EXECUTIVE SUMMARY of BEST ELECTRIC MACHINE

Bottom Line Up Front:

- Electric motors consume at least 45% of the entire global supply of electricity, which has a compounded annual growth of 4%, electric generators produce virtually all of the entire global supply of electricity, which includes electricity generated from renewable energy, and electric motors and generators (i.e., electric machines) will consume the entire 70% of additional expected growth in the global supply of electricity to provide electric propulsion as the likely primary means of transportation by circa 2035:
  - As the backbone of the electricity infrastructure, more efficient electric machines (i.e., electric motors or generators) would save considerable amounts of electricity, associated cost, and resulting environmental pollution, such as CO2. For instance, a reasonable 2% incremental improvement in electric motor system efficiency (e.g., from 90% efficiency to 92%) could save nearly 1% (e.g., Δ2% x 45% of electricity consumption) of today’s entire global supply of electricity; or by reasonably assuming 45% of all electric vehicle (EV) loss is associated with the propulsion electric machine system, the 2% incremental improvement could increase the range of a fully regenerative EV by a healthy 9% (e.g., Δ2% x 45%).
  - Always essential for decarbonization applications, such as renewable energy (e.g., wind, hydro, tidal, hydrogen, etc.), electric transportation (e.g., ships, EV, electric airplanes, trains, etc.), and industry (e.g., fans, pumps, machinery, etc.), the very competitive electric machine market (including electronic control) is well over $300B annually, all of which use the same century old electric machine circuit and control architecture with the asymmetry of a “passive rotor assembly” of permanent magnets, slip-induction dependent windings, reluctance saliencies, or DC field windings.
  - In response, professional articles are being published almost daily that effectively focus on optimizing the efficiency, cost, and size of the century old electric machine circuit and control architecture by strategically applying readily available and conveniently applicable performance enhancing material, winding, thermal, packaging, manufacturing, and control techniques (with similar results) but with the majority of articles blindly focused on the expensive neodymium-dysprosium based rare-earth permanent magnet (RE-PM) electric machine system, which are notionally considered to be the best performing but with its supply chain controlled by the Chinese Communist Party (CCP).
  - While “innovating for our clean and sustainable energy future,” Best Electric Machine (BEM) provides the only practical solution to the CCP RE-PM electric machine system with the patented invention of a new symmetric electric machine circuit and control architecture (comprising the symmetry of an “active rotor assembly,” which contributes additional active power rating to the electro-mechanical conversion process), called SYNCHRO-SYM, that immediately magnifies the performance of the century old asymmetric electric machine circuit and control architecture while reducing its cost and improving its efficiency by effectively eliminating the entire asymmetric “passive rotor assembly” where reasonably half of the electric machine cost, size, and loss per unit of active power rating occur without contributing additional active power rating to the electro-mechanical conversion process.

General Electric Motor or Generator Information:
All electric machine systems produce moving force or rotating torque with the interaction between two orthogonal vector components in accordance with Lorentz Law, which are: 1) winding magnetizing current (or instead permanent magnet coercivity) for “passively” establishing the flux density in the air-gap between the rotating and stationary bodies (i.e., static energy) and 2) winding torque current for “actively” establishing force at speed (i.e., kinetic energy or work):

- Mechanical power is the product of torque (α winding current) and speed (α winding voltage & excitation frequency) while electrical power is the product of current (α torque) and voltage (α speed).
- The difference between the electrical power converted to mechanical power calculates to loss and resulting, efficiency.
- Only a directly (i.e., terminal) excited multiphase winding set produces a moving magnetic field with force for average electromechanical energy conversion but only if the synchronous speed relation is satisfied (i.e., ±rotor excitation frequency ±stator excitation frequency ±angular mechanical speed = zero).
- The magnetizing current components of electrical and core loss can be eliminated by replacing the electrical provisioning and proportionally related volume of passive electromagnets with magnetizing magneto-motive-force (MMF), which is the product of winding-turns and winding current, with a proportionally related volume of passive permanent magnets but only with MMF competitive performance of expensive cartel-controlled RE-PM high coercivity, high energy product, and practical persistent magnetizing life (see “The Important Role of Dysprosium In Modern Permanent Magnets”).
- The slip-induction electric machine depends on the slip (or asynchronism) between the rotor winding set (which is fixed to the shaft speed) and the stator rotating magnetic field of the stator to induce current onto the rotor winding set (in accordance to the synchronous speed relation) for torque production and traditionally, the synchronous electric machine depends on a rotor shaft speed to be in synchronism with the stator magnetic field (i.e., rotor winding excitation frequency is zero) to avoid slip-induction. But to satisfy the symmetric (or wound-rotor) synchronous “doubly-fed” electric machine, which is the basis for all electric machine study, with stable operation from sub-synchronous to super-synchronous speed, experts had to hypothesize a real time emulation control means for direct rotor multiphase winding excitation to phase lock the stator and rotor magnetic fields (regardless of their winding position) in order to avoid the analysis complications of also relying on slip-induction excitation, particularly at synchronous speed where slip-induction ceases to exist, and accordingly, “Does not rely on slip-induction to energize the rotor winding set” is a more accurate definition for the synchronous electric machine.

Virtually all of today’s high-performance electric machines are electronically controlled (or electric machine “systems”) for: 1) practical operation, such as for a functional RE-PM or reluctance electric machine system, 2) optimum application balancing, such as by adjusting excitation frequency for variable speed, 3) torque and active power control, such as by adjusting torque current, and 4) higher operating speeds (e.g., extended constant horsepower speed range) and electronic reliability control, such as by adjusting magnetizing MMF, commonly known as field weakening.

- Control is adjusting the magnitude and phase of the port voltage and current excitations, such as the magnetizing current and torque current, of the active winding set (i.e., directly
A dominant proportion of any electric machine system R+D always reverts back to the CCP RE-PM electric machine system by the inherited R+D investment momentum that originally blindly disregarded CCP geopolitical consequences or the limited operating life of RE-PMs.

- The consistent offshoring of USA taxpayer funded research and manufacture is self-defeating, particularly with the pockets of the CCP as the likely end recipient because of its stealthy penetration into every aspect of the electric machine materials, manufacture, and academic research, including superconductor electric machine systems.

- Equally affected by the CCP RE-PM debacle, at least Japan has taken a more proactive and protective approach with the purchase of Metglas, which was the USA inventor of amorphous metal ribbon, to continue its empirical research in nanocrystalline derivatives, such as Nanomet and Finomet, and their practical, cost effective electric machine manufacturing method, which reduce the amount of RE-PM material in electric machines by increasing core permeability; but unlike the USA, Japan again protects its intellectual property of taxpayer funded research by forbidding offshore manufacture.

- The superior performance fixation on RE-PM asymmetric electric machine systems is more anecdotal:

  - An “optimally” designed asymmetric “slip-induction dependent” electric machine may show up to 9% (e.g., 0.09) more electrical loss (and size) than an “optimally” designed RE-PM electric machine because of the orthogonal vector of passive magnetizing MMF. For instance,
if a RE-PM electric machine shows 10 watts of electrical loss (e.g., 90% efficiency for a 100 watt rated motor), a magnetizing MMF electric machine with similar optimization, such as a slip-induction electric machine, would show a tolerable 10.9 watts of loss (e.g., 89.1% efficiency) but without the expense and geopolitical consequences of RE-PMs or without including the additional compounding loss, cost, and size of the necessary “system” gearbox and high speed electronic controller.

- The relatively recent spawning of the RE-PM recycling industry obviously shows the finite operating life expectancy of RE-PMs but more importantly, shows the lack of enough global mineable RE-PM material to support the growth in its major consumer, the RE-PM electric machine system.
- The coercivity of RE-PMs can never achieve the air-gap flux density provided by the MMF of an electromagnet for highest power density and efficiency because unlike the BH curve of an electromagnet with flux density directly proportional to magnetizing MMF, the highly temperature sensitive BH curve of RE-PMs shows flux density inversely proportional to coercivity, which calculates to infinitely larger amounts of expensive RE-PM materials to achieve the flux saturation limit of the electrical steel core (e.g., 1.25T at 100°C). In contrast, the flux density provided by an electromagnet is only limited by the winding conductor resistance, which is the reason for superconductor electromagnets.
- Although the original reason for migrating to asymmetric RE-PM electric machine systems were the elimination of electrical loss, cost, size, and electrical provisioning associated with the magnetizing MMF of slip-induction, DC Field wound, or reluctance electric machine systems, RE-PM electric machine systems are ironically re-introducing magnetizing MMF back into their asymmetric circuit and control architecture to regain its **coveted benefit of field weakening**, which provides better speed bandwidth, flux control, and electronic controller reliability (with similar associated electrical loss, cost, and size).
- Exemplifying the notional blind fixation on RE-PM persistent magnetism providing superior performance to similarly optimized magnetizing MMF electric machine systems, recent research is ironically trying to eliminate expensive RE-PMs by substituting inexpensive Ferrite PMs with the non-competitive performance of very low BH product and short persistent magnetizing life.

- With the anecdotal notion that asymmetric RE-PM electric machine systems have superior performance, original equipment manufacturers (OEMs) of EVs are acquiescing to the CCP geopolitical consequences by effectively branding the same optimized CCP RE-PM electric machine system with only marketing suggesting discernible performance differences:
  - In retrospect, all OEMs would be better served by dropping the marketing ploy to at least provide the “economy of scale” from the cooperative high volume manufacture of an industry generic RE-PM electric machine system without the nuances of branding, such as from a single source OEM component manufacturer and supplier, particularly if that OEM component manufacturer and supplier has the best protected product and manufacturing method.

**The Only Electric Motor or Generator Solution:**

- For comparison purposes, Best Electric Machine (BEM) classifies all electric machine systems into two categories: 1) the **century old, me-too, asymmetric electric machine system** circuit and control architecture that always comprises: a) an active stator assembly with a directly excited...
multiphase winding set \( (i.e., \text{active winding set}) \), which establishes the total torque and active power rating, b) a “passive rotor assembly” with the asymmetry \( (\text{and associated loss, cost, and size}) \) of slip-induction dependent \( (i.e., \text{indirectly excited}) \) multiphase windings \( (i.e., \text{asynchronous}) \), saliencies \( (i.e., \text{reluctance}) \), conventional or superconducting DC field windings \( (i.e., \text{synchronous}) \), or RE-PMs \( (i.e., \text{synchronous}) \), which establishes the static airgap magnetic field without contributing active power \( (i.e., \text{work}) \) to the electromechanical conversion process, and c) a derivative of field oriented control \( (\text{FOC}) \) or 2) the symmetric electric machine system circuit and control architecture \( (i.e., \text{symmetric multiphase wound-rotor } [\text{synchronous}] \text{ doubly-fed electric machine system}) \) that always comprises: a) an active stator assembly, which establishes the torque rating and a portion of the air-gap magnetic field, b) an operationally stable “active rotor assembly” with the symmetry of another active \( (i.e., \text{directly excited multiphase}) \) winding set, which in synchronous combination with the active stator assembly, contributes additional active power to the electromechanical energy conversion process and also establishes another portion of the air-gap magnetic field with the FR loss halved, and c) a brushless real time emulation controller \( (\text{BRTEC}) \):

- As always postulated during academic study, a practical symmetric electric machine system is only possible with the invention of a brushless, sensor-less and automatic \( (i.e., \text{emulation}) \), instantaneous \( (i.e., \text{real-time}) \), and multiphase electric machine control process guaranteeing continuously stable operation from sub-synchronous, including zero speed, to super-synchronous, including about synchronous speed where slip-induction ceases to exist, by essentially eliminating reliance on slip-induction with its elusive torque angle shifting with external line voltage or rotor perturbations.

- In effect, a practical symmetric electric machine system eliminates the entire “passive rotor assembly” from the century old, me-too asymmetric single or double fed electric machine systems where reasonably half of the electric machine cost, size, and loss per unit of active power rating occurs without contributing additional active power rating to the electromechanical energy conversion process.

- A practical symmetric electric machine system should never be confused with the traditionally unstable asymmetric wound-rotor \( [\text{asynchronous or slip-induction}] \) doubly-fed electric machine system that comprises a passive rotor assembly of reluctance saliencies or an indirectly excited multiphase winding set with the common multiphase slip-ring-brush assembly. Unfortunately, the loss of understanding of the symmetric circuit and control architecture by the formidable technical challenges of instrumental real time emulation control with available technologies has replaced its research with RE_PM electric machine system research.

- While “innovating for our clean and sustainable energy future,” Best Electric Machine (BEM) provides the only practical solution to the CCP RE-PM electric machine system by leveraging the patents of 1) a symmetric electric machine system circuit and control architecture, called SYNCHRO-SYM, as only possible with the invention of brushless real time emulation control (BRTEC), and 2) a new (and only) high speed method of 3D Printing axial-flux electric machines, called MOTORPRINTER. Validated by the only computer-aided-design (CAD) tool, called BEM-CAD, that simultaneously provides comparative design results between the asymmetric circuit and control architecture of an axial-flux slip-induction or RE-PM electric machine system and the only symmetric electric machine circuit and control architecture of an axial-flux SYNCHRO-SYM, by using the same performance enhancing material, winding, packaging, thermal, construction, manufacturing (using MOTORPRINTER), and control
techniques across contestants to guarantee an equitable comparison (see Table 1 for a scalable but non-optimized example). Together, BEM, SYNCHRO-SYM, and MOTORPRINTER uniquely provide the following:

- R+D by the tried and true old fashion way with private sweat equity and investment in innovative free enterprising solutions that did not acquiesce to government funding, which continually directs R+D and manufacturing towards me-too RE-PM electric machine systems with careless disregard to the geopolitical, free enterprise, and electric machine innovation consequences of CCP control.

- Innovation that brings the very “best” electric machine system technology and manufacturing (i.e., SYNCHRO-SYM and MOTORPRINTER) to the free enterprise market with a better performing choice to the CCP cartel-controlled RE-PM electric machine system.

- BRTEC with simple direct control of speed, torque magnitude, and leading, lagging, or unity power factor of the symmetric electric machine system but with stochastic kinetic energy, excitation frequency, or multiphase excitation phase perturbations automatically, immediately, and sensorlessly addressed, instead of state-of-art controllers of the century old me-too asymmetric electric machine systems, such as Field Oriented Control (FOC), with the detrimental reaction delays and imprecisions that are characteristic of offline processing for measurement, estimation, compensation calculation, and excitation synthesis.

- By the additional power rating of an “active rotor assembly” (in concert with the active stator assembly), simple qualitative observation easily shows the power density of the century old me-too asymmetric electric machine system is immediately twice magnified with its cost and electrical loss halved (per unit of active power) by effectively eliminating the entire “passive rotor assembly” of slip-induction windings, DC field windings, reluctance saliencies, or RE-PMs where reasonably half of the cost, size, and loss per unit of active power rating of any electric machine system occurs without contributing additional active power to the electromechanical power conversion process, particularly in an axial-flux form electric machine system (i.e., two adjacent rotor and stator disks of equal size) or a slip-induction electric machine system.

- Immediately twice magnifies the cost-performance by a factor of two active winding sets in the same package on the rotor and stator, respectively, by stably providing twice the constant torque speed range for a given torque, frequency and voltage of excitation (i.e., 7200 RPM with 2 poles and 60 Hz excitation versus 3600 RPM for all other electric machine systems).

- Immediately twice magnifies the performance improvement expected from the same performance enhancing material, winding, packaging, thermal, manufacturing, and control techniques that all century old, me-too asymmetric circuit and control architectures use for performance enhancement or so-called invention.

- At least octuple the peak torque of the century old, me-too asymmetric electric machine system nominal frame size continuous torque by the physics of a dual-ported transformer circuit topology (i.e., symmetric multiphase wound-rotor synchronous doubly-fed electric machine) that avoids core saturation by uniquely holding airgap flux density and port voltage constant with increasing torque current and resulting torque, which is essential for eliminating the compounding size, loss, cost, maintenance, and reliability of an electric vehicle gearbox.

- Steady state air-gap flux density can be designed closer to the saturation limits of electrical steel cores as only provided by winding MMF and impractical with RE-PM electric machine systems, for another level of power density and efficiency.
Saves precious and environmentally polluting CCP RE-PM materials for more strategic applications by providing a higher performance, cost, and reliability alternative to its major consumer, the RE-PM electric machine system, particularly with the imminent global expansion to efficient electric transportation.

Inherently provides adjustable leading, lagging, or unity power factor correction for dynamic VAR compensation at the electric machine installation to dramatically improve electric distribution resiliency and electricity cost.

Democratizes the manufacture of high performance amorphous or nanocrystalline axial-flux electric machines with portable, high-speed, universally programmable, additive manufacturing (i.e., 3D Printer) to at least provide distributed, non-smokestack manufacturing with similar “economy of scale” as the high-volume manufacture of a generic me-too product.

Brings superconductor electric machine systems of today closer to practical reality by brushlessly relocating the winding cryogenics to the stator assembly for improved logistics while eliminating electronic control harmonic heating.

When AC superconductors become available by aggressive on-going research, the performance of the fully electromagnetic superconductor slip-induction electric machine system will be far superior to the RE-PM electric machine system but more importantly, the fully electromagnetic superconductor SYNCHRO-SYM will be the electric machine system of choice by far surpassing the performance of the superconductor slip-induction electric machine system.

Conveniently leverages the full performance opportunities expected from WBG semiconductors, such as high temperature tolerant Silicon Carbide (SiC) semiconductors, and additive manufacturing of integrated high and low frequency axial flux cores, such as MOTORPRINTER, which are driving the next electric machine evolution of completely integrating the motor and drive (IMD) as recently revealed in Combining Motors and Drives, Incredible Shrinking Motor Drive, and Performance Comparison of State-of-Art 300A/1700V Si IGBT and SiC Power Modules, by introducing a highly integrated and tightly residential brushless solid-state high frequency electronic transformer and real time emulation computer (BRTEC) for controlling the electric machine entity instead of today’s afterthought of integrating the distinctly different components, the FOC and the electric machine entity.

In Conclusion:

With the majority of the supply chain of so-called Rare Earth (RE) materials is virtually owned and controlled by a formidable global adversary, the Chinese Communist Party (CCP), and as a result, the United States with most countries are aggressively seeking an alternative supply chain alternative solution, particularly in consideration of the rapid movement to adoption of its major consumer, renewable energy and its derivatives, such as electric transportation, and national defense, such as the military.

Ironically, an alternative to the CCP of the RE material supply chain began, since at least 2011 when the CCP restricted its export, which caused a dramatic price increase as a result of supply and demand. Until then, the RE consumers disregarded the CCP lack of human and environmental concerns needed for RE extraction and production, in favor of low prices. This oversight has made the CCP the de facto supplier, researcher, designer, and manufacture of virtually all products comprising RE.
At least two of the RE materials, neodymium and dysprosium, are critical for practical permanent magnets (PM) used for electric motors and generators, which are the backbone of the electricity infrastructure, renewable energy, and electric transportation, and with the admiration (strong mindset) for applying green technology, such as electric vehicles, electric airplanes, electric trains, wind turbines, etc., application of RE-PM electric motors and generators, which are now considered the best, is rapidly expanding, again with disregard to the obvious (without an understanding), overall control of the green technology falls outside of the USA but more sinister, falls into the hands of the CCP overall, which is devoting much of the collected resources to military build-up, which if unleashed, would cause a dramatic devastation of the essence of the green new deal.

Belatedly, governments are subsidizing or funding electric machine research to at least reduce the amount of RE-PM material but ironically, much of this research reverts back to the CCP with an inherited hold on every aspect the electric machine industry or to the CCP RE-PM electric machine with inherited adoption momentum.

With an original pioneer of green technology since late 1970 (and an oil exploration consultant) as its founder and in accordance with our mission statement, “Innovate for our clean, efficient, and sustainable energy future,” Best Electric Machine acquired at least two patent protected products, SYNCHRO-SYM, which provides a better cost-performance than the RE-PM electric machine system that is anecdotally considered to be the best, and MOTORPRINTER, which is the only practical 3D Printer for axial-flux electric machine manufacture with amorphous metal ribbon. More importantly, the magnifying performance, such as twice the power density and half the cost by completely eliminating the loss, cost, and size of the passive rotor assembly of RE-PMs, SYNCHRO-SYM provides the only cost-effective solution to the RE-PM electric machine system, which is anecdotally considered to be today’s best electric machine system. Although without exotic RE materials, SYNCHRO-SYM comprises copper (windings) and electrical steel (magnetic core) like all electric machines, including RE-PM electric machines, which are expected to rise dramatically with the embrace of green technology but unlike RE materials, copper and steel are abundantly available without CCP control, and by simple qualitative analysis, SYNCHRO-SYM effectively halves the amount of these materials per unit of power rating compared to all other electric machine systems, including the RE-PM electric machine system, and when AC superconductors become a practical reality, copper windings will be reduced if not eliminated, which will again elevate the fully electromagnetic SYNCHRO-SYM as the electric machine without rival.
Table 1

A standard axial-flux 12.5 KW SYNCHRO-SYM versus a standard axial-flux 6.5 KW RE-PM electric machine “system”

<table>
<thead>
<tr>
<th></th>
<th>SYNCHRO-SYM</th>
<th>RE-PM Electric Machine</th>
</tr>
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<tbody>
<tr>
<td>Rated Continuous Design Torque</td>
<td>100 N-M</td>
<td>100 N-M</td>
</tr>
<tr>
<td>Continuous Constant Torque Speed Region</td>
<td>0-1200 RPM</td>
<td>0-600 RPM</td>
</tr>
<tr>
<td>Continuous Constant Horsepower Range</td>
<td>&gt;1200 RPM</td>
<td>&gt; 600RPM</td>
</tr>
<tr>
<td>Continuous Rated Power</td>
<td><strong>12.5 KW @1200 RPM</strong> (doubly-fed or two active winding sets)</td>
<td><strong>6.25 KW @ 600 RPM</strong> (singly-fed or one active winding set)</td>
</tr>
<tr>
<td>Continuously Power Density</td>
<td>3.12 KW/L (BRTEC included)</td>
<td>1.56 KW/L (Electronic controller not included)</td>
</tr>
<tr>
<td>Peak Efficiency (system)</td>
<td>92.2%</td>
<td>91.7%</td>
</tr>
<tr>
<td>Weight</td>
<td>34 kg (@12.5 KW) (BRTEC included)</td>
<td>29 kg (@6.25 KW) (Electronic controller not included)</td>
</tr>
<tr>
<td>Diameter</td>
<td>328mm (@12.5 KW) (BRTEC included)</td>
<td>328 mm (@6.25 KW) (Electronic controller not included)</td>
</tr>
<tr>
<td>Length</td>
<td>100mm (@12.5 KW) (BRTEC included)</td>
<td>146mm (@6.25 KW) (Electronic controller not included)</td>
</tr>
<tr>
<td>System Cost (at continuous rated power)</td>
<td>$85/KW (dual converter BRTEC for interfacing with any power, such as DC or single and multiphase AC)</td>
<td>$121/KW</td>
</tr>
<tr>
<td>No Cooling (system)</td>
<td>10 seconds (@12.5 KW)</td>
<td>10 seconds (@6.25 KW)</td>
</tr>
<tr>
<td>Peak Torque (system/no transmission and rated electronic control)</td>
<td>Up to 800 N-M From 0-1200 RPM</td>
<td>250 N-M 0-600 RPM</td>
</tr>
<tr>
<td>Peak Power (system and rated electronic control)</td>
<td>100KW</td>
<td>16 KW</td>
</tr>
<tr>
<td>Peak Power Density (system and rated electronic control)</td>
<td>25 KW/L</td>
<td>4 KW/L</td>
</tr>
<tr>
<td>2x stack (system)</td>
<td>200mm/50Kg/25KW (1600 N-M peak torque) (BRTEC included)</td>
<td>300mm/60Kg/12.5 KW (500 N-M peak torque)     (Electronic controller not included)</td>
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