

LIGHTWEIGHT, COMPONENTIZED DIRECT DRIVE ELECTRIC GENERATOR FOR NEW OR REFURBISHED WIND TURBINES

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Abstract – By conceptually replacing the “passive rotor” of any “asymmetrical” axial-flux electric motor or generator system, such as rare-earth permanent magnet (RE-PM) rotors, with an “active rotor” as only possible by the enabling technology of brushless real time emulation control means, simple “qualitative observation” proves that the resulting brushless, stable, and “symmetrical” multiphase wound-rotor doubly-fed “synchronous” electric machine system would show half the cost, half the size, half the electrical or core loss, and up to octuple the peak torque as the original asymmetrical axial-flux electric machine system with the same voltage, air-gap flux density, air-gap effective area, and packaging art, such as materials, manufacturing, winding, and excitation techniques.

Index Terms—brushless, real-time, sensor-less, synchronous, wound-rotor, doubly-fed, electronic power transformer

I. INTRODUCTION

Wind Turbines larger than six megawatts are becoming common, particularly for offshore installations, where consolidating the power of several smaller wind turbines into one large wind turbine reduces manufacturing, installation, and sustainment costs in accordance with economies of scale. Since the overall reliability of the wind turbine is determined by the reliability of the mechanical gearbox, which converts the practical low-speed of the wind turbine rotor propeller hub (e.g., 5-20 RPM) to the variable high speed of a conventional electric generator system (e.g., two pole-pair, 60Hz, 450-1800 RPM), large wind turbines are eliminating the gearbox (and its compounded inefficiency, complexity, size, and cost) with low speed, directly driven electric generator systems; but as physics dictates, low-speed electric generator systems are necessarily large in diameter (and heavy). For example, the radial-flux, direct drive, rare-earth permanent magnet (RE-PM) electric generator of the [twelve megawatt Haliade-X wind turbine from GE](#) is approximately 11 meters (or 36 ft) in diameter and consumes a significant portion of the 20.6 meter (67.5 ft) long nacelle weight, which is over 600 metric tons (or 660 tons), all of which must be transported to the wind turbine installation site over specially prepare routes and then lifted more than a hundred-thirty meters to the tower hub. Accordingly, the

manufacture, installation, maintenance, and transportation of large wind turbine generator systems requires [uncommonly large, specialized, and expensive handling equipment](#) with [complicated transportation logistics](#).

Under an [ARPA-E program](#), the [US Department of Energy](#) is asking for a “lightweight” (or small) high power, low speed (e.g., 5-20 RPM), direct drive electric generator system for the next generation of multi-megawatt wind turbines. But a “lightweight” direct drive electric generator seemingly contradicts standard electric motor or generator (i.e., *electric machine*) design principles and trade space as follows:

- Although increasing electric machine air-gap flux density reduces the effective air-gap area with associated reduction of physical size, amount of copper magnet wire, and amount of electrical steel for a given power rating (all in accordance to Faraday’s Law), air gap flux density (and associated effective air-gap area and volume) will be similar among all optimally designed, conventional electric machines due to the flux density saturation limit of the same slotted electrical steel core and material equally used by all for a given power rating and not by: 1) the limited residual flux density potential of the RE-PM as commonly suggested (that ideally shows no electrical dissipation but adversely trades residual flux density, β , for coercivity or flux intensity, H , inversely with the fixed RE-PM energy product or BH_{max}), or 2) the [even higher flux density potential of winding magnetizing magneto-motive-force \(MMF\)](#) (that adversely shows electrical dissipation but ideally increases flux density directly with higher flux intensity).
- Although very low excitation frequency provides the best means of reducing pole-pair count (and associated electric machine diameter), all optimally designed, low speed, direct drive generators still have comparably large diameters (and physical sizes) due to the limited low frequency performance of today’s electronic control, which still necessitates a large number of pole-pairs and associated slots (or coreless framework) along the air-gap circumference for the placement and structural support of at least the necessary conventional “active” winding set that may be sinusoidally distributed (most efficient) or segmented/concentrated (least efficient), or the extraneous “passive” RE-PMs, direct current (DC) electromagnets, reluctance saliencies, or slip-induction windings (with the

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slot dimension determined by the wire gauge or RE-PM size to meet the power rating).

- Although DC superconducting electromagnets (sometimes called super permanent magnets) produce at least double the air-gap flux density than what is practical with conventional magnetizing MMF and without regard to the flux density saturation limits of the electrical steel core, the diameter of a low speed superconducting electric machine system is still dependent on the accumulation of slots (or framework) along the airgap circumference (for at least the structural support of the necessary “conventional” active winding set) and as a result, any diameter reduction is mostly due to the exceptionally low excitation frequency performance of the electronic controller (to reduce pole-pair or slot count). However, the high flux density does reduce the effective air-gap area but mostly the associated length of the radial-flux or the “outside diameter” of the axial-flux superconductor electric machine. But the overall “system” efficiency, size, cost, or weight advantage is neutralized, when considering the compounded cost, size, weight, complexity, and inefficiency issues associated with the extraneous cryogenic support equipment and electrical provisioning for superconductor electromagnet operation.
 - If ever practical, Alternating Current (AC) superconductors would allow thinner gauge winding wire (for at least the active winding set), which would directly reduce the slot cavity width and the associated electric machine diameter.
- Because of complexity, safety of assembly, and transportation issues of the RE-PM, such as manual handling or deadly back electro-motive-force (EMF) (with the slightest rotor movement), or of the superconductor electromagnet, such as the delicate superconductors, cryogenic refrigeration and connecting hydraulics, RE-PM and superconductor electric machine “systems” are necessarily factory preassembled as a large, complete system (most likely pre-installed within the wind turbine nacelle) for transport to the installation site.
- To support the enormous electromagnetic and dynamic forces, the frame and bearing assembly of any optimally designed electric machine easily consumes at least 20-30% of the overall size (and weight). In consideration, a very lofty 50% frame improvement with costly exotic or futuristic structural forms or materials would only provide a 15% improvement in electric machine overall size and weight, at most.
 - Since at least the early 1960s, the hypothetical multiphase wound-rotor [synchronous] doubly-fed electric machine circuit and control architecture was shown to provide twice the power with the same packaging art (and air-gap flux density, speed, and voltage) as all other electric machine systems, which would immediately halve the frame size and weight per unit of power, while reasonably assuming the cost of the packaging art is directly related to the amount of materials applied.
- With a cylinder (i.e., rotor) inside a cylinder (i.e., stator) form, a large diameter “radial-flux” generator (such as the

GE Haliade-X) requires an unusually deep air-gap depth to avoid collision between the rotor and stator bodies (due to structural deformity by the enormous centripetal and electromagnetic forces experienced during operation). Unusually deep air-gap depths are more conveniently accommodated with the high coercivity of extremely expensive RE-PM and as a result, virtually all direct drive wind turbine generators blindly use RE-PMs, regardless of their formidable technical, geopolitical, and environmental issues, such as high cost, restricted availability, limited operational life expectancy, persistent magnetism safety, complicated field weakening techniques, environmentally unfriendly production, etc., which are magnified again by requiring proportionally more expensive RE-PM material for more coercivity to hold a reasonable air-gap flux density with deeper air-gap depth (just like more winding magnetizing MMF for more flux intensity but winding MMF has 3X more real estate).

- With an adjacent rotor and stator disk form, a large diameter “axial-flux” electric generator may require a more substantial bearing assembly but more importantly, the axial-flux form eliminates the potential collision between the rotor and stator bodies (due to centripetal force) and allows a reasonably shallow (and shim adjustable) air-gap depth (to reduce RE-PM material or magnetizing MMF for a given airgap flux density). Also, unlike the inside-to-outside winding approach of the radial-flux form, the outside-to-inside winding approach of the axial-flux form conveniently allows automated (or additive) winding techniques and unlike the insulating effect of a rotor cylinder inside a stator cylinder (or radial-flux) form, the axial-flux form equally exposes the adjacent rotor and stator disks to the same convection ambient for better thermodynamics.
 - The best form for large diameter conventional direct drive electric generators would be a non-segmented axial-flux form with a single air-gap for the highest permeability and the lowest amount of magnetizing MMF or expensive RE-PM volume; but axial-flux enabling manufacturing tooling, knowledge, and capital is not readily available, particularly for large direct drive electric machines.

In accordance with the previous standard electric machine design principles and trade space, a low speed, direct drive electric generator “system” will necessarily be large in diameter, regardless of the flux density potential of superconductors or the deep air-gap depth conveniently supported by RE-PMs. Instead, a practical lightweight, low speed, high power, direct drive electric generator for wind turbines is only provided with: 1) a true multiphase wound-rotor [synchronous] doubly-fed electric machine circuit and control architecture (that conveniently accommodates the axial-flux form and effectively halves the frame size and weight per unit of power), 2) an electric machine circuit and control architecture (that conveniently accommodates ultra-low frequency excitation control to reduce pole-pair count and resulting diameter), 3) a 3D Printer (that conveniently

accommodates the additive manufacture of large axial-flux electric machines with the highest performance materials to reduce size, slot width but deeper slots, etc.), and 4) an electric machine circuit and control architecture (that conveniently accommodates safe separation into multiple components of transportable size, diameter, and weight that can be conveniently lifted, reassembled, and power stacked lengthwise inside the nacelle at the installation site to incrementally meet the wind turbine power rating). Items 1 through 4 are satisfied as follows:

- 1) As a true symmetric multiphase wound-rotor doubly-fed “synchronous” electric machine circuit and control architecture (as only possible by the enabling technology of brushless real time emulation control or **BRTEC**), **SYNCHRO-SYM** has two independently (and brushlessly) excited multiphase winding sets on the rotor and stator, respectively, with each “actively” contributing to “real electromechanical power” production without relying on unstable slip-induction (while providing field weakening over at least twice the constant torque speed range with a given torque, air-gap flux density, speed, voltage and frequency of excitation [or twice the power]), all within the same packaging and materials as the alternative asymmetric electric machine system (which is always with a “passive” rotor of extraneous RE-PMs, DC electromagnets, reluctance saliencies, super permanent magnets, or slip-induction windings). As a result, only **SYNCHRO-SYM** immediately halves the frame size and weight per unit of continuous power rating.
- 2) Today’s state-of-art field oriented control (FOC) of variable speed electric machines has the extreme difficulties of accurate and timely measurement and synthesis of very shallow sloped, “low frequency signals” (e.g., 4-8 Hz) from the fixed high frequency (e.g., 50/60 Hz) multiphase electric utility power grid (that are needed to reduce the diameter of direct drive electric machine systems), while simultaneously synchronizing the shallow sloped signals to the low angular speeds of the rotor under

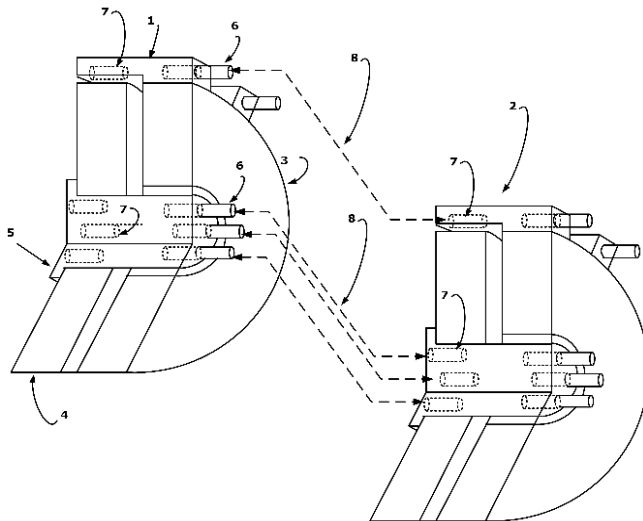


Figure 1

stochastically changing condition (all by the imprecision of an electronically processed, software “simulation and estimation” algorithm for quasi-stable variable speed control). In contrast, only the fully integrated, bi-directional, direct conversion (no DC Link Stage) **BRTEC** easily provides pure low to high frequency sinusoidal signals with any stochastic variations sensorlessly, automatically, and instantaneously synchronized to the angular speed and phase of the rotor (all by the precision of “real time electromagnetic emulation”) for stable variable speed, constant frequency (VSCF) control and comprehensive leading, lagging, and unity power factor correction. For example, only **BRTEC** automatically translates pure sinusoidal voltage and currents from one frequency (e.g., 50/60 Hz) to very low variable excitation frequency (e.g., 0-4 Hz) by electromagnetically mixing the steep sloped, “high frequency” grid input (e.g., 50/60 Hz) with the difference of a synthesized “high frequency” (e.g., 46/56 Hz), both of which are easily measured, synthesized, or controlled electronically without regard to speed or stochastic changes, and as a result, only **BRTEC** has full electromechanical power conversion control to “zero speed” (for the largest speed bandwidth of tidal or wind energy harvesting, regardless of rotor direction).

- 3) **MOTORPRINTER** conveniently 3D prints “axial-flux” cores (with integral frame assembly) from high performance electromagnetic ribbon, such as high flux saturation, low core loss amorphous metal ribbon, for the most efficient, highest permeability (i.e., lowest flux leakage) conventional electric machine core (with the lowest magnetizing MMF or smallest RE-PM size and the highest air-gap flux density). The low leakage of amorphous metal ribbon also allows narrower but deeper slots, which reduce the outside diameter of the axial-flux electric machine (by reducing the slot cavity width to one or two wire widths while spreading the remaining winding turns over the depth of the slot).
- 4) As an integrated electric machine system (without the safety and handling issues of passive RE-PMs or superconducting electromagnets) and with **BRTEC** equally divided between the rotor and stator assemblies, only **SYNCHRO-SYM** conveniently accommodates duplicate active “axial-flux” rotor and stator disk assemblies for componentization into the smallest size, diameter, weight, and inventory of components for 1) easy and safe transport by conventional means (over commonly navigable routes), 2) convenient lifting to the nacelle with a small internal nacelle crane, and 3) convenient handling and re-assembly into functional **SYNCHRO-SYMs** inside the nacelle (with lengthwise stacking to incrementally achieve the rated wind turbine power). Stacking multiple **SYNCHRO-SYMs** (as only possible by the enabling technology of brushless real time emulation control or **BRTEC**) also provides a) generator resiliency (e.g., any one failure is not a total system failure), b) high voltage (series connection), or c) high current (parallel connection) applications.

is one simple representation of stacking two fully assembled and functional SYNCHRO-SYMs (1) and (2). Each

functional SYNCHRO-SYM stands alone with its own bearing and frame assembly, axle assembly, and integrated electronic

control and as a result, the power stack shows the accumulated power of two SYNCHRO-SYMs (1) and (2), which are independent from the wind turbine rotor hub and bearing assembly. The stator (3) and rotor (4) are duplicate axial-flux disk assemblies of SYNCHRO-SYM (1) or (2). The axle assembly (5), which is attached to the rotor assembly (4), and the stator assembly (3) have bayonet plugs (6) that align and mate (8) with the bayonet sockets (7) to form a rigid but separate integrated stack of stators (3) and rotors (4) of multiple SYNCHRO-SYMs.

Another method for mating “stators” would comprise a set of sliding frames (*or rails*), which span at least the full length of the stack of SYNCHRO-SYMs. The rails are a portion of the “stator” bayonet plugs (6) with a similar portion of sockets (7) configured as channel blocks for inserting the sliding frames. With each lightweight SYNCHRO-SYM component lifted to the nacelle and positioned onto the sliding frames by an internal nacelle crane, such as the rotor (4) and axle (5) assembly, the stator (3) and bearing assembly, or each complete SYNCHRO-SYM in the stack, the component would slide along the rails for alignment and attachment to another component inside the nacelle. As a result, all stators of the SYNCHRO-SYM stack are joined as one by the stator rails (*or sliding frames*) and stator bayonet methods (6,7) and separately, all rotors of the SYNCHRO-SYM stack are joined as one by the rotor bayonet method (6,7).

The same field installation and assembly process (*using the internal nacelle crane as just discussed*) is also used for replacing or maintaining any rotor, stator, or fully functional component within the entire stack; or more importantly, for retrofitting legacy wind turbine systems, which have peaked their useful operational life. Likely, the “legacy systems” have an obsolete mechanical gearbox, generator, and electronic drive, all of which can be hastily disassembled and removed, and then replaced with a small diameter, low speed, “direct drive stack” of SYNCHRO-SYM components. Since the legacy electronic drive, gearbox, and generator upgrade is only [18% of total wind turbine cost](#), the [80/20% tax credit rule](#) is satisfied, while upgrading to a higher performing, more efficient, more reliable, integrated, variable speed wind turbine system.

Using a computer aided design tool specifically developed for the axial flux SYNCHRO-SYM manufactured with MOTORPRINTER, called BEM-CAD, TABLE 1 provides comparable specifications

TABLE 1 (compared to the GE Haliade-X Wind Turbine Generator)		
	SYNCHRO-SYM (Axial-Flux)	GE Haliade-X (Radial-Flux)
Total Stackable Power	1-20 MW	12-14 MW
Stackable Power Increments & Power (efficiency)	1 MW (96%), 2MW (93%), or 4MW (87%) <i>(Each includes Dual BRTEC and Frame, Axle & Bearings)</i> <i>(No Rare-Earth Permanent Magnets)</i>	Large, non-stackable self-contained unit. (Permanent Magnet Electric Machines must be fully assembled at the factory)
Speed	0-20 RPM	0-15 RPM
Length (shippable Length)	20 in (421 mm) <i>(Includes the integrated BRTEC)</i>	9.8 ft? (3 M?) <i>(Does not include the electronic controller)</i>
Diameter	11.7 ft (3.6 M) <i>(Includes the integrated BRTEC)</i>	36 ft (11 M) <i>(Does not include the electronic controller)</i>
Rotor or Stator Component Weight (shippable weight)	23,700 lbs. (10,745 kgs) (2) <i>(Includes the integrated BRTEC)</i> <i>(Rotor and Stator assemblies are the same with the exception of software)</i> <i>(No permanent magnets)</i>	? <i>(Permanent Magnet Electric Machines must be fully assembled at the factory and for safe transport)</i>
Total Increment Weight (shippable weight)	50,272 lbs. (22,851 kgs) (3) <i>(Includes the integrated BRTEC)</i>	?
Volume ((Dia./2) ² * π * Length)	5 M³ (1 MW increments) <i>(Includes the BRTEC)</i>	288 M³ (13MW) (1) <i>(Does not include the electronic controller)</i>
Total Stackable Units	20x (1MW) for 20MW 10x (2MW) for 20MW (Frames, Bearings, and Axles provide structure strength)	?
Total Stackable Length (20MW) 20x (1MW) 10x (2MW)	33.3 ft (10.2 M) 15.2 ft (5.1 M) <i>(Includes the integrated BRTEC)</i>	N.A. <i>(Nacelle is 67.5ft/20.6M long)</i>
Stackable Volume (20MW) 20x (1MW) 10x (2MW)	100 M³ (1) 50 M³ (1) <i>(Includes the integrated BRTEC)</i>	288 M³ (13MW) (1) <i>(Does not include the electronic controller and for 13 MW)</i>
Total Stackable Weight (20MW) 20x (1MW) 10x (2MW)	502 tons (455 tonnes) (1) 251 tons (228 tonnes) (1) <i>(Includes the integrated BRTEC)</i>	600 tons? (13MW) (1),(4) <i>(Nacelle total is 660 tons, including electronic controller, for 13 MW)</i>
(1) Consistent with the wound-rotor doubly-fed [synchronous] electric machine circuit and control architecture, as only possible by the enabling technology of brushless real time emulation control or BRTEC . SYNCHRO-SYM shows half the size, half cost, and half loss as all other electric machine systems, such as the RE-PM generator system.		
(2) 15 ton internal nacelle crane		
(3) 30 ton internal nacelle crane		
(4) 700 ton, 150 meter, external mobile crane		

between the [twelve megawatt Haliade-X wind turbine from GE](#) and a resilient power stack of twelve, small, lightweight, self-contained, one megawatt SYNCHRO-SYMs, each of which can be again separated into smaller rotor and stator components for easiest handling and transportation.

II. CONCLUSION

Only SYNCHRO-SYM can componentize large electric machine systems into smaller diameter, lighter generator units that can be shipped to the wind turbine site, lifted to the nacelle with a small internal crane, or even assembled and stacked inside the nacelle. Only BRTEC brings superconductor electric machine systems closer to reality by exciting the conventional sinusoidally distributed active winding set with pure sinusoidal excitation waveforms, which reduces cryogenic refrigeration by avoiding harmonic heating of the superconductor electromagnet, and by brushlessly relocating the superconductor electromagnet to the stationary body (stator) for convenient logistical support. NOTE: When alternating current (AC) superconductors become a reality, only the fully electromagnetic SYNCHRO-SYM will be the superconductor electric machine of choice.