Best Electric Machine
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SIMPLE TRUTH (PART 3):

- **SIMPLE TRUTH (PART 1)** -
- **SIMPLE TRUTH (PART 2)** -

COMPARISON TRADE SPACE BETWEEN ALL ELECTRIC MOTOR AND GENERATOR SYSTEMS

BOTTOM LINE UP FRONT

To provide an *equitabl*e cost, size, and loss comparison between electric machine system contestants (*per unit of power rating*), a common *Electric Machine System Trade Space and Physics Design Baseline* must be obeyed, which is simply, "*optimally designing* all electric machine contestants to the same fixed design parameters, such as maximum load speed (**MLS**) *or constant-torque speed range* with the same *continuous* torque, excitation frequency, excitation voltage, and air-gap flux density while using the same packaging of readily available performance enhancing material, winding, electronic component, thermal management, construction, and manufacturing techniques (*i.e., performance enhancing packaging techniques*)." Otherwise, violating the electric machine system trade space and physics design baseline by changing any component without providing the same opportunity to all electric machine system contestants would necessarily result in an apple to orange comparison.

Three examples of electric machine system trade space and physics design baseline *violations* are: 1) Not revealing pertinent electric machine system trade space and physics design differences between contestants that has craftily resulted in dramatic advertised performance differences between electric machine systems from different manufacturers, although all use the same "*me-too*" electric machine circuit and control architecture (**EM-CCA**) with the asymmetry of a performance wasting "passive rotor assembly" comprising rare-earth permanent magnets (**RE-PM**), reluctance saliencies, slip-induction dependent windings, or DC field windings, which should otherwise show similar results with the same electric machine system trade space and physics design baseline, 2) Operating one contestant outside the safe operating area of thermal management to dramatically improve power density over *continuously* operating electric machine system contestants, which is expected by *not* comparing with the same electric machine system trade space and physics design baseline, and 3) Insidious influence on electric motor research and discussion by a global adversary's monopoly on the RE-PM supply chain that *anecdotally* resulted in the RE-PM electric machine system considered as having significantly higher torque and power density than any other asymmetric electric machine system, although optimized copper wound rotor asymmetric induction (i.e., asynchronous) electric motor systems are realistically showing similar performance to the RE-PM electric machine system over an extended operating speed range, which is expected by comparing to the same electric machine system trade space and physics design baseline.

- The price-performance distinction between all "me-too" electric machine circuit and control architectures (EM-CCA) is simply limited to the empirical application of readily available performance enhancing packaging techniques, which would show similar comparative results if equally applied in accordance with the Electric Machine System Trade Space and Physics Design Baseline! -

ELECTRIC MACHINE TRADE SPACE AND PHYSICS DESIGN BASELINE & DESIGN AXIOMS: [For Equitably Leveling EMS Comparisons]

** Theoretically proven by a century of classic electric machine system (EMS) study, research, and publication, the *continuously rated constant-torque speed range* for the asymmetric electric machine systems (**A-EMS**) with the electromagnetic asymmetry of i) a "passive rotor" assembly of slip-induction windings, reluctance saliencies, DC field windings, or rare-earth permanent magnets (**RE-PM**), ii) the universally essential active stator with a directly excited multiphase winding set (or active winding set), and iii) a control derivative of Field-oriented Control (**FOC**), *stably and contiguously* operates up to synchronous speed with a given torque, voltage and excitation frequency, after which the constant horsepower range is entered to avoid overstressing the torque and power rating of EMS. In contrast, the *continuous rated constant-torque speed range* for the Symmetric Wound-Rotor doubly-fed *synchronous* electric machine system (**S-EMS**) with the electromagnetic symmetry of i) an active rotor assembly with a similar directly excited multiphase winding set as found on the universally essential active stator, ii) the universally essential active stator, and iii) as only provided by Brushless Real-time Emulation Control (**BRTEC**), *stably and contiguously* operates from sub-synchronous to super-synchronous speeds or twice synchronous speed with a given torque, voltage and excitation frequency, including at or about zero speed, where slip-induction is uncontrollable inefficient, or synchronous speed, where slip-induction ceases to exist (*i.e., 7200 RPM with 1 pole-pair and 60 Hz excitation versus 3600 RPM for the A-EMS*).

For the A-EMS, synchronous speed is where an active winding set reaches its maximum continuous constant-torque speed range and power rating and as a result, it is sometimes referred to as maximum load speed (**MLS**). With two active winding sets and contiguously stable operation from sub-synchronous to super-synchronous speeds, only SYNCHRO-SYM provides *twice* the MLS as the A-EMS and *twice* the power rating at half the cost and loss per unit of power rating with a) the same design constants, such as effective air-gap flux area, air-gap flux density, pole-pair count, and winding turns, etc., b) the same packaging footprint, such as physical structure, bearing assembly, and c) the same continuous torque, voltage, and excitation frequency as the axial-flux A-EMS. It follows, SYNCHRO-SYM leverages the same present or future EMS construction, manufacturing, thermal management, materials, winding, electronic component, and packaging techniques as the A-EMS.

** In fact, the classic theoretical study for any EMS always begins with the *optimal* electromagnetic symmetry of the S-EMS with two active winding sets on the rotor and stator, respectively, both of which contribute active power to the electromechanical energy conversion process from sub-synchronous to super-synchronous speeds, but only by *hypothesizing* the practical invention of a stabilizing brushless real-time emulation controller (BRTEC), which was never realized until the patented invention of SYNCHRO-SYM. The classic study becomes the study of the A-EMS by *deoptimizing* the electromagnetic symmetry with the asymmetry of passive rotor that unlike an active rotor of SYNCHRO-SYM, effectively wastes its loss, cost and size by not contributing an *additional increment* of working power to the electromechanical energy conversion process.

* Practicing EMS experts without the classic theoretical knowledge of the S-EMS, as only provided by the invention of BRTEC, are anecdotally directing all of today's EMS research towards the passive rotor A-EMS, such as a) the RE-PM A-EMS with a passive rotor of RE-PMs that is considered by many to be the most efficient with the highest power density and torque potential but is unethically monopolized by a global adversary seeking world dominance, b) the RE-PM eliminating reluctance A-EMS with a passive rotor of reluctance saliencies, or c) the RE-PM eliminating synchronous A-EMS with a passive rotor of conventional or superconductor DC field windings.

* For a simple SYNCHRO-SYM retrofit demonstration, replace the passive rotor *disk* of slip-induction windings, reluctance saliencies, RE-PM or DC field windings of a simple single air-gap axial-flux A-EMS package, which is an adjacent rotor and stator disk footprint, with another stator *disk* with the universally essential active winding set of the original A-EMS package, and also replace the control derivative of FOC with BRTEC. As a result, the retrofitted A-EMS becomes SYNCHRO-SYM with <u>twice the MLS</u> (or twice the power density) and octuple the peak torque at half the cost and loss per unit of power rating of the original A-EMS package.

Compared to any A-EMS, only SYNCHRO-SYM provides other significant advantages with extenuating benefits besides twice the MLS for a given torque, voltage, and excitation frequency:

1. Of course, no RE-PMs, which are monopolized by a global adversary seeking world dominance with grave environmental and geopolitical consequences
2. Only half of the total current (MMF) bi-directionally passes thru the rotor and stator ports (active winding sets) for twice the power but half the electrical loss per unit of power rating
3. Without rare earth permanent magnets (RE-PM), only SYNCHRO-SYM inherently provides field weakening with ½ the magnetizing MMF and ½ the loss
4. Only SYNCHRO-SYM with the patented built-in symmetrical dual-ported BRTEC with an inherent voltage leveling electromagnetic computer, gyrator, phase converter, and frequency converter provides more degrees of design freedom over the single ported A-EMS with FOC:
    a. Half of the total Torque MMF is applied at the rotor and stator multiphase winding sets for half the loss.
    b. In accordance with the conservation of energy laws of physics of a dual ported transformer, Torque MMF flux production on each side of air-gap is neutralized by the electromagnetic symmetry of directly excited multiphase winding sets (or active winding sets) on the rotor and stator, respectively, and as a result, Torque MMF (flux) can significantly increase without leading to core saturation for ultrahigh peak torque (without considering thermal management)
    c. Unlike the A-EMS with design limitations for achieving specific power and power density, SYNCHRO-SYM has another parameter, Torque Current, that can be applied at either runtime or design time for ultrahigh power density or specific power, which is essential for gearless high torque
5. Only SYNCHRO-SYM with the electromagnetically symmetric synchronous circuit and control technology under the BEM-CAD controlled additive manufacture of MOTORPRINTER allows:
    a. The BRTEC to be designed and 3D Printed within the otherwise empty rotor and stator annulus space of an axial-flux footprint for another level of power density
    b. The same SYNCHRO-SYM rotor and stator assembly for reduced component inventory and design cycle
    c. The size, loss, and cost of BRTEC is always extraordinarily included in the size, cost, loss calculations of SYNCHRO-SYM.

** All electric machine system (**EMS**) design must obey the following electromagnetic physics relations (presented in scalable form):

1. **Magneto-Motive-Force**: MMF = N x I; where N is number of winding-turns and I is the winding current; Torque MMF (**MMF_T**) = N x I_T, where I_T is torque current; Magnetizing MMF **(MMF_M)** = N x I_M, where I_M is magnetizing current; the I_M vector is orthogonal to I_T vector.

2. **Ampere Circuital Law**: H * dl = MMF_M, which is proportional to H = N x I_M/L, where H is the magnetic field (intensity) and L is the length of the magnetic path enclosing or cutting the MMF. Magnetic flux is directly proportional to MMF.
3. **B (flux density)**: H/u; where u is permeability of the magnetic path (*e.g., effectively the air-gap depth (**Lairgap**) with high permeability core path*) and as a result, B = N x I_M/(Lairgap * u_{airgap}).
4. **Synchronous Speed (RPM)** = 60 * excitation frequency/P, where P is the pole-pair count and Synchronous Speed (or constant-torque speed or maximum load speed (**MLS**)) for the asymmetric EMS (**A-EMS**). Let **$MLS_{(rev/sec)}$** = Synchronous Speed ÷ 60. For the same torque, voltage, frequency of excitation, and P, SYNCHRO-SYM has double the MLS.
5. **Faraday Law**: Voltage = [(Effective Airgap Area/P) * P * B * N] * $Speed_{Pole}$, where **Effective Airgap Area** = $Circumference_{Axial\text{-}Flux}$ (or π * $Diameter_{Effective}$) * L, L is the width of the axial-flux ring or the length of winding-turns cutting flux, $Diameter_{Effective}$ is the average Effective Diameter of the axial-flux Effective Airgap Area, and $Speed_{Pole}$ (radians per sec per P) = $MLS_{(rev/sec)}$ ÷ 2π (radians per rev) ÷ P. Therefore, Voltage = [($Diameter_{Effective}$ /2) * L * P * B * N] * $MLS_{(rev/sec)}$ or Voltage = KA * $MLS_{(rev/sec)}$, where the EMS design constant, **K_A** = [($Diameter_{Effective}$/2) * L * P * B * N], based on fixed design constants, $Diameter_{Effective}$, L, P, B, N
6. **Lorentz Force Law**: **Torque** = ($Diameter_{Effective}$ /2) * (Lorentz Force Law), where Lorentz force Law = [L * P * B * N] * I_T, or **Torque** = **K_A** * I_T
7. **Voltage/Speed = Torque/I_T**
8. In summary, Torque is directly proportional to the product of Effective Airgap Area (or EMS size) and the Torque Current in accordance with Lorentz Law, where airgap flux density is similar in all optimally designed EMS, and Voltage is directly proportional to the product of Effective Airgap Area (or EMS size) and MLS in accordance to Faraday Law.

** Designing to the highest air-gap flux density possible is the optimized design criteria for any electric machine system (EMS) and as a result, all optimally designed EMS have similar air-gap flux density, which is determined by the flux saturation limit of the same available core material and structure and not by the limited coercivity of rare-earth permanent magnet (**RE-PM**) or the unlimited magneto-motive-force (**MMF**) of an electromagnet.

* The magnitude of the limited residual flux density of a RE-PM is *non-ideally*, inversely proportional to the magnitude of the product of the RE-PM coercivity and length, which requires prohibitively more expensive RE-PM material when approaching the flux saturation of the electric machine core, but in contrast, flux density of an electromagnet is *ideally*, directly proportional to the magnitude of the product of winding-turns and winding current (**MMF**), which is the why zero-resistance superconductor electromagnet produce ultrahigh air-gap flux densities with seemingly unlimited magnetizing MMF.

** For a given K_A design, such as air-gap flux density, continuous torque, pole-pair count, winding-turns, groups, voltage, frequency, and synchronous speed design, all electric machines have similar effective airgap area, similar resulting total airgap area (*e.g., slots area, etc.*), and similar electric machine volume, in accordance with electromagnetic physics (particularly in a single air-gap axial-flux format with similar adjacent rotor and stator disks).

* To avoid the cost, ethical, environmental, and geopolitical consequences of RE-PM, ferrite permanent magnet substitutes do not have sufficient BH product or durability to be competitive with RE-PMs or electromagnets. Most likely, any material science presented to improve permanent magnet BH product would also endlessly improve core material permeability and flux saturation properties.

** Magnetic permeability is how well the molecular structure of a material will align to an applied magnetic field. For instance, wood, air, plastic, etc., with zero permeability cannot support a magnetic field and as a result, cannot be magnetized; however, electrical steel supports a magnetic flux and can be magnetized as shown by magnetic hysteresis. In consideration, permanent magnet (PM) material has high permeability but when magnetized, a PM has high permeability in the direction of the persistent magnetic field and low permeability in the direction against the persistent magnet field. Because torque MMF must synchronously align orthogonally to the direction of the RE-PM persistent field dipoles for force production in accordance with Lorentz Law, the total MMF (flux) magnitude is the vector sum of Torque MMF (or flux) and PM flux specifically across the air-gap in accordance to Ampere Circuital law with the high permeability of the PM and the core; but once the electrical core saturates with increasing Torque MMF, the core saturates and the permeability of the core becomes the low permeability of the air-gap with any additional torque MMF dissipating in loss. Note: any applied Torque MMF slightly degrades the delicate RE-PMs persistent magnetism.

* RE-PM Halbach Arrays ideally focus the RE-PM flux to the airgap while effectively eliminating the flux in the back-iron and as a result, leaving back-iron as only structural support. Without considering the trade-space between optimal design or cost constraints of permanent magnet A-EMS, RE-PM Halbach Arrays seemingly utilize air-gap area inefficiently but increase air-gap flux by reducing inexpensive back-iron with more expensive RE-PM material. Without considering thermal management constraints, electromagnets can still achieve higher air-gap flux density.

* The total air-gap flux (and flux density) of any EMS is the vector sum of the air-gap flux vector, which is produced by a winding magnetizing MMF or the persistent magnetism of a permanent magnet, and the torque MMF (*i.e., flux*) vector as only provided by a directly excited multiphase winding set (*i.e., active winding set*) that uniquely produces a moving magnetic field relative to its frame. For optimal results at synchronous speed, the magnitude of the sum of orthogonal (i.e., 90^0 torque-angle)

Torque MMF vector and RE-PM MMF vector calculates to 1.4x the developed air-gap flux density magnitude of either the RE-PM or the torque MMF. Since the peak flux density of the air-gap of the A-EMS should be optimally designed within the electrical steel saturation limit, which is approximately 1.5T, when considering the core shape, particularly at the slots, divided by 1.4x magnitude of the RE-PM flux, the air-gap flux density of a RE-PM EMS is constrained to less than 1T with no room left for peak torque potential (e.g., peak torque is the same as the continuous torque). In contrast, the air-gap flux of SYNCHRO-SYM can be closely designed to the saturation limit of the core (*i.e., 1.5T*) because like a dual-ported transformer, the electromagnetic symmetry of two active winding sets on each side of the air-gap, respectively, neutralizes the flux production of Torque MMF and as a result, Torque MMF can increase significantly without saturating the core for ultrahigh peak torque (without considering thermal management).

* All EMS design additionally includes control, structural and mechanical design anomalies, such as physical slots along the air-gap for placing rare-earth permanent magnets (RE-PM) or windings, material properties, such as flux saturation properties that limit air-gap flux density, end-turns, frame, thermal management, bearing assembly, friction, such as windage and stray losses, electronic control, etc., which realistically compound the EMS size, loss, and cost beyond the expectations of the electromagnetic design physics. For instance, winding slots consume about the same area as the effective air-gap area (with an optimized slot width of two wire widths) and as a result, halving the constant torque speed range with the same power, voltage, and excitation frequency rating by doubling the number of pole-pairs with the same slot grouping and torque MMF will increase the total air-gap area of any EMS by approximately 33% (*e.g., the same effective air-gap area plus twice the slot area with double pole-pairs [Total Air-gap Area = Total Slot Area + Effective Airgap Area, where Total Slot Area = 2x Slot Area or Total Air-gap Area = 3 x Slot Area = 3 x Effective Airgap Area]*). Likewise, doubling the cross-sectional area of the winding wire to lower winding resistance or to double the torque current will increase slot width and depth by 1.41 (*e.g., (wire area)$^{1/2}$ by assuming a square wire form*). Instead of 2x power density and 0.5x cost and loss by the straight forward example of simply replacing the passive rotor disk example for double the MLS, the power density of SYNCHRO-SYM with double the pole-pairs as the A-EMS for the same speed range but twice the power will still be an impressive 1.5x the A-EMS (instead of 2x for the simple comparison) with the cost and loss reduced by 0.33x (instead of the 0.5x for the simple comparison) per unit of power rating.

** Continuous and peak EMS Power Density, which is the power rating per EMS volume (*e.g., KW/L*), and EMS Specific Power, which is the power rating per EMS weight (*e.g., KW/Kg*), are directly proportional to a) the MLS range, which is based on synchronous speed for a given voltage and frequency of excitation, the continuous Torque Current, and b) the *peak* Torque Current potential for an optimally designed EMS with the same K_A design constants, such as effective air-gap area, pole-pair count, airgap flux density, and winding turns product in accordance to Faraday Law and Lorentz Force Law, or better packaging, manufacturing, construction, and material instead of standard frame size. Similarly, the cost per EMS power rating (*e.g., $/KW*), which is coined as EMS Cost Density, is directly proportional to the EMS amount, weight, and usage of packaging material, the unusualness of the material (*e.g., exotic RE-PM material*), the complexity of manufacturing and construction of the package (*e.g., special handling and safety of RE-PM material*), the electronic component power rating, etc.

Accordingly, EMS size is inversely proportional to speed and directly proportional to continuous torque rating, in accordance with the terms of Faraday Law and Lorentz Force Law and as a result, the higher the speed of the EMS, the smaller size of the EMS and similarly, the higher the continuous torque rating of the EMS, the larger size of the EMS. For instance, a key reason to use a much smaller ultrahigh speed RE-PM EMS (without including the size, loss, can cost of the large speed reduction gearbox) in an electric propulsion application is to reduce the amount of expensive RE-PM material with ethical, environmental, and geopolitical consequences. Without a specific application requirement, a high-speed EMS may require a gearbox to match the high speed with the load speed and although rarely the case, the compounding size, loss, cost, complexity, reliability, and maintenance of the additional gearbox should be included in the cost density, power density and specific power for practical application. All considered:

- With twice the MLS range for a given frequency and voltage of excitation as an A-EMS with the same continuously rated design constants, K_A, and packaging, such as axial or radial flux, material, thermal management, and winding techniques, *only* SYNCHRO-SYM provides half the cost density, twice the specific power, and twice the power density
- Without the limitations of torque current leading to flux saturation of the core material, *only* SYNCHRO-SYM provides at least octuple the power density and octuple the specific power of any A-EMS with the same continuously rated packaging and design constants, K_A.

** Although there are many design variables in EMS design, SYNCHRO-SYM will always show at least 1.3x - 2x higher continuous Power Density, which is power rating per EMS volume, and at least 0.33x lower cost density and lower loss as any A-EMS, such as the RE-PM A-EMS, in accordance with the Axial-Flux Design Comparison Table. But with at least 8x the peak torque potential as the A-EMS, only SYNCHRO-SYM has another design freedom, which is peak Torque MMF, for significantly higher peak Power Density and Specific Power of the A-EMS with the same design constants, K_A. The following table, which is the computer aided design result of BEM-CAD, shows the extraordinary attributes of SYNCHRO-SYM:

Axial-Flux Design Comparison Between SYNCHRO-SYM and an Optimized RE-PM EMS Contestants

[Contestants use a first pass design iteration with BEM-CAD]

	[Apple to Apple Comparison] ***[K_A design constants and packaging are the same]***		***[Orange to Apple Comparison]*** ***[K_A design constants and packaging are different between contestants and favor the RE-PM EMS. Still, SYNCHRO-SYM prevails.]***					
	SYNCHRO-SYM versus RE-PM EMS		**70 KW/4000 RPM**		**70 KW/2000 RPM**		**35 KW/2000 RPM**	
	SYNCHRO-SYM	**RE-PM**	**SYNCHRO-SYM**	**RE-PM**	**SYNCHRO-SYM**	**RE-PM**	**SYNCHRO-SYM**	**RE-PM**
Power KW	70	35	70	70	70	70	35	35
Port Voltage volt	800	800	800	800	800	800	800	800
CT Speed RPM	4000	2000	4000	4000	2000	2000	2000	2000
Pole-Pairs	6	6	6	3	12	6	12	6
Effective Area mm² (in²)	13256 (69)	13256 (69)	13256 (69)	26133 (35)	13335 (137)	26133 (35)	11000 (165)	13256 (69)
OD in (mm)	10.8 (274)	10.8 (274)	10.8 (274)	12.0 (304)	12.9 (327)	15.0 (380)	10.0 (257)	10.8 (274)
Length in (mm)	5.3 (37.6)	4.6 (117)	5.3 (37.6)	6 (150)	5.8 (117)	4.9 (125)	4.9 (124)	4.6 (117)
Weight lb. (Kg)	83 (37.6)	60 (27)	83 (37.6)	121 (55)	103 (47)	115 (52)	58.6 (26.7)	60 (27)
Torque N-M (ft-lb)	167 (123)	167 (123)	167 (123)	167 (123)	334 (246)	334 (246)	167 (123)	167 (123)
Peak Torque N-M (ft-lb) @ Efficiency	1338 (987) @ 85%	N.A.	1338 (987) @ 85%	N.A.	2675 (1973) @ 79%	N.A.	1338 (987) @ 77%	N.A.
Peak Torque Multiplier	8x		8x		8x		8x	
Efficiency %	96.9	94.5	96.9	95.4	96.7	94.7	96.4	94.5
Efficiency Multiplier	1.78x		1.5x		1.6x		1.5x	
Power Density KW/L	8.79	3.88	8.79	4.65	5.7	3.8	5.4	3.88
Power Density Multiplier	2.3x		1.9x		1.5x		1.4x	
Peak Power Density KW/L	70.3	N.A.	70.3	N.A.	45	N.A.	43	N.A.
Peak Power Density Multiplier	18x		15x		12x		11.6x	
Specific Power KW/Kg	1.86	1.29	1.86	1.28	1.49	1.34	1.31	1.29

Specific Power Multiplier	1.5x		1.5x		1.1x		1x	
Peak Specific Power KW/Kg	15	N.A.	15	N.A.	12	N.A.	10.5	N.A.
Peak Specific Power Multiplier	11.7x		11.7x		9x		8.1x	
Cost $/KW	60	149	60	125	73	143	78	149
Cost Multiplier	0.5x		0.5x		0.5x		0.5x	

1. RE-PM EMS and SYNCHRO-SYM are designed to 1.25 air-gap flux density, which leaves little room for RE-PM EMS peak torque with a 1.4x torque MMF limit to saturation. In contrast, SYNCHRO-SYM can be designed to the saturation limit of the core material and structure because Torque MMF Flux is neutralized
2. The primary design consideration of SYNCHRO-SYM was to place the integral BRTEC within the otherwise wasted annulus space of the axial-flux core with an axle size capable of supporting at least 8x peak torque and unlike the A-EMS, SYNCHRO-SYM has the same rotor and stator disk assemblies for an efficient thermal management system and for a reduced inventory, field service, redundancy, and design effort as only possible with the symmetric synchronous circuit and control topology of SYNCHRO-SYM with the additive manufacture of MOTORPRINTER under BEM-CAD,
3. All calculations include the size, loss, and cost of SYNCHRO-SYM's BRTEC or the RE-PM EMS's externally mounted FOC, which are rated for continuous power.
4. Construction is very conservative, such as lamination packing at only 84%
5. Unique liquid cooling as only provided by the additive manufacture of MOTORPRINTER is 70 L/min at peak specific power of 15 KW/Kg

- SIMPLE TRUTH (PART 1) -
- SIMPLE TRUTH (PART 2) -