The Forgotten but Best Electric Motor or Generator System: The *Brushless* Wound-Rotor *Synchronous* Doubly-Fed Electric Machine System

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Abstract— **The Next Generation Electric Machine funding opportunity (NGEM) recently awarded $22M to develop electric motors and generators, commonly called electric machine systems (EMS), with the potential of reducing energy loss by 30% and improving power density by 50%. Considering DOE's strong support for the development and deployment of advanced electric vehicles (EV), an obvious NGEN goal includes advancing EMS technologies for electric vehicle (EV) propulsion. Overall, the average $6M award does not advance innovative EMS or electronic control topologies but instead leverages enabling enhancements, such as wide bandgap semiconductors, fully integrated electronics, and high speed operation, which illustrates that EMS or electronic control topologies are considered mature technologies with little potential for additional advanced development. However, this qualitative analysis will show that the almost forgotten *brushless* and *stable* Wound-Rotor [Synchronous] Doubly-Fed EMS (BDFSM), which is only realized by the recently patented invention of Brushless Real-Time Emulation Control (BRTEC), could easily provide an additional 50% improvement in efficiency and power density beyond the NGEM expectations without incorporating exotic manufacturing or rare-earth materials, all while lowering overall system cost.**

Index Terms—**Brushless, wound rotor, doubly fed, double fed, synchronous, asynchronous, electric machine, electric motor, electric generator, electric propulsion**

I. INTRODUCTION

The Next Generation Electric Machine funding opportunity (NGEM) of the Department of Energy (DOE) recently awarded $22M to develop electric motor and generator systems, commonly called electric machine (EM) systems (EMS), with the potential for a 30% reduction in energy loss and a 50% improvement in power density by leveraging enabling technologies, such as Silicon Carbide (SiC) wide bandgap (WBG) semiconductor components, fully integrated electronics, and high speed operation.[1] Considering DOE's strong support for the development and deployment of advanced electric vehicles (EV), an obvious NGEN goal includes advancing EMS technologies for electric vehicle (EV) propulsion. All of the $6M average awards use conventional single armature electric machine system topologies from the permanent magnet (PM), reluctance, and induction (or asynchronous) EM families, which demonstrates that innovative EM system and control topologies are considered mature technologies with only advance development potential in enabling technologies, such as WBG semiconductors, etc.

All electromagnetic electric machines (EM) or electric motors and generators are basically designed by successive iteration of three simple relationships of physics, Faraday's Law, Ampere's Circuital Law, and the Lorentz Force Relation. In consideration as clearly demonstrated by the NGEM award winners, the only truly distinguishable differences between EMS topologies of today's conventional or specialty EMS manufacturers (but equally available to all) are: 1) the "investment" in manufacturing tooling or the manual skills for applying better off-the-shelf packaging techniques, such as high speed operation, 2) applying better magnetic performance core materials, 3) providing more efficient flux paths in the magnetic core, or 4) applying advanced *enabling* components, such as WBG semiconductors, high speed operation, integrated electronics, rare earth permanent magnets, multiphase slip-ring assemblies, etc. But theoretical studies show the wound-rotor doubly-fed EM has *highest* power and torque density of any EM but only with a solution for dynamic instability issues. [16] So virtually forgotten until the recently patented invention of a Brushless and Sensor-less Real Time Emulation Controller (BRTEC), which was hypothesized by electric machine experts since at least the 1960's to be essential for a truly *brushless* and *symmetrically stable* (e.g., motoring and generating) Wound-Rotor [Synchronous] Doubly-Fed EMS (BDFSM) [2], [3], [4], [11], [12], the BDFSM shows the uniquely attractive attribute of *twice the constant torque speed range for a given torque and a given frequency and voltage of excitation without speed regions of control discontinuity* [15], such as about synchronous speed where induction ceases to exist. Without control discontinuity about synchronous speed, which is the common dependency of relying on induction principles for all other doubly-fed EMS, the BDFSM exhibits controllable transition between sub-synchronous speed and super-synchronous speeds without auxiliary means. Alone, this unique attribute provides additional attractive attributes that go far beyond the anticipated expectations of the NGEM program, including ultralow harmonic content with nearly pure sinusoidal signals, fault tolerance as provided by multiphase operation, ultra-high torque and power density, and low cost. Accordingly, the BDFSM as only provided by BRTEC would

This work was supported by Best Electric Machine.

best leverage the anticipated results of NGEM enabling technologies.

A. Accurately Consistent EMS Terminology

The rapid advancement in high performance materials and brushless, sensor-less, electronic control, which happened during the last half century, have allowed variable speed electric machines to approach their electromagnetic performance, just as fly-by-wire (or electronic control) has enabled the feasibility of high performance airplanes that otherwise would be awkwardly unstable. Likewise, BRTEC has allowed the wound-rotor *induction* doubly-fed electric machine to approach the *ideal* electromagnetic performance of the symmetrically optimal, wound-rotor *synchronous* doubly-fed electric machine. In contrast, electric machine *terminology* was originally inspired by available manufacturing techniques and electro-mechanical technologies during the first century of electric machine evolution. For instance, it is common to anecdotally define "double fed or doubly-fed" as any electric machine having two electrical power ports, although the total electromechanical conversion power is provided entirely through a single electrical port, such as the stator port of the DC field-wound synchronous or the slip energy recovery induction electric machine, and yet, the operation, structure and performance of their electromagnetic cores are virtually the same as their respective counterpart that have never been considered double fed, such as the commonly applied permanent magnet electric machine or squirrel cage induction electric machine. Without consistent terminology to accurately distinguish the BDFSM [5] from all other EMS**,** the caveats of other electric machine systems easily become the caveats of the BDFSM. For instance, the BDFSM as only provided by BRTEC is commonly confused with the wound-rotor doubly-fed *induction* electric machine, which has a complex multiphase slip-ring assembly and known instability unless mechanically stabilized with high inertia loads**,** particularly when motoring. Therefore, the following systematic process of simple deductions will provide terminology according to physics, regardless of electric machine type, and as a result, provide a consistently accurate understanding of the BDFSM. (*"P" as Premise, "C" as Conclusion*):

- P1: All electromagnetic electric machines comprise a rotor body and a stator body separated by an air-gap to allow their relative movement.
- P2: In accordance with the *Lorentz Force Law*, all electromagnetic electric machines comprise two electromagnetic components for the production of torque (or force): 1) a rotating (or moving) current sheet developed on a first body, such as the stator (or stationary) body, and 2) a rotating (or moving) magnetic field or flux developed on a second body, such as the rotor (or rotating) body, that orthogonally cuts the current sheet of the first body.
- P3: Both electromagnetic components must move in synchronism for non-pulsating or average torque (or force) production. Maximum torque occurs when components are orthogonal (90 degree out of phase).
- P4: In accordance with *Amperes Circuital Law*, a current sheet (or electrical winding flowing current) produces a magnetic field (or vice versa).
- In accordance with (IAW) P1…P4 → **C1**: Either electromagnetic component of an electric machine that pulls (attracts) or pushes (repels) the other along can be an electrical winding with current or a magnetic field.
- P5: The rotor moving magnetic field (or current sheet) is developed by a moving body of: 1) permanent magnets; 2) salient poles (for changing the inductance as a result of changing the reluctance path with movement); or 3) electrical winding(s) flowing current.
- P6: Only a multiphase winding set that is flowing multiphase AC current produces a rotating or moving magnetic field (or current sheet) regardless of its motion.
- IAW C1,P5,P6 → **C2**: The stator moving current sheet (or magnetic field) is developed by a multiphase winding set flowing multiphase AC current at an excitation frequency that provides a synchronized moving magnetic field.
- P7: In accordance to *Faraday's Law*, a multiphase AC winding set produces a back-EMF (or voltage) that opposes the current flowing in each phase winding.
- P8: The electromechanical conversion power (or active power) rating of any electric machine is dependent on the product of the back-EMF and the total current flowing (in a multiphase AC winding set(s)).
- P9: DC electromagnets, salient poles, or permanent magnets, which commonly replace DC electromagnets, do not support back-EMF on their own (by physics or by design).
- IAW P7…P9 → **C3**: DC electromagnets, salient poles, or permanent magnets cannot actively contribute to electromechanical conversion power but instead, passively participate in the electromechanical conversion, such as providing a moving magnetic field component by the action of their moving body.
- P10: Induction occurs between the stator and rotor winding sets when the speed of the rotor or stator winding set is other than the speed of the synchronized magnetic fields (i.e., *slip*) and accordingly, the *slip-induction* frequency is on par with the speed of the EMS. *Note: Although not traditional EMS terminology, "slip-induction" (in contrast to "induction") for electric machines avoids confusion with other forms of induction, such as high frequency induction.*
- P11: An induction (or slip-induction) winding set of an electric machine, such as a squirrel cage winding set, does not have (or effectively use) an independent electrical port to actively contribute to the electromechanical conversion (or active) power *on its own* but instead acquires all of its electrical power by mutual inductive coupling from the "active" stator multiphase AC winding set as a result of slip.
- IAW P10,P11 → **C4**: Without an independent power port to support electromechanical conversion power on its own, a slip-induction winding set *passively* participates in the electromechanical conversion process and although separate, should actually be considered an integral design and part of the mutually coupled multiphase winding set that mutually couples the active or electromechanical conversion power.
- IAW C2,C3,C4 → **C5**: Only an independently excited (or self-excited) multiphase winding set, such as the stator winding set, *actively* contributes to the electromechanical conversion power of an electromagnetic electric machine. Because power transfer relies on self-excitation (instead of

slip-induction), the speed, position, and direction of the moving magnetic field of a self-excited multiphase winding set is independent from the speed, position and direction of the multiphase winding set without considering the electric machine criteria of two synchronized magnetic components for average torque production. *Note: Independently excited, self-excited, active power, and passive power are not traditional EMS terminology.*

- P12: In accordance with the IEEE standard Dictionary of Electrical and Electronic Terms, ANSI/IEEE Std. 100-1984, an armature is a member of an electric machine in which an alternating voltage (*or back-EMF*) is generated by virtue of the relative motion with respect to the magnetic flux field.
- IAW C3,P12 → **C6**: An *armature* cannot be a body of DC electromagnets, salient poles, or permanent magnets, which do not support back-EMF.
- IAW C4,C5,P12 → **C7**: An *armature* is a winding set that cannot rely on slip-induction for its current excitation.
- IAW C6,C7 → **C8**: By supporting current with back-EMF without relying on slip-induction, only an *armature* actively contributes to electromechanical conversion power and as a result, determines the active power rating of the electric machine.
- IAW C5…C8 → **C9**: By developing the active power of the electric machine on its own, an *armature* is simply a rotor or stator body with an independently (or self) excited multiphase AC winding set.
- IAW C9 → **C10**: The *armature of any EMS effectively occupies the same air-gap area and same physical volume* and dissipates the same electrical loss when designed to the same frequency of excitation, the same port voltage and power, and the same torque production or magneto-motive-force (MMF) under the same air-gap flux density that is within the same flux saturation constraints of the same magnetic core materials. As a result, the armature determines the same physical size regardless of EMS type, particularly in axial-flux form (or rotor-disk-to-stator-disk form).
- P13: With only two moving electromagnetic components, an electric machine can operate with: 1) one armature component on either the stator or the rotor, respectively, with a passive component on the rotor or stator, respectively, such as a rotating PM, Salient poles, DC electromagnet, or slip-induction component; 2) two armatures (at the most) on the stator that are passively coupled through the passive rotor, such as by slip-induction or reluctance; 3) two armatures on the rotor that are passively coupled through the passive stator; or 4) two armatures on the rotor and stator, respectively.
- P14: Only with stable, bi-directional power control of at least one armature, two (or dual) armatures allow operation from sub-synchronous to super-synchronous speeds by concurrently (e.g., sub-synchronous range) and serially (e.g., super-synchronous range) pulling or pushing the two moving magnetic field components at the design torque (or MMF) rating of either armature.
- IAW P13,P14 → **C11**: The total electromechanical power conversion rating of an electric machine is the sum of the power rating of its armatures but the designed torque rating is determined by one armature.
- IAW C10,P13,P14 → **C12**: The most optimum EM real estate utilization with highest power density can only be an armature on the rotor and on the stator, respectively, or a wound-rotor doubly-fed topology, because both rotor and stator bodies actively contribute to the energy conversion power together without relying on a third "passive" slip-induction rotor component (as only provided by BRTEC).
- P15: All electric machines are classified as either: 1) an *asynchronous (or induction) electric machine*, such as the squirrel cage induction electric machine; or 2) a *synchronous electric machine*, such as the reluctance electric machine, which *experiences* mutual slip-induction by changing the magnetic path *(but does not rely on slip-induction for operation)*, the DC field wound, or the permanent magnet electric machine.
- P16: The asynchronous or synchronous electric machine classification has nothing to do with the overall EMS requirement of two synchronously moving electromagnetic components (see P3).
- IAW P15,P16 → **C13**: An *asynchronous (or induction) electric machine* "*relies entirely*" on slip-induction to produce one of the two moving components for electromagnetic operation and as a result, asynchronous electric machines cannot operate at (or closely about) synchronous speed where slip-induction effectively ceases to exist.
- IAW P15,P16,C13 → **C14**: In direct contrast to an asynchronous electric machine, a *synchronous electric machine* "*does not rely entirely*" on slip-induction for operation and as a result, a synchronous electric machine can operate at synchronous speed (but may experience slip-induction by fault or by design). *Note: Traditional terminology defined by the first hundred years of EMS development suggested a synchronous electric machine operates only at synchronous speed.*
- P17: By nature, an *asynchronous (or induction) electric machine* always shows lagging (or inductive) power factor (i.e., current lags voltage) or inductive reactance. Leading, lagging, or unit power factor correction requires the introduction of electronic control with a bank of compensation capacitors with additional associated cost, size and electrical loss.
- P18: By nature, a *synchronous electric machine* with magnetic field control (or torque angle control) shows leading, lagging, or unit power factor correction (or capacitive ↔ inductive reactance).
- IAW P13 → **C15**: The *doubly-fed electric machine* has *dual (or two) armatures* (or double fed), which is the most possible while satisfying the two moving electromagnetic components of operation.
- IAW P13,C15 → **C16**: The *singly-fed electric machine* has a *single armature* while satisfying the two moving electromagnetic components of operation.
- IAW P14,P17,C13,C15 → **C17**: The *doubly-fed asynchronous (or induction) electric machine* (DFIM) with a wound-rotor topology connected through a multiphase slip-ring assembly and the so-called brushless doubly-fed slip-induction (BDFIM) or reluctance (BDFRM) electric machine [13] with the non-optimizing bulk of dual stator winding sets

of unlike pole-pairs (to guarantee brushless slip-induction) show operational discontinuity about synchronous speed where slip-induction effectively ceases to exist but operate at sub-synchronous and super-synchronous speeds as a either motor or generator (but only with a bi-directional electronic control means). Consistent with induction electric machine principles, the DFIM, BDFIM or BDFRM will always show lagging power factor without the controlled introduction of an external bank of compensation capacitance.

- IAW P14,P18,C14,C15 → **C18**: A *doubly-fed synchronous electric machine with a wound-rotor topology (DFSM)* must comprise an armature on the rotor and stator, respectively, [14] (of course with extraordinary bi-directional electronic control as only provided by BRTEC) to eliminate potential reliance on slip-inductive coupling through an extraneous but necessary passive rotor body. Closest to an adiabatic process, the DFSM shows no operational discontinuity at synchronous while operating between sub-synchronous and super-synchronous speeds as a motor or generator. Consistent with DC field controlled wound synchronous electric machine principles [15], the DFSM shows leading, lagging, and unity power factor adjustment without controlling an external bank of compensation capacitance. *Note: some suggest calling the DFSM a "hybrid" DFIM, which would confuse the asynchronous and synchronous categories with a third category. Instead, the non-traditional asynchronous and synchronous category definitions provided cover all situations without confusion.*
- IAW P13 → **C19**: Without the capability of operating super-synchronously, direct current (DC) field-wound synchronous EMS and slip-energy recovery induction electric machines are singly fed and should never be confused with doubly-fed.

II. ATTRACTIVE ATTRIBUTES OF THE BDFSM

A Singly-fed EMS has a constant-torque speed range (CTSR) that is directly proportional to the frequency of excitation and inversely proportional to the total number of pole-pairs of the armature in accordance to the synchronous speed relationship of the armature (i.e., singly-fed CTSR = (60 x frequency of excitation of the single armature) ÷ (total number of armature pole-pairs)). Therefore, the singly-fed electric machine system has a constant-torque speed range (i.e., synchronous speed) of 3600 RPM under 60 Hz of excitation with a single pole-pair on the armature body. In contrast, a doubly-fed (or dual armature) EMS has a CTSR that is up to *twice* the synchronous speed relationship of the single armature because of super-synchronous operation (i.e., doubly-fed CTSR = (60 x the sum of the excitation frequencies of each armature) ÷ (total number of armature pole-pairs)). Assuming equally rated armatures, a BDFSM has a CTSR of 7200 RPM under 60 Hz of excitation with a single pole-pair on the rotor and stator armatures, respectively. In contrast, the so-called brushless [induction] doubly-fed EMS (BDFIM) has a CTSR of 1440 RPM under 60 Hz of excitation with two armatures of unlike pole-pairs of 2 and 3, respectively, mounted on the stator body. Of course at higher speeds and frequencies of excitation, both singly-fed and doubly-fed electric machines enter the constant-horsepower speed range (CHSR). *Note*: In accordance with EM physics, higher speeds of operation, such as with a given frequency, voltage and pole-count, is a sure indication of higher EM power density but realistically, the compounded size, efficiency, and cost of the mechanical transmission to match the higher speed of the EM to the load speed must be considered in the overall cost, size and efficiency of the EMS, which is rarely the case.

All doubly-fed electric machine systems require bi-directional electronic control of the excitation power and frequency of at least one armature for characteristic sub-synchronous to super-synchronous speeds of operation. Since the 1) DFIM exhibits control discontinuity about synchronous speeds, 2) the DFSM is not brushless, and 3) both the DFIM and DFSM show instability without instantaneous control, particularly when motoring, the BDFSM as only provided by BRTEC with its attractive attributes will be the subject of study going forward. With the previous considerations and reasonably assuming the dual armatures on the rotor and stator, respectively, are similarly sized, the BDFSM would exhibit the following features:

- Symmetrically stable with no multiphase slip-ring assembly.
- Nearly twice the Power Density: Since power density is *normalized to the total power production* of the EMS, the physical size of the magnetic core of the BDFSM is effectively smaller by up to a factor of two (e.g., dual armatures) than other electric machines because the dual (active) armatures, which together provide twice the power as a single armature [2],[6],[7], are placed on the rotor and stator, respectively, with virtually no underutilized rotor real-estate, such as the passive rotor real-estate of all other electric machine systems. As a result, the BDFSM exhibits twice the power within the same physical volume as other EMSs (or half the physical volume with similar power rating). Said differently, only the BDFSM exhibits *twice the constant torque speed range for a given torque and a given frequency and voltage of excitation without regions of discontinuity*. Previous CTSR calculations already showed the BDFSM has twice the active power production as any singly-fed variety of EMS within the same package size, including the PM or reluctance EMSs, and five times the power production of the BDFIM and BDFRM.
- Nearly Twice the Efficiency: Since electrical loss and related inefficiency is *normalized to the total power production* of the EMS, the electrical loss of the BDFSM core for a given torque (or torque MMF) is comparably better by up to a factor of two than the most efficient electric machine system available under similar design constraints, such as the permanent magnet (PM) synchronous electric machine system, because the total current is split between the rotor and stator armature winding sets (for the same power rating) with electrical loss proportional to the *square* of the current flowing through each armature (i.e., I^2R) and with the electronic controller rated for half the power of the EMS or the power of the rotor armature. Said differently, the BDFSM shows twice the power rating of a Singly-fed (i.e., single armature) induction EMS but with the same electrical loss, which normalizes to half the loss (i.e., total loss ÷ total power). *Note*: Orthogonal to the torque current vector, the magnetizing current vector for the fully electromagnetic

BDFSM (e.g., 30% of torque current) adds less than 0.05% electrical loss at continuous power without considering the comparably lower electrical loss of the half rated electronic controller. With synchronous operation and magnetic field control (as only provided by BRTEC), torque current versus magnetizing current ratio can be adjusted over the entire CTSR and CHSR for additional loss savings at all speed.

- Nearly Half the Cost: By considering cost is *normalized to the total power production* of the EMS, the system cost of a BDFSM core is nearly half (or less) the cost of all other EMSs of similar power rating because the material costs, such as copper windings and electrical steel, are half by volume (e.g., twice the power density) and the power rating of the electronic controller, which contributes the significant cost of any electric machine system, is half (or less) by power rating. [6],[8],[9] As a fully electromagnetic electric machine system without dependencies on costly and delicate exotic materials, such as superconductor field windings or rare earth permanent magnets, the BDFSM accommodates lower cost legacy designs, manufacturing techniques, and applications.[1]
- Factors Higher Peak Torque[10]: Unlike the "asymmetrical" (or single-ported) transformer topology of *all* other EMS with a passive rotor assembly, only the BDFSM follows the classic operating principles of a "symmetrical" (or dual-ported) transformer circuit topology with electrically balanced primary and secondary winding sets. As a result, *conservation of energy* dictates that air-gap magnetic flux density remains relatively constant with increasing torque current because the magnetic flux production on each side of the air-gap beyond magnetizing current is mutually coupled and neutralized. With air-gap flux density remaining constant regardless of increasing torque current but without considering the same operating constraints experienced by all EMS, such as heat dissipation:
  - Torque current (and peak torque) can increase substantially above any other EMS before reaching the flux saturation limits of the magnetic steel core. With significantly higher torque density for short term acceleration, the BDFSM would be the EMS of choice for a direct drive (or gearless) electric vehicle (EV) propulsion system by potentially eliminating the compounded cost, size, and efficiency of the usual transmission;
  - With a stable air-gap magnetic flux regardless of torque current, the steady-state operating core flux of only the BDFSM can be designed closer to the saturation limits of the magnetic core for another level of higher power density, higher efficiency and lower cost.
- EM Simplicity: As the only EMS with a rotor body that equally contributes to the electromechanical conversion power within a similar footprint as the stator body, such as in an axial-flux form (which also greatly improves cooling), the symmetrical topology of the BDFSM effectively eliminates the extraneous real-estate, cost, and electrical loss of the "passive" rotor body found in all other EMSs. Field weakening capability, evenly distributed air-gap flux (e.g., smooth air-gap), leading, lagging, and unity power factor control, and fault tolerance with multiple AC phases are inherently provided.

III. BRUSHLESS REAL TIME EMULATION CONTROL (BRTEC)

The symmetrical circuit topology and electrical relationships of the BDFSM become the classic classroom study for all electric machines, such as the singly-fed permanent magnet, and the singly-fed or doubly-fed induction and reluctance EMS, by simply reverting from the optimized symmetrical topology of the BDFSM with asymmetry. So it has been known and substantiated by pioneering electric machine experts since at least the 1960's that a true BDFSM provides the attractive attributes presented but requires the invention of at least an instantaneous (or real time) control method that relies on the natural automatic control process of "emulation:" 1) *to provide symmetrically stable motoring and generating* by eliminating torque angle instability caused by at least the positive feedback from shaft perturbations, 2) *to eliminate control discontinuity about synchronous speeds* when relying on slip-induction, 3) *to provide a compact brushless means* of propagating bi-directional multiphase power to the rotor winding set, and 4) to allow simple control with *independence from speed, torque angle perturbations, and amplitude* as only provided by electromechanical commutation means. [2],[3],[10],[9],[4] Even today's most advanced state-of-art control methods derived from Flux Oriented Control (FOC) technology rely on the artificial control process of "simulation" with the characteristic long delays of sequential speed and angle measurement, process estimation, and multiphase waveform synthesis that actually encourages torque angle instability and the undesirable reliance on at least slip-induction except in generating applications with large damping inertia providing some stability, such as wind-turbines. With considerable ongoing research to overcome the problems of bulk, cost and inefficiency (compared to the DFIM), the BDFIM and BDFRM have solved only one of the four real time control issues of synchronous doubly-fed operation, which is the elimination of the slip-ring assembly for brushless operation, and as a result, a true BDFSM with the substantial leap in cost-performance from all other EMSs has been kept from practical application until the recent invention of BRTEC.[5] BRTEC is the difference between a true BDFSM and any other doubly-fed electric machine, such as the DFIM, BDFIM, and BDFRM.

Like all conventional electronic controllers, such as FOC, BRTEC is a two stage electronic converter (less any extraneous but essential active front end filtering of FOC) but in contrast to FOC, each electronic stage resides on the rotor and stator, respectively, with a direct, symmetrically bi-directional and ultra-low harmonic content AC-to-AC conversion means. So unlike FOC, BRTEC is without the temperature sensitive, large reactive, low frequency components of an intermediate DC Link Stage that consume an additional 30% of controller space and cost. Instead of the intermediate DC Link Stage, BRTEC uses a compact, low mutual inductance (e.g., ultra-low competing torque), position dependent flux, balanced multiphase, high frequency rotating transformer (PDF-HFT) on

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[1] For the viewer's information but without details, the BDFSM technology can actually bring superconductor electric machines closer to reality by at least moving the superconductors electromagnet to the stationary side.

a common shaft with the DFSM for automatically propagating synchronized leading, lagging, or unity multiphase power to the rotor armature across a single magnetic interface plane (e.g., air-gap) by modulating magnetic sharing between its primary and secondary phase winding sets IAW BRTEC.[5] Varying the resonant frequency of the BRTEC magnetizing current generator dynamically compensates for magnetic leakage. Highly integral with the EM, BRTEC approaches an adiabatic controller that provides greatest benefit from at least the higher temperature WBG semiconductors and higher operating speeds expected from NGEM. The BDFSM is a naturally symmetrical AC EMS with a single half power rated BRTEC exciting the rotor armature, since both armatures by definition require multiphase AC for operation. In other AC or DC applications, such as an electric vehicle, dual BRTEC (for instance) would excite the rotor and the stator armatures, respectively, but each controller (for instance) would be rated for the power of the individual armatures or one-half the total system power. Reasonably considering size, cost, and electrical loss is directly proportional to power rating of the armature, the total size, cost, and loss of the dual converters would be comparable (or much better) to the single electronic controller of any other similarly rated singly-fed EMS with similar power rating. By varying the frequency of excitation of a dual BRTEC topology, the BDFSM can always operate at super-synchronous speed to maximally utilize the rotor and stator armatures for lower core loss and with field weakening to provide normalized torque current versus magnetizing current ratios for high efficiency at low torque.

IV. CONCLUSION

Unlike the common DFIM or BDFIM, which always rely on speed-based (i.e., slip) induction for operation that ceases to exist about synchronous speed, the BDFSM with a contiguously stable sub-synchronous to super-synchronous speed range legitimately exhibits twice the constant-torque speed range of any other variable speed EMS for a given torque and given frequency and voltage of excitation. As a result, a true BDFSM would provide up to double the efficiency and power density beyond any other EMS topology, including the EMS topologies of the NGEM program, while at the same time nearly halving the EMS cost. However, it has been long known that a true BDFSM providing the substantial leap in cost-performance from all other EMSs required the invention of at least a real time emulation control method and as a result, the BDFSM has been kept from practical application and in virtual obscurity. Now with the recent invention of BRTEC, the expected enabling technology of the NGEM program could benefit greatest from BDFSM technology (and vice versa) with less anticipated cost and without the uncertain results from research and development of exotic rare earth materials or reluctance technologies. With EV propulsion commonly relying on singly-fed EMS technologies, such as the synchronous PM or asynchronous EMS, BDFSM would be a superior alternate for an EV propulsion system. *The question becomes, "Why pay for the extraneous real-estate or even the research and development (R&D) of extraneous rare-earth permanent magnets, Induction windings, DC field-windings, or reluctance rotor components when their simple replacement with another armature winding set under BRTEC provides up to a double increase in power and efficiency with a similar decrease in cost, all while accommodating conventional manufacturing, such as those used to manufacture induction electric machine systems, and off-the-shelf materials, such as copper wire and electrical steel! It is rare-earth material free!"*

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