Best Electric Machine
motoragent@bestelectricmachine.com

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 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! -

Axioms of the Electric Machine System Trade Space and Physics Design Baseline:

- *All magnetic electric machine circuit and control architectures (EM-CCA) must simultaneously obey the three empirically derived laws of physics without exception*, which are Ampere Circuital Law (e.g., for air-gap flux density design), Faraday's Law (e.g., for voltage and speed design), and Lorentz Law (e.g., for torque current, force, and torque design), that were generalized and integrated with time and space by Maxwell's equations.

  NOTE: Faraday's Law and Lorentz Law have two orthogonally synchronous magnetic flux vector terms, which are the *magnetizing airgap flux* vector and the *torque MMF flux* vector with the flux vector magnitude proportional to the product of a permanent magnet (**PM**) coercivity and physical depth or the product of an electromagnet winding current and winding-turns, called magneto-motive-force (**MMF**).

  NOTE: In accordance with Ampere Circuital Law, a reasonable air-gap depth, which is the boundary between rotor and stator, is an optimized design tradeoff between the cost, size, and loss of magnetizing airgap flux intensity or flux density with core permeability and saturation constraints. For instance, all electric machine design strives for shallowest possible air-gap depth to lower overall cost, size, and loss, regardless of electromagnetic or rare-earth permanent magnet (**RE-PM**) electric machine types.

- *All electric machines (i.e., electric motors, generators, and transformers) are "optimally" designed with similar magnetizing air-gap flux density* because air-gap flux density is determined by the saturation limit of the same available electrical steel core material and not by the *limited* residual flux density potential of RE-PM with flux density non-ideally *inversely proportional* to coercivity or the *boundless* flux density potential of an electromagnet with flux density ideally *directly proportiona*l with MMF.

NOTE: With ultrahigh magnetizing MMF generated flux enable by zero resistance windings and without considering the provisioning complexities of cryogenics, the superconductor synchronous electric machine system is an exception to this axiom.

NOTE: The “total magnet flux density” in the airgap is the vector sum of a) all torque MMF generated flux, b) all RE-PM generated flux, and c) all magnetizing MMF generated flux in accordance to Ampere Circuital Law with magnetic flux production beyond core saturation as electrically parasitical with wasteful heat dissipation.

NOTE: Because torque production is the cross-product of magnetizing air-gap flux density and torque MMF vectors in accordance to *Lorentz Law*, the *first* steady-state design criteria for any *highly optimized* electric machine system is establishing the highest possible magnetizing airgap flux density, which is designed within the electrical steel core saturation limit and permeability of the same available electrical steel core material in accordance with Ampere Circuital Law, and then, establishing the highest possible torque MMF, which does not magnetically saturate the core material, demagnetize any RE-PMs, or destructively overheat the electric machine system.

NOTE: Without considering air-gap depth design constraints, future advancements in permeability of the electrical steel or RE-PM residual flux density, and future advancements in RE-PM or electromagnet thermal management, present highly optimized RE-PM electric machine systems are cost and size constrained to about one Tesla of air-gap flux density before the physical depth of persistently magnetized RE-PMs approaches or even surpasses the physical depth (and size) of a replaceable electromagnet with the benefit of controllable flux weakening. This tradeoff axiom between the cost and size of RE-PMs versus the electromagnet will likely continue, because material science research to improve the residual flux density limit of permanent magnets or the saturation limit potential of the electrical steel core is complementary. *Ironically*, the so-called compactness of RE-PMs and the elimination of the size, cost, and loss of magnetizing MMF with associated provisioning were reasons for migrating to expensive RE-PMs while ignoring RE-PMs’ own unique associated provisioning, such as RE-PM retaining composite sleeves that adversely increase air-gap depth, exotic *dysprosium doping* to improve practical durability, efficiency wasting cogging and handling safety issues of persistent magnetism, and ethical disregard of their geopolitical, environmental, and exploited labor consequences of RE-PM production.

- *Only a directly excited (e.g., bidirectional), multiphase winding set (or active winding set) produces a rotating magnetic field relative to its frame and as a result, contiguously provides torque and active (or working) power to the electromechanical energy conversion process* in accordance with the vector product of speed (i.e., voltage) and torque (i.e., current).

  NOTE: All electric machines must universally have the loss, cost, and size of at least one active winding set (*i.e., singly-fed*) for electromechanical energy conversion or at most, two active winding sets *(i.e., doubly-fed*) before electric machine circuit topology duplicates.

  NOTE: Typically, the universally essential active winding set is located on the stator to avoid the complexity of provisioning multiphase electrical connections to a moving rotor and as a result, the “active stator assembly” contiguously provides working (or active) power to the electromechanical energy conversion process throughout the constant-torque speed range while consuming half of the precious electric machine loss, cost, and size (with at least core loss included). Likewise, the rotor assembly typically comprises, a) slip-induction dependent windings, which are inductively powered through the extra supporting capacity of the stator active winding set (e.g., extension of the stator winding set), b) DC field windings, c) reluctance saliencies, or d) permanent magnets, which are not directly excited multiphase windings sets (i.e., active winding sets) for torque and power production, and as a result, the “passive rotor assembly” reasonably *wastes* the other half of precious electric machine system cost, real estate, and loss (with at least core and frictional losses included) by not contiguously controlling rotor power along with the active stator assembly.

  NOTE: By simply having an electrical connection to the rotor, such as through a brush-slipring assembly, DC field wound synchronous electric machine systems (with a rotor that can be equally replaced with RE-PMs) or so-called multiphase wound-rotor asynchronous (*i.e., induction*) electric machine systems with a slip-ring assembly are customarily (but incorrectly) called “doubly-fed” electric machine systems, although comprise a passive rotor assembly that reasonably wastes half of the precious electric machine system cost, real estate, and loss (with at least core and frictional losses included) by not *contiguously* controlling rotor power at any speed along with the active stator assembly, such as at synchronous speed where slip-induction ceases to exist.

  NOTE: Because of the extraordinary cost, loss, and size for their practical implementation, so-called single-phase electric machines are outside the scope of this discussion.

- *With similar steady-state air-gap flux density, all optimally designed electric machines have, a) similar "effective" air-gap area for similar torque production, b) similar total air-gap area and stator active winding set size (real estate) for power production, which includes slots for placing windings, and as a result, c) similar total volume, which includes slots for placing RE-PMs, back-iron for closing the magnetic path and structural integrity, endplates and bearings for functional integrity, etc.,* a) when *optimally* designed to the same maximum load speed (**MLS**) or constant-torque speed range for a given air-gap flux density, continuous torque, voltage, excitation frequency, and packaging techniques, b) without considering the compounding loss, cost, and size of the electronic controller, c) regardless of the shallowness of RE-PMs versus an electromagnet, which has incorrectly been the metric for electric machine size instead of the effective air-gap area and active winding set size, and d) with the exception of super conducting electric machine systems with ultrahigh air-gap flux density potential.
- *All optimized electric machines of comparable power rating, including so-called yokeless or ironless electric machine structure topologies, have similar amounts of core electrical steel*, a) to at least provide the universally essential back-iron for optimally closing the magnetic path through the airgap, b) to effectively reduce the amount of magnetizing MMF or expensive RE-PM material by reducing the effective air-gap depth or core reluctance, c) to add structural integrity without exotic composite materials, such as carbon fiber, or unfriendly construction and manufacturing methods, and d) to reduce the amount of RE-PM materials. Although stator core loss may decrease with soft magnetic materials, so-called yokeless or ironless electric machine systems always, a) sacrifice thermal management, structural integrity, low air-gap flux density, b) increase air-gap depth by eliminating the stator back-iron (and resulting core loss), and b) increase magnetizing MMF or amount and size of expensive, geopolitical, and environmental unfriendly RE-PM material.
- *The axial-flux electric machine (e.g., side by side rotor and stator disks that are separated by an air-gap and a robust bearing assembly) is proven to provide higher electrical performance than the radial-flux electric machine (e.g., rotor cylinder inside the annulus of a stator cylinder that are separated by an air-gap and bearing assembly)*, particularly in a single air-gap configuration that at least provides: a) simpler outside-to-inside winding approach, b) incremental increases in power by conveniently stacking lengthwise, c) shallower and tunable air-gap, and d) equal cooling surfaces between rotor and stator.

  NOTE: The Axial-Flux electric machine system would be preferred, if a practical enabling core manufacturing method became available, such as an electric machine 3D Printing method as only provided by MOTORPRINTER.

- *Today, all electric machine circuit and control architectures (**EM-CCA**) or system architectures incorporate electronic frequency, voltage, and current excitation control for optimum performance or for practical operation*.

NOTE: Rarely the case, an equitable comparison between competing electric machine "systems" should always be a "full system" comparison by at least including the *compounding* loss, cost, and size of the essential electronic controller (*and possible auxiliary speed reduction gearbox, cryogenic or RE-PM provisioning, etc. for practically applied operation*) at the designed *Maximum Load RPM* (*or constant torque speed range*) and power rating. For instance, RE-PM electric machine systems are operating at very high speeds to reduce the electric machine size and associated amount of expensive RE-PM materials but as a result, the unusual compounding size, loss, cost, reliability, and maintenance of a speed reduction gearbox should be included for practical applied operation.

NOTE: The essential electronic controller introduces *compounding* effects on the overall loss, cost and size of any electric machine "system" but is often overlooked in electric machine specifications. For example, the electronic controller must control the total power of the electric machine, which includes electric machine loss and associated size and cost, and as a result, if the efficiency of the motor component is 96% and if the efficiency of the essential electronic controller component is also 96%, the actual *compounded* efficiency of the applied system is only 92% (*i.e., compounding or product of 96% for electric machine and 96% for the controller*).

- <u>*All electric machine "systems" can be characterized as either "synchronous" or "asynchronous."*</u> By definition, an *asynchronous* (or induction) electric machine systems indisputably *relies entirely on slip-induction*, which is due to the asynchronous movement (or slip) between the rotor and stator (or assemblies) to mutually induce speed synchronized *torque* MMF on the rotor core and multiphase winding set without physical electrical contact, and as a result, the *rotor assembly* of an induction electric machine cannot rotate at synchronous speed, where slip-induction ceases to exist. In contrast, a *synchronous* electric machine indisputably *does not rely on slip-induction* to produce torque MMF and as a result of control technology limitations, the rotor assembly of the *traditional* synchronous electric machine *must rotate in precise synchronism* to the revolving magnetic flux in the air-gap to avoid slip-induction and resulting damage.

  NOTE: The asynchronous (or induction) electric machine establishes the air-gap flux density by the magnetizing MMF of the stator multiphase winding set and then, establishes the torque MMF on the rotor multiphase winding set, which pushes and pulls on the movable rotor against the air-gap flux density in accordance with Lorentz Law, by the mutual slip-inductive coupling (i.e., transformer action) with a similar torque MMF on the stator winding set, which pushes and pulls on the stator frame. As a result, the stator size, cost and loss must *structurally and electromagnetically* support the electrical power, the core loss, and the electrical loss of the magnetizing and torque MMF combination, which is the vector magnitude of orthogonal magnetizing and torque flux vectors in accordance with Lorentz Force Law, and the rotor size, cost, and loss must support the friction loss, which include stray, windage, bearing, etc., the core loss, the electrical power, and the electrical loss of just torque MMF. In contrast, 1) **the DC field wound synchronous electric machine** establishes the air-gap flux density by directly applying magnetizing MMF on the DC field winding of the rotor and then directly applying torque MMF on the stator active winding set and as a result, the stator size, cost, and loss support the core loss, the electrical power, and the electrical loss of the torque MMF and the rotor size, cost, and loss support the friction loss, the core loss, the electrical power, and the electrical loss of the magnetizing MMF, 2) **the RE-PM synchronous electric machine** establishes the air-gap flux by the persistent flux of permanent magnets (instead of a DC electromagnet) with no electrical power on the rotor and as a result, the stator size, cost, and loss support the core loss, the electrical power, and the electrical loss of stator torque MMF and the rotor size, cost, and loss support only the friction loss and a small core loss, which is due to harmonics of electronic excitation control, and 3) **the reluctance electric machine** has no electrical power on the rotor and as a result, the stator size, cost, and loss support the core loss, the electrical power, and the electrical loss of the torque and magnetizing MMF combination and the rotor size, cost, and loss support the friction loss and the small core loss, which is due to harmonics with precise synchronization control.

NOTE: By *automatically*, *instantaneously* (i.e., real time), and orthogonally aligning the rotor flux synchronously to the stator single phase or DC electromagnet (i.e., winding set) at any speed with the ultralow fidelity *emulation* process of an electro-mechanical commutator (i.e., *electromechanical* computer), which is a single-phase electric machine controller with an arrangement of electromechanical switches (i.e., brushes sliding over contacting bars) that electrically connect an arrangement of rotor electromagnets in synchronism to the stator electromagnet position, regardless of rotor position or speed, the *Universal* Electric Machine System is a traditional *synchronous* electric machine system with an *electro-mechanical* means of automatically aligning the rotor and stator fluxes instead of by an indirect, estimating field oriented control (**FOC**) derivative means.

- <u>*In accordance to the classic textbook study, there are only two unique categories of electric machine circuit and control architectures (**EM-CCA**) for comparative convenience*</u>: 1) the *optimal symmetric synchronous EM-CCA, as only provided by SYNCHRO-SYM,* with the air-gap adjacent *symmetry* of a) an "active stator assembly" with the *universally essential* power and torque producing active winding set, which reasonably consumes half of electric machine loss, cost, and size while simultaneously providing working power production to the electromechanical energy conversion process, b) an "active rotor assembly" providing a *second* directly excited multiphase winding set (or active winding set), which reasonably consumes the other half of electric machine loss, cost, and size while also, providing another increment of working power production to the electromechanical energy conversion process, and c) as only possible with the patented and practical brushless, multiphase, real time emulation controller (BRTEC™), which is an *ultrahigh fidelity*, *electromagnetic* computer with *automatically exact, real time, synchronous* stabilization from sub-synchronous to super synchronous speeds, including zero and synchronous speed, in order to avoid falling into the "asynchronous" category of so-called doubly-fed *induction* electric machine systems, and 2) the *non-optimal asymmetric EM-CCA* with the "me-too" air-gap adjacent *asymmetry* of a) an "active stator assembly" with the *universally essential* power and torque producing active winding set, which reasonably consumes half of electric machine loss, cost, and size, b) a "passive rotor assembly," which comprises slip-induction dependent windings (*for singly-fed or so-called doubly-fed asynchronous*), reluctance saliencies (*reluctance synchronous and singly-fed and doubly-fed asynchronous*), permanent magnets (*for singly-fed synchronous*), or DC field windings (*for singly-fed synchronous*), which reasonably *wastes* the other half of electric machine loss, cost, and size by not providing an additional increment of working power production to the electromechanical energy conversion process, and c) as implemented by a derivative of estimating field oriented excitation control (**FOC**) or direct torque control (**DTC**).

NOTE: Because of the formidable challenges of inventing a practical brushless real time emulation controller for realizing the *symmetric synchronous* electric machine system with an "active" rotor assembly, electric machine system categories have been limited to only asymmetric electric machine systems.

NOTE: Commonly confused with the *asynchronous (or slip-induction)* doubly-fed electric machine system, which is actually an asymmetric EM-CCA with a passive rotor assembly, a practical symmetric "synchronous" EM-CCA has never materialized, because of the formidable challenges of realizing the essential BRTEC for "continuously synchronous stability" at any speed from sub-synchronous to super-synchronous speed, although early symmetric EM-CCA research began with the advent of practical high speed electronic control (circa 1960's).

NOTE: Coupled with the formidable challenges of inventing a practical BRTEC for implementing the most "optimum" EM-CCA, which is the symmetric synchronous EM-CCA, and with the advent of a high energy product rare-earth permanent magnets (**RE-PM**) (circa 1980's) of dysprosium doped neodymium that seemingly provided a practical means of effectively eliminating the provisioning, cost, size, and loss of magnetizing MMF, electric machine system research was conveniently redirected to just the development and empirical application of readily available material, such as RE-PMs, winding, packaging, high speed electronic control, and manufacturing techniques for performance enhancement of the century old, me-too, asymmetric EM-CCA, such as the RE-PM EM-CCA in particular. But *ironically*, the provisioning, loss, cost, and size of *magnetizing MMF* is again being redesigned into the RE-PM EM-CCA to regain the coveted attribute of field weakening capability for broader speed range and efficiency instead of simply optimizing the slip-induction EM-CCA that inherently provides field weakening and is without the safety, reliability (e.g., demagnetization and life expectancy), and inefficient cogging issues of persistent magnetism, which indisputably shows the decades of control dominance over all electric machine system innovation, discussion, and manufacturing by a global adversary's monopoly on electric machine RE-PM production with insidious geopolitical, environmental, and exploited labor consequences.

NOTE: Because of the expensive, geopolitical, environmental, and human exploitation consequences of producing RE-PMs, such as dysprosium doped neodymium or samarium cobalt permanent magnets, and the limited mineable and production supply chain of these minerals, there are efforts to use the abundant but low energy product ferrite permanent magnets magnet electric motor systems but these efforts have not proven to achieve comparable air-gap flux density, reliability, efficiency, and performance as an optimized induction or DC field wound synchronous electric machine system.

NOTE: *The symmetric synchronous EM-CCA inherently: a) has the coveted field weakening capability for extended speed range, b) is without the cogging drag or safety handling issues of RE-PM persistent magnetism, or c) is without the extravagant cost, environmental harm, unsustainable global supply chain, and geopolitical consequences of RE-PMs.*

NOTE: *The symmetric synchronous EM-CCA with the optimal symmetry of two equally rated "active" winding sets on the same rotor and stator, respectively, shows twice the power rating or half the loss, half the cost, and half the size (per unit of power rating*) *of the asymmetric EM-CCA with the same rotor and stator packaging but with the non-optimal asymmetry of a single equally rated active winding set on the stator assembly* and a rotor assembly of "passive" slip-induction windings, RE-PMs, reluctance saliencies, or DC field windings by reasonably assuming the rotor or stator consumes half the size, cost, and loss of any EM-CCA, which includes electrical, core, or friction losses, particularly if the EM-CCA is an *axial flux* slip-induction asymmetric EM-CCA with similar adjacent rotor and stator disks.

NOTE: *The symmetric synchronous EM-CCA has twice the constant-torque speed range for a given continuous torque, voltage, and frequency of excitation*, which is tantamount to twice the power rating (*i.e., similar constant-torque to 7200 RPM @ 60 Hz and 2 poles versus 3600 RPM for all others*).

NOTE: *The symmetric synchronous EM-CCA doubles the performance gain expected from the same readily available electric machine material, winding, packaging, and electronic component techniques*, which are empirically applied to the asymmetric EM-CCA with one active winding set for performance distinction, by the magnifying working power of *two* active winding sets on the rotor and stator, respectively. Said differently, with the same voltage and frequency of excitation, the rotor and stator ports of the symmetric EM-CCA support the full power with half the port current and one-quarter the electric loss (i.e., I^2R) per unit of power rating as the asymmetric EM-CCA.

NOTE: *The symmetric synchronous EM-CCA provides at least eight times (octuple) more peak torque potential than the asymmetric EM-CCA, including asymmetric RE-PM EM-CCA*, because unlike the asymmetric EM-CCA with increasing torque MMF quickly leading to core saturation, the torque MMF on each side of the air-gap is symmetrically neutralized in accordance with the conservation laws of dual ported transformer physics, which leaves the symmetric synchronous EM-CCA providing another level of power density and efficiency over the asymmetric RE-PM EM-CCA with at least three additional advantages: 1) inherent field weakening, 2) operational air-gap flux density can be designed closer to the flux saturation limit of the core, and 3) no permanent magnets to damage by demagnetization.

NOTE: *The symmetric EM-CCA brings superconductor electric machine systems closer to practical reality* by a) contactlessly (i.e., brushlessly or wirelessly) relocating the active winding set to the rotor assembly with BRTEC™, b) by relocating the superconductor field windings to the stator assembly for best logistical support, and c) by eliminating the harmonic heating of FOC power conditioning; but more importantly, when AC superconductors become a practical reality, the fully electromagnetic symmetric synchronous electric machine system as only provided by SYNCHRO-SYM, which is without permanent magnets, will become the electric machine system of choice.

- ***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:***

  As a result, the symmetric synchronous EM-CCA with two equally rated active winding sets on the rotor and stator, respectively, which preserves the same electric machine footprint and packaging of winding, thermal management, electronic component, and material techniques as the asymmetric EM-CCA with a single equally rated active winding set, inherently provides twice the power density, half the cost, and half the loss per unit of power rating of the

asymmetric EM-CCA with the same port voltage, excitation frequency, continuous torque, air-gap flux density, and MLS design.

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