DOUBLING PERFORMANCE OF THE MOST OPTIMIZED ELECTRIC AIRPLANE PROPULSION SYSTEMS WITH FIELD WEAKENING

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***Abstract* – Simple qualitative observation shows that by retrofitting the asymmetrical electric machine circuit and control architecture (with a "passive" rotor) of the highest performing airplane electric machine propulsion system to the symmetrical field weakening magnetizing current circuit and control architecture (with an "active" rotor) of the symmetrical multiphase wound-rotor [synchronous] doubly-fed electric machine system, now called SYNCHRO-SYM, while preserving the same electromagnetic design parameters, such as air-gap flux density, effective air-gap area, voltage, etc., and the same electromechanical design, such as materials, winding, and the same packaging art, such physical footprint, excitation waveform, materials, winding, construction, and manufacturing techniques, of the original airplane electric propulsion system and reasonably assuming the cost of the packaging art is directly related to the amount of materials being applied, will immediately double again the continuous power density, halve the cost, halve the electrical or core loss, quadruple the peak torque density, and eliminate delicate materials, such as rare-earth permanent magnets (RE-PM), of the original airplane electric machine propulsion system.**

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

I. INTRODUCTION

All electric machine systems have an "active stator" with the necessary directly excited multiphase winding set for "contributing" torque and working (or active) power to the electromechanical power conversion process. With the symmetrical multiphase wound-rotor synchronous doubly-fed electric machine system as the exception, all other electric machine systems have an asymmetrical "passive rotor" of permanent magnets, direct current (DC) field windings, slip-induction windings, or reluctance saliencies that only "participates" in the electromechanical power conversion process without contributing torque and active power, such as only setting up the air-gap flux by closing the magnetic path through the air-gap, but reasonably consumes half of the volume, material, cost, and electrical and core loss of the electric machine system. In contrast, Figure 1 shows the symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine circuit topology with its symmetrical relations, which has an "active rotor" with another directly excited multiphase winding set for contributing additional torque and active power to the electromechanical power conversion process in conjunction with the "active stator" but only by postulating that the terminals of the multiphase winding sets are directly excited by the invention of an instantaneous, sensor-less, automatic, and brushless multiphase bi-directional power control method that contiguously and automatically provides speed-synchronized power from sub-synchronous to super-synchronous speeds without relying on the classic instability of slip-induction, particularly about synchronous speed where slip-induction ceases to exist.[1,2,3,4,5,6]

Note: The optimized symmetrical relations, 4.1.19, 4.1.20, 4.1.21, 4.1.21, 4.1.23, of the symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine system of Figure 1 become the academic study for all other asymmetric electric machines with a single active stator winding set by deoptimizing the symmetrical relationships with the asymmetry of a "passive rotor" of permanent magnets, DC field windings, slip-induction windings, or reluctance saliencies.

II. ELECTRIC MACHINE OPERATING PRINCIPLES:

The two-phase symmetrical multiphase wound-rotor doubly-fed electric machine of Figure 1 is effectively a position-dependent-flux low-frequency-rotating-transformer (PDF-LFRT) with the stator and rotor phase windings mutually coupled to each other and across the air-gap by speed-based (or asynchronous slip) induction in accordance to the synchronous speed relation ($\pm W_S \pm W_R \pm W_M = 0$, *where W_R is the electrical angular frequency of the rotor phase winding excitation, W_S is the electrical angular frequency of the stator phase winding excitation, and W_M is the mechanical angular frequency of the rotor relative to the stator*). When W_M is equal (or close) to W_S, or synchronous speed, slip-induction ceases to exist and as a result, W_R is zero (but still needs a DC component (or speed synchronized low frequency) for contiguously establishing the appropriate phase angle of air-gap flux density for torque production). If the winding excitation, W_S, is equal to W_R, W_M is at twice synchronous speed or 2 x W_S and as a result, the "symmetrical" multiphase wound-rotor doubly-fed electric machine with equal power rated windings on the rotor and stator, respectively, has a "constant torque speed" range of twice synchronous speed (i.e., 2 x W_S) for a given excitation frequency (i.e., W_S or W_R) and torque or twice the power as other electric machines with a single stator active winding set with the asymmetry of permanent magnets, DC field windings, slip-induction windings, or reluctance saliencies (i.e., 7200 RPM

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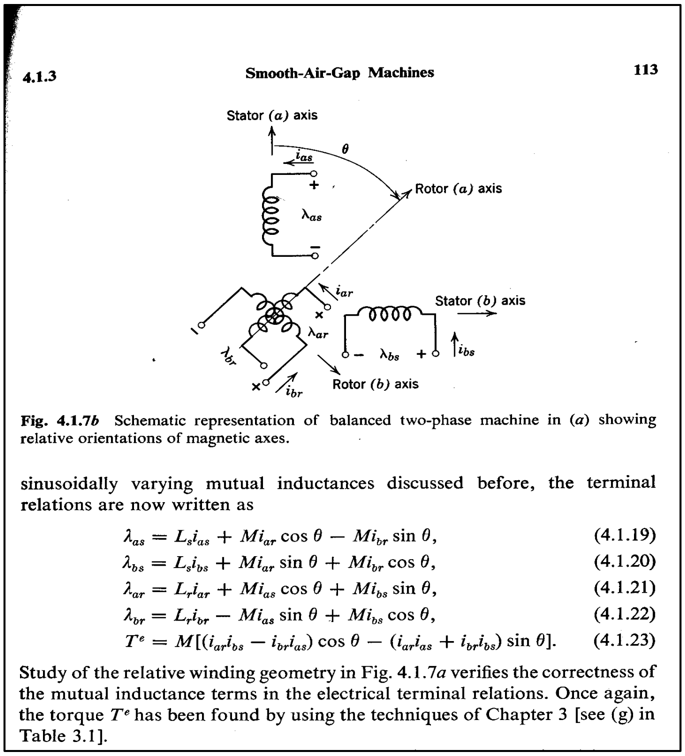

4.1.3 **Smooth-Air-Gap Machines** **113**

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

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

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

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

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

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

Study of the relative winding geometry in Fig. 4.1.7*a* 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.*

with one pole-pair excited with 60 Hz compared to 3600 RPM for all other electric machine systems).

In accordance to relation 4.1.23 of Figure 1, the torque of the PDF-LFRT is a function of the product of the mutual inductance, *M*, the rotor torque (or working) currents, and the stator torque currents. Faraday's Law dictates that the mutual inductance, *M*, and self-inductance, *L*, are functions of frequency with a position-dependent-flux high-frequency-rotating-transformer (PDF-HFRT) showing lower mutual inductance (and associated torque), smaller size, fewer winding turns, lower air-gap flux density, and lower electrical loss than a PDF-LFRT in proportion to the ratio between operating frequencies, if properly designed. Accordingly, a PDF-LFRT will necessarily have higher torque and larger size than a similarly power rated PDF-HFRT.

The classic symmetrical relations of Figure 1 easily hypothesized long ago that the brushless symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine system shows the uniquely inherent attributes of half the cost, half the size, and half the loss for a given power rating and at least eight times the peak torque for a given frame size compared to all other electric machine systems with equivalent material, winding, packaging art, and electronic control techniques, *all while electronically controlling only the power of the rotor multiphase winding set, which is half of the electric machine rated power*. But because of the formidable technical issues of brushlessly providing instantaneous, sensor-less, and automatic speed-synchronized multiphase bi-directional power to the rotor active winding set, all of today's so-called new, advanced, or invented classes of airplane 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 slip-induction windings, which only achieve distinguishable performance enhancement with a refined selection of available high performing materials, winding, packaging, or electronic control technologies with enabling manufacturing techniques.

III. WHAT IS BRUSHLESS REAL TIME CONTROL (BRTEC):

If the synchronous speed relation ($\pm W_S \pm W_R \pm W_M = 0$) and the phase angle (or torque angle) between the two synchronized magnetic rotating fields of the rotor and stator of a symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine system are precisely stabilized regardless of speed or rotor perturbation as only provided by a bi-directional, instantaneous, sensor-less, and automatic excitation control means to avoid any reliance on slip-induction, permanent magnets, DC field windings, or rotor saliencies, then air-gap flux and torque control becomes a simple function of controlling the magnitudes and positions of the rotor and stator torque currents. But if the rotor currents also rely on the asynchronous mutual induction with the stator currents (i.e., slip-Induction) of the PDF-LFRT, then stable rotor current control is lost, particularly when slip-induction ceases to exist about synchronous speed ($W_R = 0$). [7]

In accordance with the simple detailed concept of operation (CONOPS),[8] the brushless, bi-directional, sensor-less, and automatic multiphase controller, now called Brushless Real Time Emulation Control (BRTEC), comprises a PDF-HFRT with the same arrangement of windings as the symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine or the PDF-LFRT of SYNCHRO-SYM with synchronous modulators-demodulators (i.e., simple high frequency bi-directional electronic choppers) driving each of the PDF-HFRT phase winding on each side of the air-gap. The stator high frequency choppers modulate the low frequency multiphase signals supplied to the stator of the PDF-LFRT with the high operating frequency of the PDF-HFRT, which carry the low frequency stator multiphase signal envelopes. On the rotor side of the PDF-HFRT, the resulting high frequency multiphase waveforms comprise the high frequency carrier with the low frequency rotor phase signal envelopes, which are in accordance to the synchronous speed relation and the additional modulated phase angle and amplitude components of the electric machine control process. With very little filtering, the synchronous modulator-demodulators inherently provide nearly pure sinusoidal bi-directional waveforms for interfacing with the utility power and the PDF-LFRT power, while isolating the high frequency to the high frequency compatible design of the PDF-HFRT.

With the rotor axle of the PDF-HFRT, which is effectively the analog computer component of the BRTEC, connected to the rotor axle of the PDF-LFRT (i.e., $W_{M\text{-}HFRT} = W_{M\text{-}LFRT}$), which is the torque producing symmetrical multiphase wound-rotor doubly-fed electric machine entity, the frequency and phase of the demodulated multiphase power signals from the rotor multiphase windings of the PDF-HFRT are automatically, sensorlessly, instantaneously, and brushlessly the exact frequency and phase signals required to power the rotor multiphase windings of the PDF-LFRT for contiguous synchronous operation at any speed in accordance to the synchronous speed relation, including supplying the appropriate vector phase and amplitude of DC because multiphase power with the appropriate flux positioning at even absolute synchronous speed is by high frequency induction instead of slip-induction, which ceases to exist at synchronous speed. Also, the size, torque production, and electrical loss of the PDF-HFRT will be significantly lower than the torque producing PDF-LFRT in proportion to their frequencies of operation, which ideally makes the electromechanical performance of the PDF-HFRT irrelevant to the electromechanical performance of the PDF-LFRT.[9]

IV. QUALITATIVE ANALYSIS EASILY SHOWS TWICE THE CONTINUOUS POWER DENSITY AT HALF COST:

By conceptually replacing the passive rotor circuit topology of permanent magnets, field windings, slip-induction windings, or rotor saliencies and the likely field oriented controller derivative of the stator active winding set of the highest performing electric machine system for airplane propulsion with the active rotor circuit topology of a directly excited multiphase winding set and the brushless real time emulation controller of the new symmetrical multiphase wound-rotor "synchronous" doubly-fed electric machine circuit topology (as only provided by brushless real time emulation control of the rotor active winding set), while preserving the same electromechanical design, such as the same voltage, air-gap flux density, effective air-gap area, etc., and packaging art, such as materials, winding, construction and manufacturing techniques, and reasonably assuming the cost of the packaging art is directly related to the amount of materials being appl, for the most equivalent comparison, a few of the performance magnifying results can be easily surmised by simple qualitative observations (please refer to the references for quantitative or analytical analysis):

- With twice the constant-torque speed range for a given frequency of excitation, continuous torque, air-gap flux density, pole-pair count, port voltage, and frame size design is tantamount to twice the continuous power density for a given frame size or *half the size per unit of power rating.*[10]
- With both the rotor and stator contributing to active power for a given frame size is tantamount to double the continuous power rating for a given frame size or *half the size per unit of power rating.*[11,12]
- With half the electronic control rating for the stator or rotor active power and with half the amount of electrical steel and copper (e.g., half the size for a given power rating) is tantamount to *half the cost per unit of power rating* without including the size, weight, and cost savings from eliminating the expensive, exotic, or wasteful "passive" rotor components, such as RE-PMs. [13]
- With twice the continuous power density or half amount of material is tantamount to *double any improvement enabled by materials, winding, packaging art, or electronic control techniques*.
- With half the size and resulting electromagnetic core loss, with the small orthogonal vector magnitude of magnetizing current to establish air-gap flux and to provide field weakening for higher efficiency at various speeds, and with much lower compounded system loss associated with the rotor or stator torque currents, each of which provides one-quarter the electrical loss (I^2R) of the single but fully rated electronically controlled stator active winding set of other electric machines for the same power rating, is tantamount to *half the electrical and core loss per unit of power rating*.
- With air-gap flux density remaining constant with increasing torque current in accordance with the natural core saturation avoiding physics of an ideal dual ported transformer circuit topology (e.g., conservation of energy) as only provided by the rotor and stator current control of BRTEC is tantamount to *at least octuple peak torque for a given frame size.* [14]
- With active winding sets on the rotor and stator, respectively is tantamount to *elimination of the extraneous cost, inefficiency, and complexity of passive rotor permanent magnets, field windings, slip-induction windings, and reluctance saliencies*.

V. CONCLUSION:

By retrofitting the highest performing airplane electric machine system with the fully electromagnetic circuit topology of SYNCHRO-SYM with field weakening magnetizing current, simple qualitative observation of the retrofit shows twice the continuous power density, half the cost, lower electrical and core loss, and the elimination of expensive rare-earth materials for flying higher, faster, and longer while improving reliability.

When superconducting electric machines become a practical reality, the fully electromagnetic circuit and control architecture of SYNCHRO-SYM would be the choice for DC superconductor or AC superconductor airplane electric machine systems.

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[1] "Direct Torque and Frequency Control of Double-Inverter-Fed Slip-Ring Induction Motor Drive," Gautam Poddar and V. T. Ranganathan, VOL. 51, NO. 6, December 2004, pp 1329-1337. *[see page 1333, column 2, paragraph 2]*

[2] D. W. Novotny and N. L. Schmitz, "Parametric Pump-Down of Synchronous Machine Oscillations," AIEE Great Lakes District Meeting, Fort Wayne, Ind., April 25-27, 1962. Page 652-657. *[Page 652 paragraph 1]*

[3] D. W. Novotny and N. L. Schmitz, "Parametric Pump-Down of Synchronous Machine Oscillations," AIEE Great Lakes District Meeting, Fort Wayne, Ind., April 25-27, 1962. Page 652-657. *[Page 652 paragraph 2]*

[4] V.L. ABDEL-MAGID, A.H.M.A. RAHIM, M.A. Al-Yadoumi, ""A Quasi-optimal Stabilizing Control of Power/System With Dual-excited Machines," 1991 IEEE Industry Applications Society Annual Meeting, 28 Sept.- 4 Oct. 1991. *[page 1651, column 1, paragraph 4]*

[5] A.H.M.A. Rahim, "Stabilizing Controls For The Doubly Fed Synchronous-Induction Machine," IEEE Transactions on Energy Conversion, Vol. 3., No. 4, December 1988. *[Page 799, Column 2, Paragraph 1]*

[6] N.L. Schmitz, V.D. Albertson, "The Stabilized Doubly Fed Synchronous-Induction Machine: Test Results and Computer Solutions," IEEE Winter Power Conference, New York, February 2-7, 1964. *[Page 858, Column 1, Paragraph 1]*

[7] A.D. Mansell, H.M. Power, "Stabilisation of Doubly-Fed, Slip-Ring Machines Using The Datum-Shift Method," IEE Proc, Vol. 127, Pt. B, No. 5, September, 1980. *[Page 294, Column 1, paragraph 2]*

[8] http://bestelectricmachine.com/file_download/Sensorless_BWRSDF.pdf

[9] http://bestelectricmachine.com/file_download/Sensorless_BWRSDF.pdf

[10] "Sensorless Field-Oriented Control for Double-Inverter-Fed Wound-Rotor Induction Motor Drive," Gautam Poddar and V. T. Ranganathan, IEEE Transactions On Industrial Electronics, VOL. 51, NO. 5, October 2004, pp. 1089-1096. *[see page 1089, column 2, 1st paragraph]*

[11] "Direct Torque and Frequency Control of Double-Inverter-Fed Slip-Ring Induction Motor Drive," Gautam Poddar and V. T. Ranganathan, VOL. 51, NO. 6, December 2004, pp 1329-1337. *[See Abstract]*

[12] "Direct Torque and Frequency Control of Double-Inverter-Fed Slip-Ring Induction Motor Drive," Gautam Poddar and V. T. Ranganathan, VOL. 51, NO. 6, December 2004, pp 1329-1337. *[See page 1329, 2nd column, paragraph 3]*

[13] Rajib Datta and V.T. Ranganathan, "A Simple Position-Sensorless Algorithm for Rotor-Side Field-Oriented Control of Wound-Rotor Induction Machines," IEEE Transactions On Industrial Electronics, Vol. 48, No. 4, August, 2001, pp. 786-793. *[page 787, column 1, paragraph 1]*

[14] Norbert L. Schmitz and Willis F. Long, "The Cycloconverter driven Doubly-fed Induction Motor," IEEE Transactions on Power Apparatus And Systems, Vol. PAS-90, No. 2, March/April 1971, pp. 526-531. *[page 526, column 1, paragraph 6]*