EXECUTIVE SUMMARY of BEST ELECTRIC MACHINE

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SYNCHRO-SYM Bottom Line Up Front:

Simply retrofitting any electric motor or generator system package with the "active" rotor circuit and control architecture of SYNCHRO-SYM will double the original core power density, halve the cost, and halve the loss per unit of power rating by the power contribution of two active winding assemblies, will octuple the peak torque by holding the air-gap flux density below saturation in accordance to the physics of a symmetrical or dual ported transformer, and will effectively eliminate the entire loss, cost, and size of the "passive" rotor assembly of precious rare-earth permanent magnets, slip-induction dependent windings, reluctance saliencies, or field windings.

Electric motor and generator systems are the backbone of the electricity infrastructure. For instance, *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 the entire global supply of electricity, which includes electricity generated from renewable energy, and together, *electric motors and generator systems* (*or electric machine systems*) will produce and consume virtually the entire 70% of additional expected growth in the global supply of electricity for serving electric propulsion as the customary means of transportation by circa 2035. Electric machine systems are *fundamental* for renewable energy (*e.g., wind, hydro, tidal, hydrogen, etc.*), electric transportation (*e.g., ships, electric vehicles, electric airplanes, trains, etc.*), and industrial efficiency and automation (*e.g., fans, pumps, robots, machinery, etc.*). Without argument, continuous improvement of the electric machine system provides enormous opportunities for the efficiency, cost, power density, and future of our energy infrastructure, for decarbonization, and for combating climate change but with the shared belief that any electric machine circuit and control architecture that could be invented has been invented, electric machine system research and development (**R+D**) is instead specifically focused on strategically applying readily available and conveniently appliable performance material, winding, packaging, manufacturing, and thermal management techniques that enhance *the 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 direct current (DC) field windings*.

Without considering the extravagant cost, the potential to demagnetize with fading operating life, and the safety, environmental, and manufacturing issues, the *neodymium-dysprosium* rare-earth permanent magnet (**RE-PM**) electric machine system is *notionally* considered to be the most efficient and best performing of the century old asymmetric electric machine circuit and control architectures. As a result, the majority of R+D is blindly focused on enhancing the RE-PM electric machine system with its rapid application into electric transportation, including electric airplane propulsion, and large direct drive wind turbines but paradoxically, its supply chain is not expected to meet future demand and is overwhelmingly controlled by a global adversary with its main goal of world domination with disregard of environmental, human labor, free enterprise

innovation, and geopolitical consequences of mining, processing, and using RE-PM materials. Fortunately, a new *symmetric synchronous electric machine circuit and control architecture*, called SYNCHRO-SYM, doubles the power density, halves the cost, and halves the loss with octuple the peak torque (*per unit of continuous power rating*) expected from the RE-PM electric machine system with the same performance enhancing material, winding, packaging, manufacturing, and thermal management techniques but with the precious rare-earth permanent magnet materials conveniently eliminated for deployment to other more strategic applications without a SYNCHRO-SYM solution and to greatly reduce global RE material demand. BEM-CAD also interfaces to the only programmable 3D Printer of axial flux electric machine systems (with amorphous or nanocrystalline) metal ribbon, called MOTORPRINTER.

SYNCHRO-SYM Verification Basis:

The leap in performance of SYNCHRO-SYM has been verified by lengthy analytical analysis, by several progressive stages of prototyping, including pre-production prototyping, and more importantly, by a SYNCRO-SYM customized computer aided design tool (BEM-CAD) that simultaneously provides side-by-side RE-PM and Induction electric machine system comparisons, all of which are designed to the same electrical and mechanical parameters with the same winding, material, packaging, thermal management, and control techniques for absolute fairness.

With superconductor electric machine system as the exception, the *basic electric machine design axioms* from Electric Machine Design Distinctions and Constraints reasonably show all *optimally designed* electric machine systems, including RE-PM electric machine systems, with similarly applied performance enhancing material, winding, packaging, manufacturing, thermal, and control techniques will have similar air-gap flux density by design, which in accordance with the basic design relationships of Faraday's Law, Lorentz Force Law, Ampere Circuital Law, and the Synchronous Speed Relation, will have a similar size active winding set with similar continuously rated "synchronous speed" torque and effective air-gap area, when designed for the same voltage and frequency of excitation, pole-pair count, and thermal considerations. Likewise, a similar air-gap area and active winding set reasonably assumes a similar overall electric machine size and volume, particularly in a similar disk-to-disk (or axial-flux) format. Therefore, the true cost-performance differentiators between *equally design optimized* electric machine systems, including RE-PM electric machine systems, must be: 1) the continuous constant-torque speed range or Maximum Load RPM (*at a given synchronous speed design torque*) for a given voltage and frequency of excitation, 2) the associated overall loss or efficiency per unit of power rating, and 3) the peak torque and peak power capabilities that go beyond the century old, singly-fed or doubly-fed electric machine system circuit and control architecture with the passive rotor of *slip-induction dependent* multiphase windings, reluctance saliencies, DC field windings, or RE-PMs.

In addition to the *basic electric machine design axioms*, all electric machine systems should be grouped into just two categories of circuit and control architectures for comparison convenience:

1) the *century old* asymmetric electric machine system circuit and control architecture, which comprises: a) the *associated loss, cost, and size* of an "active stator" assembly with an active winding set for establishing the continuous torque and power rating, b) the similar *associated loss, cost, and size* of a "passive rotor assembly" with the asymmetry of a *slip-induction dependent* multiphase winding set (*i.e., asynchronous electric machine*), reluctance saliency set (*i.e., synchronous or asynchronous reluctance electric machine*), or a DC field winding (e.g., electromagnet) or RE-PM set (*i.e., traditional synchronous electric machine*) for establishing the airgap magnetic field without contributing additional active power (*i.e., work*) to the electromechanical conversion process, and c) the *compounded* loss, cost, and size of the field oriented excitation controller derivative (**FOC**) for establishing the speed-synchronized excitation by the delays and estimations of offline electronic measurement and *simulation* (*e.g., software*) computation that always introduces unstable components of slip-induction or random torque angle phase shifts;
2) the symmetric synchronous electric machine system circuit and control architecture (*or the brushless, symmetric multiphase wound-rotor [synchronous] doubly-fed electric machine system*), called SYNCHRO-SYM, which in place of the "passive rotor" assembly and FOC of the asymmetric electric machine system, comprises an "active rotor" assembly with another similar active winding set (*which also inherently provides the sought after efficiency of a copper wound rotor*) that in conjunction with the active stator winding set, synchronously contributes *additional* working power to the electromechanical conversion process from sub-synchronous to super-synchronous speeds without the unstable reliance on slip-induction (and as a result, will operate at synchronous speed as a synchronous electric machine) and with automatic and instantaneous response to any rotor or line perturbation (*e.g., hunting*), particularly at or about synchronous speed where slip-induction is vague or ceases to exist, all of which is only possible by a brushless, *bi-directional,* instantaneous (*i.e., real time*) and sensor-less and automatic (*i.e., emulation*) excitation controller (*i.e., brushless real time emulation controller or* ***BRTEC***):

- Akin to BRTEC, the "electromechanical commutator" of the *symmetric "single phase" wound-rotor [synchronous] doubly-fed electric machine system*, called the AC/DC Universal Motor, automatically and instantaneously (*i.e., real time emulation*) provides a speed-synchronized but choppy, high harmonic content, low resolution, and low voltage magnitude "single phase" excitation waveform directly to the rotor active multiphase winding set (*i.e., armature*) by a mechanically fixed displacement of speed-synchronized rotating set of contacting mechanical switches. In contrast, BRTEC of the SYNCHRO-SYM *brushlessly*, automatically, and instantaneously provides speed-synchronized "multiphase," and pure sinusoidal excitation waveforms of high resolution and with any voltage or current magnitude directly to the rotor active winding set by high speed, AC-to-AC electronic power conditioning with an analog electromagnetic computer (*instead of the FOC offline electronic computer for sensor measurements and imprecise waveform synthesis*):
    - Disregarding the reliability, the maintainability, and the short life of electromechanical commutation or the complicated multi-segmented arrangement of compensatory damping winding sets but providing the highest peak torque

found in industry, the Universal Motor is the only practical example of a stable "symmetric" synchronous electric machine system.
  - Regardless of the frequency of excitation of the power supply, such as AC or DC, the speed range of the Universal Motor is only limited by mechanical switch constraints.
  - Torque control is a simple function of torque current magnitude control with the synchronized frequency and phase of excitation instantaneously and automatically provided by the electromechanical computer (or commutator).
  - The Universal Motor operates from sub-synchronous to super-synchronous speed, including synchronous speed (*i.e., 3600 RPM, single pole-pair, and 60 Hz excitation*) with a constant-torque speed range (or Maximum Load RPM) of twice synchronous speed, which already demonstrates controllable torque ride-through synchronous speed and the non-reliance on slip-induction by real time emulation as expected of a true symmetric synchronous electric machine system.

SYNCHRO-SYM Verification by Empirical Observation:

In concert with the *basic electric machine design axioms* applied to all electric machine systems and without the usual lengthy analytical analysis, the following *simple straight-forward empirical observation will verify the performance* between SYNCHRO-SYM and the asymmetric electric machine system architectures: [1]

- Only SYNCHRO-SYM *twice magnifies the constant-torque speed range (or twice the Maximum Load RPM) for a given pole-pair count, continuous rated torque, and packaging at a given frequency and voltage of excitation, and packaging* by stably operating from sub-synchronous, such as zero speed, to super-synchronous, such as at synchronous speed or twice synchronous speed, which is tantamount to twice the core power density at half the cost and loss per unit of power rating of the asymmetric electric machine system:
  - e.g., Constant-Torque speed range of 7200 RPM for SYNCHRO-SYM with 2 poles and 60 Hz excitation (*with the sum of equally applied rotor and stator excitation frequencies in accordance with the Synchronous Speed Relation*) versus 3600 RPM for the asymmetric electric machine system (*with the rotor frequency at zero in accordance with the Synchronous Speed Relation*).
- Only SYNCHRO-SYM *twice magnifies the power density while halving the cost and loss (per unit of active power)* by fundamentally eliminating the entire loss, cost and volume of the "passive rotor assembly" and replacing with an "active" rotor assembly, which together with the active stator assembly, provides double the power rating within the same electric machine packaging of loss, cost, size, materials (*less RE-PM*), and windings:
  - By uniquely establishing a smooth air-gap surface (*i.e., non-salient*) that most effectively utilizes the air-gap area and eliminates reluctance saliencies or cogging, as only provided by two balanced multiphase winding sets on the rotor and stator, respectively.

[1] V. Seshadri Sravan Kumar, D. Thukaram,"Alternate Proof For Steady State Equivalent Circuit of a Doubly Fed Induction Machine," IEEE Transaction on Power Electronics, January 23, 2015.

  - By establishing the air-gap magnetic flux density with half of the magnetizing MMF I^2R loss of the slip-induction electric machine system by sharing magnetizing MMF (*i.e., product of magnetizing current and winding turns*) between two active winding sets on the rotor and stator, respectively.
  - By particularly considering the asymmetric slip-induction electric machine system or an axial-flux form of asymmetric electric machine system (*with adjacent rotor and stator disks of comparable size*), such as the 3D Printed amorphous axial-flux electric machine by MOTORPRINTER.
- Only SYNCHRO-SYM *twice magnifies the performance improvement (per unit of active power) from the same performance enhancing material, winding, packaging, thermal, manufacturing, and control techniques* that all asymmetric electric machine systems are compelled to use for their performance enhancement or so-called invention *but multiplied by the power of two active winding sets*.
- Only SYNCHRO-SYM *provides up to octuple the peak torque (per unit of active power)* of the asymmetric electric machine system by symmetrically balancing the flux on each side of the airgap in accordance with the conservation of energy physics of a dual-ported transformer circuit topology (*i.e., the symmetry of an active winding set on the rotor and stator, respectively, as only provided by BRTEC*), which avoids reaching core saturation by uniquely holding airgap flux density and port voltage constant with increasing torque current (and resulting torque):
  - High peak torque potential is essential for eliminating the compounding size, loss, cost, maintenance, and reliability issues of the customary electric vehicle gearbox.
- Only SYNCHRO-SYM shows the lowest core losses *(per unit of active power)*, such as eddy and hysteresis losses, of any electric machine system at any speed: a) by neutralizing the torque flux and resulting core loss on each side of the air-gap between the rotor and stator, b) by driving the windings with pure sinusoidal excitation, as only provided by BRTEC, instead of driving the windings with the high harmonic content and filtering losses of synthesized excitation by FOC that can reach the core loss of magnetizing MMF flux, and c) by showing half the core volume per unit of power rating and half the combined torque and magnetizing flux core loss of the slip-induction asymmetric electric machine or the moving coercivity (and volume) of the RE-PM asymmetric electric machine.
- Only SYNCHRO-SYM provides field weakening capability with half the loss, cost and size of magnetizing MMF (*per unit of power rating*) by sharing the magnetizing MMF between the rotor and stator active winding sets.
- Only SYNCHRO-SYM designs the steady state air-gap flux density closer to the saturation limits of electrical steel cores for another level of power density and efficiency by uniquely holding air-gap flux density constant, which is impractical with the unbalanced physics of the asymmetric RE-PM electric machine systems.
- Only SYNCHRO-SYM inherently provides comprehensively adjustable leading, lagging, or unity power factor correction for distributed dynamic volt-amp-reactive (VAR) compensation at the electric machine installation for a distributed inertial hybrid synchronous compensator (HSC) for the flexible AC transmission system (FACTS).
- Only SYNCHRO-SYM saves precious RE-PM materials for more strategic applications by replacing a major consumer, the RE-PM electric machine system,

with a higher performing, more reliable, lower cost, and environmentally friendlier RE-PM free electric machine system alternative.

- Only SYNCHRO-SYM provides the inherently failsafe operation of a symmetrical circuit and control architecture that upon circuit or control failures reverts to the asymmetric slip-induction circuit and control architecture.
- Only SYNCHRO-SYM provides comparable superconductor electric machine system performance without the complexity of cryogenic superconductors, high flux density, and passive or active shielding by providing twice the power density and half the loss and cost of the RE-PM electric machine system.
- Only SYNCHRO-SYM brings superconductor electric machine systems of today closer to practical reality by a BRTEC that conveniently and brushlessly relocates the superconductor winding, cryogenics, and active or passive shielding provisioning to the stator side for improved superconductor logistics, while eliminating electronic control harmonic heating with pure sinusoidal excitation.
- Only SYNCHRO-SYM will be the electric machine system of choice by far surpassing the performance of the fully electromagnetic superconductor slip-induction asymmetric electric machine system with the expected availability of AC superconductors resulting from aggressive on-going research, which will be far superior to the RE-PM asymmetric electric machine system.
- Only SYNCHRO-SYM conveniently leverages the full performance opportunities expected from wide bandgap (WBG) semiconductors, such as high temperature tolerant Silicon Carbide (SiC) semiconductors, which are driving the next electric machine system 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, with a brushless solid-state high frequency electronic transformer and real time *emulation* electromagnet computer (BRTEC) that is inherently paired to the symmetric synchronous electric machine entity; instead of today's afterthought of adapting and integrating distinctly different circuit and control components, such as the FOC with the asymmetric electric machine entity.
- Only SYNCHRO-SYM conveniently integrates BRTEC in the empty annulus space of an axial-flux formfactor by the compact symmetry of the circuit and control topology without the bulky reactive components of a DC Link Stage to provide another level of higher power density and the symmetry of duplicate rotor and stator assemblies for fewer parts inventory and shipping.
- Only SYNCHRO-SYM is a synchronous electric machine without the need of damping windings to avoid hunting for stability and accommodates a smooth air-gap for efficient use of air-gap area.
- Only SYNCHRO-SYM allows scalable componentization for small, low weight shippable rotor and stator components with easy field assembly by eliminating the safety, manufacturing, and assembly complications of RE-PMs.

SYNCHRO-SYM Conceptual Realization:

By conceptually considering an axial-flux RE-PM electric machine system with adjacent rotor and stator disks that are separated by an air-gap, simply replace the FOC with

BRTEC and replace the passive rotor disk of RE-PMs with another active stator disk (*duplicate stator disk but with a rotor bearing assembly*) with the resulting SYNCHRO-SYM doubling the power density (*with the power of two active winding sets in the same rotor-stator package as the original RE-PM electric machine system with one active winding set*), halving the cost per unit of power rating (*with the same core material but two active winding sets of copper with no expensive RE-PMs*), halving the loss per unit of power rating (*with the core and electrical loss of two similar stators divided by twice the power rating of two active winding sets*), and octuple the peak torque potential (*with the airgap flux holding constant with increasing torque MMF or flux*). Note: SYNCHRO-SYM shows half the Magnetizing MMF loss of an induction asymmetric electric machine by symmetrically sharing magnetizing current between the two active winding sets on each side of the air-gap and nearly the same overall loss (per unit of power rating) as the RE-PM asymmetric electric machine; but without considering the optimizing option of field weakening (and associated magnetizing MMF loss) or the compounding loss, cost, and size of the inherent *half power rated BRTEC* versus the *full power rated FOC* of the induction or RE-PM asymmetric electric machine system.

SYNCHRO-SYM Conclusion:

With the majority of the so-called Rare Earth (RE) material supply chain owned and controlled by a formidable global adversary with its main goal of world domination with disregard of environmental, human rights, free enterprise innovation, and geopolitical consequences of mining, processing, and using RE-PM materials, it is essential to seek an alternative solution to the RE-PM electric motor or generator system, which is rapidly being applied in electric transportation and wind turbines by its *notional* efficiency and power density performance attributes.

As the only symmetric synchronous electric machine system circuit and control architecture, SYNCHRO-SYM provides the only practical cost-performance solution to the RE-PM electric machine system with twice the power density at half the loss and cost per unit of power rating in the same package of materials (less RE-PMs), winding, and thermal management techniques, while also significantly reducing global RE-PM material demand by eliminating the RE-PM material from its major consumer, which is the RE-PM electric machine, for other strategic applications without a SYNCHRO-SYM solution. Like all electric machine systems, SYNCHRO-SYM does comprise copper (windings) and electrical steel (*e.g., fully electromagnetic core*) with their material demand expected to rise dramatically by embracing green electric technology but unlike RE materials, copper and steel are abundantly available without cartel control. More importantly, simple quantitative observation shows that only SYNCHRO-SYM effectively halves the amount of these materials per unit of electric machine power rating and when AC superconductors become a practical reality, copper and steel will again be reduced, if not eliminated, which will elevate the *fully electromagnetic* SYNCHRO-SYM as the electric machine system of choice without rival.