SYNCHRO-SYM™: Physics-Based Comparison Framework for EM Systems

Purpose

This handout explains how to compare electric motor-generator systems (EMS) on the basis of fundamental electromagnetic physics and why SYNCHRO-SYM™ innovation with "active-rotor symmetry" delivers twice the nominal performance of today's EMS with "passive-rotor asymmetry."

Contents

Glossary of Acronyms

AC	Alternating-Current
A-EMS	Asymmetric Electric Motor-Generator System
BEM	Best Electric Machine
BPC	Basic Physical Configuration
BRTEC	Brushless and Sensorless Real-Time Emulation Control
CAGR	Compounded Annual Growth Rate
CCP	Chinese Communist Party
CTSR	Constant-Torque Speed Range
DC	Direct-Current
DTC	Direct-Torque Control
EESM	Electrically Excited Synchronous Machine
EM	Electric Motor-Generator Component
EMF	Electromotive Force
EMS	Electric Motor-Generator System
EV	Electric Vehicle
FOC	Field-Oriented Control
MMF	Magneto-Motive-Force
PM	Permanent Magnet
PRC	Peoples Republic of China
RE-PM	Rare-Earth Permanent Magnet
S-EMS	Symmetric Electric Motor-Generator System
SoS	System of Systems
WRSM	Wound-Rotor Synchronous Machine

Comparison Baseline

1. The EMS as a System of Systems (SoS)

Key Points:

For practical or variable-speed applications—such as electric-vehicle propulsion—an **electric motor-generator system (EMS)** must be evaluated as a **system of systems (SoS)** as applied, comprising (a) an electric motor-generator (i.e., **electric machine or EM**), (b) a power-excitation controller, and, where required, (c) a gearbox to optimally meet load speed and torque. For example, a compact high-speed EMS is often substituted for a simple, efficient direct-drive EMS chiefly to reduce the quantity of precious rare-earth permanent magnets (RE-PMs); however, this approach shifts the penalty to the system level by introducing a gearbox whose losses, mechanical complexity, maintenance burden, wear mechanisms, and reliability risks compound across the SoS.

Each subsystem carries its own distinct mass, loss, cost, thermal burden, and service requirements—each governed by different operating, engineering, marketing, and manufacturing principles. Historically, this separation has typically led manufacturers to evaluate EMS subsystems in isolation, producing inaccurate SoS performance assessments by ignoring their compounded impact from the electrical source to the output shaft.

High-efficiency EMS subsystems deliver mediocre system-level efficiency and performance when placed in series for real application. Even if each subsystem achieves 95% efficiency, the overall system efficiency drops to ~85.7% (i.e., motor-generator 95% x controller 95% x gearbox 95%), because losses compound across the series of subsystems.

Takeaway:

Subsystem-level metrics—often singly flaunted in marketing to inspire product distinction—do not indicate real system-level metrics of the EMS as practically applied.

2. EMS Baseline of Understanding

Key Points:

The **basic physical configuration (BPC)** of an electric-machine (EM) subsystem consists of one stator assembly and one rotor assembly separated by a single air gap. Configurations employing multiple rotors, stators, or air gaps represent replicated instances of this BPC—that is, multiple motor-generator units enabled through more complex manufacturing and assembly processes but with back-iron consolidation.

Only a **directly-excited (or independently powered) multiphase alternating current (AC) winding set (i.e., active-winding set)** independently produces a moving magnetic field that actively delivers working power to the electromechanical energy conversion process. Unlike an active winding set, **Permanent magnets (PM), slip-induction multiphase windings, rotor saliencies, or direct-current (DC) field-windings are passive devices** that cannot actively deliver working power. Without duplicating the BPC, all EMs have at least one active-winding set (i.e., **singly-fed**)—typically on the stator for convenient multiphase electrical provisioning—and at most two active-winding sets on the rotor and stator, respectively (i.e., dual-action or **doubly-fed**).

Note: In strict electromagnetic active-power port terms, a wound passive-rotor EM should never be considered doubly-fed (i.e., dual-action). With no active-power electrical port to the rotor, a PM passive-rotor EM is not doubly-fed and by identical operation, a DC field-wound passive-rotor EM is not doubly-fed. The so-called brushless doubly-fed EM with directly-excited multiphase winding sets of unlike pole-pair strategically placed on the stator to guarantee passive-rotor slip-induction operation is not doubly-fed.

EMS performance metrics are quantified by ratios between system mass, volume, loss, and cost over the nominal power output. Equitable comparative metrics must be under similar torque, speed, voltage excitation frequency, packaging, and continuous thermal operating area—for a given power rating, liquid cooling increases power density over air cooling and standard frame sizes are heavier and larger than custom frames.

Takeaway:

For equitable comparison, the EMS must be reduced to its BPC to distinguish electromagnetic taxonomy from marketing terminology.

3. Electromagnetic Determinants of Torque, Speed, Size, and Power

Key Points:

EMS torque-density and performance is governed by how efficiently Torque-MMF and orthogonal air-gap flux-density can be packed into the air-gap area of the BPC packaging under a given voltage and excitation frequency design. Speed is governed by the port voltage and excitation frequency design.

According to electromagnetic physics governed by Faraday's law, Lorentz law, and Ampere Circuital law, under linear mathematics and unified by Maxwell relations, (1) flux is governed by the product of coercivity and thickness of a PM or the product of the current and winding-turns of an electromagnet **magneto-motive force** (**MMF**) in accordance with Ampere Circuital Law, (2) *rated torque* of the motor-generator subsystem is governed by the air-gap electromagnetic physics of (a) air-gap flux-density, (b) orthogonal torque-MMF density, (c) effective air-gap area, and (d) pole-pair count, (3) rated **constant-torque speed range (CTSR)** is governed by: (a) voltage, (b) stator and rotor winding excitation frequency, and (c) pole-pair count according to the synchronous speed relationship, (4) the **synchronous speed relationship** is governed by **($\pm W_R \pm W_S = p \cdot W_M$)** where ($W_R$) is the rotor winding electrical frequency, (W_S) is the stator winding electrical frequency, (W_M) is the relative speed of the rotor (i.e., CTSR), and (p) is the pole-pair count, and (5) *continuous output power* is governed by the product of rated torque and rated CTRS or rated torque-current and voltage.

The amount of EM subsystem core material—copper, electric steel, or PMs—for a given power rating is further reduced by optimally redesigning to the highest operating speed (but with the addition of an extraneous, performance-absorbing speed-reduction gearbox) or shallowest air-gap depth.

Until ultimately limited by flux saturation of available electrical steel core material-structure (*excluding the ultra-high flux-density potential of lossless superconductors*), rated air-gap flux-density is governed by the vector sum of all flux producing electromagnets and PMs on the rotor and stator. **Note**: Superconductor electromagnetics—sometimes called super permanent magnet—are effectively loss-less and as a result, capable of ultra-high MMF produced air-gap flux density.

It follows that the resulting effective air-gap area and depth of the power-rated active-winding-set of the universally essential active stator is determined by the similarly optimized air-gap flux density design, where power-rating is product of torque and speed, not by the high B_rH_c energy product of RE-PMs or the higher air-gap flux density potential of electromagnets with thermal constraints, as commonly assumed. Likewise, the resulting physical volume of the motor-generator subsystem core (less chassis) is also fundamentally constrained by the air-gap flux-density and area design.

Takeaway:

Optimized EM Design Criteria:

1. Air-gap Flux Density is optimally designed close to the flux-density saturation limit of the core material and slot structure**—equally optimized EMs have similar air-gap flux density**. The EM air-gap flux-density design must compensate for the vector sum effects of increasing torque-current on the core saturation—excluding superconductors.
2. (1.) implies EMs have similar "air-gap area" for a given torque under a given excitation frequency/synchronous speed, and voltage design of the active-winding set design.
3. (2.) implies the air-gap area and chassis structure of an optimized EM predominantly determines its mass and volume. The high B_RH_C energy product of rare-earth permanent magnets has a minor effect without considering the extra amount of RE-PM depth and material to achieve air-gap flux density close to the saturation limit of the core or to compensate for temperature resiliency (see Appendix B: Permanent-Magnet Motor Saturation Behavior).
4. (3.) implies **all *optimally designed* EMs have similar mass and volume for similar design torque**, as demonstrated by BMW and Mahle advanced RE-free wound-rotor synchronous EMS (**WRSM**), a.k.a electrically excited synchronous machine (**EESM**).

All *optimally* designed motor-generators have similar effective air-gap area and resulting mass and volume for a given nominal *torque* under similar air-gap flux-density, pole-pair count, excitation voltage/frequency, synchronous speed (CTSR), and package structure—regardless of marketing terminology.

4. Symmetric And Asymmetric Circuit and Control Categories of the EMS

Key Points:

The applied EMS of today is limited to an EM subsystem with the asymmetry of an active stator with an active-winding set and a passive-rotor using permanent magnets, slip-induction windings, DC field windings, or reluctance saliencies.

The foundational EMS theoretical study begins with the optimal symmetric circuit and control architecture comprising an active-winding set on both the rotor and stator, respectively, and an enabling control means that brushlessly, directly, and automatically provides continuously speed-synchronized, multiphase power to the rotor active-winding set from sub-synchronous to super-synchronous speeds, including synchronous speed, for stable operation without regard to random axle or line perturbations. Because of the formidable control challenges at the time, the study deoptimized the dual-active symmetry with a practical asymmetric circuit and control architecture comprising an active stator, a passive-rotor using permanent magnets, slip-induction windings, DC field windings, or reluctance saliencies, and a less stringent signal measurement and synthesis, field-oriented control (**FOC**) method or derivatives, such as direct-torque control (**DTC**).

By simulating the enabling brushless and sensorless real-time emulation control means, the foundational study, **backed by controlled laboratory studies**, validated **the symmetric EMS (S-EMS)** with an active-rotor and active-stator (double active winding sets) stably operates from sub-synchronous, such as zero speed, to super-synchronous, including synchronous speed. In contrast, **the asymmetric EMS (A-EMS)** with a passive-rotor and an active-stator (single active winding set) provides practical operation from zero to synchronous speed with the same torque, voltage, and excitation frequency.

According to the synchronous speed relationship ($\pm W_R \pm W_S = p \cdot W_M$) for any EM, the rotor revolution-per-minute CTSR design is (60 x Excitation Frequency ÷ Pole-Pair-Count) for an A-EMS ($W_R = 0$ or $W_M = W_S$) and (120 x Excitation Frequency ÷ Pole-Pair-Count) for an S-EMS ($W_R = W_S$ or $W_M = 2 \cdot W_{R,S}$)—an S-EMS provides twice the CTSR as the A-EMS for a given torque, voltage, and excitation frequency design, which is tantamount to delivering twice the nominal power with similar torque and power-rated active-rotor and active-stator as the A-EMS active stator.

Only a small subset of electric-machine specialists recognizes the performance potential of the S-EMS found in controlled laboratory studies. The S-EMS is **not** a control enhancement of the A-EMS but a **distinct electromagnetic circuit class**, leaving market comparisons between passive-rotor A-EMS architectures (permanent-magnet, slip-induction, DC-field, or reluctance-salient machines).

Note: The S-EMS is often confused with the wound-rotor doubly-fed induction EMS; however, DFIG is fundamentally a **slip-induction A-EMS**. The single-phase AC Universal EMS—with electromechanically commutated symmetric excitation—exhibits unusually high torque-density, lightweight, and high-speed, making it a **partial analog** of S-EMS behavior.

Takeaway:

EMS architectures can be fundamentally classified into only two categories: Asymmetric EMS (A-EMS) and Symmetric EMS (S-EMS). This classification follows directly from electro-magnetic circuit and control theory, even though it is not recognized in contemporary motor taxonomies. In an S-EMS, both stator and rotor have independent multiphase electrical ports for electric-to-mechanical energy conversion, whereas in an A-EMS, the passive rotor lacks a multiphase electrical power port.

For identical voltage, excitation frequency (and thus synchronous speed), air-gap flux density, effective air-gap area, electromagnetic torque, and package geometry, an S-EMS delivers approximately twice the nominal power as an A-EMS. This arises because electromagnetic power is processed symmetrically by two active circuits on the rotor and stator rather than being constrained by a single active stator circuit driving a passive rotor.

Importantly, this performance difference is not due to materials, packaging, or manufacturing methods. Both A-EMS and S-EMS are constructed using the same legacy laminations, windings, conductors, and mechanical structures. The advantage of S-EMS is purely electromagnetic and architectural, not a consequence of fabrication technology.

5. The Foundational Symmetric Motor-Generator Model

Key Points:

The [foundational theoretical model for EMS study] assumes the optimal electromagnetic symmetry: an active-stator + active-rotor, each independently contributing MMF and working power to the electromechanical energy conversion, and a precisely speed-synchronized, bidirectional, multiphase power flow control means for instantly stabilizing stochastic rotor or line perturbations (without the destabilizing delays of signal measurement and synthesis, particularly shallow slope signals, of today's control methods).

Historically, implementation of electromagnetic symmetry was never realized due to control limitation—not by physics. As a result, industry adopted the non-optimal asymmetric electromagnetic architecture: active stator + passive-rotor (PMs, induction cages, reluctance saliencies, or DC field windings) and sufficient control with imprecise FOC and direct-torque control derivatives.

Unlike an "active-rotor" contributing an additional 50% of "working power" (along with the active-stator), a "passive-rotor" contributes 0% but on the order of ~50% of motor-generator mass, loss, and cost.

Takeaway:

[Proven by controlled laboratory studies] and over fifty man-years of BEM R+D and prototyping, only the symmetric active-rotor architecture doubles the CTSR and nominal power of an asymmetric EMS package footprint under identical voltage, excitation frequency, pole-pair count, and torque design.

6. Asynchronous versus Synchronous EMS

Key Points:

Today, the asynchronous or synchronous EMS is actually categorized by rotor electrical provisioning, rotor physical movement, and control constraints for average torque production, not by the electromagnetic fluidity of the synchronous speed relationship ($\pm W_R \pm W_S = p \cdot W_M$).

Enabled by rotor provisioning (e.g., terminal port for multiphase winding access) and control, **the asynchronous (or slip-induction) EMS relies on the physical slip (asynchronism) between the rotor body and the moving air-gap flux** to *indirectly* induce *operational* torque current onto the rotor multiphase winding set (i.e., passive-rotor) via indirect mutual coupling capacity with the stator active-winding set. With W_R never equal to zero, the passive-rotor only operates below synchronous speed (or above with an extraneous prime mover means to get there) but never at (or even closely about) synchronous speed, where slip-induction ceases to exist. In contrast, not to functionally operate but to avoid packaging, rotor provisioning (e.g., PM or DC field windings), and control damage due to slip-induced electro-motive-force (**EMF**), today's **synchronous EMS must not allow mechanical slip between the physical rotor and the moving air-gap flux** and as a result, the passive-rotor only operates at synchronous speed ($W_R = 0$).

Both traditional asynchronous and synchronous definitions do not fit the operation of the S-EMS with independently excited active-winding sets on the rotor and stator, respectively, which do not rely on slip-induction for torque production when operating from sub-synchronous to super-synchronous speeds. To fit S-EMS operation, BEM defines **the asynchronous EMS as *relying* on slip-induction for practical operation and the synchronous EMS as *not relying* on slip-induction** to follow S-EMS electromagnetic physics and control, which is unconstrained by packaging, electrical provisioning, and control—**the S-EMS is a synchronous EMS**.

Note: Typically, categorizing the S-EMS as an asynchronous-synchronous hybrid contradicts the definition of the rotor active-winding set (that independently contributes active power) as simultaneously being a passive-winding set (that *cannot* independently contribute active power).

Takeaway:

Accurately redefined, an asynchronous EMS *relies* on slip-induction and a synchronous EMS *does not rely* on slip-induction. Accordingly, BEM accurately categorizes the S-EMS as a synchronous EMS.

7. The Real RE-PM vs Electromagnet Trade-Space

Key Points:

Today's extraordinary marketed differences in performance metrics are often derived by comparing highly-optimized, high-speed RE-PM motor-generator packaging to low-speed, readily-available, sub-optimized, frame-standardized induction motor-generator packaging, not by the high energy product of RE-PMs as typically assumed.

Fundamentally-bounded by material science, permanent magnet (PM) residual flux-density potential decreases as coercivity requirements increase, necessitating substantial magnet thickness (and associated volume and cost) to ideally sustain an air-gap flux density close to the saturation limit of the core. Since their invention (circa 1980), RE-PMs have been the only practical passive-rotor PM material capable of competing against magnetizing-MMF in many high-performance applications; however, they introduce cogging losses, safety concerns, finite life expectancy, and vulnerability to thermal stress and saturation margins—together with high cost, environmental burden, supply-chain fragility, and geopolitical risk due to concentrated production

Unlike RE-PMs, the thermally resilient electromagnet is capable of providing continuously variable, theoretically unlimited air-gap flux-density potential by controlling the flow of current (i.e., coveted field-weakening trade-space between torque, power density, and speed) but dissipates electrical loss with cooling constraints. Providing maximum sustainable air-gap flux-density *optimally designed* close to the saturation limit of the electrical steel core (i.e., >1T), an electromagnet is likely to exhibit similar if not shallower footprint than a RE-PM array under the same thermal considerations.

A-EMS manufacturers are diversifying A-EMS design to reduce or eliminate RE-PMs and associated consequences. Magnetizing-MMF is counterintuitively being re-introduced into RE-PM motors to provide coveted field-weakening (a.k.a., variable flux by BYD) for additional performance gain from extended speed range, instead of simply optimizing RE-PM-free slip-induction and DC field-wound A-EMSs with inherently more efficient field weakening capability. Some motor manufacturers are returning to iron-based PM alternatives that always exhibit performance below slip-induction, reluctance, or DC field passive-rotor A-EMSs. These developments illustrate how supply-chain concentration can shape technology adoption pathways—often favoring RE-PM-dependent designs even when credible technical alternatives exist.

Without the practical realization of a S-EMS (until SYNCHRO-SYM), the EMS of today is limited to an A-EMS with a passive-rotor of PMs, slip-induction windings, reluctance saliencies, or DC field windings, of which the RE-PM A-EMS is considered to be today's highest performing. The Slip-induction and DC field-wound (WRSM) A-EMS have controllable air-gap flux-density (i.e., field weakening by magnetizing-MMF). In contrast, the RE-free PM A-EMS has low flux-density potential and durability but are without the provisioning or electrical loss of magnetizing-MMF and the Reluctance A-EMS are difficult to control.

Takeaway:

Delicate RE-PMs do not determine the high limit of air-gap flux-density but the electrical-steel core does—higher flux density equates to higher performance. RE-PMs provide convenience—not fundamental performance advantage. In contrast, resilient electromagnets scale with MMF, not material limits. Depending on the level of air-gap flux density, the RE-PM A-EMS may have today's edge in package density and efficiency but never in cost, sustainment, or thermal resiliency.

8. Limits of Packaging-Centric Motor-Generator System Innovations

Key Points:

Universally applied, EMS Packaging, which includes (a) copper or aluminum windings, electrical steel laminations electromagnetic materials, (b) axial, radial, or transverse flux form-factors, (c) chassis structure and bearings, and (d) electronic control, plays a similar significant factor in A-EMS or S-EMS (less RE-PMs) performance, complexity of manufacturing, and overall costs but with the S-EMS effectively doubling the performance results. For example, the axial-flux EMS has not been popularly applied because of lamination manufacturing complexities compared to the radial-flux EMS, although the axial-flux EMS was the original prototype form of Faraday with proven performance advantage over the radial-flux EMS.

High-speed RE-PM, yokeless axial-flux, segmented stators, hairpin windings, and multiple-air-gap A-EMS do not change electromagnetic physics but are examples of legacy electromechanical packaging geometries and techniques that would provide similar performance results if equally applied. A dual rotor (e.g., from DeepDrive) or dual stator is a dual-air-gap A-EMS with double the effective air-gap area or simply two A-EMSs conveniently packaged together, not a A-EMS that doubles torque without a corresponding increase in effective air-gap area under the same voltage/frequency constraints.

Takeaway:

Packaging innovations may similarly reduce EMS mass, loss, and cost but never change the governing fundamentals of electromagnetic physics. With a process evolution in manufacturing, the axial-flux form would be the EMS of choice.

EMS Market Impact

1. The EMS Market

Key Points:

The EMS is the backbone of the global electricity infrastructure, consuming the majority of all electricity generated and generating nearly all electricity consumed (30,000 Terawatt-hours 2024).

Takeaway

Performance-centric, the United States EMS market for electric vehicle propulsion, alone, is expected to reach US$42.83B by 2028, with a CAGR of 14%. Note: Published EV motor and inverter market sizes should be treated as lower bounds, not as economic reality, because vertically integrated OEM production is largely invisible to market-revenue reporting despite representing a major fraction of actual propulsion hardware cost.

2. Market and Geopolitical Implications

Key Points:

Global concentration of RE-PM production creates systemic vulnerabilities in cost, supply stability, and innovation. As the largest consumer of RE-PMs, the EMS exerts the highest impact by diverting large portions of these critical materials away from other strategic applications. With the USA rapidly falling behind, billions of dollars are being globally invested to reduce reliance on RE-PMs by turning to the long-established, asymmetric, passive-rotor EMS architecture that would:

- eliminate RE-PMs by replacing them with slip-induction windings, reluctance saliencies, DC field windings, or low energy product PMs that degrade A-EMS performance,
- reduce RE-PM mass by decreasing the air-gap depth with similar air-gap flux-density, or
- reduce RE-PM mass by replacing a low-speed, direct-drive A-EMS with a compact, high-speed A-EMS mated to an extraneous speed-reduction gearbox.

Still, the accelerating shift to offshore manufacturing and associated erosion of domestic intellectual property continue unabated.

Takeaway

Despite billions of dollars in investment and years of research, no fundamentally new electromagnetic circuit and control architecture has emerged—only incremental repackaging of the passive-rotor A-EMS with the WRSM A-EMS as the best possible RE-PM-Free alternative. With the absence of a redefining manufacturing method, reliance on offshore production continues to accelerate for low-cost labor or favored RE-PM access. Neither trend reduces geopolitical vulnerability.

3. Physics, Materials Dependence, and Geopolitical Consequences

Key Points:

The dominance of RE-PM A-EMS in EVs and wind turbines is not a consequence of superior electromagnetic physics, but of material availability and supply-chain control. Because EMS architectures remain constrained to passive-rotor asymmetry, markets that demand high performance becomes structurally dependent on rare-earth permanent magnets. Where control of those materials is monopolized, market dominance follows.

Considered the highest performing **electric motor-generator system (EMS)**, the **rare-earth permanent magnet (RE-PM)** EMS still rules, particularly for **electric vehicles (EV)** and wind-turbines. According to Permanent Magnet Market Forecast 2025-2033, the EV EMS consumes approximately 2Kg of RE-PM per 100KW (≈0.02 Kg/kW), which is roughly one-tenth the RE-PM material consumed by the wind-turbine EMS (≈2000Kg per 10 Megawatts, or 0.2 Kg/kW). This disparity reflects fundamental system-level physics: the high-speed EV EMS is more compact and material-efficient per kW of power rating than the low-speed, direct-drive wind-turbine EMS, without including the additional size, cost, maintenance, and efficiency penalties imposed when direct drive is abandoned in favor of inline speed-reduction gearboxes.

Because the **People's Republic of China / Chinese Communist Party** (**PRC/CCP**) maintains a globally dominant monopoly over rare-earth mining, processing, supply chain, and permanent-magnet manufacturing—while granting favored access to domestic firms—this material monopoly has effectively propagated to the EV and direct-drive wind-turbine EMS markets that remain dependent on the performance of RE-PM EMS. EMS companies whose performance and cost structure depend on RE-PMs face growing existential risk unless they secure priority access to the PRC-dominant magnet supply chain—often via offshore manufacturing alignment—resulting in financial distress in multiple cases (e.g., Exro).

Constrained to **asymmetric EMS (A-EMS)** circuit and control architectures with passive rotors—whether based on slip-induction windings, permanent magnets, reluctance saliency, or DC field windings—the EV and wind-turbine markets are now strategically reconsidering continued reliance on the RE-PM A-EMS through a limited set of trade-offs:

- pushing to even higher operating speeds to reduce RE-PM mass per kilowatt, while accepting the compounding size, cost, maintenance, and efficiency penalties imposed by enabling speed-reduction gearboxes;
- navigating the rare-earth magnet conundrum by accepting reduced performance from RE-PM-free A-EMS alternatives, such as the wound-rotor synchronous A-EMS (WRMS), the iron-based PM A-EMS, and the reluctance A-EMS;
- offsetting the continually rising cost of RE-PMs through incremental elimination or consolidation of other EV assembly steps and components.

Long held in the realm of theory rather than practice, few EMS practitioners are familiar with the **symmetric EMS (S-EMS)** employing an active-rotor. Yet this architecture has been verified by more than a century of controlled laboratory studies to deliver 2× nominal power and substantially higher peak torque potential in packaging similar to the passive-rotor A-EMS but only by simulating an enabling **brushless, sensorless, multiphase, real-time emulation control** (**BRTEC**) means. Therefore, the S-EMS is among the only known RE-PM-free EMS alternative that exceeds the performance of the RE-PM A-EMS. As such, it provides the first credible, performance-positive path for reversing the PRC/CCP effective monopoly over EV and wind-turbine systems.

Reliable, low-speed, direct-drive naval electric propulsion represents another demanding application in which the RE-PM A-EMS is increasingly treated as the preferred solution—often without fully accounting for the resulting national-security implications for the U.S. Navy or the long-term competitive pricing consequences for the broader naval market. In the absence of a performance-positive, RE-PM-free alternative, continued reliance on RE-PM propulsion architectures risks enabling the same outcome already observed in EVs and wind turbines. As the only known RE-PM-free EMS that delivers superior performance, the S-EMS provides a credible path to preventing the PRC/CCP from extending its existing material-driven dominance into global naval electric-propulsion systems.

With uncompromising requirements for power density (kW/L), specific power (kW/kg), and operational resiliency, electric aircraft propulsion is currently treated as an application effectively locked into the RE-PM A-EMS. In the absence of a performance-positive, RE-PM-free alternative, this dependence risks repeating the same material-driven market capture already observed in EVs and wind turbines. As the only known RE-PM-free EMS that exceeds the performance of RE-PM-based machines, the S-EMS provides a credible path to preventing the PRC/CCP from extending its existing dominance into global electric-aircraft propulsion systems.

Takeaway

Absent a viable, performance-positive EMS alternative to the RE-PM asymmetric EMS (A-EMS), the same material-driven market capture already observed in electric vehicles and wind turbines should be expected to extend into electric aircraft and naval electric-propulsion markets, enabling the PRC/CCP to establish comparable dominance. An S-EMS invention would reverse this trend.

The SYNCHRO-SYM™ Solution

1. SYNCHRO-SYM™: Implementing the Original Symmetric EMS

Key Points:

SYNCHRO-SYM™ is the first practical realization of the optimal S-EMS model: an active stator + active-rotor circuit and an integrally unified BRTEC™ invention (Brushless & Sensorless Real-Time Emulation Control), which is a compact, solid-state, high-resolution, direct multiphase AC-to-AC control architecture that regulates only half the required controlled current of today's asymmetric control architectures, while avoiding the intrinsic response delays associated with offline measurement and synthesized excitation.

As a conceptual retrofit visualization, remove the passive-rotor disk and FOC in the same axial-flux A-EMS package footprint and replace with the active-rotor disk (i.e., SW reconfigured stator disk with the bearing assembly) and BRTEC of SYNCHRO-SYM, the resulting S-EMS eliminates RE-PMs but immediately delivers:

- 2× constant-torque speed range with coveted field-weakening,
- 2× nominal power,
- >8× peak torque,
- ~50% reduction in cost/loss per kW of nominal power rating by controlling half the current, eliminating the DC-link, and eliminating passive-rotor materials and electromagnetic losses.

Takeaway

SYNCHRO-SYM™ improves performance through physics, not just packaging.

2. Historical Context of SYNCHRO-SYM and Independent Validation

Key Points:

The symmetric circuit and control architecture of SYNCHRO-SYM™ has been examined and discussed across academic and industrial settings for several decades, often preceding the institutional frameworks, funding mechanisms, and control technologies required to practically realize symmetric, active-rotor electric-machine systems. Early evaluations occurred during a period when electric-machine development was dominated by asymmetric, passive-rotor architectures, and therefore attempted to interpret SYNCHRO-SYM within legacy machine classifications rather than as a distinct electromagnetic circuit and control class.

Subsequent academic interest acknowledged the architectural significance of symmetric excitation and active rotor participation, but advancement was constrained by misalignment with prevailing funding priorities and by industry emphasis on incremental optimization of established passive-rotor systems through materials, packaging, cooling, and control refinements.

More recently, multiple well-funded public and private research programs—including megawatt-class electric-aircraft motor initiatives—have independently undertaken extensive efforts to determine the ultimate performance limits of passive-rotor electric-machine architectures. These programs have demonstrated that, even with advanced materials and aggressive thermal management, passive-rotor systems remain fundamentally constrained by electromagnetic asymmetry and system-level complexity.

Takeaway:

These independent outcomes validate the foundational premise of SYNCHRO-SYM™: that further step-change improvements in electric-machine performance require an architectural transition to symmetric electromagnetic circuits in which both stator and rotor actively contribute working power. SYNCHRO-SYM™ represents the practical realization of this symmetric model, enabled by modern control, power-electronics integration, and manufacturing methods.

3. SYNCHRO-SYM Commercialization Path

Key Points:

BEM requires ~$10M to finalize scalable commercialization, focused on manufacturing scale-up, not technology risk—recoverable within the first lot of units sold, especially with its patented MOTORPRINTER™ additive-manufacturing platform (with BEM-CAD™ interface) that cost-effectively (a) simplifies axial-flux EM manufacture with integral frame over conventional laminated radial-flux manufacture, (b) enables reprogrammable manufacturing, (c) enables high power, high frequency amorphous metal transformer cores, (d) tightly unifies the BRTEC into the axial-flux annulus, (e) manufactures the same rotor and stator cores that are reconfigured by SW, (f) provides a proprietary high performance cooling system, and (g) easily scales with additional compact MOTORPRINTER footprints.

Takeaway

Providing the only EMS architecture that is RE-PM-free, simpler than the WRSM but delivers better performance than the RE-PM A-EMS, and the convenience of a scalable, domestic additive-manufacturing method of MOTORPRINTER™, programmed by BEM-CAD™, only BEM's SYNCHRO-SYM™ fundamentally shifts the strategic landscape for EVs, aerospace, and energy systems.

Summary

Where others claim extraordinary performance improvements by benchmarking optimized legacy packaging against raw, standardized-off-the-shelf AC motors, SYNCHRO-SYM benchmarks truly unmatched performance against those same optimized systems—validated by the fundamental physics of electromagnetic symmetry, in which both rotor and stator actively contribute working power.

Electric motor-generator systems are widely assumed to be mature technologies, with improvement limited primarily to materials, packaging, cooling, and manufacturing refinement. This perception persists precisely because electric motors are ubiquitous and familiar.

However, contemporary EMS or asymmetric EMS (A-EMS) practice is constrained to a single asymmetric electromagnetic architecture: an active stator driving a passive rotor. The original, physically optimal symmetric architecture—employing active winding sets on both rotor and stator—has long been known to deliver fundamentally higher electromagnetic utilization, but remained impractical until the recent invention of brushless, sensorless, real-time emulation control.

SYNCHRO-SYM™ represents the first practical realization of the symmetric EMS (S-EMS) model. Appendix A: Executive Technical Summary provides a framework that establishes why this architectural distinction—not just packaging—defines the next step change in electric-machine performance.

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Appendix A: Executive Technical Summary (BOTTOM LINE UPFRONT)

Electric motor-generator system (EMS) foundation:

(1) The symmetric electric motor-generator system (**S-EMS**) with the optimal electromagnet symmetry of an active rotor and active stator, each comprising an active-winding set for combined working power production, and an enabling brushless, sensorless, real-time emulation control (**BRTEC**) means for automatic, speed-contiguous (continuous-across-speed) stabilization against random external axle or line perturbations, is the fundamental electromagnetic study for any electric motor-generator system (**EMS**).

(2) By deoptimizing the electromagnetic symmetry, (1) becomes the study for today's asymmetric EMS (**A-EMS**) with the non-optimal electromagnetic asymmetry of a passive rotor comprising slip-induction windings, reluctance saliencies, DC field windings or permanent magnets (**PM**), an active stator, and an extrapolating field-oriented control (**FOC**) means.

(3) Based on (1) and (2), the S-EMS is also the foundational study for all EMS packaging styles and techniques, including today's A-EMS packaging.

(4) Based on (3), the S-EMS is mature straightforward technology just as today's rare-earth permanent magnet (**RE-PM**) A-EMS is mature straightforward technology.

Why isn't there a practical S-EMS?

At least a century of controlled laboratory studies have shown the S-EMS (with an active rotor) delivers 2x nominal performance and significantly higher torque than the A-EMS (with a passive rotor) but concluded the essential enabling brushless, stabilizing real-time control means was beyond technology of the time. With the practical invention of high energy-product RE-PMs (circa 1980), S-EMS research (circa 1960) was largely abandoned and forgotten.

What absolute defining attribute of the S-EMS has been validated by BEM?

BEM has more than 50 years of S-EMS R&D and prototyping, including a contract to convert a major electric-motor manufacturer's product line. This body of work successfully demonstrated the defining S-EMS attribute: **stable and continuous motoring and generating operation across the full speed domain—from sub-synchronous through synchronous to super-synchronous speeds**, including at and near synchronous speed.

By validating this defining attribute, BEM is the only known S-EMS developer to have experimentally demonstrated that:

1. **Active rotor excitation can be sustained brushlessly;**
2. **The system can be controlled sensorlessly and automatically in real time**, via BEM's Brushless Real-Time Emulation Control (BRTEC);
3. **The rotor's active power contribution produces a true net performance increase**, confirmed by repeatable measurements (not benchmarking artifacts).

Where is the performance data?

BEM's $10M Statement of Work (SOW) executes the re-engineering of the validated radial-flux prototypes—the first practical realizations of the S-EMS—into a validated, modular axial-flux SYNCHRO-SYM platform with upgraded hardware and software. Upon completion, this SOW delivers certified performance data and establishes an in-house, 2,000-unit production line that is readily scalable and re-programmable without retooling inventory. In contrast, comparable industry efforts to re-engineer asymmetric EMS packaging and control—predominantly RE-PM A-EMS examples—typically require $10M to $30M for validation, followed by an additional ~$300M to establish conventional overseas production lines and favored access to constrained RE-PM supply chains.

The RE-PM EMS geopolitical consequences are now critical

Today, the RE-PM supply chain is monopolized by a geopolitical competitor asserting harmful geopolitical consequences. Widely regarded as the best performing, the RE-PM EMS is the EMS of choice for electric vehicles (EV) and direct-drive wind-turbines and as a result, the geopolitical competitor has also monopolized EV and wind-turbine production. Belatedly concerned, EMS development efforts are directed to reducing (if not eliminating) RE-PMs with A-EMS alternatives.

SYNCHRO-SYM differentiating risks

Low Technical Risk — Active Rotor Electronics: Active electronics on the rotor represent a low technical risk. Passive rotor-mounted electronics in the A-EMS—such as diodes and thyristors—have been used for decades, particularly in brushless turbo-alternators to improve reliability and eliminate mechanical brushes. While less common, active rotor electronics incorporating control functionality have also been successfully demonstrated, disproving the common assumption that rotor-mounted electronics are inherently vulnerable to rotational stresses or reduced reliability. Unlike FOC, BRTEC is a compact, solid-state, high-resolution, direct multiphase AC-to-AC control architecture without the DC-link stage using bulky, structurally vulnerable reactive components.

Highest Program Risk—Intellectual Property Protection: the greatest risk is protecting BEM's intellectual property from state-level adversaries. The PRC/CCP has a well-documented history of large-scale intellectual property theft from U.S. companies, particularly in strategically critical technologies. Transformational EMS architectures that threaten the PRC/CCP's rare-earth permanent-magnet (RE-PM) supply-chain dominance—such as SYNCHRO-SYM™—represent high-value targets for misappropriation or sabotage.

To mitigate this risk, BEM has deliberately adopted a controlled commercialization strategy that emphasizes tight internal governance, compartmentalization of trade secrets, and direct ownership of core IP by trusted family-member principals with proven integrity and extensive experience in engineering, marketing, commercialization, and classified-level security. This governance structure minimizes exposure during the most vulnerable phases of commercialization while preserving long-term control of SYNCHRO-SYM™ technology.

Appendix B: Permanent-Magnet Motor Saturation Behavior

Permanent-magnet (PM) motors must be designed well below the magnetic saturation limits of the core material because the total flux in the machine is the vector sum of the fixed PM excitation and the torque-producing current (Iq). This combined flux density must never approach the saturation knee of the stator or rotor steel.

In PM motors, the magnets provide a constant magnetizing MMF that is always present in the magnetic circuit. When torque is demanded, the q-axis current adds additional MMF to the existing PM flux. As Iq increases, the resulting flux can drive localized regions of the iron—especially stator teeth, back-iron, and rotor pathways—toward or into magnetic saturation.

Once saturation is approached:

• The iron's incremental permeability collapses, reducing effective inductance.
• Losses rise sharply due to hysteresis and eddy current effects.
• The nonlinear flux response destabilizes field-oriented control (FOC).
• Localized overheating may occur, which can weaken or irreversibly demagnetize the magnets.
• Torque per amp decreases, causing torque collapse and efficiency degradation.

Because the PM flux cannot be reduced (except by injecting negative d-axis current at the cost of increased losses), PM motors have inherently limited overload torque capability—typically no more than 2× to 3× their rated torque safely.

In contrast, systems such as SYNCHRO-SYM™ avoid this limitation because their flux is produced by controllable magnetizing MMF rather than fixed PM excitation. The symmetric active-rotor and active-stator MMF allow flux to remain balanced and within the linear range of the core material even during high torque events, enabling >8× peak torque without saturating the magnetic core.

This fundamental difference explains why PM motors must operate conservatively below core saturation, while symmetric electric machine systems do not suffer such inherent constraints.