A Disruptive Technological Leap for The Electric Vehicle or The Smart Grid: Brushless Multiphase Self-Commutation Control (BMSCC)

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Abstract— **By implementing the only Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Machine (i.e., electric motor or generator) System (BWRSDF-EMS) or the only Power Electronic Transformer (PET) with comprehensive adjustment of frequency and phase synchronization (for leading, lagging, or unity power factor adjustment) by high frequency magnetic power sharing between phases of a position dependent flux high frequency multiphase transformer instead of electronically conditioning large capacitor banks of reactive power, the patented Brushless Multiphase Self-Commutation Control (BMSCC) Technologies leveraged by Best Electric Machine (BEM) provide a disruptive technological leap for the electric machine system, the Smart Grid, or the propulsion and micro-distribution power bus of the electric vehicle (EV). Ongoing advancements in high performance electric machines are becoming more dependent on special pre-manufactured high performance materials, such as amorphous and nanocrystalline metal ribbon, that are difficult to manufacture into an electric machine or transformer core structure by at least the materials adversity to machinability. As a result, Best Electric Machine also leveraged the patent of the only Laminated Object Manufacturing (LOM) 3D Printer that additively manufactures axial-flux electric machine cores of virtually any size from off-the-shelf high performance materials, such as amorphous metal ribbon, with an integral frame from off-the-shelf structural building materials. This paper discusses the foundation for the claims just presented.**

***Index Terms*—Brushless, wound rotor, doubly fed, double fed, synchronous, asynchronous, electric machine, electric motor, electric generator, electric propulsion, power electronic transformer, PET, smart grid, real time emulation control, RTEC**

GLOSSARY OF TERMS

ABS	Antilock Braking System
AC	Alternating Current
BEM	Best Electric Machine (company)
BMSCC	Brushless Multiphase Self-Commutation Control Technology
BRTEC	Brushless Real Time Emulation Control
BWRSDF-EMS	Brushless and Symmetrically Stable Wound-Rotor [Synchronous] Doubly-fed Electric Machine System
DC	Direct Current
EV	Electric Vehicle
HFT	High Frequency Transformer
LOM	Laminated Object Manufacturing
PDF-HFT	Position Dependent Flux High Frequency Transformer
PET	Power Electronic Transformer or Solid State Transformer (SST)
PM	Permanent Magnet

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I. INTRODUCTION

An electric motor or generator, classically known as an electric machine, comprises a rotating assembly (i.e., rotor) and a stationary assembly (i.e., stator), which are separated by an air-gap that is rigidly maintained by a robust frame and bearing assembly to support the extreme magnetic forces between the rotor and stator regardless of movement. Because of logistical convenience of stationary electrical connection, the stator electromagnetic real-estate comprises an Alternating Current (AC) multiphase winding set that is independently excited at its electrical terminals for "active" participation in the electro-mechanical power conversion. The rotor electromagnetic real-estate comprises either permanent magnets, salient poles, or squirrel cage windings for at least the completion of the magnetic path and the "passive" maintenance of the air-gap flux. Constrained by a rotational connection and control, the rotor electromagnetic real-estate may also comprise AC or Direct Current (DC) conventional winding sets, or DC (or AC when available) superconducting winding sets, such as provided by E-Thrust, or a similar independently excited AC multiphase winding set as the stator winding set that actively provides additional electro-mechanical power conversion in conjunction with the stator winding set. By nature, all electric machines are AC devices and must include at least one (i.e., singly-fed) or at most two (i.e., doubly-fed) multiphase AC winding sets that are independently powered for active participation in the electromechanical power conversion process. The power rating of the electric machine is determined by the sum of the active winding sets.

As the major consumer (e.g., motoring) or producer (e.g., generating) of electricity, one should continually strive for energy efficient electric motor and generator (i.e., electric machine) innovation regardless of one's position on global warming. High efficiency electric machines lower cost for the frugal and lower carbon footprint for the environmentalist. For instance, electric machines provide the most compatible interface, which is electricity, for utilizing virtually any derivative of renewable energy, such as wind and solar. The superior performance and mechanical simplicity of a vehicle electric machine drivetrain alternative to the mechanical drivetrain is well known and as a result, continued improvement of electric machine efficiency, power density, and cost is a critical enabler of the electric vehicle (EV) future by at least extending the range of the EV battery with efficiency and energy capture. Compared to the conventional mechanical drivetrain, electric machines improve overall reliability (with fewer moving parts under extreme stress), lower overall maintenance (with lower mechanical complexity and no lubricating fluids, assuming transmission-less direct drive), and improve overall comfort and safety (with more responsive and higher resolution of antilock braking (ABS), traction, and stability control) of the EV.

II. Brushless Wound-Rotor Synchronous Doubly-fed electric Machine system (BWRSDF-EMS)

The patented Brushless and Symetrically Stable (e.g., motoring or generating) Wound-Rotor [Synchronous] Doubly-fed Electric Machine System (BWRSDF-EMS), which is in the technology portfolio leveraged by Best Electric Machine referred to as Brushless Multiphase Self-Commutation Control technologies (BMSCC), is the only electric machine that actively utilizes the electromagnetic real-estate of the rotor in the electromechanical power conversion process in addition with the stator's electromagnetic real-estate through-out its unique constant torque speed range of twice synchronous speed under a given frequency (and voltage) of excitation and without operational discontinuity about synchronous speed.

Only a multiphase AC winding set with its own AC power port develops a rotating (i.e., moving) magnetic field vector in the airgap that can perform work (i.e., active power) relative to the frame of the winding set. The other means of developing an air-gap moving magnetic field vector is by a rotor assembly with: 1) salient poles that change the reluctance of the magnetic path (and magnetic field vector) by rotor movement, 2) permanent magnets (PMs) or DC field winding that change the magnetic field vector by rotor movement, and 3) moving multiphase AC winding sets that are without an independent power port but instead excited by inductive coupling with the stator independently excited multiphase AC winding set as a result of the asynchronous relative movement or slip (i.e., slip induction) between the rotor and stator. With no power port, salient poles (reluctance) and PM are obviously *passive* devices. Not being a multiphase AC winding set, DC field windings are *passive* devices. Multiphase AC winding sets without an independent power port but excited by slip induction may be *active* or *passive* devices (only when there is slip) but the stator power alone must be rated for both the electromechanical conversion power with associated cost, size, and loss plus the rotor slip induction power with associated cost, size, and loss, which proportionally compounds the cost, size, and loss of the entire electric machine while lowering power density.

Notably by a patented Brushless Real-Time Emulation Control (BRTEC) method provided by BMSCC, the BWRSDF-EMS "synchronously and without electrical contacts (i.e., brushlessly)" excites both rotor and stator multiphase AC winding sets through their independent electrical power ports and as a result, the BWRSDF-EMS is the only doubly-fed electric machine that does not rely on slip induction with the operational discontinuity about synchronous speed and with the compounded cost, size, and inefficiencies associated with slip induction. By reasonably assuming a rotor assembly shows similar combination of loss, cost and size to the active stator assembly (as recognized in at least an axial-flux induction electric machine form factor), the unique but simple concept of operation of BMSCC where the rotor real-estate actively combines with the power production of the stator real-estate (*as only provided by a wound-rotor dual ported rotating transformer topology operating under synchronous principles and not slip induction principles*) effectively doubles the BWRSDF-EMS power density (Power Output/Volume) and improves the BWRSDF-EMS efficiency (Power Output/Power Input) while halving the BWRSDF-EMS cost ($/Power Output) over present or futuristic electric machine technologies.

III. BWRSDF-EMS High Power Density And Low Cost Claim

With the patented brushless connection and seamless control of BMSCC, the BWRSDF-EMS conceptually replaces the passive rotor electromagnetic real-estate of the classic electric machine (with associated size, loss and design complexities) with another "active" electromagnetic assembly that is similar to the stator active assembly (with associated size, loss and design complexities) but with bearing and electrical connection assemblies for rotational capability.

- With twice the electro-mechanical conversion power (i.e., Power Out) provided by combining the power of two active electromagnetic assemblies within the same electric machine package structure and size, the power density (Power Output/Volume) of the BWRSDF-EMS calculates as double that of all other electric machine, including high performance permanent magnet electric machines, where the rotor is a passive device that occupies real-estate (and dissipates loss) without electromechanical power production.
- With twice the electro-mechanical conversion power (i.e., Power Out) within the same electric machine package structure and size and with the same amount and types of material, the cost ($/Power Output) of the BWRSDF-EMS calculates as halved that of any other electric machine.
- With similar electromagnetic structure and form, present or evolving motor performance enabling technologies are equally (or even more) adaptable to the BWRSDF-EMS, such as Silicon Carbide wide bandwidth semiconductors (SiC), high performance magnetic materials, exotic form factors, rectangle wire, etc.
- Although the BWRSDF-EMS form factor topology and circuit control topology are different from all other electric machine systems, their design and manufacture are virtually the same. So, the manufacturing processes for the BWRSDF-EMS are no different from any other electric machine but as a fully electromagnet electric machine, the manufacturing processes may even be more compatible for the BWRSDF-EMS.

IV. BWRSDF-EMS High Efficiency Claim

Consider: 1) Efficiency is basically the Total Power Output divided by the Total Power Input, 2) P_S is the electromechanical power conversion (Power Output) of the stator assembly that is only provided by an independently powered multiphase AC winding set (i.e., active power), 3) P_{LS} is the electrical loss of the stator assembly due to the stator torque current, which for this study, includes associated magnetic core loss as a result of stray induction, harmonics, or magnetic path change as a result of movement, 4) P_{MS} is the electrical loss due to stator magnetizing current that establishes the air-gap magnetic flux density, which for this study, includes associated magnetic core loss as a result of stray induction, harmonics, or magnetic path movement, 5) P_R is the active (Power Output) of the rotor assembly that is only provided by an independently powered multiphase AC winding set (P_R equal to zero for a "passive" rotor assembly), 6) P_{LR} is the electrical loss of the rotor assembly due to rotor torque current, which for this study, includes associated magnetic core loss as a result of stray induction, harmonics, or magnetic path movement but does not include windage and friction losses (P_{LR} equal to zero for a "passive" rotor assembly), 7) P_{MR} is the electrical loss due to stator magnetizing current that establishes the air-gap magnetic flux density, which for this study, includes associated magnetic core loss as a result of stray induction, harmonics, or magnetic path movement, and 8) Magnetizing Current magnitude, which establishes the air-gap flux density for electric machines without permanent magnet, could be as high as 30% of torque current magnitude but always with the magnetizing current vector orthogonal to the torque current vector.

At full power for the Permanent Magnet (PM) Electric Machine (*with a passive rotor assembly*, $P_R = 0$, $P_{LR} = 0$, $P_{MS} = KP_{LS}$, *where K represents rotor losses from stray induction, harmonics, or moving magnetic field or path. The higher the K the higher the rotor electrical loss*).
The Total Power Input for the Conventional Electric Machine = $P_S + P_{LS} + KP_{LS}$;
The Total Power Output for the Conventional Electric Machine = P_S; (*the power of a single independently powered active multiphase winding set on the stator or singly-fed*);
The Total Power Loss $\approx (1 + K)P_{LS}$;
The Total Efficiency for the Conventional Electric Machine = $P_S \div (P_S + (1+K)P_{LS})$;

At full power for the BWRSDF-EMS (with a *synchronously active rotor assembly*, $P_S = P_R$, $P_{LS} = P_{LR}$, $P_{MR} = P_{MS} = (0.3/2)^2 P_{LS}$, *where Magnetizing Current is evenly shared between rotor and stator MMF and can be up to 0.3 (i.e., 30%) of the torque current magnitude (steady state) or more for extremely high air-gap flux density as expected from a double ported transformer topology. Note: Electrical Power Loss is I^2R, where I is current magnitude and R is winding resistance*).
The Total Power Input for the BWRSDF-EM = $P_S + ((P_{LS})^2 + (P_{MS})^2)^{1/2} + P_R + ((P_{LR})^2 + (P_{MR})^2)^{1/2} = 2P_S + 2((P_{LS})^2 + (P_{MS})^2)^{1/2} = 2P_S + 2((P_{LS})^2 + (0.3/2)^4(P_{LS})^2)^{1/2} = 2P_S + 2P_{LS}(1 + (0.3/2)^4)^{1/2} = 2P_S + 2P_{LS}(1.0225)$;
The Total Power Output for the BWRSDF-EM = $2P_S$; (*the combined power of two independently powered active multiphase winding sets on the rotor and stator, respectively, or doubly-fed*);
The Total Power Loss $\approx 1.0225P_{LS}$; $K \approx 0.0225$;
The Total Efficiency for the BWRSDF-EM = $P_S \div (P_S + 1.0225P_{LS})$;

At full power for the Induction Electric Machine (*with a passive rotor assembly*, $P_R = 0$, $P_{LR} = 0$, $P_{MS} = (0.3)^2 P_{LS}$).
The Total Power Input for the Conventional Electric Machine = $P_S + ((P_{LS})^2 + (P_{MS})^2)^{1/2} = P_S + ((P_{LS})^2 + ((0.3)^2 P_{LS})^2)^{1/2} = P_S + 1.09P_{LS}$;
The Total Power Output for the Conventional Electric Machine = P_S; (*the power of a single independently powered active multiphase winding set on the stator or singly-fed*);
The Total Power Loss $\approx 1.09P_{LS}$; $K \approx 0.09$;
The Total Efficiency for the Conventional Electric Machine = $P_S \div (P_S + 1.09P_{LS})$;

Considering the previous analysis, the BWRSDF-EMS and the PM electric machine systems are always more efficient than other electric machines that operate with slip frequency induction principles, where $K \approx 0.09$ (e.g., 9% of the electrical loss of the induction electric machine is associated with magnetizing current and associated stray induction, harmonics and core loss). The BWRSDF-EMS ($K \approx 0.0225$) is more efficient than the PM electric machine, if the PM electric machine $K > 0.0225$. Likewise, the BWRSDF-EMS is less efficient than the PM electric machine system, if the PM electric machine $K < 0.0225$. However, the BWRSDF-EMS will always be half the cost and half the size of any electric machine system and in particular, significantly lower cost than high-performance PM electric machines with very expensive rare-earth PMs.

It is undisputable that electronic control of electric machines (i.e., electric machine system) significantly increases the overall system efficiency and as a result, it is anticipated that all electric machines will eventually be electronically controlled. The PM (or synchronous), the reluctance, and the BWRSDF-EMS electric machine systems require electronic control for practical operation. But with the electronic controller rated for only half the power rating of other electric machines, the BWRSDF-EMS should provide additional cost, size and efficiency over all other electric machine systems, regardless of the PM electric machine K value and as a result, making BWRSDF-EMS the most efficient electric machine system.

Although the magnetizing current vector produces a component of electrical loss (albeit, orthogonal to the torque current vector component of loss), magnetizing current provides coveted field weakening capability for extended speed range and higher peak air-gap flux density and torque (albeit based on dissipation) than high performance PM electric machine systems. After all, magnetizing current is the working of superconductors, which have the highest flux density potential by far (albeit because of very low resistivity and resulting dissipation). Paradoxically, high performance PM electric machine systems are introducing magnetizing current components (with associated cost, size, and electrical loss with the potential of PM stress and demagnetization) to provide at least field weakening capability, which begs the question, "*Why use low or high performance permanent magnets in the first place*."

A March 2017 article in Power Magazine with reference articles, "A 100% Renewable Grid: Pipe Dream or Holy Grail?," indicated material resources, in particular rare earth elements (REE) for high performance Permanent Magnets (PM) use in electric motors and generators (i.e., electric machines), such as neodymium, are a major impediment to the 100% renewable grid because the entire global supply of RRE would not meet the expected demand for electric machines, if wind turbines and electric vehicles became the necessary norm. The article did not consider an important doping element for high performance PM, dysprosium, which is much rarer and more expensive than neodymium. The article goes on to suggest that electric machine alternatives, which are without high performance permanent magnets and as a result, show lower power density, must be pursued to meet the 100% renewable grid. SYNCHRO-SYM is an electric machine system that is without high performance or RRE PMs but shows higher power density, lower cost, and higher efficiency.

V. BMSCC Attribute Overview

The patented brushless wound-rotor synchronous doubly-fed electric machine system a.k.a. SYNCHRO-SYM is the only available "*synchronous*" and "*symmetrically stable*" doubly-fed electric machine system *while motoring or generating* between sub-synchronous to super-synchronous speed, including at zero speed and about synchronous speed; hence, the name SYNCHRO-SYM for "*synchronous*," for "*symmetrically stable*," and for "*symmetrical doubly-fed circuit topology*." In consideration, SYNCHRO-SYM should never be confused with any conventional *induction (or asynchronous)* doubly-fed electric machine system, such as the slip-energy recovery induction electric machine system with a multiphase wound-rotor connect through a multiphase slip-ring-brush assembly (or even a circular rotating transformer) or the so-called brushless doubly-fed electric machine systems with dual stators of unlike pole-pairs. As a "*synchronous electric machine system*" with four quadrant operation, SYNCHRO-SYM does not rely on slip-induction for operation nor does SYNCHRO-SYM exhibit operational discontinuity about synchronous speed where slip-induction ceases to exist.

Electric Machine design iteration has many variable that are based on electric machine construction, packaging, material, and design optimization, which are available to all, such as cooling, airgap flux density, winding conductor gauge and material, frame, standard sizing, flux saturation limit of the core, etc. but have dramatic effect on size, weight, performance, heat dissipation, etc. For fair comparison between other electric machine systems and SYNCHROSYM, the same construction, packaging, material, and design optimization (available to all) must be equally applied. Only then, the following unique but natural attributes of SYNCHROSYM stand out from all others:

- SYNCHRO-SYM is the only electric machine with twice the *continuous* constant-torque speed range for a given frequency (and voltage) of excitation (e.g., 7200 RPM @ 60 Hz with 2 Poles), which is a natural indicator of at least high power density, and the only electric machine with both the rotor and stator (or the entire electric machine real-estate) "*actively*" contributing to electromechanical power production. Considering the "active" rotor of SYNCHRO-SYM is unlike the "*passive*" squirrel cage (e.g., induction electric machine), salient pole (e.g., reluctance electric machine), permanent magnet (e.g., synchronous electric machine), or field winding (e.g., synchronous electric machine) rotor of all other electric machine systems, all of which consume virtually half of the entire electric machine real estate while showing additional loss and cost but do nothing other than support the air-gap magnetic flux path with half the *continuous* constant-torque speed range under the same frequency (and voltage) of excitation (e.g., 3600 RPM @ 60 Hz with 2 Poles), which is a natural indication of at least lower power density.
- SYNCHRO-SYM has an exclusive dual-ported symmetrical circuit and control topology for optimum electromagnetic performance.
- Virtually every aspect of electric machine design is well known, including radial-flux, axial-flux, and transverse-flux form factors. As a fully electromagnetic electric machine, the traditional wound-rotor doubly-fed electric machine entity of SYNCHRO-SYM (but without the multiphase-slipring-assembly) leverages the same knowledge base as any other electric machine.
- SYNCHRO-SYM does not require exotic and expensive materials or technology, such as rare earth permanent magnets.
- SYNCHRO-SYM can leverage legacy or future electric machine design, manufacturing, technologies, and off-the-shelf components.
- SYNCHRO-SYM provides leading, lagging, or unity power factor correction in an AC power environment,
- SYNCHRO-SYM operates under DC, single phase AC, or multiphase AC, 6) SYNCHRO-SYM has field weakening capability, and
- The classic dual ported (symmetrical) transformer (electric machine) topology (as only provided by SYNCHRO-SYM) neutralize the primary and secondary active MMF across the air-gap above magnetizing MMF and as a result, increasing active currents (called torque current) can increase dramatically without saturating the core to provide factors of higher peak torque and power than all other electric machines, which are asymmetrical transformer electric machines, such as squirrel cage induction, reluctance, field wound, permanent magnet (PM), and induction doubly-fed electric machines, where the air-gap flux density increases with increasing torque current, which always leads to core saturation and limited peak torque. High peak torque density is a necessity for transmission-less (direct drive) propulsion drives, such as for electric vehicles.
- The steady state flux density of all electric machines is designed to the same flux density saturation limit of the core material available to all. However, the steady state flux density of conventional asymmetrical transformer electric machine cores must be design lower than the core's saturation limit to compensate for increasing torque MMF that leads to core saturation but the flux density of only the symmetrical (dual-ported) transformer SYNCHRO-SYM core can be designed close to the saturation limit of the core for higher steady state air-gap flux without concern for core saturation.
- The power rating of any electric machines is based on the power rating of the stator active multiphase AC winding set. Considering the steady state flux density of the core is virtually the same amongst electric machines optimally designed to the saturation limits of the core material available to all, all stators show the same power density when optimally designed, particularly in an axial-flux form factor, regardless of the category of electric machine (with the exception of the induction electric machine stator that also supports the magnetizing current induced on the rotor winding). Note: Obviously, permanent magnets (or DC field windings), salient poles, and squirrel cage windings are passive devices that do not contribute to power rating and a doubly fed electric machine has two active multiphase AC

winding sets with double the power rating.

- SYNCHRO-SYM has copper windings on the rotor and stator, respectively, albeit both are active copper windings. Already copper squirrel cage rotor induction machines with only an active stator winding are showing nearly similar power density, cost, and efficiency as the high performance permanent magnet electric machines.
- Without permanent magnets, SYNCHRO-SYM needs magnetizing MMF to establish the air-gap flux density but the magnetizing MMF is vector shared between the rotor and stator multiphase winding sets and as a result, magnetizing MMF loss is one-quarter induction electric machines (I^2R).
- With magnetizing current, SYNCHRO-SYM has field weakening which increases speed bandwidth (i.e., constant horsepower speed range). Ironically, PM electric machines are adding magnetizing current (and associated cost, size, and electrical loss) to duplicate the intrinsic benefit of magnetizing current electric machines, such as SYNCHRO-SYM, so why not just go to copper rotor induction electric machines (or better still, go to SYNCHRO-SYM, which has half the loss, half the cost, and twice the power density of an induction electric machine) instead of the expensive high performance PM electric machines.
- The size, cost, and electrical loss (efficiency) quantification of any electric machines is related to the conversion power rating (per kilowatt). For instance, an electric machine with the same size assembly as another electric machine but supports twice the conversion power, such as SYNCHROSYM, shows twice the power density as the other electric machine. An electric machine with the same amount of the same material (in the same assembly) as another electric machine but supports twice the conversion power, such as SYNCHROSYM, shows half the cost per KW as the other electric machine. An electric machine that shows the same electrical loss as another electric machine, such as the induction electric machine, but supports twice the conversion power, such as SYNCHROSYM, shows half the electrical loss per Kw as the other electric machine.

SYNCHRO-SYM is a fully integrated electric machine system with a proprietary Brushless Real Time Emulation Controller (or BRTEC a.k.a. BMSCC) that is shared across the rotor and stator assemblies without contact. In an axial-flux form factor, SYNCHRO-SYM's rotor and stator assemblies and BRTEC are mirror images (symmetrical components), which simplify design and manufacture while providing the most optimum electromagnetic performance. Acknowledged by doubly-fed electric machine experts for over a half century, the invention of BRTEC is essential: 1) for realizing a brushless and symmetrically stable wound-rotor [synchronous] doubly-fed electric machine system, 2) for providing a rotor that "actively" contributes to electromechanical power production with the stator assembly, 3) for nearly pure sinusoidal winding excitation, and 4) for eliminating today's dependence on rare earth permanent magnets while providing higher power density and lower cost. The integrated BRTEC is also a direct AC or DC to AC or DC solid state (or power electronic) transformer (or SST/PET) with an inherent and unique compact high frequency step-up transformer for high voltage winding excitation (regardless of the input voltage specification) and for absolute resolution of position and speed. BRTEC is without a DC Link stage comprising large chokes or capacitors that significantly reduce controller reliability and efficiency while increasing controller size and cost. Side Note: Without going into detail, BRTEC can make the superconductor electric machine system a practical reality by easily and conveniently relocating the superconductor field windings and cryogenic refrigeration support to the stator body.

VI. BMSCC Evolving Products

Since AC windings and core show more dissipation than DC field windings and with the extravagant size, inefficiency, complexity, and cost associated with supplying 60 watts of extraneous cryogenic cooling power for every 1 watt of superconducting winding dissipation, today's superconductor windings are relegated to the passive rotor DC field winding set of an electric machine. But by implementing BMSCC technologies in superconducting electric machine, the passive superconducting DC field windings can at least be uniquely, conveniently and inexpensively relocated on the stator assembly for simpler cryogenic cooling while brushlessly relocating the active multiphase winding set to the rotor assembly with perfect synchronization and virtually no harmonic distortion. Realizing every electric machine must include at least one multiphase AC winding set, where the majority of loss occurs, a viable multiphase AC superconductor winding set is today's holy grail of electric machine performance research. But as a fully electromagnet synchronous electric machine (with only multiphase AC windings on the rotor and stator, respectively), a viable AC superconductor would again make the BWRSDF-EM the holy grail of all electric machines by doubling power density and efficiency while halving cost over all other AC superconductor electric machines.

With size, cost, and efficiency dependent on higher frequencies, High Frequency (HF), High Power (HP) Electromagnetic Transformers (HFT) are essential for the ongoing future of electronic power conditioning and conversion of electricity as required by the Smart Grid or high voltage, high frequency micro-distribution bus for propulsion systems. A position dependent flux HFT or position dependent flux high frequency transformer (PDF-HFT) as only provided by the patented BMSCC technologies enables direct AC/DC to AC/DC conversion by a power electronic transformer (PET) [1] method that uniquely provides high frequency magnetic power sharing between phases of a position PDF-HFT for comprehensive adjustment of grid frequency synchronization and phase synchronization (e.g., leading, lagging, or unity power factor adjustment) without electronically conditioning large capacitor banks of reactive power. As the most costly, delicate, life limited, inefficient, and overall unreliable component of any PET, reducing (or eliminating) the size and cost of storage or smoothing capacitors is the goal. Also, the circuit topology of BMSCC provides isolated multi-leveling capability while conveniently using the inherent junction capacitance of the power semiconductors for soft switching (resonant switching). In the BWRSDF-EMS configuration, BMSCC becomes a brushless real time emulation controller (BRTEC). Truly independent of frequency and line amplitude by eliminating the process delays and inaccuracies of speed and position measurement, particularly at low speeds, offline process simulation (or modeling), and synthesizing speed synchronized variable frequency sinusoidal excitation, such as performed by the process model of any derivative of conventional and field oriented control, BRTEC has been envisioned by experts for decades to be the only enabler of a brushless and symmetrically stable (i.e., motoring and generating) wound-rotor [synchronous] doubly-fed electric machines, if ever invented.

VII. 3D Manufacturing Products of BMSCC Technologies

All electric machines (and conceivably high frequency high power transformers) mainly comprise: 1) stacks of thin laminated electrical steel specially processed for high magnetic permeability and high electrical resistivity to mitigate the negative effects of stray magnetic core induction by changing magnetic fields or paths and 2) multiple turns of thinly insulated copper wire or magnet wire to improve winding packing density while reducing electrical loss and magneto-motive-force (MMF) under a given port voltage. In addition to mechanical bearings and frame assemblies, magnet wire and electrical steel are specially manufactured under mature, atomically tailored processes that ideally provide the highest volume, lowest cost, and lowest waste results. Secondary manufacturing processes, such as 3D Printing, are greatly limited by the complexity of multiply isolated assemblies, by the multiply diverse materials, or by the poor ductility of the material to manufacturing, such as extreme hardness, but worse, secondary processes adversely change the special electrical and magnetic atomic properties of the pre-processed materials, such as permeability, flux saturation density, magnetic loss, and structural strength that cannot be replicated on the atomic level without the original tailored processing. More importantly, high performance electric machines or high frequency, high power transformers are becoming more reliant on higher performing electrical core materials, such as amorphous or nanocrystalline metal ribbons, to at least meet pending efficiency standards. Accordingly, a viable secondary manufacturing means must be invented that does not compromise the superior properties of high frequency, high permeability, high saturation density, low loss, high strength when manufactured into a magnetic core structure.

Fortunately, electric machines (or conceivably high frequency high power transformers) are limited to only three form factors, such as axial flux, radial flux, and the very uncommon transverse flux, with simple scaling of dimensions for power rating. As a result, the only critical electromagnetic and electromechanical design variables are the slots and the slot channel shapes (where the windings, permanent magnets, or salient poles reside), which are easily formed in a layered two-dimensional plane that specifically accommodates Laminated Object Manufacturing (LOM) 3D Printing of axial-flux electric machines and high frequency high power transformers. Without leveraging the legacy inventory of slot channel shapes (for at least winding slots), critical electromagnetic and electromechanical design analysis for LOM 3D Printer program input (for instance), such as finite element analysis (FEA), is similarly focused on the slot shape. In addition, the axial-flux form factor is commonly known to have higher efficiency and power density while using 10-20% less copper and steel over the three form factors of electric machines but some argue that the axial-flux form has frame and bearing assembly challenges, particularly with high performance PM electric machines, and manufacturing challenges of aligning or cutting slots channels in a wrapped core of thin electrical steel ribbon.[2] Best Electric Machine has leveraged the patent of the only LOM 3D Printer, called MotorPrinter, that additively manufactures axial-flux electric machine cores of virtually any size from tailored off-the-shelf high performance, ultrathin electrical steel ribbon with perfectly align slot channels and an accommodating integral frame assembly from inexpensive off-the-shelf raw structural steel or aluminum materials, such as bar stock, instead of the usual inventory of preordered castings of specific designs. Because of the divergent and delicate properties of the bearing assemblies and winding materials, no 3D Printer has yet been conceived that can successfully additively manufacture these materials and assemblies into a core structure as does MotorPrinter. As a result, optimally manufactured off-the-shelf bearing and winding components will be automatically assembled and wound to provide high packing density and low waste. The holy grail of 3D Printing is rapid manufacture by layering atomically raw material as input with no waste as output but all 3D Printers input specially manufactured raw materials that are specifically compatible with the workings of the 3D Printer brand, such as powders or filaments of special metal or plastic mixtures, and output a low volume of waste that is generally sent back for reprocessing. But unlike all other 3D Printers, which input specially processed materials for compatibility, MotorPrinter inputs raw off-the-shelf highest performance core materials and insulated conductors, such as amorphous metal ribbon, raw structural building materials, and magnet wire, that are optimally manufactured themselves for lowest waste and cost and outputs comparably low slot waste that can be easily reprocessed. [3]

Notably with no viable result after investing millions of venture dollar by at least ABB, the Persimmon 3D Printer of electric machines (and conceivably high frequency high power transformers) is the only known potential alternative to MotorPrinter. Persimmon uses an innovative deposition method that sputters microscopic droplets of molten metal mixture simultaneously with an insulating oxide coating into a layered core design that can optimally assume virtually any shape. But the non-homogenous properties of Persimmon's soft or composite magnetic material dramatically reduce core loss (by proportionally approaching the high electrical resistivity of the oxide coating barrier) but also, dramatically increase the core reluctance to magnetic flux (by proportionally approaching the low magnetic permeability of the oxide coating), which effectively increases air-gap depth and lowers core flux density under a given magneto-motive-force (MMF). Likewise, the structural strength and heat dissipation of the core are proportionally limited by the poor structural strength and low heat conductivity of the oxide coating. In contrast, the solid homogenous properties of amorphous ribbon used by MotorPrinter achieve nearly the same core resistivity as soft magnetic cores but with considerably higher magnetic permeability and flux density under a given MMF, which also reduces core size and increases core efficiency. In addition, the structural strength and heat conduction of the core approaches the high structural strength and heat conduction of the solid amorphous ribbon but the core form is limited to the optimal axial-flux form factor. Where the magnetic and electrical performance properties of soft magnetic composites are on the particle and or even nano-particle level, the electromagnetic performance properties of amorphous metal ribbon are on the atomic level.

High performance electric machine and transformer materials, such as amorphous metal ribbon and rectangle magnet wire, are already available from off-the-self stock but because of their poor ductility and extreme hardness, these materials have yet to be practically applied in electric machines or axial-flux transformers without compromising their optimized properties. So why 3D Print axial-flux electric machine and high frequency transformer cores with integral frame as *only* provided by MotorPrinter:

- MotorPrinter is the only additive means of manufacturing electric machine and high power high frequency transformer cores with amorphous or nanocrystalline ribbon, which is the strongest, highest performing electromagnetic material available but have poor ductility to manufacturability, and with a robust integral frame.
- MotorPrinter manufactures the axial flux form, which has been shown to use the least amount of copper and electrical steel but provide the highest torque with the most efficiency.
- MotorPrinter's additive raw input materials are readily available from off-the-shelf material stock, such as amorphous metal ribbon, which are already optimized at the atomic level (structural, heat conductive, electromagnetic, efficiency, etc.) with specialized manufacturing processes for the highest performance possible but with the lowest waste, lowest cost, and highest volume possible.
- MotorPrinter is an enabling technology for the patented Brushless Multiphase Self-Commutation Control (BMSCC) technology or Real Time Emulation Control (BRTEC) that is the enabling technology for smart grid electronic conversion but more importantly, for the only synchronous wound-rotor doubly-fed electric machine technology, all of which rely on the combination of low and high frequency magnetics with magnetic power sharing instead of large capacitors banks, which is only practical with amorphous or nanocrystalline ribbon cores.
- An electric machine expert and industry icon, Mr. John Petro wrote, "An axial motor stator can be wound around a mandrel and built up in layers. One interesting patent in this area is U.S. 8,505,351, where an axial motor stator is constructed in a rolled-up assembly."
- MotorPrinter will globally democratize high performance electric machine manufacture with the highest performance materials available by stabilizing distribution and equalizing manufacturing.

VIII. Conclusion

There is still room for advances in electric machine and power electronic transformer (PET) technologies as illustrated by the numerous and recent professional articles in at least the fields of electric propulsion and Smart Grid. [1],[4],[5],[6]. Brushless Multiphase Self-Commutation Control technologies (BMSCC) is a new circuit technology that implements the only Brushless Wound-Rotor Synchronous Doubly-fed Electric Machine System (BWRSDF-EMS) and the only Power Electronic Transformer (PET) with comprehensively adjustable frequency and phase synchronization, which go beyond industry's present research and invention for electric vehicles and Smart Grid. Still, all future advances in electric machine and power electronic transformer (PET) technologies will likely rely on manufacturing techniques, such as 3D Printing (or additive manufacturing) as only provided by MotorPrinter, that enable the use of forever evolving high performance, high power, and high frequency electromagnetic materials, such as amorphous metal, that continually improve the size and efficiency of the electric machine and Smart Grid technologies while reducing the cost.

References

[1] Jonas E. Huber and Johann W. Kolar, "Solid-State Transformers," IEEE Industrial Electronics Magazine, Sept. 2016, page 19-28).

[2] Zahra Nasiri-Gheidari, Hamid Lesani, "A Survey on Axial-Flux Induction Motors," PRZEGLAD ELEKTROTECHNICZYN, ISSN 0033-2097, R.88 NR2/2012.

[3] Best Electric Machine formulized and then conducted empirical studies with several Fiber Laser Cutter companies, such as IPG Photonics, Oxford, Ma., and an amorphous metal ribbon manufacturer (i.e., Metglas) that showed high speed cutting of slots on a layer of amorphous metal ribbon is possible by at least tuning the performance of the laser cutter.

[4] MOTORPRINTER is essential for manufacturing high frequency, high power transformers (with amorphous metal) for at least BMSCC power electronic (or solid-state) transformers.

[5] Quing-Chang Zhong, "Virtual Synchronous Machines," IEEE Power Electronics Magazine, Dec. 2016, page 18-27).

[6] Bulent Sarlioglu, Casey T. Morris, Di Han, Silong Li,, "Driving Toward Accessibility," IEEE Industry Applications Magazine, Jan-Feb.. 2017, page 14-25).