# Electric Generators and Motors: an overview

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(Invited)

***Abstract*—Starting with Faraday's law of electromagnetic induction in 1831, electric (electromagnetic) machines have been developed ever since as "assembles" of electric and magnetic coupled circuits that convert mechanical to electrical energy (in generators) and vice versa (in motors), via magnetic energy storage. Generators and motors are reversible.**

**The Maxwell four equations (laws) later in 19th Century have prompted the rapid development of all basic (DC. brush and travelling field AC machines by 1900. Then by 1930 AC (alternating current) power (energy) systems evolved by connecting in parallel electric synchronous generators (with voltage boost and buck electric transformers for efficient AC power transmission lines) of rather constant frequency and voltage, driven by turbines (prime movers) that harness fossil (coal, gas or nuclear fuels), thermal or hydro energy.**

**The last 50 years have witnessed a dramatic extension of generators power/unit, renewable energy generators and of variable speed AC motor drives in applications with variable output such as ventilators, pumps compressors, conveyors, orr-mills, electric transport (mobility), industrial automation, robotics, home appliances and info – gadgets.**

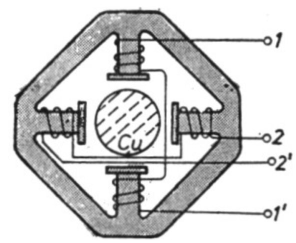
**This formidable development, required by the need of more but cleaner energy, was mainly driven by power electronics, better materials, better modeling, design methodologies and digital control. This humble inaugural overview attempts to combine a brief history of electrical generators and motors with recent progress and trends in their design and control, for representative applications.**

***Index Terms*—Electric generator, linear electric machines, induction, synchronous machines.**

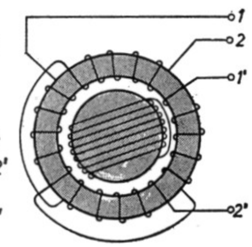
## I. INTRODUCTION

MODERN electric (electromagnetic) generators and motors have started with the "Law of electromagnetic induction" attributed to Faraday (1831), but recently found by us formulated as an experimental fact in Lucretius book: "The Nature of Universe" 1st century B.C., in Rome, in terms of repelling and attraction electromagnetic forces of a moving magnet on a copper cap above it. After Faraday's homopolar and heteropolar DC brush machines, induction AC cage – rotor (brushless) machines have been introduced, with paramount contributions by Siemens brothers, Galileo Ferraris and Nikola Tesla.

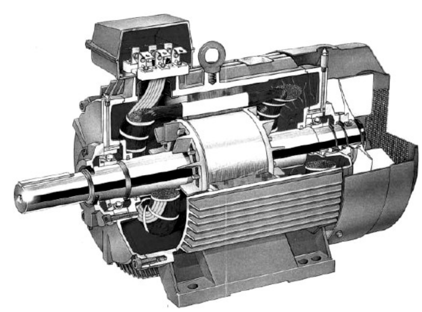
The patents of first induction motors (Fig. 1a,b)[1] showed great promise – as travelling field brushless AC machines – but their topologies were rather primitive and thus efficiency was low. Soon after that, before 1900, the windings have been put in slots (as of today) by Dolivo Dobrovolski and others, to produce practical performance.




(a) Galileo Ferraris patent




(b) Nicola Tesla patent (1886)



(c) contemporary IM

Fig. 1. Induction motors. (a) Galileo Ferraris patent;(b) Nicola Tesla patent (1886); (c) contemporary IM

Even before 1900 DC excited–rotor AC (synchronous) generators have been introduced, even with additional PMs on the rotor and with today's popular tooth-wound stator a.c. windings as in an AEG 1896 patent (with 36 slots and 42 rotor poles).

Based on these "building bricks", DC and then AC power grids have been developed, first local, then regional, national and continental from 1900 to 1960. Power grids rely on paralleling AC synchronous generators (whose power per unit increased to 1800 MW for turbo generators and 770 MW recently for hydrogenerators on Yantze River) controlled with a small droop in frequency (less than 0.5 Hz) and in voltage (a few %) control to allow input power sharing from different generators based on energy availability, demand, reliability and cost.

Electric installed power and electric energy grew steadily over the last century with a particular surge in the last 20 years due to the emergent economies in large population areas (in Asia, Africa, S. America). But so did the environmental concerns. This is how "renewable energy" emerged at the forefront (Fig. 2 a, b) [2].

Renewable energy sources (hydro, wind, waves, solar – thermal) do not bring more energy (heat) on earth, while fossil

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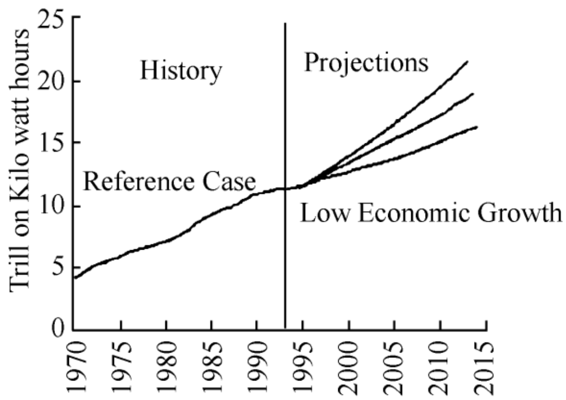
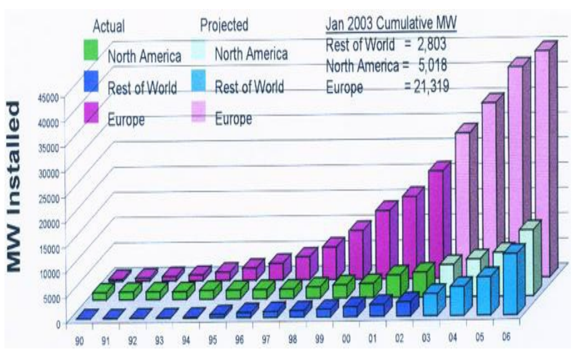
fuel sources do; they also do less harm to the environment. But they are characterized by load power density (nuclear power turbine + generator weights 50 times less than a wind turbine – generator per kW). Consequently, the need for better harnessing renewable energy turbine–generator systems is imperative.



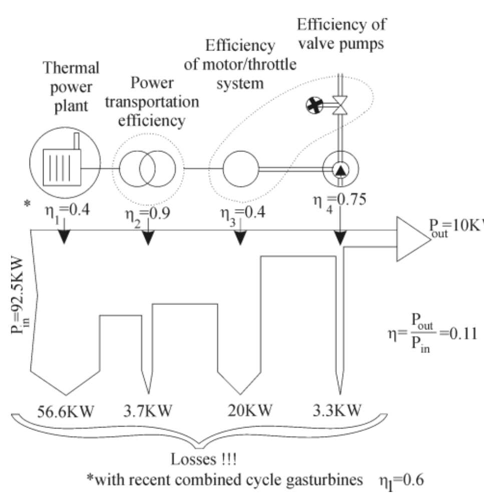

(a) Electric annual energy world requirements



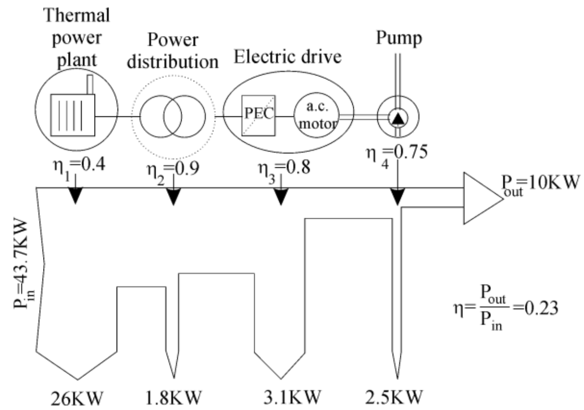

(b) renewable energy mix, over the years

Fig. 2. (a) Electric annual energy world requirements; (b) renewable energy mix, over the years.

On the other end, saving electric energy by its more intelligent usage, to do “mechanical useful work by electric motors”, has led to variable speed motor drives (Fig. 3a,b) [3].




(a) with valve ofering flow rate control




(b) with variable speed control

Fig. 3. Energy flow from fossil – fuel power plant to electric motor pump: (a) with valve ofering flow rate control, (b) with variable speed control

The advantage of variable speed in electric generators has been capitalized mainly in the last 10 years in wind generator systems with AC–DC–AC power electronic interfaces. It was soon realized that, even for limited variable speed range (and power electronics fractional p.u. ratings), besides increased efficiency, the flexibility gains in electric power faster control are even more important. The first breakthrough was represented by 400 MVA pump–storage hydroplants with variable speed wound–rotor induction generators (DFIGs), introduced in Japan, in 1994 [4].

Recently 230 MVA such variable speed DFIG system was introduced to pump storage hydro-plants in Europe [5].

But the renewable distributed energy resources led to massive introduction of power electronics (and variable speed) in distributed (intelligent) power grids. In view of the wide spectrum of electric generator and motor systems and the rich heritage of books, articles and patents on them (see [6] for selected references) in what follows we will concentrate on recent progress and future trends in a few representative applications:

- Electric generators in high power systems, Section2
- Renewable energy variable speed generators in distributed power systems, Section 3
- Autonomous electric generators in transport and industry, Section 4
- Industrial electric drives, Section 5
- Electric propulsion systems, Section 6
- Electric drives in residential applications, Section 7
- Electric actuators in info-gadgets, Section 8
- Line start higher efficiency motors, Section 9

Note. Another valid approach would have been, perhaps, to treat recent progress and future trends by looking into: principles, topologies for various speed and power ranges, multi-physics modeling and optimal design methodologies, control methods by power electronics, testing, commissioning, monitoring, maintenance, while mentioning, in passing, selected applications. As most potential readers are rather familiar academically with the subject, [6] we selected here the more practical criterion of applications which is not without shortcomings, either.

## II. Electric Generators In High Power Systems

High power electric systems are defined as rather constant frequency and voltage AC systems with synchronous 3 phase generators in parallel and voltage boost and buck power transformers to transport and distribute power at long distances (up to 1000 km or even more) and above 100 MVA (in general), to consumers at medium (6 – 12 kV) and low (690, 380, 220 V) line voltage.

Consumers "use" electric power (energy) for lighting, heating / cooling or in electric motor drives, for "mechanical useful work". To share input power from various generators the frequency of each generator is allowed to droop (less than 1%) so that, at a unique frequency, by the droop ramp, the individual contribution of active electric power is varied.

The voltage droop principle with reactive power increase is also used in controlling the voltage in such power systems (Fig.4).

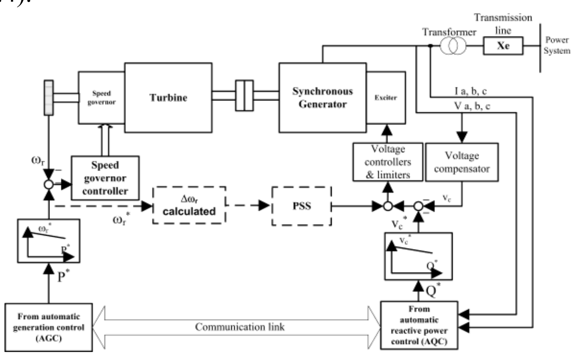



Fig. 4. Frequency and voltage droop control principles in power systems[3].

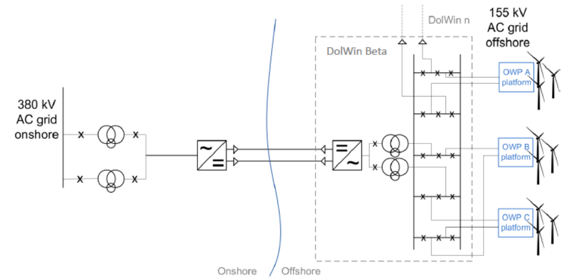
The same principle, but of smaller droop control, is used to connect in parallel large power electronics converters used in standard and distributed AC power systems.

The main asset of such a high power AC system is that its equivalent impedance is low and thus each individual consumer is small enough to be incapable to destabilize alone the system, in principle.

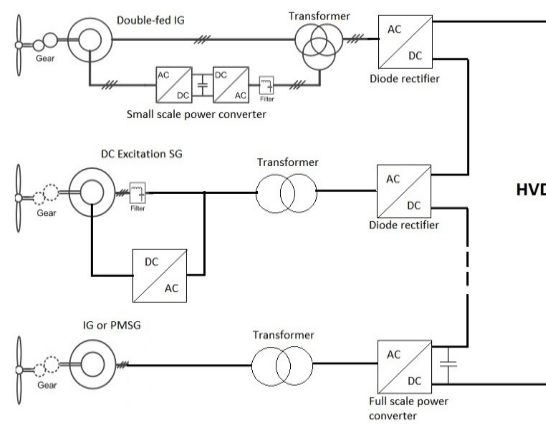
But as more and more power is transported through such rigid AC power transmission lines, fed from rigid (synchronous) generators, a large electric power load disturbances, which is quick (milliseconds), cannot be handled stably (easily) by electric generators with inertia in the range of (8–15) seconds in relative units.

This is how parallel and series power filters etc. have been added mainly for voltage fast control and recovery in what is called flexible AC power transmission systems (FACTS) [5].

But the main source of "rigidity", the synchronous generator, remains there because of other important assets. On the other end, high voltage direct current (HVDC) power transmission lines have been introduced for powers in the range of 1000 MVA (and more) and voltages up to 0.5 to 1 MV, for distances above a few hundred kms, to be economical. HVDC needs ultimately full power high voltage AC – DC – AC static power converters, but they are far more stable and allow more power transmission for given power lines (cable) outer diameter, with less voltage recovery needs along large distances at lower total transmission line losses (Fig. 5a,b).




(a) with fixed frequency generator systems




(b) DFIG DC excited SG with variable frequency, PMSG (IG) with variable frequency

Fig. 5. HVDC transmission lines: (a) with fixed frequency generator systems; (b) DFIG DC excited SG with variable frequency, PMSG (IG) with variable frequency.

The variable frequency generators and transformers (Fig. 5b) with a single step full power static power converter to HVDC might be a way of the future but the whole design of standard synchronous and other electric generators (Fig. 5b) and transformers of high power has to be revisited.

With such an arrangement the variable speed will allow the usage of kinetic energy of the turbine–generator system to "damp" large and quick electric power disturbances in the power system, making the generators much more flexible (Fig. 5 b).

But, in this eventuality, PM (or PM assisted) synchronous generators perhaps up to powers/units of 1500 MVA at 3 krpm (which correspond in size to a 5 MVA, 10 rpm directly–driven wind DC excited synchronous generators, already commercial) may be considered.

More than that, doubly fed (wound rotor) induction generators (DFIGs), already introduced for hydro–pump –storage power plants at 400 MVA could be considered, but now with variable stator frequency, for variable speed and thus allowing only 5% slip power static power converter ratings for a (1.3/0.7) speed regulation range by allowing 2/1 stator frequency change [8].

Today's commercial DFIG, which make 50% of wind generator power, are still designed at constant stator frequency.

As visible in Fig. 5b, the DC excited generator may be provided with an oversized excitation system (10% rating) to preserve constant voltage (with power increasing with speed) for the entire speed range, while a full power modular diode rectifier would suffice to deliver power to the DC high voltage bus.

The simplicity of such a scheme (Fig. 5b) is “burdened” by unity power factor operation at all power levels and by the generator current harmonics.

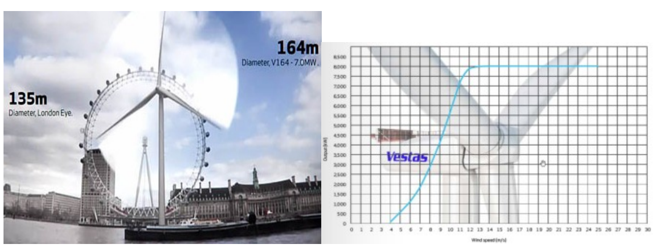
The PMSG scheme (Fig. 5b) requires a full power forced commutation active rectifier with voltage boosting at lower generator speeds, to interface with the modular AC–DC HVDC converter.

Finally, the variable speed and stator frequency DFIG (Fig. 5b) requires basically a 5% AC–DC–AC power converter connected to the rotor winding and a diode rectifier with a strong DC link capacitor, to handle a 1.3/0.7 speed range with an (1.8-2)/1 stator frequency range. CRIG (Fig. 5b) is also suitable for the cause. None of the schemes in Fig. 5b has been tested in full power but they seem to deserve full attention, both for high power systems and also for large HVDC wind offshore parks (at even only 60 kV DC and 100 MVA, for 60–100 km distances to shore). The variable stator frequency allows also easy “synchronization” with the HVDC AC–DC converter. But more work is required in this area before industrialization.

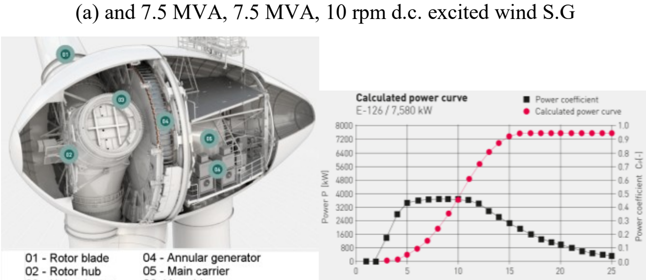
## III. Variable Speed Generators For Wind Energ

Wind energy conversion has reached 400 GW installed power in 2016 and is expected to grow further in the next 20 years by at around 10% average/year.

Though small wind and micro – hydro generator systems can be built even for residential applications (for 3-10 kVA rated power), we will emphasize here the two largest so far commercial wind generators (Fig. 6a,b) [9].




(a) and 7.5 MVA, 7.5 MVA, 10 rpm d.c. excited wind S.G

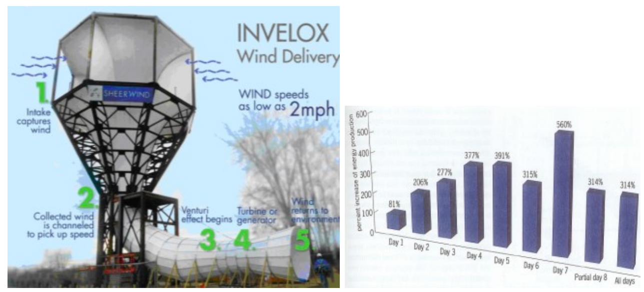



(b)http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/V164 80MW/V16480MW/ ; http://www.enercon.de/en/products/ep-8/e-126/

Fig. 6. Eight MVA , 480 rpm wind – PMSG, (a); and 7.5 MVA, 7.5 MVA, 10 rpm d.c. excited wind S.G, (b); http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/V16480 MW/V16480MW/ ; http://www.enercon.de/en/products/ep-8/e-126/

The 8.0 MVA PMSG at about 480 rpm (with mechanical transmission) reflects the trend of using less high energy PMs per kW as the availability of such magnets is limited and thus their price is still above/around 100 USD/kg. On the other end, the DC cited SG at 7.5 MVA for about 10 rpm (directly driven) reflects the trend of eliminating the mechanical transmission. The already high tower (Ø 164/127 m diameter of turbine rotor at around 8 MVA) and the low turbine speed (10 rpm) implies high weight/kW wind turbine plus generator systems, which means heavy nacelle and thus heavy (costly) towers.

A novel wind harvesting method via a flexible smaller tower with a Venturi tube to accelerate the captured wind that allows to place the turbine-generator in the tube (close to ground level) to run at 5 times the usual speed (above/about 50 rpm for 10 MVA), has been proposed recently (Fig. 7a,b) by INVELOX [10].




(a) The invelox wind energy system (b) p.u. captured energy for a given site

Fig. 7 (a) The invelox wind energy system; (b) p.u. captured energy for a given site.

If this solution that claims a 30% reduction of energy cost per kWh at 2-3 time more energy harvested per given site comes true, with today’s technology wind generators at 50 MW and 50 rpm could be contemplated. At such speeds even the DFIG could be tried for the scope.

Cage rotor induction generators (CRIGs) and other PM (or PM less) counter-competitors have been recently proposed for high (MW range) power wind energy conversion, but the bettering of AC excited SGs, DFIG, PMSG systems will, in our view, constitute high weighing industrial trends in the field for the coming decade.

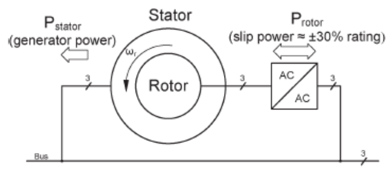
## IV. Autonomous Electric Generators

With applications on Diesel – electric locomotives, aircraft marine vessels, hybrid electric automobiles, trucks, motor bikes or as auxiliary generators for cogeneration in industry, emergency generators in hospitals, banks Telecom power relays, or auxiliary generators on trucks etc., autonomous (or small group) electric generators represent a strong world-wide industry with powers per unit from a few kVA to tens of MVA. They may operate at rather constant speed regulated on the prime mover–marine vessels etc., or at variable speed (avionics etc.). So far two main variable speed generator schemes have been proposed in avionics and marine vessels to produce electric power on board in the range of a few MVA /unit:

- With AC output at variable frequency and controlled voltage
- With DC output controlled voltage.

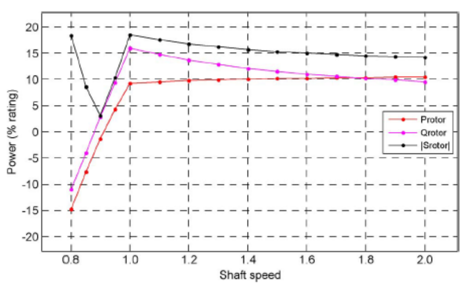
- Traditionally, a DC excited SG with controlled enhanced excitation (with a machine – exciter on the shaft) is used for the scope [11], but the slow power response, high volume topology and rather moderate efficiency limitations ask for better solutions.

DFIG and dual stator winding CRIGs with partial rating static power converters and variable stator frequency or with DC output and controlled voltage have been recently proposed (Fig. 8)[12, 13].

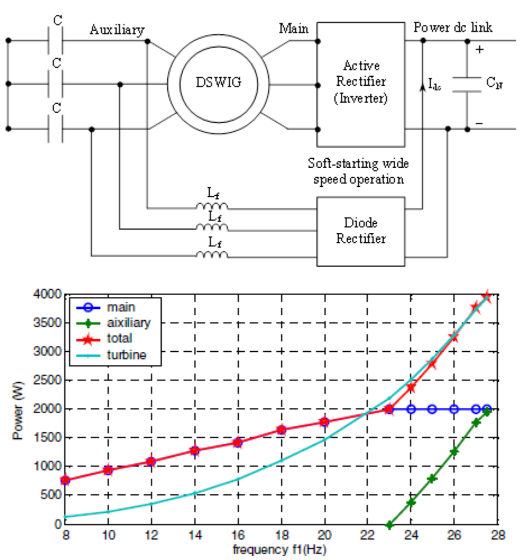



GENERATING MODES AND CONVERTER RATING SUMMARY

| Generating mode | Mechanical speed range | Electrical frequency range | Converter rating (% system rating) |
|---|---|---|---|
| *Constant frequency* | 2:1 (±33%) | 1:1 | 76% |
| *Constant frequency (synchronous cruise speed)* | 2:1 (-24%, +52%) | 1:1 | 59% |
| *Frequency-limited* | 2.5:1 | 2:1 | 18% |




(a) DFIG with variable stator frequency and constant voltage [12]




(b) dual stator winding CRIG with d.c. output [13]

Fig. 8. Avionics generator proposals: (a) DFIG with variable stator frequency and constant voltage [12]; (b) dual stator winding CRIG with d.c. output [13]

Multipurpose auxiliary PM generators use power electronics heavily (Fig. 9) [14] or use simplified 1 phase voltage AC output control for constant speed operation (Fig. 10) [15]. Efficiencies of 90 % for 3 kW at 3000 rpm, 50 Hz, and ±5% voltage regulation with step capacitor control was reported for a 10 kg, 1 phase PMSG prototype [15].

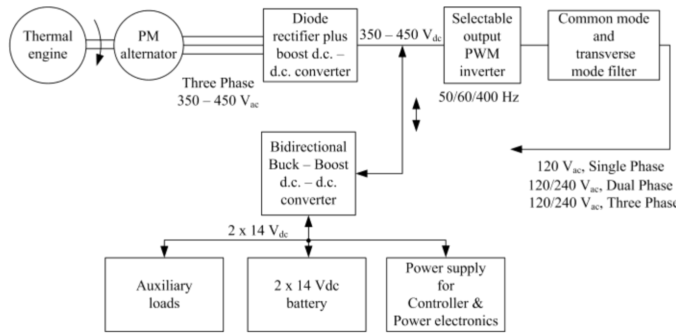



Fig. 9. Multipurpose PM generators [14].

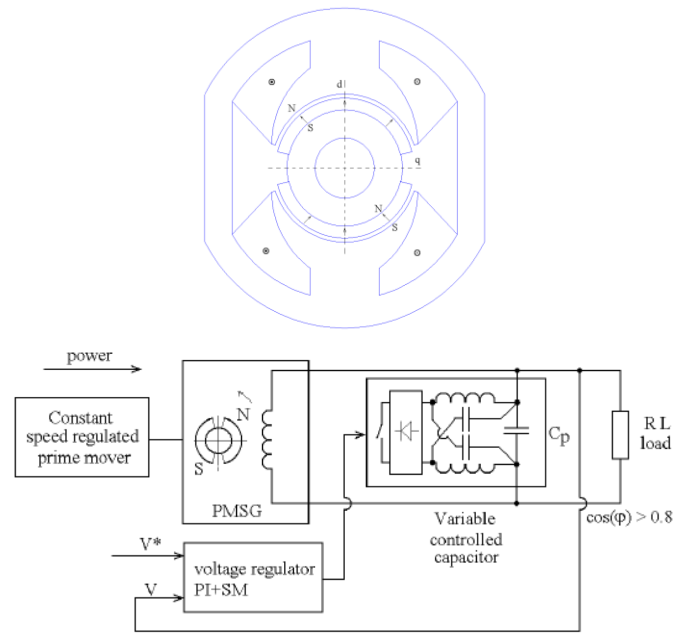



Fig. 10. Three kW, 3000 rpm, 50 Hz, 1 phase a.c. PM generator with step capacitor ±5% voltage control down to 0.8 lagging power factor loads [15].

High speed high power PM generators with a.c.–d.c.–a.c. converter interface, driven by gas turbines up to 3 MVA at 15 krpm, have been successfully implemented also.

## V. INDUSTRIAL VARIABLE SPEED ELECTRIC MOTOR DRIVES

From orr – mills at low speed high power (ex: 5 MW, 11 – 17 rpm) and hot (or cold) steel sheet – strip mills (ex: 1 MW, ±800 rpm) and 50 MW, 60 kV (with power former) variable speed gas compressor drives, down to industrial conveyors (tens and hundreds of kW, below 500 rpm) and robotic actuators (Nm drives with positioning precision control etc.), motion (energy flow) control in industry is performed by variable speed electric motor drives.

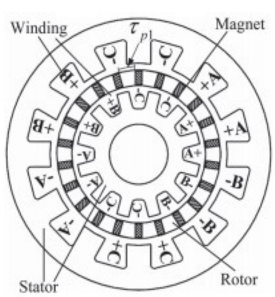
They may be classified in high power medium voltage (a few kV) drives and medium and low power (low voltage – less than 690 V) drives.

The progress in this field of applications has been staggering in the last two decades and consisted mainly in:

- Dramatic extension of PM brushless DC and AC motor drives [15-18].
- Field oriented, direct (even dead–beat) torque and flux control of all AC (induction, PMSM, DC excited SMs, [19-38] PM tooth-wound coil with and without stator or rotor PM assistance [39-42]) motors.
- Advanced nonlinear analytical models of brushless motors, complimented by Magnetic equivalent circuit (MEC) models [43] and FEM models for preliminary and optimal design up to multi-objective FEM–only–based optimal design codes [33] to produce robust designs to fabrication and to materials properties tolerances.
- The robust torque, speed, position control by variable structure or predictive control strategies [44-52] with and without encoders.
- The recent launch of a series of reluctance synchronous motors variable speed drives with distributed windings and powers up to 500 kW (even to 1.5 MW) and multiple flux-barrier rotors, with 3%-1% efficiency gain over similar IMs but, at 7% - 8% less power factor, though at lower cost [53-54].
- The aggressive investigation of:

- Vernier PM motor drives [55-58], (Fig. 11) switching-flux and flux-reversal [59-62] (Fig. 12).
- Transverse flux PM machines [63] (Fig. 13).
- Magnetic gear two rotor PM motor drives [64], (Fig.14) with 107 Nm/liter [64] for 250 Nm at 9 krpm and 95% efficiency.

They all are proposed for higher torque density, high efficiency, moderate power factor and moderate cost low and medium speed direct drives, where the mechanical transmission elimination is mandatory.



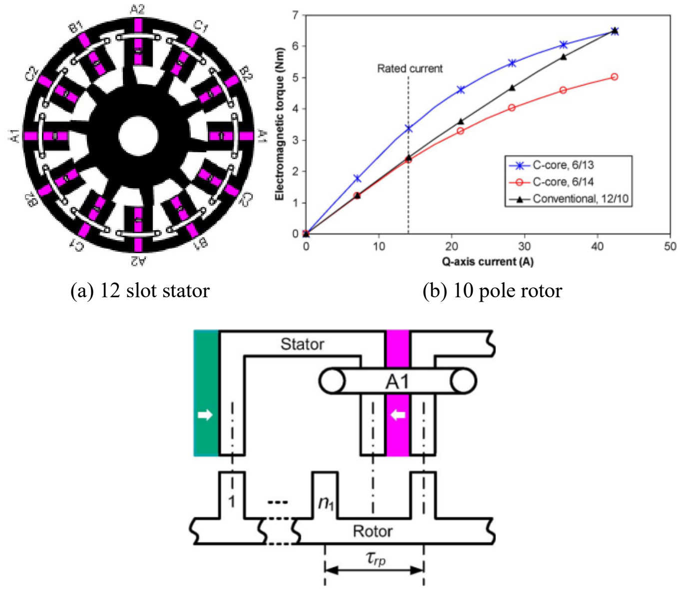

(a) geometry [59]

COMPARISON OF SIMULATION AND MEASURED PERFORMANCE INDEXES

| | Simulation value | Measured value |
|---|---|---|
| Torque | 2000 Nm | 1920 Nm |
| Speed | 30RPM | 30RPM |
| RMS line current | 23.6A | 23.6A |
| Power factor | 0.85 | 0.83 |

(b) performance table [59]

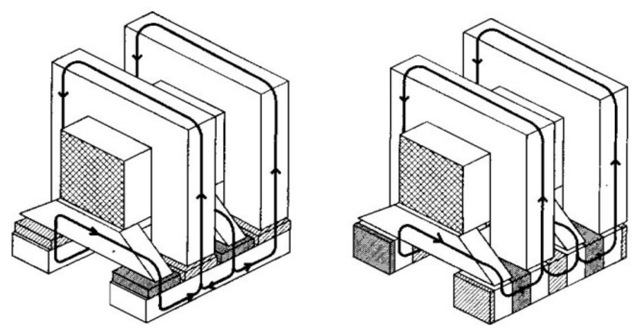
Fig. 11. Vernier Ferrite–PM machine: (a) geometry [59]; (b) performance table [59]




(a) 12 slot stator (b) 10 pole rotor

(c) cross – section illustration

Fig. 12. Stator PM (switched flux) 12 slot/12 poles machine: (a) 12 slot stator, (b) 10 pole rotor; (c) cross – section illustration



(a) with surface PMs (b) with PM flux concentration

Fig. 13. Transverse – flux PM – rotor machines: (a) with surface PMs; (b) with PM flux concentration.

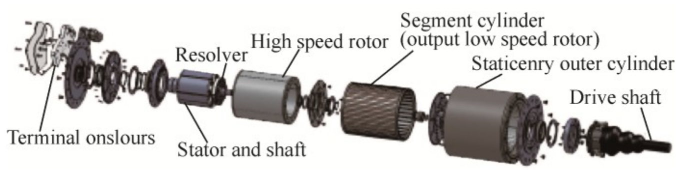
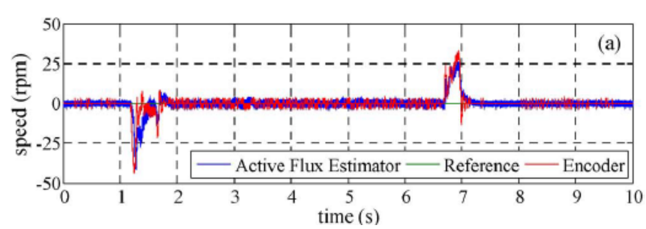
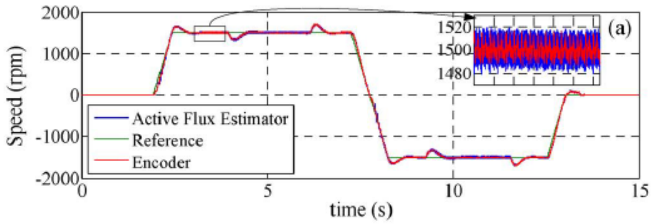



Fig. 14. Integrated PMSM and magnetic gear.

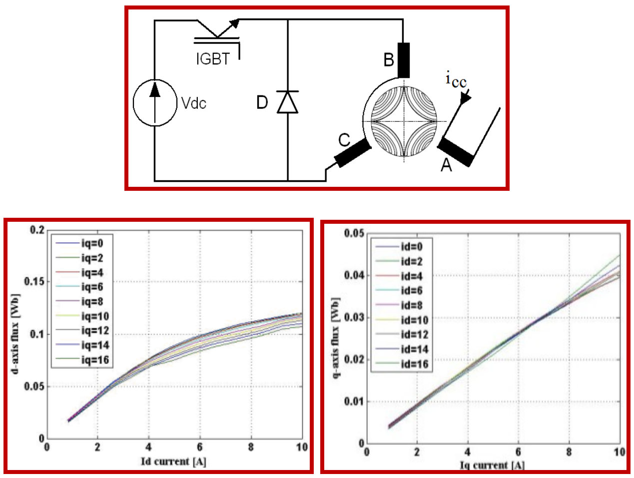
As an example, the case study of a small power reluctance synchronous motor encoder-less drive with field – oriented active – flux – based control is illustrated in Fig. 15 for zero speed operation (with signal injection) and ± 1500 rpm transients [65].




(a) zero speed operation with 1 Nm full torque




(b) ±1500 rpm transients




(c) motor drawing and characteristics ($R_s$=0.61Ω) [65]

Fig. 15. Relsyn motor encoderless drive with active – flux – based flux oriented control from zero to 3000 rpm: (a) zero speed operation with 1 Nm full torque; b) ±1500 rpm transients; c) motor drawing and characteristics ($R_s$=0.61Ω) [65].

## VI. Electric Propulsion Systems

Electric propulsion here refers mainly to hybrid electric or electric vehicles (HEVs and EVs) but it could be extended to multi-motor electric propulsion for street – cars, subways, trains and marine vessel [66]. We will also refer briefly to linear electric motor propulsion in wheeled vehicles and in MAGLEVs [67].

There are already a few millions (from a total of a billion total) of HEVs on the roads. They combine thermal engine and electric propulsion with one (or two) electric machines and their power interfacing power electronics to a power battery of about 220 Vdc or so, to provide electric travel independence for 60–100 km or more (the latter with slow plug-in charging one/two times a day for a few hours). The gas mileage is increased by as much as 40-50% in urban driving and 25-30% in highway driving.

The return time on the electric extra equipment investment is still corresponding to about 100,000 km driving, but the energy savings and local (in town) pollution reduction suffice to justify it [68]. EVs have reached 160 km independence but there are forecasts for 400 km and more, with more advanced batteries.

Both copper–cage–rotor induction motors and IPMSMs are applied; the IM has a better efficiency at high speeds (under flux weakening) while the IPSM has better efficiency at peak (low speed) torque. The IM lacks the magnets (with their problems of demagnetization risks) while it claims 15-20% more volume under the hood.

In the mean time Ferrite – PM – assisted RelSyn [70-71] switched reluctance [72], DC excited SM (with contactless power transfer to the rotors [73]) have been tested up to 100 kW for HEVs and EVs with competitive performance per cost. Multiphase motor configurations of the above machines for higher fault tolerance or even PM – less BLDC multiphase reluctance machine [74], controlled like DC brush machines, stator PM tooth-wound coil PM machines, Vernier PM machines etc. have also been investigated lately for HEVs and EVs. The HEVs with extended electric independence (by better batteries) and by plug-in charging overnight may be the main e–vehicle as it depends less on the renewable proportion in the energy mix than otherwise needed for EVs.

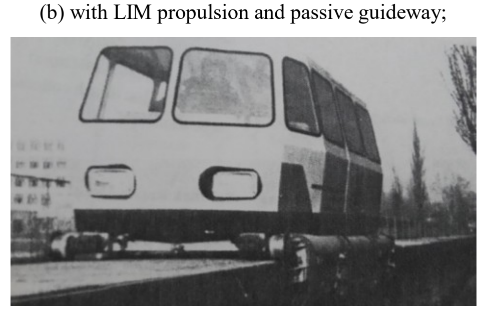
As a warning call for enthusiasts, here we present sample results from [69] on energy consumption in two identical EVs: one with IPMSM and the other with copper – cage IM electric propulsion, in the same in – town driving cycle [Table I]. Yes, formula E in car racing will thrive, but mainly due to local pollution reduction nearby the track.

Utility and public transport vehicles for down town have the best chance and should become EVs.

Last but not least, let us mention here Linear induction motor (LIM) propulsion urban people movers [67] and suburban and high speed interurban MAGLEVs with integrated Linear Synchronous motor (integrated controlled propulsion and levitation) and active guideway (Fig. 16 a) or passive guideway (Fig. 16b) which reduce the energy/passenger/km by as much as 30% for same commercial speed, but require larger investments (in the active guideway track, especially).

Public electric transport of people and goods may have in MAGLEVs a technology of the future, as power electronics performance/cost improved dramatically in recent years, and so did MW range mechanical-contact-safe-power-transfer on board of vehicles at high speeds.


(a) with linear synchronous motor and active guideway;
(b) with LIM propulsion and passive guideway;



(c) with linear homopolar synchronous motor propulsion and levitation and passive guide way (MAGNIBUS-0.1) [67]

Fig. 16 MAGLEVs with attraction force levitation and guidance: (a) with linear synchronous motor and active guideway; (b) with LIM propulsion and passive guideway; (c) with linear homopolar synchronous motor propulsion and levitation and passive guide way (MAGNIBUS-0.1) [67].

TABLE I
EXPERIMENTAL AND SIMULATION RESULTS FOR ENERGY EFFICIENCIES UNDER RATED AND OPTIMAL FLUX IM AND IPMSM FOR THE VALIDATION DRIVE CYCLE

| | Experiment | | | | Simulation | | | |
|---|---|---|---|---|---|---|---|---|
| Machine | $E_{in}$ (Wh) | $E_{out}$ (Wh) | $E_{loss}$ (Wh) | α (%) | $E_{in}$ (Wh) | $E_{out}$ (Wh) | $E_{loss}$ (Wh) | α (%) |
| IM(rated) | 44.16 | 28.42 | 15.74 | 64.3 | 39.57 | 26.96 | 12.61 | 68.1 |
| IM(opt) | 41.34 | 28.24 | 13.09 | 68.3 | 40.55 | 28.99 | 11.56 | 71.4 |
| IPMSM | 39.64 | 28.92 | 10.72 | 72.9 | 37.25 | 27.51 | 9.73 | 73.8 |

## VII. ELECTRIC MOTOR DRIVES IN HOME APPLIANCES

Small power electric motor drives are as present in our residences as they are for different auxiliary services on vehicles.

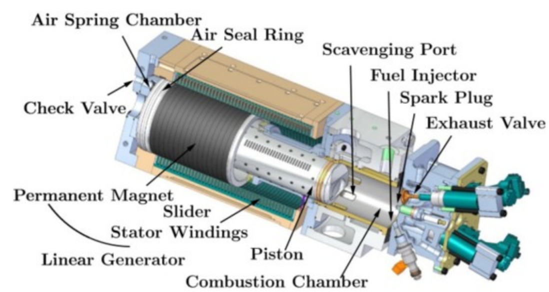
Intelligent cities will perhaps rely on intelligent transport and intelligent residences, besides limited size, to reduce energy pollution and waste per capita.

Supplied so far from the 1 phase a.c. local power grid (but in the future, perhaps, also, from a local (even in house) DC-voltage bus grid) at powers/unit in the tens of watts to 1(1.5) kW, small motors characterize most home appliances. With line start constant single (or dual) speed electric motors, higher efficiency is the main target such as (in refrigerator compressor motors of split-phase-capacitor type) with cage rotor, without and with multiple flux barriers and PMs in the rotor. From 85% efficiency at 100 W, 2900 rpm with IMs to 89 (90)% efficiency at almost same cost with line-start PM assisted IMs at 3000 rpm, the road was travelled in the last 5 years to improve performance/cost in residential refrigerators. Optimal design methodologies played here a key role. Also, variable speed compressors for refrigerators make use of PMSMs with higher efficiency, but exploit also the increased compressor performance at variable speed and thus cover for the added cost of the inverter interface and control.

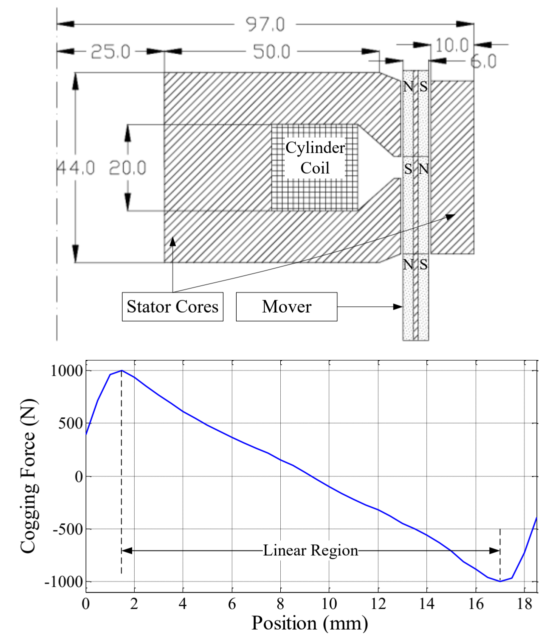
Ferrite-PMs are called for the replace sintered NdFeB magnets for lower initial costs but almost similar performance obtained by optimal design, outer rotor or other Ferrite-PM flux linkage increasing methods [75].

Yet another way to improve linear-motion piston small compressor refrigerator drive performance is to use short-stroke (less than ± 15 mm) 1 phase PM linear oscillatory resonant motors with either PM – mover or with stator PM and iron-mover [67]. A sample such linear PM generator driven by a linear thermal engine is shown in Fig.17a, while a potential topology capable of resonant operation, by using “cogging force” as a magnetic spring to replace the useful mechanical spring (made of beryllium-copper disks): $f = (1/2\pi)\sqrt{k/m_{mover}} = f_e$ ($f_m$-mechanical eigen frequency, $f_e$-electrical frequency), is visible in Fig. 17b [67].

Resonant operation (with phase current in phase with emf, roughly) provides high electrical efficiency, while the rotary to linear motion transmission elimination cancels notable compressor mechanical losses. The linear PM motor compressor drive may work at variable load optionally by just reducing the voltage amplitude and keeping the frequency constant (for resonance, which is for minimum current follow up).




(a)generator driven by linear thermal engine




(b) potential springless resonant device with PM mover and magnetic (cogging) “virtual spring” [67]

Fig. 17. One phase linear PM oscillatory resonant generator-motor: a)generator driven by linear thermal engine (a mechanical spring may be used for resonant operation in other applications); (b) potential springless resonant device with PM mover and magnetic (cogging) “virtual spring” [67].

Note. There are many other home appliances such as the hair dryers, vacuum cleaners, kitchen robots that work at high speed and still wait for even better power electronics control. Washing machines already, in some variable speed configurations, benefit of power electronics control for variable speed (through direct belt driven tooth – wound ferrite PM multipole rotor synchronous motor drives) though many still use dual speed (dual pole number) winding IMs (one for washing and one for rinsing), to reduce initial and maintenance costs at the price of more energy for a given job done.

## VIII. Electric Actuators For info Gadgets

We mean here by info gadgets devices like: cellular phones, computer panels, desktop computers, sound and image producers, timers that use very small power motors with power electronics control for variable or fix frequency (speed).

Microphones and loudspeakers [67, Chapter 17] are typically linear oscillatory PM motors (generators) with coil movers and their optimal design to save space (for the screen) and energy are crucial in cellular phones. And so is the ringer-motor-drive made from a rotary PM motor drive or of a linear PM oscillatory motor drive, to make it flatter and reduce power by increasing the resonance (ringing) frequency of the cellular phone frame.

Small (less than 15 mm diameter) high speed small power rotary PMSMs (25 W, 15 krpm) are used to drive the compressor that may be used for cooling the central unit of many desk computers [67]. Sub watt power energy harvesters (including those driven by the back – pack oscillation during the mountain hiking) or for contactless local power production via door handle opener rotation by the tourist to engage then the solenoids that unlocks the door in a hotel room etc.) have also been produced lately and expected to extend in wireless sensors or in medicine dispatchers to human body etc.

## IX. Line Start Higher Efficiency ac Motors

We left at the end the line start AC motors though they use almost half of electric energy. For them low cost and constant mechanical work power in time are necessary (with a few stops and starts per day). Applications range from hot water 100 W range pump motors in residential gas-heaters to 8 MW cooling pumps in high power electric plants. Increasing efficiency even by 1 % in such devices makes a world of good in terms of energy bill reduction such that it can "buy" the motor within 1 year for powers above 1 kW/unit.

Classes of higher efficiency (up to 5) have been introduced as recent standards by IEC and NEMA. For classes 4 and 5 IM may hardly qualify even after exhaustive optimal design attempts and better materials usage, due to additional (stray) losses, cage losses and large magnetizing current (in low power motors, even with 4 poles). Not to mention that high class efficiency induction motors have in general larger starting current ratio: Istart/Irated>6.8-7, which implies larger local grid transformer and power switch ratings and costs).

So, line start copper cage IMs and PM assisted induction motors without and with PMs and multiple flux barriers rotors have been proposed to reach classes 4, 5 of efficiency with only moderate extra initial costs and reasonable starting current ($I_{start}/I_{rated}<6.3$) [76]. The PM braking torque, augmented by complex magnetic saturation anisotropy reluctance torque oscillations during heavy on-line starting [77], are still a high obstacle in extending the PM-assisted IMs use for high efficiency: 93% at 4 kW, 1500 rpm [78]. The use of higher anisotropy cage rotor in 2(4) pole IM-reluctance synchronous motor with ferrite – PMs for higher power factor might be the practical way out of this difficulty in line start 3 or 1 phase source AC high efficiency motors. The way to this target means probably better core materials (with high permeability and low losses, such as metglass etc.), better designs with compressed windings made even of aluminum, shorter coil-ends in 2 pole axial-airgap motors by using Gramme-ring windings for dual (twin) rotors.

TABLE II
Efficiency classes by IEC [76]

| Standard & Year Published | State |
|---|---|
| IEC 60034-1, Ed, 12, 2010, *Rating and performance.*<br>*Application*: Rotating electrical machines | Active |
| IEC 60034-2-1, Ed, 1, 2007, *Standard methods for determining losses and efficiency from tests(excluding machines for traction vehicles.)*<br>Establishes methods of determining efficiencies from tests, and also specifies methods of obtaining specific losses.<br>*Application*: DC machines and AC synchronous and induction machines of all sizes within the scope of IEC 60034-1. | Active But under revision |
| IEC 60034-2-2, Ed.1, 2010, *Specific methods for determining separate losses of large machines from tests-supplement to IEC60034-2-1.*<br>Establishes additional methods of determining separate losses and to define an efficiency supplementing IEC 60034-2-1. These methods apply when full-load testing is not practical and result in a greater uncertainty<br>Application: Special and large rotating electrical machines. | Active |
| IEC 60034-2-3, Ed. 1, 2011, *Specific test methods for determining losses and efficiency of converter-fed AC motors.*<br>*Application:* Converter-fed AC motors. | Not Active Draft |
| IEC 60034-30, Ed. 1, 2008, *Efficiency classes of single-speed, three-phase, cage induction motors(IE code).*<br>*Application*: 0.75-375kW, 2,4 and 6poles, 50 and 60Hz. | Active But under revision |
| IEC 60034-31, Ed. 1, 2010, *Selection of energy-efficient motors including variable speed applications- Applications guide.*<br>Provides a guideline of technical aspects for the application of energy-efficient, three-phase, electric motors. It not only applies to motor manufactures, original equipment manufacturers, end users, regulators and legislators, but to all other interested parties.<br>*Application*: Motors covered by IEC 60034-30 and variable frequency/speed drives. | Active |
| IEC 60034-17, Ed. 4, 2006, *Cage induction motors when fed from converters-application guide.*<br>Deals with the steady-state operation of cage induction motors within the scope of IEC 60034-12, when fed from converters. Covers the operation over the whole speed setting range, but does not deal with starting or transient phenomena.<br>*Application*: Cage induction motors fed form converters. | Active |

## X. Conclusion

- Electric (electromagnetic) machines (EMs) started with Faraday's law of "electromagnetic induction" (1831) found, spelled as an experiment with attraction and repulsive (induced currents) forces, in Lucretius "The nature of Universe", book, the year 60 B.C.
- EMs convert mechanical energy to electric energy (generator mode) or vice – versa (motor made) via stored magnetic energy. Energy balance is crucial in analyzing EMs.
- EMs may develop (experience) rotary or linear or hybrid

motion.

- Standard EMs developed already by 1900 classify into DC (AC) brush (fixed field) machines and AC (traveling field) machines: asynchronous/induction and synchronous.
- Electric energy is obtained through electric generators (except for photovoltaic energy) with powers/unit up to 1800 MVA (turbgenerators driven by fossil or nuclear fuel turbines) and up to 770 MVA in hydrogenerators (recently on Iantze River)
- More than 60% of electric energy is producing "mechanical useful work" in electric motors, which may be line – started (fix speed) or fed from PWM static power converters (for variable speed).
- The last 50 years witnessed staggering progress in:
  - Lighter and more efficient large power generators
  - Optimal multi-physics design methodologies using magnetic equivalent circuit (MEC) and FEA
  - The extension of PM usage in variable speed synchronous machine drives (with PWM AC-DC-AC static converter interfaces); from subwatt to a few MW power (3 MWA, 15 rpm PMSGs for wind energy conversion).
  - As the offer of quality (high energy) magnets is limited, it is anticipated that PMs will be used only when the cost is not the first target, but weight and efficiency are (low PM weight/kW), when high speed applications are favored.
  - Combining lower cost magnets on rotor and on stator with single and (or) double magnetic saliency in "brushless" motors has led to an avalanche of "novel" topologies, augmented by tooth-wound stator windings in the last 20 years; some are close to worldwide market entrance.
- The present paper presents a summary of the recent progress in EMs, rotary and linear (MAGLEVs, included) following eight important application domains, with key literature citations, and infer some avenues for further developments.
- The paper is by no way complete or fully objective and inevitably reflects both the horizon and the limits of the author. Consequently, criticism is welcome.

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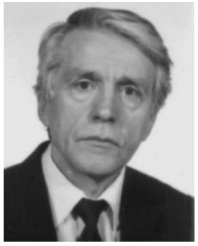

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