficiency.[2] Generally, direct-drive generators are mostly custom built with the rest of the wind turbine and generator design standards such as the IEC 61400-1 or national derivations thereof are applied. Typical megawatt direct-drive permanent magnet (PM) generators have mean air-gap diameters (D_{airgap}) between 4–6 m. Machines may weigh about $0.6T^{0.6}$ in ton[3] where T is the rated torque in kNm and cost approximately $219P$ in US dollars[3] where P is the rated power in kW. The generator structural stiffness requirements are mainly dominated by the magnetic-induced normal stress acting at the rotor/stator electromagnetic interface. The magnetically induced tangential stress limitation varies between 25–50 kN m^{-2}. This paper distinguishes between iron and air cored radial flux generator topologies, followed by the discussion on the different iron-core topology configurations. Configuration considerations such as bearing types and arrangements, shaft/axle load supports, rotor type, and generator-hub interface options are discussed. Generator rotor and stator, active and inactive, substructures are also investigated. Lastly, the mounting of active components such as conductors and PMs are addressed. Figure 1 presents a typical direct-drive PM generator design and declares the terminology applied.

2. RADIAL FLUX GENERATOR TOPOLOGIES

Generally, two radial flux generator topologies exist of which examples are shown in Figure 2(a),(b). The conventional iron-cored topology (Figure 2(a)) utilizes a single set of PMs and is the most popular over a wide capacity range, whereas the unconventional air-cored topology (Figure 2b) includes a double set of PMs.[4] The latter is costly and falls in the small-scale class. Various design configurations exist for both topologies.

The design of the conventional iron-cored topology involves a combination of various configuration choices[1] such as generator rotor/stator inactive substructure geometries, ancillary component interfaces, etc. The configuration choices discussed in this paper are as follows:

- Generator location.
- Single, double, or triple bearing arrangements and bearing types.
- Internal or external stator/rotor arrangement.
- Generator rotor support with a rotating or non-rotating (axle) shaft.
- Generator and wind turbine rotor interfaces.

Generator configuration design is a complex balance of wind turbine rotor to tower load paths with structural stiffness requirements[1] that influence generator energy conversion efficiency and costs. An optimal configuration ensures wind turbine rotor torque isolation from aerodynamic-induced and gravitational-induced loads by means of the shortest, cost-effective load transfer path. Such loads may either enter the generator through stator or rotor structure. Load transfer via the stator structure adversely affects generator performance to wind condition sensitivity. Load path design also impacts rotor bearing arrangement, rotor/stator aspect ratio, rotor configuration, and air-gap radial deformation limitation.[5] Generator/wind turbine bearing type, stiffness, conditioning, and arrangement influence rotor/stator structural stiffness requirements, design compactness, reliability, and scalability. Table I presents and compares typical conventional generator configurations classed by bearing arrangement, and Figure 3 provides the corresponding sketches.

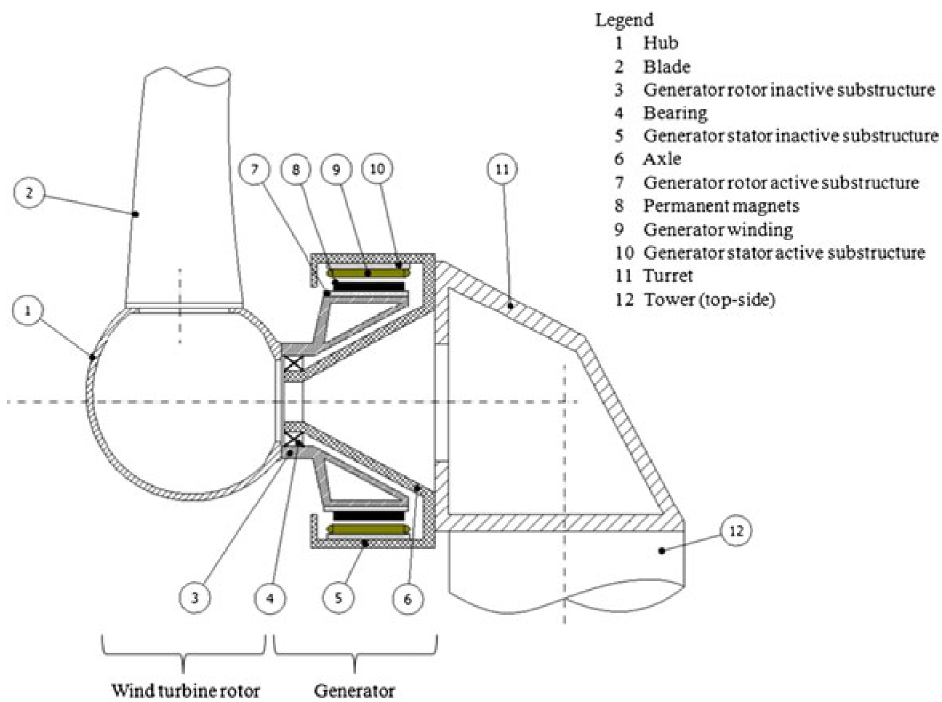

Figure 1. A typical direct-drive PM generator design.

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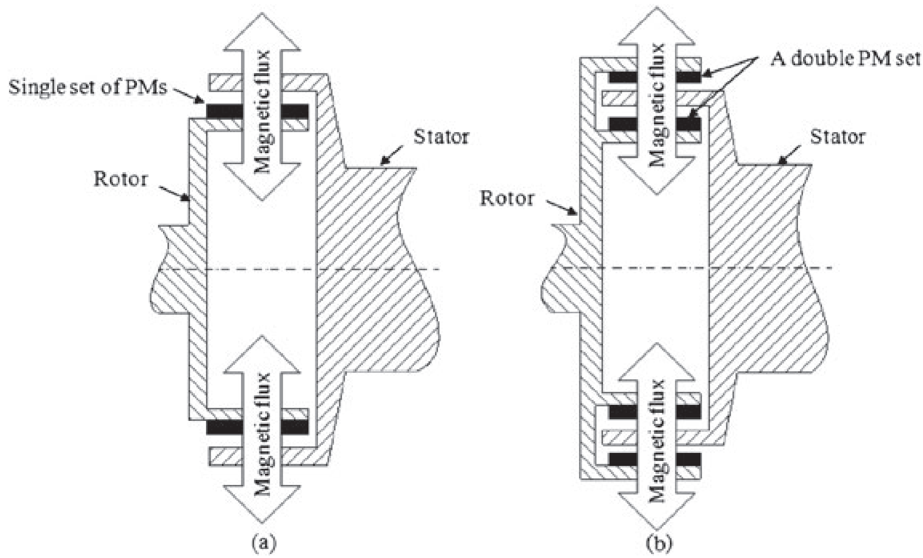

Figure 2. Radial flux generator topologies: (a) common iron-cored and (b) unconventional air-cored types.

2.1. Generator location

Generators are placed upwind or downwind relative to the tower. Downwind placement (e.g., Siemens and Mutsubishi), typical to the geared drive train, requires a generator of lower structural stiffness at the expense of a low-speed shaft/spindle, additional bearing support, and coupling components. The needed shaft relates to the additional torque and bending moment fluctuations that affect coupling and bearing support design. Such a generator placement increases the overall rotating mass, serviceability, accessibility and allows replacement without wind turbine rotor removal. Upwind placement (e.g., Goldwind) is most common since it yields a compact drive train and allows a single bearing rotor support. However, generator access is compromised, and structural and interface stiffness requirements are intensified. Furthermore, axial loading is increased since the generator is tilted horizontally upwards by 5°. Although not studied, it is assumed that upwind placed generators yields lighter drive trains because the large base frame is replaced with short turret.

2.2. Bearing arrangements and types

Bearings or bearing systems are the critical mechanical component[11] in direct-drive generator designs since all wind turbine rotor loads are transferred to the tower via bearings to axle/spindle/shaft or generator stator structure. Bearings support both generator and wind turbine rotors and are arranged in single, double, or triple arrangements located in front of, straddled, or downwind of generator stator. Bearings may even be placed at the air-gap diameter, e.g., *NewGen* concept.[9] The single bearing arrangement yields a short load path and simple assembly at the expense of stiffer rotor and stator structures and interfaces. Such an arrangement is constraint to short axle rotor support and currently limits generator scalability. A generator with a double bearing (straddled) arrangement requires more structural material of less complex design. A triple bearing arrangement has similar attributes as a double bearing arrangement; however, smaller diameter bearings may be used. Bearing selection and arrangement are based on its loading, component stiffness, cost, operating environment, and subsystem (e.g., lubricant cooling system) dependency. Detailed bearing load and behavior studies specific to the direct-drive generator application are yet to be performed.

A number of different bearing types of varying bore diameters are used and proposed for large generators. This paper presents the mechanical, magnetic, buoyant-hydrostatic, and *NewGen* bearing systems as shown Figure 4(a)–(d), respectively.

2.2.1. Mechanical bearings.

Mechanical roller bearings (Figure 4(a)) with bore diameters of about 1.5 m are common.[11,12] Typically, tapered cylindrical, cylindrical, or toroidal rollers manufactured from high-tensile alloy steel or ceramic alloys[13–16] are secured in sealed or non-sealed raceways. Bearing lubrication is either once-off or continuous.[17] Once-off lubrication relates to bearing greasing prior to assembly, whereas continuous lubrication entails continuous supply and cooling of lubricant with an

Table I. Conventional radial flux generator design configurations.

Configuration (refer to Figure 3)	Bearings		Rotor configuration	Stator support	Hub support	Loads affecting air gap	Air-gap diameter	Examples
	Type	Locations relative to stator						
A1	All	Upwind	Inner	Cantilever	Stator axle	rad.[a] & tan.[b] magnetic	≤ 5 m	Leitwind, Zephyros[6,7]
A2	All	Upwind	Outer	Central axial	Stator axle	rad. & tan. magnetic	≤ 5 m	Siemens, Goldwind[6]
B1	Mechanical/magnetic	Upwind & straddled	Inner	Cantilever	Stator axle	rad. & tan. magnetic & aerodyn.[c]	≤ 5 m	Vensys[6]
B2	Mechanical	Upwind	Inner	Cantilever	Stator axle	rad. & tan. magnetic & aerodyn.	≤ 5 m	Enercon[6]
B3	Mechanical/magnetic	Downwind & internal	Inner	Cantilever	Rotor spindle/shaft	rad. & tan. magnetic & aerodyn.	All	GE[6]
B4	Mechanical/magnetic	Upwind & internal	Outer	Central axial	Rotor spindle/shaft	rad. & tan. magnetic & aerodyn.	≤ 5 m	Gensys[6]
B6	Mechanical/magnetic	Upwind & downwind	Inner	Both sides	Rotor spindle/shaft	rad. magnetic & aerodyn.	All	MTorres[6]
B7	Mechanical/magnetic	Upwind & downwind	Outer	Both sides	None	rad. magnetic & aerodyn.	≥ 5 m	WERG-85[6,8]
B8	All	Upwind & internal	Outer	Central axial	Stator axle	rad. magnetic & aerodyn.	≥ 5 m	NewGen[9]
C1	Mechanical/magnetic	Upwind & internal	Inner	Both sides	Stator axle	rad. magnetic & aerodyn.	All	Handler design[10]
C2	Mechanical/magnetic	Upwind & internal & downwind	Inner	Both sides	Rotor spindle/shaft	rad. magnetic & aerodyn.	All	Handler design[10]

[a]Radial loads.
[b]Tangential loads.
[c]Aerodynamic loads transferred from rotor.

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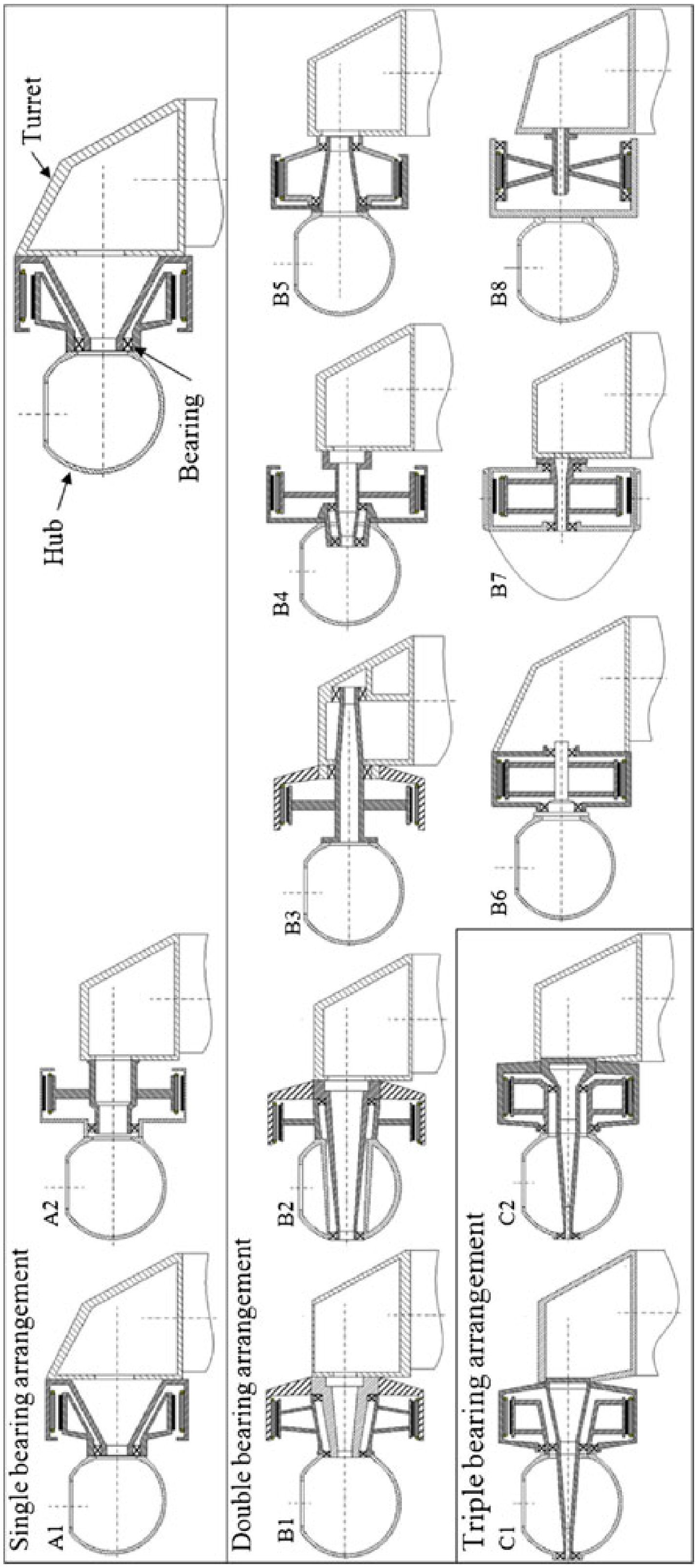

Figure 3. Representation of direct-drive wind turbine generator design configurations.

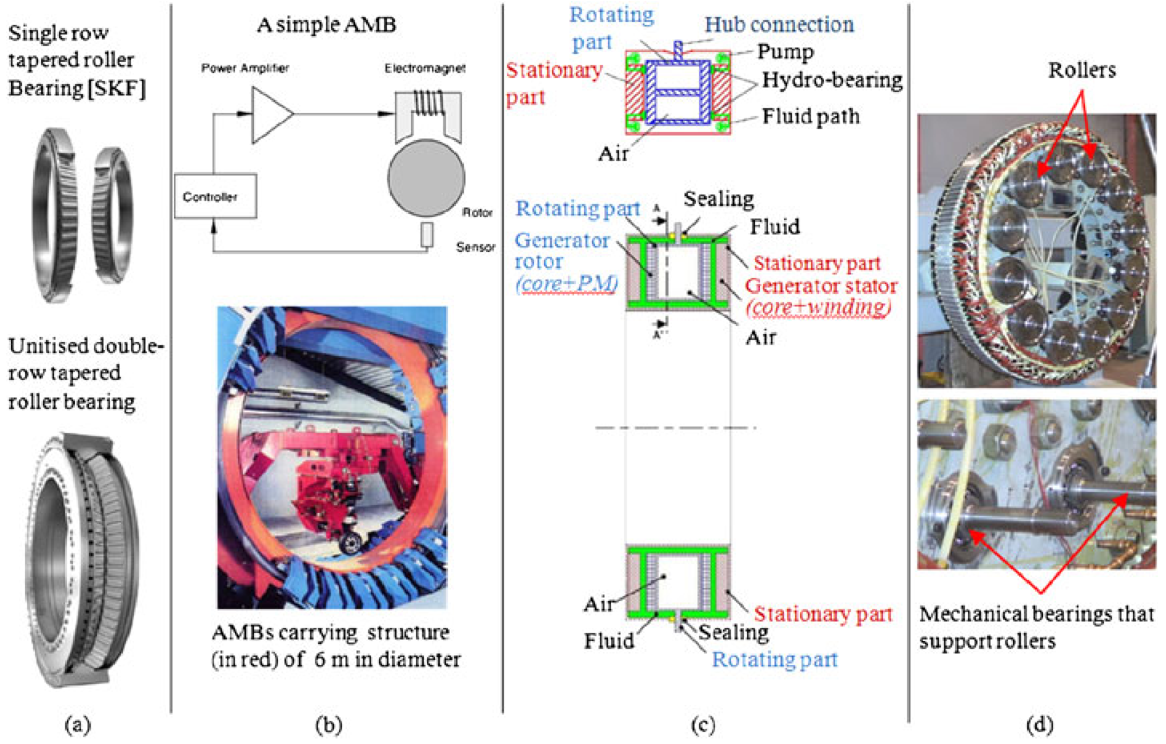

Figure 4. Presentations of the (a) mechanical, (b) magnetic, (c) buoyant-hydrostatic and (d) external roller-rail bearing systems.

external system. Generally, single or double row roller bearings, of which the latter may be unitized or separated, are used. Bearing fixtures are accomplished with either designed bolt-on features or by press fitting to housing. The bearing interface stiffness and alignment accuracy are governed by manufacturing tolerances. Currently, large bore diameter bearings are costly to manufacture and cumbersome to transport, assemble, and install. However, in comparison with static-buoyant and magnetic bearings, a mechanical roller bearing aligns and supports the rotor during all load conditions.

2.2.2. Magnetic bearings.

The magnetic bearing system (Figure 4(b)) is utilized in various dynamic load environments in which large diameter heavy rotary structures are supported, for example, gas turbine rotors.[18] These bearings are either of an active,[18–20] i.e., electromagnetic (reluctance-force or Lorentz-force design) or a passive,[21,22] i.e., PM nature. Advantageously, these bearings require no lubrication and allow active vibration control. The load carrying capacity depends on the type of magnetic field excitation, i.e., permanent or electromagnets, the arrangement and geometry of such magnets, the material magnetic properties, and the control system design. Typically, the bearing stiffness and continuous alignment precision depend on the control current, the power supply frequency, and the sensitivity of proximity sensory equipment.[22] Magnetic bearings can support large diameter generator rotors and increased generator reliability. Furthermore, generator structural mass reductions are expected.[23] However, rotor touchdown under static load conditions or due to control faults may be prevented with mechanical bearings. Alternatively, static loads may be accommodated by inducing generator rotor eccentricity or by using additional PMs to offset the generator rotor.[22]

2.2.3. Buoyant-hydrostatic bearings.

A buoyant-hydrostatic bearing (Figure 4(c)) concept is proposed[24–26] to support large diameter (i.e., > 5 m) generator rotors. In concept, the generator rotor radial suspension relies on the density difference between an enclosed, hollow ring-shaped rotor structure and a supporting fluid. An encapsulated hollow stator structure acts as a supporting fluid reservoir. Fluid leakage at the rotor-stator interface is prevented with pressurized flexible, wear-resistant seals. The rotor axial alignment may be controlled with active hydrostatic bearings. Unlike conventional generators, the air gap is replaced with a fluid gap. The fluid may enhance magnetic flux distribution, but viscous friction can incur substantial losses. The technical feasibility of such a bearing type is yet to be investigated, and the structural mass savings claimed is debatable.

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2.2.4. External roller-rail bearing.

The external roller-rail (*NewGen*; Figure 4(d)) bearing concept can support a large rotor structure by using specific shaped rollers racing in external rails.[9,27,28] These disk-shaped rollers, supported by shafts and small mechanical bearings, are fixed to generator rotor. An external raceway pair is embedded in the stator structure. Such a bearing can be placed at the generator air gap; hence, generator rotor/stator structural stiffness requirements and mass are lowered. The roller geometry and the number of rollers, raceway configuration, roller-rail tolerances, and materials determine the bearing stiffness. As with mechanical bearings, more rollers increase the load carrying capacity. The bearing modularity simplifies manufacturing. However, its high component count may adversely affect the reliability and induce additional noise and vibration issues.

Of the four bearing types discussed, the mechanical and magnetic bearings are considered capable of supporting medium to large generator rotors. The buoyant-hydrostatic and roller-rail bearings are yet to be field tested in multimegawatt generator designs. In comparison, the mechanical bearing system has the lowest component count, needs no active control, and is reliable.

2.3. Rotating and non-rotating shafts

Generator rotor bearings are either fixed to a shaft, spindle (short shaft), or axle. These load carrying components are located between the turbine rotor hub and tower top. These structures are manufactured from nodular/gray cast-iron or post-machined weldment steel assemblies[1] and may be cylindrical or conical in shape and of hollow or solid design. Furthermore, these structures may be modular in design or integrated with turret or generator stator. Typical shaft/spindle/axle stiffness constraints are the allowed generator air-gap deformation, wind turbine rotor and generator loading, mass, and cost. The effective axle/shaft/spindle stiffness is reduced by increased generator poles,[29] whereas the diameter-to-length ratio influences the fluctuating bending moment impact on the air-gap deformation. Shaft/spindle/axle structural stiffness is enhanced by increasing wall thickness and diameter or by the use of high alloy steels. The conical, hollow cast-iron axle of high diameter-to-length ratio in combination with a single bearing arrangement yields a compact generator design. Such a design also eases access to generator or rotor hub. The shaft/spindle option requires a double bearing support and yields an increased rotor inertia.

2.4. Internal or external generator rotor

Conventionally, generators are configured with internal rotors (e.g., Enercon) for robustness. Typically, the rotor houses PM pole pairs on its outer periphery. An internal rotor design supports all bearing arrangements but spatially limits the multipole generator design and requires forced rotor cooling techniques to maintain safe magnet temperatures. However, the cooling of the external stator is simpler. An outer rotor generator design (e.g., Vensys) needs a stiffer support structure that leads to more structural mass and geometry complexity. However, the increased rotor periphery area is advantageous to a multipole generator design.[30,31] Cooling of generator rotor is simplified, whereas stator cooling is adversely affected since the rotor structure acts as a thermal barrier. By comparing the two rotor options, the inner rotor generator configuration yields a short hub-tower load path, a higher air-gap flux density, and a lower stator thermal load, whereas an outer rotor machine has a smaller volume and allows a *hubless* drive-train design. The energy conversion efficiency difference between an inner or outer rotor generator design is small. Therefore, the design decision is governed by transportable size and cost.

2.5. Generator and wind turbine rotor interfaces

A generator may be integrated with the wind turbine blades in two ways (Figure 3): coupling via the hub or a direct generator rotor fixture. Within all wind turbine direct-drive trains, the rotor and generator rotor planes of rotation are axially separated. Hubs support the rotor blades and transfer aerodynamic and gravitational loads to the generator. These hubs are either cast-iron or welded steel structures. The direct bearing of blades by generator rotor or hubless configuration is typical to small-capacity wind turbines. Such a design is proposed for megawatt machines[6,8] and is limited to external rotor generators. All blade loads are directly transferred to the generator rotor structure. Therefore, generator performance sensitivity to wind conditions may be adversely affected. Prototypes of design are yet to be seen. Most direct-drive generators are rigidly coupled to wind turbine rotor hubs. Mechanical dampers and fuses in axle/shaft/spindle designs are seldom used. Such rigid coupling adversely affects the generator structure, its component interface integrity, and its energy conversion behavior. A turbine-generator coupling utilizing a radial damper in a large diameter machine is investigated.[18,24]

3. ROTOR AND STATOR STRUCTURES

Generator rotors and stators are assemblies of electromagnetically active and inactive substructures. The active substructure, i.e., rotor/stator yoke, distributes the magnetic flux and enables the energy conversion within the machine,[32–34] whereas the inactive substructure supports the active substructure, the active materials (PMs), and the ancillary components.[1] In some generator designs, no distinction between active and inactive substructures exist. Some typical rotor and stator structural design considerations are as follows:

- Rotor configuration options: inner or outer rotor.
- Diameter-to-length aspect ratio.
- Modular, segmented, or continuous structural design.
- Interfaces with wind turbine rotor and tower.
- Radial support arrangement, e.g., single-sided rotor/stator support.

The typical active substructures design considerations involve the following:

- Permanent magnet energy density governing magnet placement: surface or buried.
- Mounting of conductors and winding type.
- Core material and its geometry.
- Thermal management method and heat exchange components.

The main inactive substructure design requirements concern the following:

- Sufficient stiffness to maintain the design air-gap clearance.
- Safe overall strength to accommodate transient rotor loading.
- Adequate surface area and material thermal properties to assist in generator thermal management.
- Support of artillery components.
- Low mass and transportable size.

3.1. Active substructures

An active substructure consists of material that distributes magnetic flux and houses the active components. Furthermore, it transfers the mechanical loading, i.e., torque and thermal energy, to the inactive support substructures. The substructure material type, i.e., laminated[35,36] or solid;[37,38] geometry, i.e., slotted[35,36] or slotless;[32,39] and assembly[35] affect the generator energy conversion efficiency-cost ratio,[32,39] its force density,[40,41] its mass, cooling method,[42] and construction, i.e., modular.[35,43–46]

Most rotor/stator active substructures comprise stacked insulated ferromagnetic plates.[46] These laminated stacks are designed with piloting, clamping. and coolant conduit features. The fixed electric steel sheet dimensions lead to segmented or modular substructure designs (pole pieces). Solid segmented/modular substructures, with or without surface grooves,[47] are used if the generator-operating frequency is low. These structures are manufactured from cold-rolled or sintered[48,49] steel alloys. The active substructure slot geometries vary in shape and size.[35,36] The slotless (in air-gap) substructure design is typical to air-cored or high-frequency generators.[39] In such a design, the conductors are embedded in a non-magnetic material (glass fiber reinforced epoxy) or clamped to a stator periphery with pole shoes.

The PM energy density governs its placement and component size. This affects the geometry, material mass, and manufacturing cost of the rotor active substructure. Typically, surface and buried PM (flux concentration) mounting are performed. The mounting of high-energy magnets to the rotor surface is most popular since less active material of simpler geometry is required. In general, the total active mass, i.e., substructures and components, accounts for about 20–30%[50] of the generator total mass. The mass is also inversely proportional to the mean air-gap diameter.[42] Therefore, the larger the active substructure volume, the larger the radial load and inactive substructure mass.

3.2. Inactive substructures

Most rotor/stator inactive substructures are thin-walled ($0.002D_{\text{airgap}}$ to $0.005D_{airgap}$), large diameter cylinders of small diameter-to-length ratios, i.e., $D_{\text{airgap}}/l = 0.2 - 0.3$, stiffened in the radial direction. Substructures with mean air-gap diameters less than 4 m (EU) or 5 m (USA) are constructed as continuous (single structure) structures, whereas larger diameter structures are segmented.[1,51] Segmentation ease manufacturability and transportability.

The structural stiffness and the load capacity of segmented structures and interfaces are controlled by manufacturing tolerances.[52] In theory, thermal behavior being excluded, the rotor/stator substructures are designed to limit air-gap deformation to less than 0.1–0.2% of the mean air-gap diameter.[5,53] Therefore, these substructures are mainly radially stiffened. Stiffening is mostly achieved by configuring the structure geometry rather than using stiffer materials, e.g., composites. Stator/rotor yoke structures are supported in various ways: on a single side (cantilever/Z-profile), in the middle (E-profile), or on both sides (H-profile). The support configuration depends on whether axle/shaft/spindle bearing support is used. Typical supporting geometries are simple disks, structural profiled spokes/tension rods, ribs, or support arms.[7,50,53–56] Additional stiffening rings or axial ribs may also be incorporated. Simplified rotor/stator inactive substructure geometries are presented in Figure 5.

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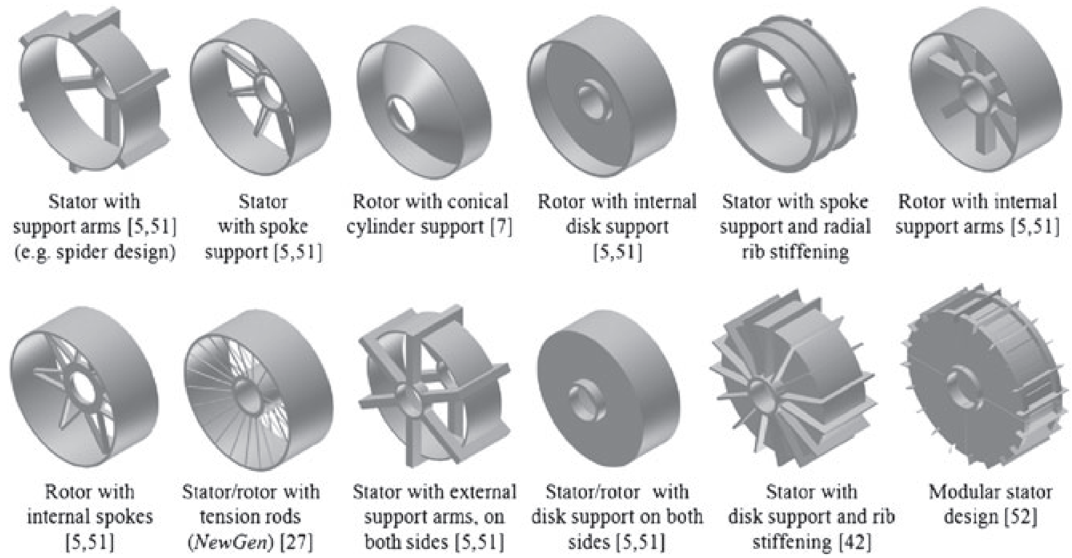

Figure 5. Generator rotor/stator inactive substructure support options.

These stator/rotor substructures are manufactured as either continuous cast-iron or segmented steel weldment assemblies.[1,53] Cast nodular/gray iron allows cheap, simple large diameter structures. Steel weldment assemblies yield stiffer structures per unit mass at higher costs. Modular designs, i.e., bolted assemblies, that simplify manufacturing have been proposed and tested.[51] Such designs are not commercialized for assembly tolerance management, noise, and vibration issues are highly complex and expensive to minimize.

4. MOUNTING OF ACTIVE COMPONENTS

Active components are current carrying conductors and PMs. Conductors may be copper, aluminum, or high-temperature superconductor alloys.[57] The mounting of such active components are governed by the electrical and environmental insulations, winding type and insulation, magnet shape (e.g., curved), etc. These active components are manufactured as modular units to reduce costs and to ease generator assembling.

4.1. Mounting of conductors

Conductors are ductile metals that are unitized as either random or form wounded coils.[58,59] The form wound coils, pressed[49] or not, ease assembling. By convention, conductors are secured in stator slots with insulation packing and slot wedges. Modern insulation systems mostly comprise glass fiber tape bounded in thermosetting epoxies.[59] Slot-winding and end-winding vibration are the major cause of generator failure since loose conductors leads to cracked insulation, wire abrasion followed by short circuitry. The needed end-winding mechanical support[58] is usually accomplished by an insulated (polyester-epoxy or glass-epoxy) steel bracing ring. Alternatively, a favorable concentrated winding[60] may be used. Winding vibration originates from magnetic-induced forces: $F = kI^2/d$ where I is the RMS current and k the slot fill factor. Interstrand movement and air pockets within windings are omitted with resin vacuum impregnation. Therefore, insulation systems determine the structural stiffness and thermal energy transfer of windings. Modern generator insulating materials comprise[59] the following:

- Winding wire and conductor insulation.
- Stack consolidation materials.
- Main wall insulation.
- Impregnating resins and varnishes.
- End-winding tapes.
- Slot insulation and wedging.
- Finishing coatings.

The mechanical properties affecting insulation selection are abrasion resistance, stiffness, thermal resistance, and degradation.

4.2. PM fixture

Rare earth PMs (NdFeB and SmCo), sintered or bonded, are expensive. Magnet material cost about 10 times higher than generator active steel/iron.[5] Magnet shapes[39] and geometric features, e.g., surface grooves,[61,62] are optimized to reduce the needed material and to increase machine performance. Structurally, magnet materials have anisotropic mechanical properties[63] and are brittle and hard. Such properties adversely affect manufacturing and assembly costs. PM energy storage capabilities are sensitive to temperature fluctuations and corrosion (off-shore application). Typically, the maximum magnet temperature should not exceed 100°C. Magnet corrosion prevention is achieved by coating it with nickel, tin, or organic, e.g., Teflon.[64] General magnet-to-rotor fixing considerations involve magnet placement, i.e., surface[32,39,60] or buried[65]; magnet thermal management; manufacturing tolerances; and assembling, e.g., automated and magnetization scheme (pre-assembling or post-assembling).[66] Practical magnets fixture are accomplished by[67] the following:

- Mechanical fasteners.
- Welding (e.g., laser or tungsten inert gas welding (TIG)).
- Pressure clamping, i.e., potting or pre-machined slots.
- Press fitting.
- Cementing (e.g., cyanoacrylate adhesives).

The advantages and disadvantage of each fixing method are described in 'Fastening and securing magnets'.[67]

5. CONCLUSION

The PM-excited radial flux generator powered by a wind turbine is still a custom-built technology. Market share limiting issues such as cost and mass may be solved by generator component/subassembly standardization. Such is possible if a modular structural and active component design approach is followed. Furthermore, generator upscaling is constraint by the available bearing technologies. The industry norm indicates that a direct-driven PM generator, placed in front of tower, using a single unitized mechanical bearing for rotor load transmission yields a compact, lightweight, and expensive drive train.

ACKNOWLEDGEMENTS

This work was funded by the Centre of Renewable and Sustainable Energy Studies (CRSES). CRSES is a division of the South African National Energy Research Institute (SANERI). Web site: http://academic.sun.ac.za/crses/

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