SUPERIOR ALTERNATIVE TO RARE-EARTH PERMANENT MAGNET ELECTRIC MOTORS AND GENERATORS

Frederick William Klatt
Best Electric Machine
fred.klatt@BestElectricMachine.com

***Abstract* – By conceptually replacing the "passive rotor" of any "asymmetrical" axial-flux electric motor or generator system, such as rare-earth permanent magnet (RE-PM) rotors, with an "active rotor," as only possible by the enabling technology of brushless real time emulation control means, simple "qualitative observation" proves that the resulting brushless, stable, and "symmetrical" multiphase wound-rotor doubly-fed "synchronous" electric machine system would show half the cost, half the size, half the electrical or core loss, and up to octuple the peak torque as the original asymmetrical axial-flux electric machine system with the same voltage, air-gap flux density, air-gap effective area, materials, manufacturing, winding, and excitation techniques.**

***Index Terms*—brushless, real-time, sensor-less, synchronous, wound-rotor, doubly-fed, electronic power transformer**

I. INTRODUCTION

By conceptually replacing the "passive rotor" of any "asymmetrical" axial-flux electric motor or generator system, such as rare-earth permanent magnet (RE-PM) rotors, with an "active rotor," as only possible by the enabling technology of brushless multiphase real time emulation control (BRTEC), simple "qualitative observation or analysis" conveniently proves that the resulting brushless, stable, and "symmetrical" multiphase wound-rotor doubly-fed "synchronous" electric machine system would show half the cost, half the size, half the electrical or core loss, and up to octuple the peak torque as the original asymmetrical axial-flux electric machine system: a) with the same electromechanical construction and formfactor, such as the same effective airgap area, the same airgap flux density, the same voltage rating, the same electrical or core loss, the same amount and cost of materials (less any extraneous components, such passive RE-PMs, saliencies, slip-induction windings, etc.), b) with the same packaging art, such air-gap flux density, physical footprint, excitation waveform, materials, winding, construction, and manufacturing techniques, and c) by reasonably assuming the cost of the packaging art is directly related to the amount of materials being applied.

II. TECHNOLOGY BACKGROUND

All electric motors and generators (traditionally called electric machines) are polyphase alternating current (AC) electric machines because only a multiphase AC winding set "directly" excited at its terminals (or "active" winding set) independently establishes a "moving" magnetic field that pushes or pulls on the other magnetic field of the rotor or stator bodies for "active" participation (*and power contribution*) to the electrical to mechanical (or electromechanical) power conversion process. Today's electric machine "systems" commonly employ electronic control of the "active" winding excitation waveform to tune the speed or torque for optimum performance or fpr at least providing practical operation, such as for permanent magnet and reluctance electric machine systems.

The rotor of virtually all electric machines comprises either slip-induction dependent windings that are fundamentally "leakage" winding extensions of the stator active winding set, a DC field winding that is generally connected through a single phase slip-ring assembly, permanent magnets, or reluctance saliencies in order to avoid the formidable technical challenges of directly providing precision speed-synchronized "multiphase" AC electrical excitation power to the terminals of a rotating "active" winding set from sub-synchronous speeds, such as zero speed, to super-synchronous speeds, such as twice synchronous speed, and including at or about synchronous speed. Without a directly excited multiphase AC winding set, the rotor assembly reasonably consumes half of the volume, half of the cost, and half of the electrical (or core) loss of the electric machine system but can only "passively" participate in the electromechanical power conversion process, such as simply completing the magnetic path through the air-gap or establishing steady-state air-gap flux density, which leaves the entire electromechanical "power production" exclusively to the "active" winding set of the stator assembly (i.e., singly-fed electric machine).

With direct excitation at the terminals of multiphase winding sets on the rotor and stator, respectively, uniquely providing: 1) independent precision control of the position and amplitude of the rotor and stator synchronized rotating magnetic fields (or magneto-motive-force i.e., MMF) without regard to the rotor winding time constant, speed, or position but with at least *field weakening* capability for improved efficiency and extended speed range, 2) freedom from relying on the time-constant imprecision of winding speed-based (or slip) current induction that ceases to exist about synchronous speed, and 3) a dual ported transformer circuit topology (i.e., doubly-fed electric machine), the resulting "symmetrical" electromagnetic circuit relations at the terminals of the symmetrical multiphase wound-rotor doubly-fed "synchronous" class of electric machine (see Figure 1) formulized more than a century ago become the classic study for all other types of electric machines by deoptimizing their symmetry with the "asymmetry" of

Notice:

substituting the rotor "active" winding set with "passive" DC field windings or permanent magnets for synchronous electric machines, saliencies for reluctance electric machines, or slip-induction windings for asynchronous electric machines (i.e., "asymmetrical" electric machines).

Although the inherently unique and attractive attributes of the "symmetrical" multiphase wound-rotor doubly-fed "synchronous" electric machine system were postulated long ago from its "symmetrical" electromagnetic circuit relations, such as half the size, half the electrical and core loss, half the cost, and octuple the peak torque as any asymmetrical electric machine system with the same electromechanical construction and formfactor, the postulated enabling inventions of a practical sensorless and automatic (i.e., emulation) control means to instantaneously (i.e., real time) compensate for any instability, such as the result of external rotor perturbations when motoring about synchronous speed where slip-induction ceases to exist and a practical brushless means to propagate "multiphase AC excitation power" directly to the rotor "active winding set," were essential but inconceivable until the advent of high speed electronic power semiconductor switching, high frequency electromagnetics, and electronic control technologies for electric machines, which triggered a renaissance of pioneering research since the 1960s, such as by the University of Wisconsin.[1],[2],[3],[4] Although a practical means of brushless real time emulation control was never fully realized, research revealed that the fully electromagnetic (or without RE-PM) brushless and symmetrical multiphase wound-rotor doubly-fed "synchronous" electric machine system would be the ideal electric machine system. In consideration, all of today's so-called new, advanced, or invented classes of electric machine systems are actually the same century old electric machine circuit and control architectures with the asymmetry of a "passive" rotor assembly of reluctance saliencies, permanent magnets, DC field winding, or a slip-induction winding set that are actually enhanced with a refined selection of off-the-shelf but better performing packaging art materials or electronic control technologies.

III. TECHNOLOGY ATTRIBUTES BY QUALITATIVE OBSERVATIONS

By conceptually modifying any available "asymmetrical axial-flux electric machine system," which comprises a "passive" rotor disk adjacently separated from an "active" stator disk by an airgap (instead of the cylinder-inside-cylinder radial-flux formfactor), such as the form of today's advanced rare-earth permanent-magnet electric machine systems, a "symmetrical" multiphase wound-rotor doubly-fed "synchronous" axial-flux electric machine system is conveniently realized by simply replacing the "passive" rotor disk(s) and bearing assembly with another "active" stator disk from the original asymmetrical axial-flux electric machine system (but fitted with the rotor bearing assembly) and also, replacing the usual field-oriented controller derivative with the hypothetical "brushless real time emulation controller" for guaranteeing symmetrical stability between "active" rotor and stator bodies. Since the resulting

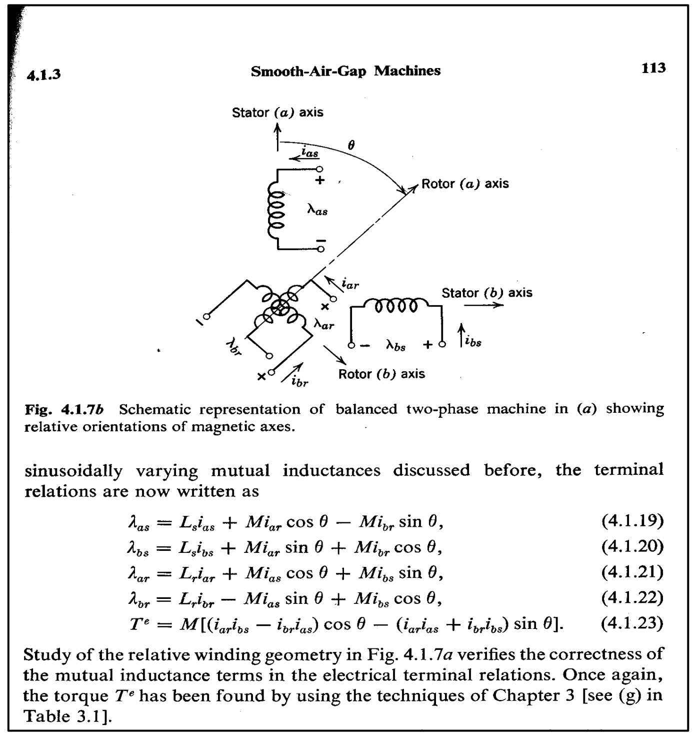
4.1.3 Smooth-Air-Gap Machines 113

Fig. 4.1.7b 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

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

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

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

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

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

Study of the relative winding geometry in Fig. 4.1.7a verifies the correctness of the mutual inductance terms in the electrical terminal relations. Once again, the torque T^e has been found by using the techniques of Chapter 3 [see (g) in Table 3.1].

Figure 1 - *Herbert H. Woodson and James R. Melcher, "Electromechanical Dynamics, Part 1: Discrete Systems," page 113, John Wiley & Sons, 1968.*

"symmetrical" multiphase wound-rotor doubly-fed "synchronous" axial-flux electric machine system brushlessly incorporates the cumulative power of two "active" stator disks or *twice the continuous power rating* of the original asymmetrical axial-flux electric machine but keeps the same electromechanical construction and formfactor, the same effective airgap area, the same airgap flux density, the same voltage rating, the same electrical (or core) loss, the same amount and cost of materials (less any passive components, such RE-PMs, saliencies, slip-induction windings, etc.), and the same packaging art and reasonably assuming the cost of the packaging art is directly related to the amount of materials being applied, a few of its inherently unique and attractive attributes are reasonably proven by simple qualitative observation (please refer to the references for quantitative or analytical analysis):

- Twice the "constant torque speed range" with a given torque, air-gap flux density, effective air-gap area, voltage, and frequency of excitation of the original asymmetrical electric machine effectively doubles the continuous power density (i.e., 7200 RPM with two poles and 60Hz excitation versus 3600 RPM).
- Twice the continuous power rating with the same packaging art, the same electrical (or core) loss, and the same electronic controller loss of the original asymmetrical electric machine system, which effectively doubles the

continuous power density while halving the cost and electrical (or core) loss per continuous power rating.

- Up to octuple more peak torque before reaching the core saturation (and potential for RE-PM damage) of the original asymmetrical electric machine system because only the "symmetry" of active winding sets on the rotor and stator, respectively, with full direct precision control of the position and amplitude of the MMFs provides a true dual-ported transformer circuit topology, which in accordance with electromagnetic physics (e.g., conservation of energy), ideally keeps air-gap flux density constant with increasing active (or torque) current.
- Elimination of the "extraneous" cost, real estate, inefficiency, environmental impact, limited life expectancy and handling safety of persistent magnetization, safe operating regions, or political volatility introduced by "passive" permanent magnets, rotor saliencies, slip-induction dependent windings, or DC field windings of the original asymmetrical electric machine system.
- Double the expected performance improvement of applying present or future electromagnetic materials, packaging art, or excitation techniques by the compounding power effect of two active winding sets instead of a single active winding set of the original asymmetrical electric machine system.

IV. TECHNOLOGY CONCLUSION AND FUTURE WORK

Where others acquiesced to the formidable technical challenges, Best Electric Machine (BEM) [5] continued research and development (R+D) to provide the essential complement of vertically integrated inventions for a practical brushless, compact, multiphase real time emulation controller (BRTEC) [6], a practical 3D Printer of low or high frequency amorphous metal axial-flux transformers or electric machines (called MOTORPRINTER) [8], a practical "symmetrical" multiphase wound-rotor doubly-fed "synchronous" electric machine system (call SYNCHRO-SYM) [7], a practical bi-directional, balanced multiphase, high frequency, electricity micro-distribution bus system for electric vehicles and ships that reduces system of systems electronic stages while improving efficiency [9] [10], and a practical bi-directional, inherent soft-switched, symmetrical multiphase smart-power-converter circuit topology (called Brushless Multiphase Self-Commutated Controller or BMSCC). [11] Without considering the future integration strategy or benefits of the "essential complement of inventions," the details of a straight-forward retrofit of SYNCHRO-SYM [12] [13] into the same performance package of today's so-called new, advance, invented, or best RE-PM asymmetric electric machine system comparatively provides:

- An electric machine system with double the continuous power density for enabling higher, faster, and longer flying electric or solar powered airplanes. [15]
- An electric machine system with up to octuple more peak torque potential for enabling direct drive (or gearless) electric vehicles with higher reliability, lower maintenance, and longer driving range. [14]
- An electric generator system without the handling and safety limitations of RE-PM but with direct low frequency conversion precision of only BRTEC for enabling compact, self-contained (with circuit and control architecture), componentized generator system units for easy transport, lifting, field assembling, power stacking, or spare replacement into very large wind turbine. [16]

Also, BRTEC brings superconductor electric machine systems closer to practical reality by the convenience of brushlessly relocating the "superconductor DC field winding set" to the stator and the "conventional active winding set" to the rotor and by isolating superconductor exposure to harmonic heating expected from the electronic power conditioning of field-oriented control. When superconductor AC active winding sets become a practical reality, the fully electromagnetic, brushless and symmetrical multiphase wound-rotor doubly-fed "synchronous" superconductor electric machine system would be the best electric machine system.

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