WHY BOTHER WITH INFERIOR RARE-EARTH PERMANENT MAGNET ELECTRIC MOTORS

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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, materials, manufacturing, winding, and excitation techniques.**

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

I. INTRODUCTION

The high energy-product (*or* BH_{max}), Neodymium rare-earth permanent magnet (**RE-PM**) was discovered in the early 1980s and later, Dysprosium doping was discovered to provide reasonable RE-PM magnetization life by sacrificing the precious high energy-product of Neodymium with improved coercivity and higher temperature operation. Despite ongoing research and development (**R+D**) for at least a viable Dysprosium alternative, strategically tailoring doping with extremely rare and expensive Dysprosium still provides the best permanent magnet for a practical electronically controlled RE-PM electric motor and generator (or electric machine) system (**EMS**), which is now considered to be the highest performing (*and most expensive*) EMS available.

When discovery, the RE-PM was economically viable and provided the allure of eliminating the electrical provisioning and inefficiency of magnetizing magneto-motive-force (**MMF**), which blindly directed virtually all electric machine R+D to the RE-PM EMS (**RE-PM-EMS**) without considering the environmental issues and geopolitical consequences of the RE-PM supply chain. As supporting evidence, today's EMS R+D is again blindly directed to *awkwardly retrofitting* magnetizing MMF into the RE-PM-EMS (*for its coveted attribute of controlling air-gap flux density for improving EMS efficiency and reliability at varying speeds*), which ironically ignores the original intent of RE-PMs, which was to actually eliminate magnetizing MMF already conveniently provided by the slip-induction EMS that was being replaced.

With the increasing application of the RE-PM-EMS, it became evident that the RE-PM global supply chain could not satisfactorily meet demand. Now with strategic ownership of the global Neodymium and Dysprosium reserves, China cartel controls the ever rising price of RE-PMs and for the foreseeable future to the chagrin of the original RE-PM R+D investors, China has become the de facto manufacturer of the RE-PM-EMS. In response, EMS R+D, such as the 2011 ARPA-E REACT program, is devoted to finding RE-PM *alternatives* but after nearly a decade, the results are mixed. For example, one aspect of the program developed high frequency electronic control for higher speed operation (*with comparable power*) and therefore smaller RE-PM-EMS (*with less precious RE-PM material*) but seemingly ignored the neutralizing effect of the "compounded" inefficiency, cost, size, and complexity of the necessary load matching gearbox addition on the overall system performance. More troubling, the RE-PM-EMS has become the EMS of choice for at least electric vehicles, airplanes, and advanced wind turbines with "recycling" RE-PM-EMSs (*at the end of their finite magnetization life*) as the supply chain solution.

II. RE-PM-EMS ALTERNATIVE

While "*Innovating for our clean, efficient, and sustainable energy future*," Best Electric Machine (**BEM**) pursued R+D into the symmetrical multiphase wound-rotor "synchronous" doubly-fed EMS (**S-MWRSDF-EMS**), which electric machine experts have hypothesized since at least the 1960's to be the best EMS possible because of the optimized electromagnetic symmetry of two independent and electrically accessible balanced multiphase winding sets (i.e., dual ported or doubly-fed) on the rotor and stator bodies, respectively, but required the invention of a real time (*or instantaneous*) emulation (*or sensor-less and automatic*) control means, which was far beyond any technology of the time or even today's state-of-art field-oriented control (**FOC**), in order to avoid the slightest stochastic control dependency on the deoptimizing electromagnetic asymmetry of slip-induction and as a result, guarantee stable and contiguous "synchronous" doubly-fed control of air-gap flux (*for field weakening*), speed, torque, and torque angle (*for leading-to-lagging power factor*) from zero (*or sub-synchronous*) to super-synchronous speed, particularly about synchronous speed where slip-induction unstably ceases

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to exist. Unless mechanically damped (*as in modern wind turbine "generator" systems*), even the multiphase wound-rotor induction doubly-fed EMS of today experiences unstable rotor oscillation from the slightest rotor perturbation as a result of at least the "slip-induction" dependency caused by delays and inaccuracies of FOC waveform measurement or synthesis (*particularly with shallow slope or slow waveforms*). In contrast, by eliminating the multiphase slip-ring-brush assembly and any dependency on stochastic slip-induction by a brushless, sensorless, automatic, and instantaneous control means that provides bi-directional, sinusoidal, perfectly speed synchronized (*e.g., frequency and phase*), including at synchronous speed, multiphase excitation power "directly" to at least the rotor active multiphase winding set, **SYNCHRO-SYM** is today's only example of a true (*and brushless*) S-MWRSDF-EMS (*as only provided by the Multiphase Brushless Real Time Emulation Control or* ***BRTEC*** *that comprises standard off the shelf technology*).

Considering a common axial-flux RE-PM-EMS footprint (*with adjacent rotor and stator disks separated by an air-gap instead of the cylinder inside cylinder radial flux form*), it is reasonable to assume that 1) the power rating and associated electrical and core losses are determined by the "active" stator disk (*that generates or motors electromechanical power via an active multiphase winding set*), 2) the physical size and amount (*and cost*) of materials are similar between the "active" stator disk and the "passive" rotor disk (*that dissipates electromechanical power with at least an electrical steel core of passive RE-PMs, slip-ring assemblies, reluctance saliencies, field windings, or slip-induction multiphase windings*), and 3) the axial-flux form inherently provides better performance and winding structural integrity by avoiding rotating body collision with a smaller air-gap depth. Then by simply replacing the asymmetrical "passive" rotor disk (of RE-PMs) with another "active" stator disk and replacing the FOC with BRTEC, simple qualitative observation shows SYNCHRO-SYM (*with the continuous power rating of two symmetrically "active" winding sets on the stator and rotor disks, respectively*) immediately provides at least the following conceptually obvious transformational advantages:

- Double the power rating without changing the air-gap flux density, physical footprint, and packaging art, such as materials, winding, construction, and manufacturing techniques, of the original axial-flux RE-PM-EMS being retrofitted (*or any other retrofitted EMS*) and reasonably assuming the cost of the packaging art is directly related to the amount of materials being applied, which is tantamount to:
  - Half the size, weight, or cost (*per kilowatt of total power*) or twice the power density at half the cost, *without including the additional size, weight, and cost savings of eliminating the expensive, exotic, or wasteful "passive" components, such as RE-PMs;*
  - Up to half the electrical and core loss (*per kilowatt of total power*) *by including the electrical loss associated with the electromagnetic core, the small orthogonal vector magnitude of magnetizing MMF, and the much lower compounded system loss associated with the rotor or stator active winding set of SYNCHRO-SYM controlled by BRTEC, each of which is half the total power rating (or one-quarter the I^2R electrical loss) of the single stator active winding set of the RE-PM-EMS controlled by FOC;*
  - Double the performance enhancement (*per kilowatt of total power*) enabled by the best packaging art, *which today's most advanced EMSs are constrained to strategically use for performance enhancement or invention, such as square copper wire, on the same century old "asymmetric" (i.e., passive rotor or single ported) transformer circuit and control architecture.*
- At least quadruple the peak torque density of the original axial-flux RE-PM-EMS, *because in accordance with the classic operating physics of the "symmetric" (or dual ported) transformer circuit and control architecture (as only provided by SYNCHRO-SYM), air-gap flux density remains constant with increasing torque current (beyond magnetizing MMF) according to conservation of energy, which is unlike the alternative passive rotor (or "asymmetric") EMS, such as the RE-PM-EMS.*

III. CONCLUSION

By retrofitting the RE-PM-EMS (*or any EMS*) with SYNCHRO-SYM, significant portions of the limited supply of precious and expensive RE-PM materials are saved for other more strategic applications and warnings of supply chain deficiencies due to RE-PM-EMS proliferation is resolved! With *twice the power density* of the best RE-PM-EMS, electric airplanes will fly higher, faster, and longer while reliability will improve! With *at least quadruple the peak torque* of the best RE-PM-EMS, electric vehicles will be without the compounded size, weight, cost, unreliability, and inefficiencies of a gearbox system for longer battery range! Without the safety or assembly issues associated with the persistent magnetisms of RE-PMs, direct drive wind turbine generators can be componentized into smaller diameter and lighter entities for easy shipping, power stacking, and field assembly (*in the nacelle*) at the refurbished or new wind turbine installation.