BRUSHLESS REAL TIME EMULATION CONTROLLED MOTOR SYSTEM

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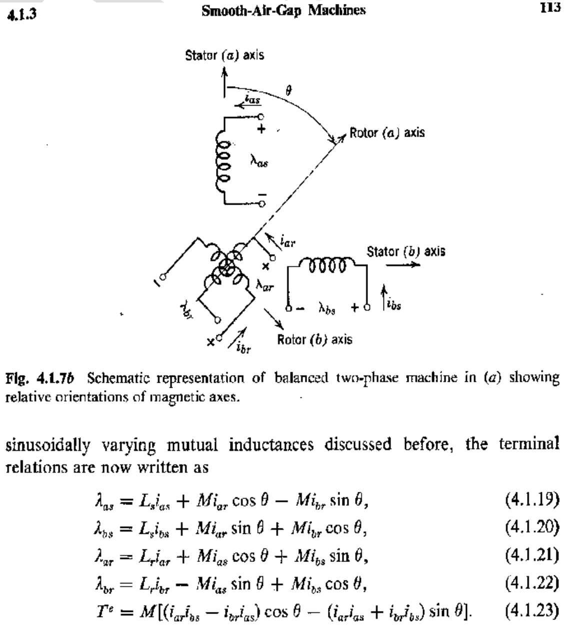
***Abstract*—As the backbone of electric vehicle, airplane, ship, and smart-grid electrification infrastructures, performance improvement to the electric propulsion motor or generator (*i.e. electric machine*) circuit and control architecture (*i.e., system*) would tactically advance the global electrification to an efficient fossil free society but after nearly two centuries of evolution and study, formidable technical challenges persistently limit electric machine system performance improvement to simply applying *commonly available* material, winding, packaging, electronic component, and manufacturing *techniques*, such as better permanent magnets and WBG semiconductors. Yet, the classic introductory study for all electric machine systems confirms the *notional* brushless symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine system (BWRSDF) by hypothesizing the invention of a stabilizing Brushless Real Time Emulation Controller (BRTEC), as only provided by SYNCHRO-SYM revealed in this article, provides twice the power density at half the cost, half the loss, and octuple the peak torque per unit of continuous power rating of *all other* electric machine systems with the same *techniques* and design constraints.**

Keywords—electric machine, synchronous, brushless, real-time, emulation, self-adaptive, wound-rotor, doubly-fed

I. INTRODUCTION

The classic study of electric motors and generators (*i.e., electric machines*), as shown in **Fig. 1**, begins with the *notional* brushless symmetrical multiphase wound-rotor synchronous doubly-fed electric machine system (**BWRSDF**) with the symmetry of two similar directly excited multiphase winding sets (*or active winding sets*) strategically placed on the stator and rotor, respectively, but only by hypothesizing the invention of a brushless, instantaneous (*i.e., real time*), sensorless, automatic, and deterministic (*i.e., emulation*) control means or brushless real time emulation controller (**BRTEC**) to guarantee stable *synchronous operation* from sub-synchronous speeds (*e.g., absolute zero speed*) to super-synchronous speeds (*e.g., twice synchronous speed*) with speed-synchronized, bi-directional, multiphase excitation power applied directly to the "active rotor" multiphase winding set through a rotor electrical port instead of *relying* on slip-based induction excitation that ceases to exist about (*or at*) synchronous speed. The classic study becomes the follow-on study for all other electric machine systems by *deoptimizing* the BWRSDF symmetry with the asymmetry of a "passive rotor" with rare-earth permanent magnets (**RE-PM**) (*synchronous*), slip-induction dependent windings (*asynchronous*), reluctance saliencies (*asynchronous and synchronous*), or DC field windings (*synchronous*).

By making the rotor an *additional* working (*or "active"*) power contributor to the electromechanical energy conversion process together with the *universal* active stator with automatically synchronized rotor and stator flux vectors, the classic study confirms that a BWRSDF provides *twice* the constant torque speed range or *Maximum Load Speed* (**MLS**) per unit of continuous power rating of all other electric machine systems with the same *design parameters*, such as port



4.1.3 **Smooth-Air-Gap Machines** 113

Fig. 4.1.7*b* Schematic representation of balanced two-phase machine in (*a*) showing relative orientations of magnetic axes.

sinusoidally varying mutual inductances discussed before, the terminal relations are now written as

$$\lambda_{as} = L_s i_{as} + M i_{ar} \cos\theta - M i_{br} \sin\theta, \tag{4.1.19}$$

$$\lambda_{bs} = L_s i_{bs} + M i_{ar} \sin\theta + M i_{br} \cos\theta, \tag{4.1.20}$$

$$\lambda_{ar} = L_r i_{ar} + M i_{as} \cos\theta + M i_{bs} \sin\theta, \tag{4.1.21}$$

$$\lambda_{br} = L_r i_{br} - M i_{as} \sin\theta + M i_{bs} \cos\theta, \tag{4.1.22}$$

$$T^e = M[(i_{ar} i_{bs} - i_{br} i_{as}) \cos\theta - (i_{ar} i_{as} + i_{br} i_{bs}) \sin\theta]. \tag{4.1.23}$$

Woodson, Herbert H., and James R. Melcher. Electromechanical Dynamics. 3 vols. (Massachusetts Institute of Technology: MIT OpenCourseWare). http://ocw.mit.edu (accessed 01 03, 2022). License: Creative Commons Attribution-NonCommercial-Share Alike.

Page 113 demonstrates the classic textbook study for all electric machines begins with the symmetrical relationships (i.e., 4.1.19, 4.1.20, 4.1.21, 4.1.22, and 4.1.23) of a multiphase wound-rotor doubly-fed electric machine but only by imagining a

Fig. 1 The Classic Electric Machine Study

voltage, frequency of excitation, torque, pole-pair count, and air-gap flux density (*e.g., 7200 RPM for 60 Hz and two poles versus 3600 RPM*). As a result, the BWRSDF is known to provide up to twice the power rating (*and power density*), half the loss and cost, and octuple the peak torque per unit of continuous power rating *of all other electric machine systems* within the *same packaging*, including half the total I^2R loss by *sharing* the total active current between the rotor and stator active winding sets (*i.e., product of two active winding sets of equal resistance and the square of half the current equals half the loss*).

Commonly confused with the traditional slipring wound-rotor induction (*i.e., asynchronous*) doubly-fed electric machine system, which is unstable without the wasteful damping inertia of a prime mover, such as a wind turbine, for quasi-stable synchronous speed ride-through, a *practical* BWRSDF has never been realized because of the formidable challenges of inventing the enabling BRTEC. Instead, vast RE-PM R&D discovered a viable replacement for the size, cost, loss, and provisioning of *Magnetizing* Magneto-Motive-Force (**MMF**) by ignoring the obvious geopolitical and environmental consequences of the RE-PM supply chain and now, the RE-PM electric machine system is considered the best performing electric machine system. Ironically, the size, cost, and loss of Magnetizing MMF provisioning is being reintroduced into RE-PM electric machine systems to regain the coveted attribute of field weakening, which is already more efficiently and affordably provided in the higher performing BWRSDF.

II. Sixty Years of Selected BWRSDF Studies

The following selected studies confirm that the BWRSDF doubles electric machine performance but is impractical without the enabling BRTEC:

“*The double-armature machine has many merits…continuous power rating is double…in addition…a maximum pull-out torque of…eight times nominal frame size torque rating.” [See page 95, Column 1, Section Paragraph 2]* [1]

“…the power electronic converter only has to handle a fraction of the total power…losses in the power electronic converter can be reduced…the cost…becomes lower. [See page 227, column 1, section paragraph 1]” [2]

“The power converters rating…is substantially lower than the machine rating…” [See page 787 column 1, paragraph 1] [10]

“…peak-power capability of this machine when acting as a motor is greater than that of any comparable form of machine.” [See Abstract][7]

“*…the doubly-fed synchronous electric machine…which allows full advantage…from the possibility of delivering energy to both the rotor and stator…create unstable operation…the desirable steady-state features of this machine are not available…” [See page 653 Column 1]* [3]

“The problem of inherent instability…uncontrollable torque angle is an old one … the problem of accelerating the machine and synchronizing it to the power system has continued.” [See page 526, Column 2, Paragraph 2] [9]

“*The controller requires too many measurements and off-line computations…”* [4]

“If possible, the controller bandwidth should be set higher…at least the change rate of the flux reference…” [See page 1651 column 1 section paragraph 3] [5]

“Since realization of such a control which requires…zero time is almost impossible...” [See page 803 paragraph 6] [6]

“The operation of an ideal control circuit would be independent of the amplitude and frequency of the input signal.” [See page 656 3rd column paragraph 1][3]

III. Reasonable Considerations

For equitable cross-comparisons, the following basic electric machine characteristics are reasonably assumed:

1) Derived from Maxwell’s Equations, all electric machines follow three basic laws of physics for design without deviation, Ampere Circuital Law, Faraday’s Law, and Lorentz Force Law. The only design difference is maximum load speed for a given torque at a given frequency and voltage of excitation with two ports of active power delivery (*i.e., doubly-fed*) showing twice the maximum load speed (and twice the power) within the same packaging;

2) Instead of the term “induction,” such as the “induction” electric machine, which occurs by the asynchronous rotation or movement (*i.e., slip*) between energized stator or rotor winding sets, this article more accurately uses the term “slip-induction” to avoid confusion with *non-slip* induction, such as high frequency induction;

3) *Asynchronous* (*i.e., Slip-Induction*) electric machines *rely* on slip-induction for operation and therefore, *cannot* operate at synchronous speed. In contrast, *Synchronous* electric machines *do not rely* on slip-induction and *can* operate at synchronous speed;

4) All electric machines *universally* have a directly excited multiphase AC (*or active*) winding set or armature (*i.e., singly-fed*) for torque production and for *contributing active* power to the electromechanical energy conversion process, which is generally located on the stator for simple electrical provisioning, or at

most two active winding sets or armatures (*i.e., doubly-fed*) before the electric machine architecture duplicates;

5) All *optimized* electric machines (*with similar design parameters*) have similar air-gap flux density, because air-gap flux density is chiefly determined by the flux density saturation limit of *available* core material and not by the flux density potential of RE-PMs, which are size constrained by temperature and an awkward *inverse* flux density to flux intensity design relationship, or by the even higher flux density potential of electromagnets, which have an optimal *direct* flux density to flux intensity design relationship but are constrained by heat dissipation and size. Accordingly, *optimized* electric machines with similar air-gap flux density will reasonably show: a) similar effective airgap area (*and resulting continuous torque and size*) with the essential frame, backiron, and active winding set, b) arguably, similar package cost and loss (*less expensive RE-PMs*), and c) similar size, cost, and loss between the rotor and stator, particularly under slip-induction operation or with an axial-flux structure of proportionally *similar* adjacent rotor and stator disks, instead of a radial-flux structure of *dissimilar* rotor cylinder inside the annulus of a stator cylinder;

6) All *optimized* electric machines have similar amounts of core or backiron on the rotor, stator, or both to reduce magnetic flux leakage by closing the flux path through the air-gap and to reduce the air-gap depth and associated amount of magnetizing MMF or expensive RE-PM *per unit (e.g., KW) of* electric machine *active power rating*. Replacing the backiron or core material with more RE-PM material of similar specific density may reduce core loss but is not cost effective. For instance, so-called *air-core* or *coreless* electric machines will always have a significantly larger air-gap, which jeopardizes mechanical, cooling, magnetic integrity, and larger amounts of RE-PM material with its associated environmental, geopolitical, and environmental consequences;

7) Slip-induction dependency or Magnetizing MMF burdens the active winding set with *additional* size, cost, and inefficiency of supporting the entire rotor slip-induced power or Magnetizing MMF but since Magnetizing (*or passive*) MMF is orthorgonal to Torque (*or active*) MMF, vector arithmetic shows Magnetizing MMF magnitude has much less impact on total system loss, cost, and size, particularly when considering the coveted benefits of field weakening;

8) All performance electric machine "systems" comprise an integral electronic control component and accordingly, its *compounding* loss, cost, and size should always be included in equitable system comparisons;

9) All electric machine *systems* belong to two *basic* circuit and control architectures, the *notional* Symmetric Electric Machine Circuit and Control Architecture (*i.e., BWRSDF*), which comprises an "active rotor" with a *bi-directional* electrical port for the "synchronous" control of *another* directly excited *multiphase* winding set that contributes an *additional increment* of active power to the electromechanical energy conversion process *together* with the *universally essential* active stator winding set by not *relying* on slip-induction (*i.e., synchronous doubly-fed*), or the Asymmetric Electric Machine Circuit and Control Architecture, which comprises a "passive rotor" with the *asymmetry* of slip-induction *dependent* windings, reluctance saliencies, permanent magnets, or DC field windings that are without a direct multiphase winding electrical port for active power contibution;

10) Long delays and inaccuracies of offline electronic measuring, estimating, predicting, calculating, and synthesizing shallow sloped signals inhibit any state-of-art derivative of field-oriented control (**FOC**) from stabilizing a true BWRSDF, where random rotor time constant (**RTC**), torque angle shift, or slip-induction injections, which are instigated by at least rotor temperature, rotor shaft, or supply line perturbations, *quickly* lead to destabilization without an instantaneous and deterministic control response, particularly with long settling times where signal slopes flatten to DC *about* synchronous speed.

IV. The Classic Electric Machine Study

Instead of the simple electric machine model of **Fig. 1** with the symmetrical two-phase flux (*or current*) relationships (*4.1.19 – 4.1.22*), which show two terms of magnetic sharing between the two phase windings, this classic study will consider the more applicable but complex three-phase model with the symmetrical flux or current relationships showing three terms of magnetic sharing between the three phase windings:

$$\begin{aligned}
&\lambda_{as} = AL_sI_{as} + AMI_{ar}\mathrm{Cos}(\theta) + \\
&AMI_{br}\mathrm{Cos}(\theta+120) + AMI_{cr}\mathrm{Cos}(\theta+240); \\
&\lambda_{bs} = AL_sI_{bs} + AMI_{ar}\mathrm{Cos}(\theta-120) + \\
&AMI_{br}\mathrm{Cos}(\theta) + AMI_{cr}\mathrm{Cos}(\theta+120); \\
&\lambda_{cs} = AL_sI_{cs} + AMI_{ar}\mathrm{Cos}(\theta-240) + \\
&AMI_{br}\mathrm{Cos}(\theta-120) + AMI_{cr}\mathrm{Cos}(\theta); \\
&\lambda_{ar} = AL_rI_{ar} + AMI_{as}\mathrm{Cos}(-\theta) + \\
&AMI_{bs}\mathrm{Cos}(-\theta-120) + AMI_{cs}\mathrm{Cos}(-\theta-240); \\
&\lambda_{br} = AL_rI_{br} + AMI_{as}\mathrm{Cos}(-\theta+120) + \\
&AMI_{bs}\mathrm{Cos}(-\theta) + AMI_{cs}\mathrm{Cos}(-\theta-120); \\
&\lambda_{cr} = AL_rI_{cr} + AMI_{as}\mathrm{Cos}(-\theta+240) + \\
&AMI_{bs}\mathrm{Cos}(-\theta+120) + AMI_{cs}\mathrm{Cos}(-\theta),
\end{aligned} \tag{1}$$

where $\theta = W_M T + \alpha_M$ is the rotor scalar component, W_M is the *mechanical angular speed*, α_M is the *mechanical angular phase shift*, and T is *time* with the same relationships for rotating or linear electric machines.

By expanding the symmetrical relationships of the three-phase model with the following multiphase AC input signals applied at the stator winding terminals:

$$\begin{aligned} PHASE\_A_S &= A_S COS(W_S T + \alpha_{SA} + 0_{\deg}), \\ PHASE\_B_S &= B_S COS(W_S T + \alpha_{SB} + 120_{\deg}), \\ PHASE\_C_S &= C_S COS(W_S T + \alpha_{SC} + 240_{\deg}), \end{aligned} \tag{2}$$

one induced rotor signal, which easily represents all phase windings with the appropriate phase shift, is:

$$PHASE\_A_R = k * \frac{3}{2} * \begin{bmatrix} A_S COS(W_S T + \alpha_{SA} + 0_{\deg}) * COS(\alpha_M) \\ + B_S COS(W_S T + \alpha_{SB} + 120_{\deg}) * COS(120_{\deg} - \alpha_M) \\ + C_S COS(W_S T + \alpha_{SC} + 240_{\deg}) * COS(240_{\deg} - \alpha_M) \end{bmatrix}, \tag{3}$$

where the k factor comprises static design parameters, such as the rotor and stator winding-turns ratio, and design anomalies, such as unbalanced winding sets.

With further expansion, the resulting multiphase signals at the rotor winding terminals become:

$$\begin{aligned} PHASE\_A_R &= kA_S W_R COS(W_R T + \alpha_{RA} + 0_{\deg}), \\ PHASE\_B_R &= kB_S W_R COS(W_R T + \alpha_{RB} + 120_{\deg}), \\ PHASE\_C_R &= kC_S W_R COS(W_R T + \alpha_{RC} + 240_{\deg}), \end{aligned} \tag{4}$$

where W_S, W_R and α_S, α_R, are the stator and rotor *electrical* angular frequencies and phase shifts with: a) the "Synchronous Speed Relation," $\pm W_S \pm W_R \pm PW_M = 0$, satisfied for average torque production with pole-pair count, P, b) the "Torque Angle Relation," $\pm P\alpha_M \pm \alpha_S \pm \alpha_R = \pm\alpha_T$, phase-locked for torque stablility, and c) rotor phased-vectored DC (i.e., $\pm\alpha_R$) convergently and deterministically applied to hold airgap flux steady when slip-induction excitation ceases to exist at ($W_R = 0$) or about ($W_R << slip$) synchronous speed.

For analysis, the *classic study* of the *symmetric* electric machine would control A_S, B_S, & C_S while conveniently imagining a BRTEC means that instantaneously and automatically provides the precise rotor excitation signals (4) for continuous synchronous operation in accordance to the synchrononous speed and torque angle relations, including the burden of *precisely* supplying extremely shallower slopping rotor signals that converge to phased DC *(i.e.,* $\pm\alpha_R$) as the Wr factor converges to zero when approaching synchronous speed from either sub or super synchronous speeds. In contrast, the rotor signals of the *asymmetric* electric machine with a passive rotor of slip-induction dependent windings, reluctance saliencies, DC field windings or permanent magnets are nonexistent ($W_R=0$) or asymmetrically different ($W_R=Slip$), which complicates the electric machine study but allows *non-optimal* FOC control with known rotor position and *estimated* RTC.

In order of control complexity: 1) the *symmetric synchronous* electric machine of **Fig. 1** has *twelve* sub to super synchronous speed (±) parameters, $\pm W_S$, $\pm W_R$, $\pm W_M$, $\pm\alpha_M$, $\pm\alpha_S$, & $\pm\alpha_R$, with four rotor inaccessible parameters, $\pm W_R$ and $\pm\alpha_R$, but MLS=$2W_S$ when $W_S=W_R$, 2) the sub-synchronous *asymmetric induction* machine has *six* parameters, W_S, $W_R=Slip$, W_M, α_M, α_S, α_R, with two rotor inaccessible parameters but MLS=W_S - $Slip$.

V. BWRSDF-BRTEC CONCEPT OF OPERATION

By referencing the "example" of **Fig. 2**, which is similar to the well understood electronic solid-state power transformer, only BRTEC comprises a position-dependent-flux high frequency (**HF**) transformer (**PDF_HFT**) with the same arrangement of rotor and stator multiphase winding sets as the *torque producing* symmetric multiphase wound-rotor doubly-fed electric machine entity of **Fig. 1**, which is also a position-dependent-flux but low frequency (**LF**) transformer **(PDF_LFT)**. The PDF-HFT is isolated between two stages of Synchronous Modulator-Demodulators (**SMODEMs**), which are simple solid-state "bidirectional" choppers commonly found in the popular FOC Matrix Converter but with the fractional power rating for classic BWRSDF control. The rotor or stator

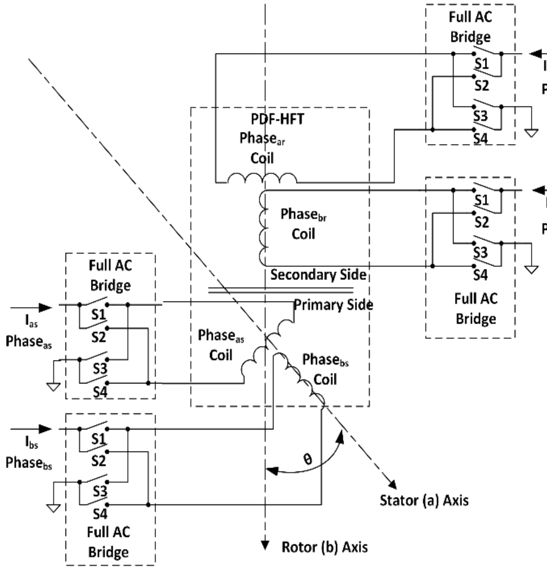


Fig. 2 BRTEC Full Bridge Example

SMODEMs naturally modulate or demodulate in accordance with the direction of power conversion.

The SMODEMs modulate the same stator phase signals applied to the PDF-LFT (2) with a bipolar HF carrier, because unlike the PDF-LFT, the PDF-HFT brushlessly propagates power by the HF carrier and not by the LF modulation envelopes of the stator multiphase signals (2). With the rotors moving together, the PDF-LFT and PDF-HFT follow the same electromagnetic process of sharing (*i.e., vectoring*) magnetic energy between phase windings with rotor position dependency; but since physics dictates mutual inductance, torque, winding-turns, loss, and size are inverse to operating frequency, the loss, size, and torque of a 24 kHz PDF-HFT example with high frequency compatible core material are up to 1/400th of a 60 Hz BWRSDF PDF-LFT (*i.e., 60/24000*). Also, the *synchronously* chopped (*i.e., bipolar*) HF carrier(s) *inherently* provides EMI filtering for purest sinusoidal excitation and resonant (*or soft*) switching opportunity for higher operating frequency, lower switching loss, stress, and noise.

Without expanding the entire Fourier Series for studying switched (*i.e., chopped*) periodic signals, one stator phase signal after SMODEM modulation is:

$$PHASE\_A_{SC} = A_{SC}COS(W_{C}T)COS(W_{S}T + 0_{\text{deg}}), \tag{5}$$

with W_C as the carrier high frequency and A_{SC} as the magnitude of the modulation envelope, which includes at least the SMODEM power conditioning factor by modulating the HF carrier.

One PDF-HFT computed rotor phase signal is:

$$PHASE\_A_{RC} = \frac{3}{2}A_{SC}W_{C}SIN(W_{C}T)COS(\pm W_{S}T \pm W_{M}T + \alpha_{ARC}). \tag{6}$$

The PDF-HFT computed rotor multiphase signals after SMODEM demodulation are:

$$\begin{aligned} PHASE\_A_{RC} &= k_{C}A_{SC}W_{C}COS(W_{R}T + \alpha_{ARC} + 0_{\text{deg}}),\\ PHASE\_B_{RC} &= k_{C}B_{SC}W_{C}COS(W_{R}T + \alpha_{BRC} + 120_{\text{deg}}),\\ PHASE\_C_{RC} &= k_{C}C_{SC}W_{C}COS(W_{R}T + \alpha_{CRC} + 240_{\text{deg}}). \end{aligned} \tag{7}$$

With mechanical and electrical connection, the PDF-HFT rotor signals (7) are sensorlessly, automatically, instantaneously, and deterministically the precise multiphase rotor signals (4) for *synchronous* PDF-LFT operation at any speed, including excitation converging to phased-vectored DC about synchronous speed, because the PDF-HFT rotor signals (7) have no zero converging W_R factor of the PDF-LFT rotor signals (4). Crucial for stable operation, all PDF-LFT rotor *or stator* parameters are seamlessly translated to the BRTEC stator port frequency, position, and amplitude.

Only the fully integrated, bi-directional, direct conversion (*no DC Link Stage*) **BRTEC** easily provides pure sinusoidal signals with any stochastic variations *sensorlessly*, *automatically*, and *instantaneously* synchronized to the angular speed and phase of the rotor (*all by the precision of "real time electromagnetic emulation"*) for stable variable speed, constant frequency (**VSCF**) control and comprehensive leading, lagging, and unity power factor correction. For example, only BRTEC *automatically* translates pure sinusoidal voltage and currents from one frequency (e.g., 50/60 Hz) to very low variable excitation frequency (e.g., 0-4 Hz) by *electromagnetically mixing* the steep sloped, "high frequency" grid input (e.g., 50/60 Hz) with the difference of a synthesized "high frequency" (e.g., 46/56 Hz), both of which are easily measured, synthesized, or controlled electronically without regard to speed or stochastic changes, and as a result, only BRTEC has full electromechanical power conversion control to "zero speed."

BRTEC is a compact, brushless multiphase "electromagnetic" commutator of the BWRSDF with a simple *self-adaptive* control resolution and efficiency of electromagnetically computing (*i.e., exact analog twin or emulation*) the phase-speed-frequency synchronization without the delays and inaccuracies of offline electronic algorithmic computing (*i.e., inexact digital twin or simulation*) of FOC. BRTEC may be functionally compared to the simple control of the *venerable* high power density Universal Motor with an "electromechanical" commutator comprising brushes riding across contacts for switching phase windings to automatically control speed-frequency synchronization but with only a single input phase, with *mechanically* fixed rotor phase shift, and with significantly higher harmonic content, lower control resolution, larger footprint, and lower reliability.

VI. BWRSDF CONCEPTUAL COMPARISON

For a simple conceptual comparison, consider an *axial-flux* asymmetric electric machine system with a given torque, voltage, and *resulting* 1x MLS comprising an "active" stator disk (*with the active winding set*) adjacent to a "passive" rotor disk (*with the asymmetry of RE-PMs, slip-induction dependent windings, reluctance* *saliencies, or DC field windings*), which are articulated by a rigid frame and bearing assembly for air-gap integrity. The rotor and stator disks reasonably show: a) similar size, structural frame, and core backiron, which are chiefly determined by the axial-flux air-gap diameter and area, b) similar loss, such as windage, and cost (*less any expensive RE-PMs*), and c) arguably, similar electrical and core loss, particularly under slip-induction operation, and similar windage and stray losses. By eliminating the entire loss, cost, and size of the passive rotor disk with the replacement of another active stator disk of similar loss, cost, and size but with an additional increment of active power (*providing 2x MLS*) and also, by eliminating the loss, cost, and size of a *full rated* FOC with the replacement of a *fractionally rated* BRTEC with half the loss, cost, and size of similar electronic components, the original asymmetric electric machine system package and structure becomes an axial-flux BWRSDF with: 1) double the power density *per unit of continuous power rating* with the combined power of two active winding sets (*i.e., twice the power ÷ same package size or weight*), 2) half the cost *per unit of continuous power rating* with the same cost/amount of materials (*less expensive RE-PMs*) but with the *compounding* cost of a *full power* rated FOC replaced with the lower cost of a *fractionally rated* BRTEC (*i.e., same (or less) cost ÷ twice the power*), 3) half the loss *per unit of continuous power rating* with the loss of the passive rotor replaced with the similar loss of an active stator but with the *compounding* loss of a *full rated* FOC replaced with the lower loss of a *fractionally rated* BRTEC (*i.e., same (or less) loss ÷ twice the power*), 4) octuple the peak torque *per unit of continuous power rating* of the original asymmetric electric machine system in accordance with the conservation of energy physics of the classic symmetric or dual ported transformer circuit topology, which neutralizes the combined air-gap flux production with increasing *torque* current and effectively, 5) double the expected performance gain *per unit of continuous power rating* of the original asymmetric electric machine system from applying performance enhancing material, winding, electronic, cooling, and manufacturing techniques.

VII. Conclusion And Future Work

As understood by over a half century of classic electric machine study [1][2][3][4], the *axial-flux* BWRSDF, as only possible with the fractional rated, self-adaptive BRTEC of this article with the automatically synchronized rotor and stator flux vectors, provides at least: 1) double the core power density and octuple the "peak" torque *per unit of continuous power rating* of *all other electric machine systems*, including RE-PM electric machine systems, with the same (*e.g., legacy*) design parameters, such as port voltage, frequency, torque, packaging, and manufacturing, by combining the active power of two similar *active* winding sets strategically placed on the rotor and stator, respectively, to preserve same form and fit to all other electric machines, 2) half the cost, loss, and size *per unit of continuous power rating* by at least eliminating the passive rotor, 3) double the expected gain *per unit of continuous power rating* with the same performance enhancing techniques, such as wide-bandgap semiconductors or high-speed operation, and 4) elimination of RE-PMs and associated cogging. Also, the *axial-flux* BWRSDF provides: 1) coveted field weakening control with half the cost, loss, and size by uniquely sharing Magnetizing MMF between rotor and stator windings, 2) comprehensive leading-to-unity-to-lagging power factor control, 3) universal DC, single or multiphase AC operation with dual fractional power BRTECs, 4) automatic grid synchronization without electro-mechanical governing, 5) true *transactive* energy harvesting, 6) modular control of individual phases with IoT, and 7) identical rotor and stator assemblies.

As a direct power conditioner with its unique symmetrically bi-directional SMODEMs and PDF-HFT combination and control *with no DC Link Stage comprising bulky chokes and capacitors*, the compact BRTEC *inherently* provides isolated multilevel power conditioning and common mode rejection to realize high power gyrators, frequency or impedance matching synchroconverters, virtual synchronous machines, or a multiphase HF micro-distribution bus that halves the cost, loss, size, and total number of active stages in a system of systems application, all of which provide a holistic approach for land, air, naval, and smart grid electrification to an efficient fossil free society.

By contactlessly swapping the location between the rotor DC field winding and the stator active winding set to simplify cryogenic logistics and with pure sinusoidal excitation, BRTEC can bring the asymmetric superconductor (*e.g., super permanent magnet*) electric machine system closer to practice; but when AC superconductors become a practical reality, the fully electromagnetic BWRSDF will be the electric machine system of choice.

As sole keeper of the BWRSDF knowledge base (*with the self-adaptive BRTEC*): 1) a textbook detailing the theory of operation was composed with non-proprietary information already professionally vetted and published, 2) multiple prototyping, including pre-production prototyping, successfully verified the BWRSDF, which were developed by retrofitting available radial-flux electric machines with PDF-HFT cores of ferrite or thin electrical steel ribbon, 3) a computer aided design tool for the *axial-flux* BWRSDF (**BEM-CAD**), which simultaneously provides equitable cross-comparative designs of highly integrated RE-PM and slip-induction motor systems with the same airgap flux density, port voltage, and packaging, was successfully developed and validated against prototyping results and available state-of-art axial-flux electric machine specifications, 4) a proprietary and only CAD programmable 3D Printer, called MOTORPRINTER, which was empirically verified by orchestrating and directing relevant experimental studies with renown fiber laser and amorphous metal companies (*without exposing trade secrets*), is being fabricated for the high-speed *additive* manufacture of axial-flux electric machines for another level of "system" power density with at least: a) integrated low (*e.g., PDF-HFT*) and high *(e.g., PDF-HFT*) frequency compatible cores, b) perfectly aligned slots and flat air-gap area between material layering, c) integrated frame assembly that also serves as the electronic controller heat sink and chassis, and d) readily available and higly optimized pre-manufactured materials, such as nanocrystalline or amorphous metal ribbon *core* and high strength structural *frame* materials, all *without* secondary finishing processes or damage to the delicate material properties, and 5) alliances are being pursued for the *axial-flux* BWRSDF design, prototyping, test, publication, and distributed additive manufacture under the digital environment with BEM-CAD.

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