
FREQUENTLY ASKED QUESTIONS:

*ADVANCED,
BRUSHLESS,
WOUND-ROTOR,
[SYNCHRONOUS],
DOUBLY-FED,
ELECTRIC MOTOR OR GENERATOR SYSTEM
- BWRSDFS –
OR
- SYNCHRO-SYM -*

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* Patented *

* Patents Pending *

What Is an Electric Motor (or Generator) “System”?
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What Is an Electric Motor (or Generator) “System”?

As defined in this paper, an electric motor (or generator) “system” is a multiple component package that includes the electric motor or generator entity mated with an electronic controller for obtaining peak performance and efficiency or in some cases, for functional operation.

Only the Induction Motor operating from a multiphase AC (Alternating Current) source or the antiquated but venerable mechanically self-commutated motor (i.e., the DC motor) operating from a single-phase AC or DC (Direct Current) source exhibits startup torque without electronic control, albeit without optimum performance either.

Today’s most state-of-art and efficient electric machines cannot function without electronic control and the entire “system” (i.e., electric machine and controller together) should be analyzed for efficiency, cost, and power density, which is rarely the case.

It is predicted that all electric motors (or generators) will become “systems” because of the dramatic improvement in overall performance, reliability, and efficiency.

Name the Categories of Electric Motor (or Generator) Systems?

All electric motor (or generator) systems belong to only two categories, the Singly-Fed or the Doubly-Fed category.

*Virtually the entire installed base of electric motor (or generator) systems belongs to the Singly-Fed category, because true Doubly-Fed electric machines have been difficult to realize: until the advent of the **BWRSDFS** technology offered by Best Electric Machine. The Singly-Fed category includes familiar types such as Asynchronous (i.e., Induction Squirrel Cage or Induction Wound-Rotor), Synchronous (i.e., Permanent Magnet or Field Excited), and Reluctance electric motor (or generator) systems.*

What Is A Singly-Fed or A Doubly-Fed Electric Motor (or Generator) System?

Singly-Fed electric motor (or generator) systems have one Active Winding Set. In contrast, Doubly-Fed electric motor (or generator) systems have two Active Winding Sets, which is the maximum allowed by physics without duplication of the singly-fed or doubly-fed entity.

An “Active” Winding Set (i.e., Armature Winding Set) is a multiphase Alternating Current (AC) winding set with an independent port for bi-directional electrical excitation. As a result, an “active” winding set actively participates in the

electromechanical conversion process and determines the power handling capacity of the electric motor (or generator) system. Examples of active winding sets are the stator winding set of an Induction, Permanent Magnet, and Reluctance electric machine.

A “Passive” Winding Set does not participate in the energy conversion process. Examples of “Passive” Winding Sets are the electromagnet (i.e., field winding or field wound), which does not support bi-directional AC power, and the squirrel-cage induction winding, which does not have an independent electrical power port. For instance, a field winding is commonly replaced by a permanent magnet array, which can never “actively” participate in the energy conversion process because permanent magnets have no terminal for electrical power

The power handling capacity of any electric motor (or generator) system is the total aggregate power rating of its Active Winding Set(s) (i.e., Armature Winding Sets).

Examples of Singly-Fed electric machines, which are commonly but incorrectly referred to as doubly-fed electric machine are:

- The Wound-Rotor Induction Electric Machine (i.e., Slip energy recovery) is a singly-fed electric machine because the rotor winding set is not designed to support bi-directional power flow!
- The Field-Excited or Field Wound (i.e., electromagnet) Synchronous Electric Machine is a singly-fed electric machine because the rotor winding set is not designed to support bi-directional power flow!

Explain the Advantages of Doubly-Fed Electric Motor (or Generator) Systems?

For a given voltage and frequency of operation, Doubly-Fed electric machines have a constant torque speed range of twice synchronous speed (i.e., 7600 RPM @ 60 Hz, 2 poles for the Wound-Rotor Doubly-Fed Electric Machine compared to 3600 RPM @ 60 Hz, 2 poles for synchronous singly-fed electric machines). This equates to less core material (up to half the material), more efficiency (up to half the electrical loss), and higher power density (up to half the physical size) for a given power rating.

“Recently, it has been shown that a grid-connected wound-rotor [doubly-fed induction] motor with current injection on the rotor side can be operated in super-synchronous mode to produce up to two times the rated nominal power”¹ [see page 1089, column 2, 1st paragraph]

¹ “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. <http://ieeexplore.ieee.org/xpl/periodicals.jsp>

*“Since the full torque can be obtained up to twice rated speed, the power output (of the doubly-fed electric machine), can be up to twice the rating of the machine.”*² [See page 1329, 2nd column, paragraph 3]

*“Simulation and experimental results are presented from a 50-hp drive, demonstrating that the drive can deliver full torque from 0 to 2-p.u. [twice rated power]”*² [See Abstract]

For full electronic control of the electric motor or generator, at least one Active Winding Set must be electronically controlled. The single Active Winding Set and electronic controller of the *Singly-Fed* electric motor (or generator) must be rated for the full electrical current (or power) of the motor (or generator). In contrast, the dual Active Winding Sets and the single electronic controller of the *Doubly-Fed* electric motor (or generator) system must each be rated for one-half the current (or power) of the motor (or generator).

*“...each inverter rated for 1 p.u. [1/2 power rating] is capable of producing rated torque at rated frequency....Thus, the motor output power becomes twice the rated power.”*¹ [See page 1093, column 2, 1st paragraph]

Since electrical loss is directly related to the “product-squared” or “self-product” of the current through each Active Winding Set (and any additional field winding set, i.e., passive winding sets) and since the electronic controller conditions less than half the power conversion capacity, the Doubly-Fed motor (or generator) system will experience up to half the electrical loss as the Singly-Fed motor (or generator) system (i.e., induction motor system) with a similar electromechanical conversion rating. Because component cost is directly related to current (power) handling capacity, the Doubly-Fed motor (or generator) system shows significant reduction in cost.

*“The rating of the power converters used in the rotor circuit (of the doubly-fed motor) is substantially lower than the machine rating and is decided by the range of operating speed (around synchronous speed).”*³

Doubly-Fed Machine – *“...This is mainly due to the fact that the power electronic converter only has to handle a fraction (20-30%) of the total power. Therefore, the losses in the power electronic converter can be reduced, compared to a system (singly-fed) where the converter has to handle the total power. In addition, the cost of the converter becomes lower.”*⁴ [See page 227, column 1, 1st paragraph]

Why Are Doubly-Fed Electric Motor (or generator) Systems Rarely Installed?

² “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.
<http://ieeexplore.ieee.org/xpl/periodicals.jsp>

³ 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.

⁴ “Evaluation of Current Control Methods for Wind Turbines Using Doubly-Fed Induction Machines,” Andreas Petersson, Lennart Harnfors, and Torbjorn Thiringer, IEEE Transactions On Power Electronics, Vol. 20, No. 1, January 2005, pp. 227-235.

Traditionally, there are two “practical” classes of Doubly-Fed Electric motor (or generator) systems, the self-cascaded (or so-called Brushless) Induction Doubly-Fed and the multiphase Slip-Ring (not brushless) Wound-Rotor Synchronous Doubly-Fed.

The self-cascaded Brushless Induction Doubly-Fed Motor (or generator) operates under low frequency (or speed based frequency) induction principles by adjacently placing two Active Winding Sets with unlike pole-pairs on the same stator body (i.e., self-cascaded) with a complex rotor assembly that attempts to reduce cross-coupling by focusing the moving magnetic fields between the two adjacently placed stator active winding sets. The stability of self-cascaded types of Doubly-Fed Electric Motor (or Generator) is more forgiving over a limited speed range where speed-based-frequency induction principles continue to hold. However, they cannot achieve the theoretical efficiency, cost, and power density expected from Doubly-Fed Motors (or Generators).

“One notable development in this direction is the two-stator (self-cascaded) induction machine...the stator winding into two displaced identical windings ...is actually a drawback...The reason is the mutual coupling between the two stator windings will cause circulating harmonic currents which will lead to extra stator losses.”⁵ [See page 315, column 1, 1st and 2nd paragraph]

In contrast, the Multiphase Slip-ring (not brushless) Wound-Rotor Synchronous Doubly-Fed Motor (or Generator) operates under synchronous principles by directly exciting (via the multiphase slip-ring assembly) the Active Winding Sets with similar pole-pairs and power capacity that are placed on the Rotor and Stator bodies, respectively (i.e., wound-rotor doubly-fed). By placing an active winding set on the rotor body, the rotor body real estate, which would otherwise be the passive body for all other electric machines, now actively participates in the energy conversion process. The Multiphase Slip-ring Wound-Rotor Synchronous Doubly-Fed Motor (or Generator) has the most optimal and symmetrical electromagnetic winding arrangement of any electric motor (or generator) system. No wonder the balanced phase wound-rotor doubly-fed electric machine is the classic study for all electric machines!

The Multiphase Slip-ring Wound-Rotor [Synchronous] Doubly-Fed Motor (or Generator) can operate over an extended constant-torque speed range (i.e., sub-synchronous, synchronous and super-synchronous range) for a given voltage, frequency, and air-gap area, which is the fundamental metric for low cost, high efficiency, and high power density. Otherwise, all electric machines follow the same physics, use the virtually the same material science and manufacturing. As a result, all electric machines display similar torque density, regardless of marketing hype. Unfortunately, the Multiphase Slip-ring Wound-Rotor [Synchronous] Doubly-Fed Motor (or Generator) has two major problems: 1) It is unstable without incorporating extraordinary control means that “instantaneously” supplies speed/frequency and position synchronized electrical power for synchronous operation throughout the speed range; and 2) It incorporates a multiphase brush, slip-ring assembly. These problems cancel the cost, reliability, and

⁵ “A New Energy Recovery Double Winding Cage-Rotor Induction Machine,” Lili Bu, Chun Li, Jeff Krukowski, Wilsun Xu, and Xian Liu, IEEE Transactions On Energy Conversion, VOL. 18, NO. 2, June 2003, pp. 315-320. <http://ieeexplore.ieee.org/xpl/periodicals.jsp>

efficiency attributes expected from the Wound-Rotor Synchronous Doubly-Fed Motor or Generator.

“The higher cost of the machine (due to the slip rings of the Doubly-fed machine) is compensated by a reduction in the sizing of the power converters (of the Doubly-Fed Machine).”⁶ [See page 414, column 2, 3rd paragraph]

“At very low rotor flux frequency [synchronous speed for the doubly-fed or zero speed for the singly-fed], it is very difficult to maintain the rotor (flux) constant...At very low stator frequency, the DTC algorithm also fails due to ...inaccurate estimation of the stator resistance drop”² [see page 1333, column 2, paragraph 2]

The problem of inherent instability (hunting) uncontrollable torque angle is an old one ... the problem of accelerating the machine and synchronizing it to the power system has continued.⁷ [page 526, column 2, paragraph 2]

Synchronous electric machines and electric machine systems are subject to oscillatory behavior similar to that associated with a simple spring-mass mechanical system. These oscillations occur because the principle torque produced by the machine is proportional to a position variable. Thus, the motion is approximately characterized by a second order differential equation in which the dominant terms are the inertial torque and the position-dependent (synchronizing) torque.⁸ [Page 652 paragraph 1]

Another interesting and potentially useful device in which the absence of proper damping torques creates a stability problem is the doubly-fed synchronous machine. The velocity dependent torques produced during hunting in this machine are in a direction to increase the oscillation and render the machine unstable. Unfortunately, the conditions which allow full advantage to be derived from the possibility of delivering energy to both the rotor and stator (reduced frame size for a given output at twice normal synchronous speed) are the same conditions which create unstable operation. Thus the desirable steady-state features of this machine are not available because of the stability problems.⁹ [Page 652 paragraph 2]

What about copper utilization?

All electromagnetic motors (or generators) must include at least one armature winding for interacting with (or generating) a moving magnetic field. The voltage across the terminals of the winding obeys Faraday's Law:

$$V \propto N \times A \times B$$

⁶ “Variable-Speed Wind Power Generation Using Doubly Fed Wound Rotor Induction Machine – A Comparison With Alternative Schemes,” Rjib Datta and V. T. Ranganathan, IEEE Transactions On Energy Conversion, VOL. 17, NO. 3, September 2002, pp. 414-421. <http://ieeexplore.ieee.org/xpl/periodicals.jsp>

⁷ 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.

⁸ 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.

⁹ 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.

V is the terminal voltage of the winding. N is the number of winding turns. A is the area enclosed by the winding. β is the magnetic flux density in the area, A . The length of each turn in the winding is proportional to the factor $N \times A$.

Understanding Faraday's Law shows only three methods to decrease the amount of copper in any electric machine supplied by a given voltage source:

1. Increase the Flux Density (β) in the air gap:

Increasing the Flux Density, β , requires an equal decrease in the $N \bullet A$ factor to keep the voltage fixed. Since all conventional electric machines achieve nearly the same air gap Flux Density, Flux Density plays no discernable difference between electric machines. In contrast, the super-conductor electromagnet (i.e., field winding synchronous singly-fed) electric machine can achieve higher air gap flux density than the conventional electric machine. Since the superconductor electric machine cannot operate without exotic construction and support equipment, such as cryogenic coolers, the additional weight, size, and cost of supporting equipment and construction should be included in the package, which far exceed any savings resulting from reduced copper usage.

2. Decrease the number of winding sets:

The permanent magnet (i.e., synchronous singly-fed) electric machine replaces the electromagnet winding (i.e., field winding or wound field component) of the singly-fed synchronous electric machine with a permanent magnet assembly, which has no electrical power port and shows no loss. However, the cost of the exotic permanent magnetic material and manufacturing process can far exceed the savings resulting from reduced copper usage. Furthermore, today's high energy permanent magnet raw material is strategically located to just a few countries with lax environmental concerns.

3. Utilize Wound-Rotor Doubly-Fed Electric Machine Technology:

The Wound-Rotor Doubly-Fed Electric Machine, which has two armature windings, contains twice the number of windings and as a result, twice the loss and twice the copper usage. Because the two armature windings actively and cumulatively participate in the energy conversion process, the Wound-Rotor Doubly-Fed Electric Machine shows twice the power output. In effect, the Wound-Rotor Doubly-Fed Electric Machine shows the same copper usage as the Permanent Magnet electric machine but without the additional cost and placement of expensive and exotic Permanent Magnet assembly.

Further, the Wound-Rotor Doubly-Fed Electric Machine requires an electronic controller with half the power rating (or less) of the Permanent Magnet (synchronous) electric machine. The electronic controller is several times the cost of the electric machine being controlled, regardless of the amount of copper in the electric machine.

If cost, efficiency, and size are the determining factors for selecting an electric machine, the Wound-Rotor Doubly-Fed Electric Machine would be the machine of choice in virtually all cases if a viable solution were available for eliminating the slip-ring assembly and the instability.

How Does Magnetizing Current Affect Efficiency of Electric Machine Systems?

Permanent magnet electric machine systems being the exception, magnetizing current through an electrical winding of an electric machine develops the air-gap flux density. Transformer type electric machines, such as induction and wound-rotor doubly-fed electric machines, and field wound (i.e., electromagnet) electric machines, such as non-permanent magnet synchronous electric machines, are examples of electric machines that rely on magnetizing current to setup the air-gap flux density. Generally, the maximum magnitude of magnetizing current for transformer type electric machines is restricted to 30% of the maximum torque current. Magnetizing current is always orthogonal to torque current and unlike torque current, which contributes to real power, magnetizing current contributes to imaginary power. With the maximum magnitude of magnetizing current 30% of torque current, the normalized “total current” magnitude for transformer type electric machines is 1.044 according to the Pythagorean Theorem versus the normalized “total current” magnitude of 1 for permanent magnet electric machines. Considering only magnetizing current that is confined to the electric machine (and not propagated back to the electric utility grid), the losses of a transformer type electric machine is 1.09 the losses of permanent magnet electric machines (i.e., loss is proportional to the square of the current), which is insignificant.

Electric machine systems that can isolate magnetizing current to the electric machine, itself, and away from the electrical source by power factor control will prevent any associated effects from the electrical source, as well. Furthermore, only the wound-rotor doubly-fed electric machines can share the magnetizing current between the rotor and stator winding sets, which further reduces the losses associated with magnetizing current.

Magnetizing Current is associated with the desire attribute of Field Weakening capability, which is inherent in fully electromagnetic electric machines. Field Weakening, which is not inherent in PM electric machines with persistent magnetic flux, allows an electric machine to operate beyond the designed frequency of excitation without electrical damage.

What Electric Motor (or generator) Systems Have the Highest Torque Density?

[http://en.wikipedia.org/wiki/Electric_motor] All electric motors or generators (i.e., electric machines) have a rotor (i.e., rotating) body and a stator (i.e., stationary) body that are separated by an air-gap for relative movement between the bodies. The air-gap flux density is constrained by the saturation of the magnetic core, where the active winding set

resides, and core dimensions are constrained by teeth and slots dimensions for placement of the active winding set. When optimally designed for a given active current (i.e., torque current), voltage, pole-pair number, number of phases, excitation frequency (i.e., synchronous speed), and core flux density, all categories of electric motors or generators will exhibit virtually the same maximum continuous shaft torque (i.e., operating torque) within a given physical size of electromagnetic core (i.e., torque density). However, some applications require bursts of torque beyond the maximum operating torque, such as short bursts of torque to accelerate an electric vehicle from standstill. Always limited by magnetic core saturation or safe operating temperature rise and voltage, the capacity for torque bursts (i.e., torque capacity) beyond the maximum operating torque differs significantly between categories of electric motors or generators.

Torque Density of Electric Machine Systems with Large Number of Phase Windings:

All electric machines need at least two AC excited phase windings for average torque production (i.e., non-pulsating torque). Through the years three AC phases has shown to be optimal and has become the norm. Certainly, increasing the number of phases in any electric machine proportionally increases the electro-mechanical complexity and size of the electric machine system but does nothing to increase the torque density, which is constrained by three relations of physics (i.e., Faraday's Law, Ampere's Circular Relation, and Lorentz Relation). However, it may be appropriate in high voltage applications to increase the number of phase windings (with a proportional increase of electronic power switches controlling the phase winding nodes), which decreases the voltage stress between windings or the electronic power switches, rather than increasing the voltage ratings of the winding insulation or power switches.

Torque Density of Superconductor Electric Machine Systems:

The nature of a superconductor field (i.e., synchronous) electric machines achieves very high air-gap flux densities. Two electric machine relations of physics (i.e., Faraday's Law and Lorentz Relation) show high flux density should decrease size while increasing torque and efficiency but after appropriately including the cryogenic refrigeration, the electronic control, the slip-ring assembly, the Faraday shields, and more, superconductor electric machine "systems" are a long way from practical application or torque density.

Torque Density of Permanent Magnet Electric Machine Systems:

Permanent Magnet (PM) electric machine systems are attractive because the air-gap magnetic field is setup without magnetizing current and any need to propagate electrical power across the air-gap, such as through brushes and slip-rings, is eliminated. Compared to MMF (i.e., windings with current), the high coercivity of high performance PM materials allows a smaller magnet footprint and approximately a 20% larger air-gap depth. However, PM electric machines have a persistent flux density with a practical limit (i.e., $\approx 0.7\text{-}0.8$ T with the highest performance PM materials) and do not have inherent field weakening capability. The persistent magnetic field has safety and reliability issues and the lack of field weakening has speed range issues. Providing field

weakening in PM electric machines, which is always desirable, requires an extraneous means to provide magnetizing current, which is inherent in other electric machines. Furthermore, high capacity permanent magnet material is considerably more expensive than copper, which it effectively replaces, and is difficult to handle, assemble, or manufacture. The raw material source for high performance permanent magnets is virtually limited to countries with limited concern to the devastating environmental effects of mining these materials, which is now one country of origin, China. Considering the environmental costs, the limited practical minable sources, and the expected rise in demand as the world turns to electricity, permanent magnet materials will continue to be a globally expensive strategic resource.

Why Do Wound-Rotor Doubly-Fed Electric Motor (or generator) Systems Have High Torque (Power) Capacity?

Electric machines without a transformer circuit topology, such as Field-Wound (i.e., electromagnet) or Permanent Magnet (PM) Synchronous electric machines, cannot realize bursts of torque higher than the maximum designed torque without saturating the magnetic core and rendering any increase in current (i.e., torque) as useless because torque current vectorially sums with the air-gap flux. Furthermore, the permanent magnet assembly of PM synchronous electric machines can be irreparably damaged, if bursts of torque exceeding the maximum operating torque rating are attempted.

Electric machines with a transformer circuit topology, such Induction (i.e., asynchronous) Singly-Fed electric machines, Induction Doubly-Fed electric machines (so-called brushless), and Induction or Synchronous Wound-Rotor Doubly-Fed (WRDF) electric machines, exhibit very high bursts of torque because the active current (i.e., Magneto-Motive-Force or the product of real [or torque] current and winding-turns) induced on either side of the transformer oppose each other and as a result, the active currents contribute only to torque production with no contribution to core flux density that leads to core saturation.

Electric machines that rely on Induction or Asynchronous principles short-circuit one port of the transformer circuit and as a result, the reactive impedance of the transformer circuit becomes dominant as slip increases, which limits the magnitude and phase of active (i.e., real) current. Still, bursts of torque that are two to three times higher than the maximum design torque are realizable.

The Synchronous Wound-Rotor Doubly-Fed electric machine (or Synchro-Sym) is the only electric machine with a truly dual ported transformer circuit topology (i.e., both ports independently excited with no short-circuited port). The dual ported transformer circuit topology is known to be unstable and requires a multiphase slip-ring-brush assembly to propagate limited power to the rotor winding set. If a precision means were available to instantaneously control torque angle and slip for synchronous operation during motoring or generating while simultaneously providing brushless power to the rotor winding set, the active current of the Synchronous WRDF electric machine would be independent of the reactive impedance of the

transformer circuit and bursts of torque significantly higher than the maximum operating torque and far beyond the practical capability of any other type of electric machine would be realizable. Torque bursts greater than eight times operating torque have been calculated, which is nearly four times greater torque capacity than the nearest competitor.

By simply increasing torque current proportionally, only the BWRSDFS exhibits torque density greater than eight times operating torque without concern about saturating the magnetic core or damaging permanent magnets. Like any electric machine, the BWRSDFS would exhibit a temperature rise based on the square of the current (i.e., eight times current or eight times torque calculates to sixty four times the temperature rise constant). For example, consider a BWRSDFS pushing eight times continuous torque to accelerate an electric vehicle with a thermal time constant of 30 minutes, which is common for continuous rating: the thermal time constant would be reached within thirty seconds (30 minutes \div 64), which is well within practical application (assuming the appropriate cool down is achieved between accelerations).

The merits of the double armature, doubly excited, wound-rotor machine as a low reactance, high torque energy converter configuration are well known. Its continuous power rating is double that normally associated with a given frame size; in addition, it has a maximum pull-out torque of approximately eight times nominal frame size torque rating. [page 526, column 1, paragraph 6] ¹⁰

What Is the Advanced Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Machine System (BWRSDFS)?

The **BWRSDFS** is an outside-of-the-box approach that is the only technology to simultaneously achieve the two necessary characteristics to completely realize a brushless Wound-Rotor Synchronous Doubly-Fed Electric Machine System including its distinctive attributes of highest efficiency, lowest cost, and highest power-density:

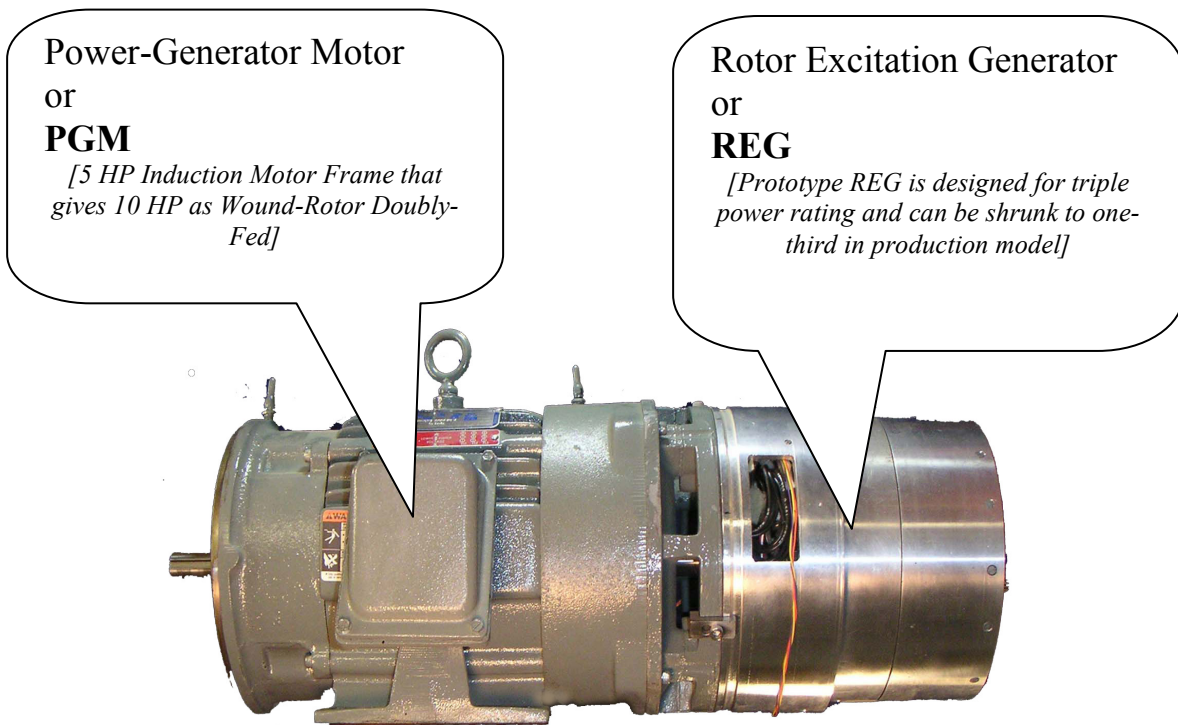
1. The BWRSDFS is the only Wound-Rotor [Synchronous] Doubly-Fed Electric Motor (or Generator) System that is brushless and stable throughout its entire constant torque speed range, which is twice synchronous speed (including absolute synchronous speed).
2. The BWRSDFS is the only electric motor (or generator) system that incorporates a patented, brushless, servo-quality means of control, referred to as Real Time Emulation™, which maintains synchronous operation at all speeds by electronically conditioning only the electrical power of the Rotor Active Winding Set (i.e., doubly-fed).

“The Advanced Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Machine, which uses low cost conventional technology, is beyond recent efficiency, power density, and cost claims that continually inspire expensive

¹⁰ 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.

research and development investments into futuristic Superconductor Electric Machine Technology.”

“Only the technology of the Advanced Brushless Wound-Rotor Synchronous Doubly-Fed Electric Machine System instantaneously converts sinusoidal poly-phase AC waveforms between the fix frequency power grid and the variable frequency winding excitation, which is exactly synchronized to the speed and position of the moving body (i.e. rotor) without electronic transformation processing, without electromechanical brushes or slip-rings (i.e., brushless), without a DC Link Stage (i.e., intermediate stage) for another level power quality, and virtually without introducing harmonic content on the AC waveforms due to high frequency modulation.”¹¹



**Advanced Brushless Wound-Rotor Synchronous Doubly-Fed Electric Machine
“Radial Flux Prototype”**

“Based on sound electromagnetic principles and using simple off-the-shelf components and technology, the Advanced Brushless Wound-Rotor Synchronous Doubly-Fed Electric Machine System shows:

¹¹ A major AC drive manufacturer has introduced an electronic control model that uses matrix converter technology, which has been in concept for over ten years and has no DC intermediate stage. The manufacturer says the elimination of the DC stage reduces harmonic distortion by one-third and offers bi-directional power flow (i.e., line regeneration).

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- *Nearly 50% reduction in cost:
(lowest cost)*
 - *Nearly 50% reduction in electrical loss:
(most efficient)*
 - *Nearly 50% improvement in power density:
(smallest footprint - lowest weight)*
 - *Absolute Accuracy:
(including absolute zero and synchronous speeds because no control estimation
nor Field Oriented Control)*
 - *Highest Reliability and Lowest Maintenance:
(fully electromagnetic - no permanent magnets)
(No Brushes or Slip Rings)*
 - *Symmetric Mode of Operation:
(motoring or generating)*
 - *Power Factor Adjustment:
(leading, lagging, or unity)*
 - *Virtually No Harmonic Content:
(clean sinusoidal waveforms at the power source and at the windings)
(no bearing or winding insulation damage)”*
 - *Rock-solid frequency regulation, regardless of rotor speed*

Additional Information:

- Internationally patented Electric Motor or Generator “System” with patents pending;
- Only the Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Motor or Generator System is “brushless” (no multiphase-slip-ring-assembly);
- Only the Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Motor or Generator System is inherently “stable” at any speed.
- Only the Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Motor or Generator System does not use Flux Vector Control (or derivatives of Flux Vector Control).
- Only the Brushless Wound-Rotor [Synchronous] Doubly-Fed Electric Motor or Generator System has rotor and stator active winding sets (i.e., two armatures only) with directly controlled connections, which gives servo-quality dynamic response as any electric machine with only an armature to directly control, such as Permanent Magnet servo electric machines.
- Performance Expectations Backed-up by recently published results of industry conducted Analysis, Simulation, and Prototyping.

Describe The Distinctive Features of BWRSDFS Technology?

“No other Electric Motor (or Generator) System can beat BWRSDFS technology in cost, efficiency, or power density!”

Preliminary evaluations of **BWRSDFS** technology by industry experts, including an electrical apparatus company with a household name, have been affirmative. After an

intensive evaluation by the engineering staff of one such company, the President stated BWRSDFS technology is “revolutionary”.

How Can The BWRSDFS Beat Competitor Cost?

1. By incorporating an electronic controller with its *unique* circuit topology:
 - No DC Link Stage with associated costly, bulky, and inefficient Storage Components (such as low frequency chokes and capacitors) but pure AC to AC conversion;
 - All power switches (semiconductors) are placed in line with each AC Phase, which gives the power-switches a power to cost advantage of $\sqrt{3}$ -to-1 in a 3-phase topology or 2-to-1 in greater than 3-phase topologies, compared to conventional methods that place the power switches across the higher AC Phase-to-Phase voltage or DC Link Stage;
 - Servo comparable control performance at any speed and without extraneous and costly speed/position transducers;
 - Power Supply (Utility Grid) experiences pure sinusoidal feedback:
 - No extraneous filtering or compensation components for power quality improvement;
 - No filtering high frequency modulation harmonics;
 - No Common Mode Voltage;
 - Winding Set experience pure sinusoidal signal drive:
 - No direct high frequency modulation;
 - No Common Mode Voltage;
 - No high frequency stress on insulation and bearings;
 - No losses (or heat) due to high frequency harmonics;
 - Inherently accommodates Soft Switching (i.e., Resonant Switching):
 - Electrical components can be de-rated for additional cost savings without effecting reliability;
 - Lowers electrical component stress;
2. By incorporating an electronic controller that conditions half (or less) of the full power of the motor (or generator) for full control;
3. By inherently accommodating power factor compensation (i.e., leading, lagging, or unity PF) without extraneous equipment;
4. By supplying speed synchronized, multiphase power directly to the rotor Active Winding Set without a multiphase brush and slip-ring assembly.
5. Contains no exotic, delicate, or internationally strategic materials, such as rare earth permanent magnet materials.
6. With no persistent magnetic field (i.e., permanent magnets), safety issues and manufacturing or shipping logistic issues are eliminated.

How Can The BWRSDFS Beat Competitor Efficiency?

1. The power electronics conditions half (or less) of the full power of the motor (or generator), which calculates to half the electrical loss (or less) of electronic controllers of Singly-Fed electric machine systems, including the controller of today’s

most efficient electric machine system available, the Singly-Fed Permanent Magnet (synchronous) electric machine system.

2. For a given voltage and frequency of operation, the Wound-Rotor [Synchronous] Doubly-Fed Electric Machine System operates at twice the speed with the same torque as a Singly-Fed Electric Machine System:
 - Lower Eddy Current losses.
 - Lower Electrical Loss for a given unit of power output.
3. The electromagnetic arrangement makes the electrical loss of the two Active Winding Sets (not including the losses of the electronic controller) comparable to today's most efficient electric machine system available, the Singly-Fed Permanent Magnet (synchronous) electric machine system.
4. The unique and proprietary circuit topology inherently accommodates soft switching, which further reduces switching losses, core losses, and circuit losses.
5. The proprietary means of supplying speed synchronized, multiphase power to the Rotor Active Winding Set without the associated losses of a multiphase brush and slip-ring assembly.
6. With comprehensive leading, lagging, or unity power factor control, any losses associated with magnetizing current are confined to the electric machine.
7. Magnetizing current can be developed on the rotor winding set, the stator winding set, or shared between the rotor and stator winding set for lower associated losses.

How Can The BWRSDFS Beat Competitor Power Density?

1. Its true transformer circuit topology allows burst torque that is at least eight times more than continuous torque rating.
2. Its extended constant torque speed range (twice synchronous for a given voltage, frequency, and air-gap area) is tantamount to twice the conversion power for a given physical size, when packaged accordingly.
3. Its proprietary means of supplying speed synchronized, multiphase power to the rotor Active Winding Set without the associated real-estate of an extraneous multiphase brush and slip-ring assembly and chassis contained electronic controller.
4. The real estate allocation for the conventional electronic controller is Housing and Fan (36%), Power Module (6%), DC-Link (12%), Connections (6%), DC/DC Transformer (4%), Heat Sink (13%), and PCB (23%).¹² Since the BWRSDFS electronic controller (REG) is an integral part of the chassis of its doubly-fed electric machine (PGM), the Housing and Fan real estate (36%), the Connections real estate (6%), and the Heat Sink real estate (13%) are omitted. Since the REG uses high frequency AC-to-AC conversion, another level of power density is introduced because there is no DC Link or associated passive components and the DC-Link real estate (12%) is omitted. The REG can easily replace the DC/DC Transformer real estate, which operates at a much lower frequency and as a result, is much larger. Without considering the reduction in PCB and Power Module real estate offered by the low power requirements of the REG (controls only half of the power for full control of the machine) and its simple control algorithm, the REG shows a 67%

¹² Peter Beckedahl and Aseem Wahi, Semikron International, "Trends in the Development of New Power Electronic Modules," August/September, 2005, E-Drive magazine (www.e-DriveOnline.com), pp. 12-13

reduction in real estate over a conventional electronic controller of comparable power rating.

Is There A Foreseeable Technology That May Be Better Than BWRSDFS Technology?

The most futuristic electric motor (or generator) technology is based on Low or High Temperature Superconductors. These futuristic synchronous singly-fed motor (or generator) systems are relegated to specialized installations to compensate for their extravagant cost and logistical support of unconventional technology, the superconductor electromagnet with complementary cryogenic support.

Ironically, the technology of BWRSDFS, Real-Time-Emulation,™ can bring Superconductor motor (or generator) systems closer to reality. BWRSDFS Technology has the means to relocate the superconductor field winding from the rotating to the stationary body for optimum logistical support without electromechanical or fluid contact and it has the means to prevent superconductor quenching by eliminating the high frequency harmonics or by eliminating the potential of synchronization loss that are typical of conventional electronic control. Further, BWRSDFS Technology, Real-Time-Emulation™, can be extended to any Singly-Fed Synchronous Electric Machine, such as Permanent Magnet machines. Similar to any Singly-fed technology, the Real-Time-Emulation™ must be rated for the full power of the application.

How Can BWRSDFS Technology promote the “SMART GRID?”

Technology, such as the BWRSDFS, that introduces little harmonic content, promotes power quality, tunes to the work load, and can be remotely controlled for dynamic power factor compensation and symmetric modes of operation (i.e., motoring or generator), has much to offer the Smart Grid concept. For instance, the BWRSDFS can look capacitive or inductive (as well as neutral or unity power factor) to compensate for (or to neutralize the effects of) other apparatus on the grid, which look inductive or capacitive to the grid, respectively, for a unity impedance (i.e., high efficiency) utility grid. Furthermore, BWRSDFS measures power factor, which can be tagged with a global position and transmitted to a central control station for grid management. By timing the symmetric motoring or generating events between at least two BWRSDFS (referred to as energy reciprocity by this author), energy consumption can be dramatically reduced. For instance, adjusting the events of a crane lifting a load (motoring against gravity) simultaneously with another crane lowering a similar load (regenerating with gravity) could reduce the energy consumption of the dual processes to loss due to the inefficiencies of the dual processes.

Integral technology of the BWRSDFS can also provide electronic variable frequency transformers (VFT) and electronic transformers (ET), which provide a compact highly efficient means of synchronously transferring electrical energy between different electrical power with leading, lagging, or unity power factor control.

How Can BWRSDFS Technology Enhance Renewable Energy and Energy Conservation (i.e., Energy Efficiency)?

Electricity is such an efficient, clean, and technologically advanced distribution system, it is expected to grow 40% by 2030. Nearly every renewable energy resource concept or operation converts the renewable energy source to an energy distribution medium, most likely electricity, which is then remotely converted to mostly motional work, such as lifting an object, pumping a liquid, etc. Rotating (and linear) electric motors or generators are the dominant electrical devices that generate electricity or convert electricity to work and as a result, electric motors or generators should always be considered the motivator or contributor of any renewable energy project. Furthermore, the BWRSDFS should be the electric motor or generator system of choice because it is the most energy efficient, the most reliable, the most cost-effective, and without country specific permanent magnet material, the most strategically benign electric motor or generator technology available.

Wind Turbine Example:

Publications report the conventional wound-rotor doubly-fed electric generator (WRDFG) is installed in more than 70% of wind turbines greater than 100 KW. Although this trend has continued, permanent magnet machines are beginning to become a viable but considerably more expensive alternative because overwhelming research to eliminate the high maintenance slip-ring-brush assembly and the instability characteristics of the conventional WRDFG focused on permanent magnet machines. The BWRSDFS is similar to the familiar venerable WRDFG technology installed in the majority of wind turbines but without the associated high maintenance brush-slip-ring assembly, without the associated instability issues, with more efficiency, with considerably less cost than the permanent magnet generator technology, and finally, without delicate and strategically sensitive permanent magnet materials.

Electric Vehicle Example:

The two distinctive components of the any electric vehicle are the energy storage medium (i.e., battery) and the electric motor/generator system. Dominant attention is focused on batteries because appropriate battery technology is distant. The lithium battery is the most promising battery technology. Although developed in the United States, most authorities expect lithium batteries for electric vehicles to be manufactured in Asia, which has the most experience manufacturing lithium batteries because of widespread application in Asian dominated consumer electronic industry. If the United States wants to be a player in at least the electric vehicle business, it is unarguably essential to domestically re-establish battery manufacturing. Perhaps a more pressing strategic concern for at least the United States should be the electric motor/generator component. The reserves of composition materials, neodymium and dysprosium, etc., used in high performance permanent magnets for electric motors and generators are virtually sourced in one country, China. Under the present volume of consumption, there may be no strategic concern for these raw materials. But if the electric motor and generator industry adopts

permanent magnet technology as predicted to meet our green goals or if electric vehicle volumes reach the scale of conventional vehicles as predicted to meet our green goals, permanent magnet material will become a strategic concern, if nothing more than by supply and demand. Better than just a strategic alternative to the permanent magnet electric motor or generator, the BWRDFS, which uses only off-the-shelf materials, such as copper and iron, is more efficient, considerably less costly, more reliable, and more compact than any permanent magnet electric motor or generator technology. Without the persistent magnetic field of permanent magnets, safety and field weakening, which are wishes for permanent magnet machines, are inherent features of the BWRDFS. As a result of its unique transformer circuit topology, the BWRDFS has the highest burst torque of any electric machine system, which can easily exceed four times the burst torque of the closest competitor, for seamless electric vehicle acceleration. Furthermore, the BWRDFS is brushless (no slip-ring-brush assembly) and optimally controlled by electronics, which were the original motivating features for adopting permanent magnet motors and generators.