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New Applications of Synchronous Generators

Abstract. *High-speed synchronous generators rated in the power range of megawatts have been discussed. These generators are nowadays necessary for new aerospace missions. Requirements, ferromagnetic materials, magnetic circuit, electromechanical design and cooling techniques for high-speed multimegawatt generators have been discussed. First prototypes (1 MW and 2.5 MW) have been outlined.*

Streszczenie. *Artykuł dotyczy prądnic synchronicznych o wysokiej prędkosci obrotowej oraz mocy rzędu megawatów stosowanych w aparatach latających. Prądnice takie są obecnie konieczne do misji specjalnych w przestrzeni powietrznej. Omówiono wymagania, materiały ferromagnetyczne, obwody magnetyczne, elementy projektowania elektromechanicznego oraz techniki chłodzenia prądnic o wysokiej prędkości oraz mocy rzędu megawatów. Przedstawiono pierwsze prototypy takich prądnic (o mocach 1 MW oraz 2.5 MW).* ***(Nowe zastosowania generatorów synchronicznych)***

Keywords: synchronous generators, multimegawatt, aerospace, magnetic circuits, cooling systems, design, first prototypes
Słowa kluczowe: prądnice synchroniczne, moc rzędu megawatów, przestrzeń powietrzna, obwody magnetyczne, układy chłodzenia, projektowanie, pierwsze prototypy

Introduction

The speed of a.c. machines increases with increase in the input frequency. The electromagnetic torque is proportional to the electromagnetic power and number of pole pairs and inversely proportional to the frequency. High speed and high frequency armature current reduce the dimensions and mass of electrical machines.

At present, the maximum power of high speed (over 5000 rpm) aerospace synchronous generators does not exceed 500 kW. Several airborne power missions are now evolving that will require lightweight multimegawatt electrical power systems, e.g., directed energy weapon (DEW) and airborne radar (AR) [1, 12, 10, 19]. New high power airborne and mobile military systems will require 1 to 6 MW of electrical power generated at speeds 10 to 20 krpm or higher. Potential candidates as multimegawatt generators are [4, 6, 9, 10, 11, 18, 19, 20]:

- high power density classical synchronous generators with electromagnetic excitation (wound-field rotor)
- synchronous generators with high temperature superconducting (HTS) excitation winding
- homopolar generators with stationary d.c. HTS excitation winding
- all cryogenic generators (synchronous or homopolar)

Requirements

Basic design requirements for high speed machines include, but are not limited to:

- high power density (output power-to-mass);
- brushless design;
- compact design;
- minimum number of components;
- ability to withstand high temperature;
- low subtransient time constant (pulse operation);
- minimum *cost–to–output power* ratio and *cost–to–efficiency ratio*;
- high reliability (the failure rate < 5% within 80 000 h);
- high efficiency over the whole range of variable speed;
- low total harmonics distortion (THD).

It is also desired that modern airborne generators have some fault tolerance capability. However, generating mode with one damaged phase winding of a three phase machine and then normal operation after the fault clears is normally impossible.

Reliability data of airborne high-speed generators are very scattered and limited to generators rated at maximum 250 kVA. The mean time between failure (MTBF) values up to approximately 47 000 h as calculated from short-term maintenance record [18].

The stator laminations are about 0.2-mm thick for frequencies below 400 Hz and about 0.1-mm thick for frequencies above 700 Hz. Low-loss, high-saturation, thin silicon steel laminations or iron-cobalt laminations are used for stator and rotor stacks.

To minimize the subtransient time constant, i.e., to eliminate eddy-current effects in the rotor pole shoes, the rotor - similar to the stator - must be in most cases laminated instead of made of solid steel. The rotor is often protected against centrifugal forces with the aid of *retaining sleeves* (cans) [8]. The retaining sleeve can be made of nonferromagnetic metals, e.g., titanium alloys, stainless steels, inconel 718 (alloy based on NiCoCr) or carbon-graphite composites. Good materials for retaining sleeves have high permissible stresses, very low electric conductivity, high thermal conductivity, and low specific density.

The higher the speed (frequency) and more efficient the cooling system, the smaller the volume and mass. Application of direct liquid cooling results in further increase of power density (*output power-to-mass* or *output-power-to volume*).

High efficiency means the reduction of the input mechanical power (prime mover) through the reduction of power losses. The lower the losses, the lower the temperature rise of a generator and easier the thermal management.

Directed energy weapons

It was believed before the World War II that electromagnetic waves could be used to destroy aircraft. For example, in 1935, Sir R.A. Watson-Watt[1] was asked by the Committee for Scientific Study of British Air Defence to investigate the ability of transmitting radio frequency waves of high enough power to boil the blood of German pilots and soldiers.

Directed energy weapons (DEW) take the form of lasers, high-powered microwaves, and particle beams [10]. They can be adopted for ground, air, sea, and space warfare. DEWs irradiate the target with electromagnetic energy. The so-called *fluence* is the energy density, i.e.,

$$E = \frac{P_{dout} \Delta t S}{A} \qquad \mathrm{J/m^2} \tag{1}$$

where P_{dout} is the DEW output power, Δt is the duration of the DEW pulse, $0 \leq S \leq 1.0$ is the dimensionless transmission number, also called Strehl[2] ratio, and A is the spot area

[1] Scottish physicist Robert A. Watson-Watt (1892-1973), inventor of radiolocators (British equivalent of radar) to detect airplanes.
[2] named after German physicist and mathematician Karl Strehl (1864-1940).

on the target. To destroy soft targets, i.e., fabrics, plastics, etc., approximately 1000×10^4 J/m^2 are required, but extremely hard targets, i.e., tanks, mine resistant vehicles, armored trucks, etc., might require $100\,000 \times 10^4$ J/m^2. Once the target has absorbed this energy, it will begin to heat up and even burn out.

The only difference between lasers and high-energy microwaves, which are both made up of photons, is their energy level. The photon energy

(2) $$E = hf = h\frac{c}{\lambda}$$

is a function of the frequency f, where $h = 6.626 \times 10^{-34}$ Js is Planck's constant, $c = 299\,792\,458$ m/s is the speed of light, and λ is the length of wave.

The power generation capabilities of electron microwave tubes (MTs), i.e., klystrons, magnetrons, gyratrons, gridded tubes and cross-field tubes range from watts to megawatts at frequencies from 300 MHz to 300 GHz (Fig. 1). *Klystrons* are the most efficient MTs and are capable of the highest peak and average powers. A klystron is a specialized vacuum tube called a linear-beam tube. The pseudo-Greek word *klystron* comes from the stem form *klys* of a Greek verb referring to the action of waves breaking against a shore, and the end of the word *electron*.

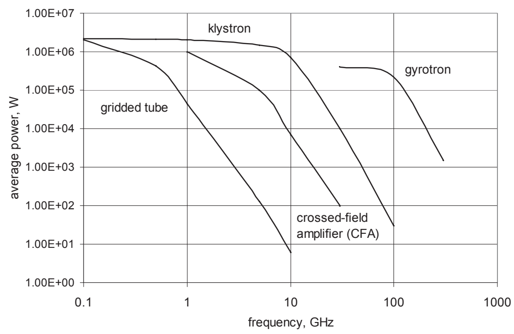

Fig. 1. Average output power versus frequency of state-of-the art microwave tubes (MTs).

High power microwave

High-power microwave (HPM) weapons produce either beams or short pulses of high-frequency energy in the megawatt range. For comparison, a typical microwave oven generates less than 1.5 kW of power.

The term HPM denotes sources producing coherent electromagnetic radiation from 1 GHz to over 100 GHz with an instantaneous power of at least 100 MW. Gigawatt-class HPM sources include *magnetically insulated line oscillator* (MILO), *relativistic magnetron*, *relativistic klystron amplifier* (RKA), *relativistic klystron oscillator* (RKO), and *reltron* [12]. Fig. 2 shows a comparison of the peak and average power characteristics for conventional and HPM sources.

When the microwave energy encounters unshielded current conducting bodies, semiconductors or electronic components, it induces a.c. current in them. The high frequency electric current causes the equipment to malfunction without injuring the personnel (Fig. 3). If the energy is high enough, the microwaves can permanently *burn* out the equipment.

The equivalent depth of penetration of electromagnetic wave into human skin is

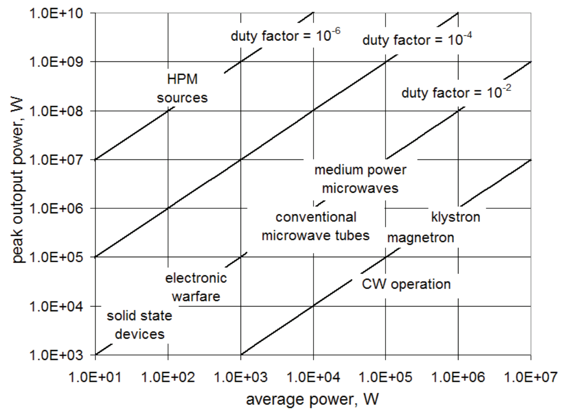

Fig. 2. Peak power versus average power domains for microwave production. CW — continuous wave mode [12].

(3) $$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}} \quad \mathrm{m}$$

where f is the frequency, $\mu_0 = 0.4\pi \times 10^{-6}$ H/m, μ_r is the relative magnetic permeability and σ is the electric conductivity. Assuming the conductivity of human tissue $\sigma = 2$ S/m at $f = 3 \times 10^{10}$ Hz = 30 GHz, and $\mu_r = 1$, the eqivalent depth of penetration $\delta = 2.05$ mm. The tissue is not damaged. Only a burning pain is produced which forces the affected person to escape. Current HPM research focuses on pulsed power devices that create intense, ultrashort bursts of electrical energy.

Fig. 3. The HPM uses microwave energy to disable or damage vehicle electronic control modules/microprocessors that control vital functions of engines. Image courtesy of Defense Intelligence Agency (DIA).

Lasers

Lasers produce either continuous beams or short, intense pulses of light in every spectrum from infrared to ultraviolet. The power output necessary for a weapons-grade high-energy laser (HEL) ranges from 1 kW to 10 MW. When a laser beam strikes a target, the energy from the photons in the beam heats the target to the point of combustion or melting. Since the laser beam travels at the speed of light, HELs can particularly be used against moving targets such as fighters, rockets, missiles, and artillery projectiles (Fig. 4). X-ray lasers may be possible in the not too distant future.

Most HELs being developed and tested for military applications have laser powers ranging from tens of kilowatts to 100 kW for tactical-level employment and up to multi-megawatt for strategic class applications [1]. For comparison, a power laser pointer that emits less than 1 W can cause permanent eye damage in less than 1 s, while average power outputs of 300 W to 1 kW are commonly used for industrial laser cutting.

Fig. 4. Russian 1987 mobile HEL defending an airfield. Image courtesy of DIA.

Fig. 5. Russian Beriev A-60 (modified IL-76MD) with HEL turret and nose mounted radar. 1.1-MW HEL turret, 2 — radar for detecting aerial targets, 3 — compartment for 2.1 MW turboalternator. Photograph taken at Taganrog Yuznyi Airport in May 2011 by O. Ziminov, RovSpotters Team.

Fig. 6. GBU-54 laser joint direct attack munition under F/A-18 *Hornet* wing [1].

The Beriev A-60 Russian research program which started in the 1970s was aimed to demonstrate an airborne HEL DEW capability and provide a baseline for the development of operational weapon. So far, two demonstrators were built, i.e., 1A1 A-60 flying in 1981, 1A2 A-60 flying in 1991 and again in 2009 (Fig. 5). A large bulge on the upper back of A-60 is a sliding port for a 1-MW laser turret [5]. For feeding the laser, two turboalternators AI-24WT rated at 2.1 MW were mounted at each side of the fuselage. The nose mounted turret is equipped with Ladoga-3 radar for detecting aerial targets [5].

In 2008, the US Army formally recognized the potential of HEL technology for future weapons by awarding a contract to Boeing for the HEL technology demonstrator [1]. The ability of aicraft to conduct counterair warfare is greatly enhanced by a HEL weapon (Fig. 6). A HEL weapon can automatically identify, acquire, target, and engage an enemy missile or aicraft.

Particle beam weapon

A *particle beam* (PB) weapon is a type of DEW which directs an ultra high energy beam of atoms, electrons or protons in a particular direction by a means of particle projectiles with mass. The target is damaged by hitting it, and thus disrupting its atomic and molecular structure. In the case of electric current conductive target, a resistive heating occurs and an electron beam weapon can damage or melt its target. Electric circuits and electronic devices targeted by electron PB weapon are disrupted, while human beings and animals caught by the electric discharge of an electron beam weapon are likely to be electrocuted.

The use of space-based PB weapons was first explored in the late 1960s in the Soviet Union. The high-velocity PB weapon can target satellites or intercontinental ballistic missiles.

Airborne radar

Airborne radar (AR) systems can be carried by military, special mission and research aircraft. Military applications of AR include:

- targeting of hostile aircraft for air-to-air combat;
- detection and tracking of moving ground targets;
- targeting of ground targets for bombing missions.

Both civil and military applications include but are not restricted to:

- accurate terrain measurements for assisting in low-altitude flights;
- assisting in weather assessment and navigation;
- mapping and monitoring the Earth's surface for environmental and topological study.

ARs generally operate in the C or X bands, i.e., around 6 GHz or around 10 GHz, respectively. AR includes three major categories:

- air-target surveillance and cueing radars mounted in rotodomes (Fig. 7);
- nose-mounted fighter radars (Fig. 5 and Fig. 8);
- side-looking airborne radar (SLAR) for ground reconnaissance and surveillance (Fig. 9).

Fig. 7. AR mounted in rotodome on E-3B Sentry (Boeing 707 adapted to military functions).

The latter is the smallest sector of the airborne radar market and is dominated by synthetic aperture radar (SAR) and ground moving target indicator (GMTI) sensors. SAR, an active all-weather sensor, primarily is used for two-dimensional (2D) ground mapping. Radar images of an area help detect fixed targets. GMTI radar picks up moving targets or vehicles. A commercial version of SAR-GMTI, called HiSAR, is an X-band radar that can see from about 100 km away.

Fig. 8. Modified C-18A (converted Boeing 707) as EC-18B advanced range instrumentation aircraft (ARIA) with 2.1-m diameter radar dish on the nose.

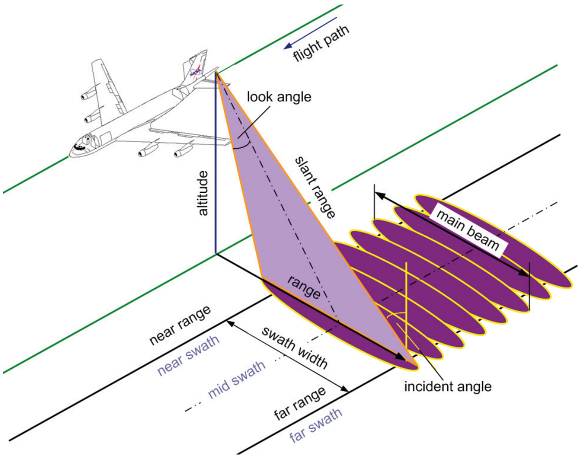

Fig. 9. Side-looking viewing geometry of imaging radar system. Sketch drawn by the author on the basis of http://www.radartutorial.eu

Airborne early warning (AEW) systems and weather radars use megawatt klystrons.

Technology challenges

There are two technically difficult challenges:

- the high voltage continuous electric power required for DEW systems must be in the range of megawatts;
- a large amount of heat rejected from DEW system during operation must be managed.

The *thermal management* challenge becomes difficult when the large heat flux is coupled with a small airframe, e.g., a fighter. The electrical power and thermal management subsystem of a conceptual generic airborne electrical DEW system is shown in Fig. 10. So far, the electrical power and thermal management systems for airborne DEWs are in early development.

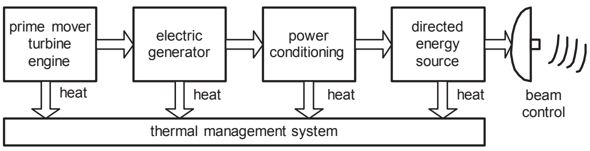

Fig. 10. System block diagram for a generic electrically powered airborne DEW system.

Classical wound-field synchronous generators in the range of megawatts for airborne applications are rather heavy. Synchronous generators with HTS rotor excitation windings are investigated as a possible solution [9, 19]. Large power, high speed HTS generators, if available, would be lighter and more compact than conventional copper wire-wound or permanent-magnet rotor generators. On the other hand, windings of HTS generators operate at cryogenic temperature of 77 K, i.e., the temperature of liquid nitrogen. This requires refrigeration systems, which increase the mass of airborne power plant. So far, the research is oriented towards airborne generators of classical construction, i.e., not requiring cryogenic installation.

Ferromagnetic materials

To minimize the overall dimensions of airborne multi-megawatt generators, high saturation, low core loss ferromagnetic thin laminated materials are used. Iron-cobalt alloys with cobalt contents ranging from 15 to 50% have the highest known saturation magnetic flux density, about 2.4 T at room temperature. They are the natural choice for applications not only as aerospace generators but also as aerospace motors [20], transformers and magnetic bearings [3], where mass and space saving are of prime importance. Additionally, the iron-cobalt alloys have the highest Curie temperatures of any alloy family and have found use in elevated temperature applications. The nominal composition, e.g., for Hiperco 50 from Carpenter, PA, U.S.A. is 49% Fe, 48.75% Co, 1.9% V, 0.05% Mn, 0.05% Nb and 0.05% Si. Hiperco 50 has the same nominal composition as Vanadium Permendur and Permendur V. The specific mass density of Hiperco 50 is 8120 kg/m^3, modulus of elasticity 207 GPa, electric conductivity 2.5×10^6 S/m, thermal conductivity 29.8 W/(m K) , Curie temperature $940°$ C, specific core loss about 44 W/kg at 2 T, 400 Hz and thickness from 0.15 to 0.36 mm. The magnetization curve of Hiperco 50 is as follows: 2.14 T at 800 A/m, 2.22 T at 1600 A/m, 2.26 T at 4000 A/m, 2.31 T at 8000 A/m and 2.34 T at 16 000 A/m.

Similar to Hyperco 50 is Vacoflux 50 (50% Co) cobalt-iron alloy from Vacuumschmelze, Hanau, Germany, typically used for manufacturing very high flux density pole-cores and pole-shoes of synchronous generators.

Electromechanical design

Multimegawatt generators are typically three-phase salient-pole synchronous generators with outer stator and inner rotor. The stator double-layer winding is distributed in slots. The rotor field winding has a form of concentrated-parameter coils wound on salient ferromagnetic poles.

The output electric power, as a function of dimensions, electromagnetic loads, winding parameters, and rated parameters, according to the author[3], is

(4)
$$P_{out} = \frac{\pi^2}{6\sqrt{2}} \frac{1}{\epsilon} k_{w1} k_{fill} (k_y^2 - 1) n_s D_{1in}^3 L_i j_a B_{mg} \eta \cos\phi$$

where $n_s = f/p$ is the synchronous speed, f is the stator current frequency, p is the number of pole pairs, k_{w1} is the stator winding factor for the fundamental harmonic, D_{1in} is the stator core inner diameter, L_i is the effective length of the stator core, j_a is the stator (armature) winding current density, B_{mg} is the peak value of the stator magnetic flux density, k_{fill} is the stator slot fill factor, k_y is the stator core outer diameter-to-stator yoke inner diameter (measured at the bottom of slots) ratio, ϵ is the EMF-to-voltage ratio, η is the efficiency, and $\cos\phi$ is the power factor. For $1 \leq p \leq 20$ the coefficient k_y can be estimated as

(5)
$$k_y \approx 1.05 + \frac{1}{1.5p}$$

For example, for $n_s = 15\ 000$ rpm $= 250$ rev/s, $2p = 8$, $k_{w1} = 0.9$, $D_{1in} = 0.21$ m, $L_i = 0.22$ m, $j_a = 16.1 \times 10^6$ A/m^2, $B_{mg} = 0.9$ T, $k_{fill} = 0.48$, $\epsilon = 1.07$, $\eta = 0.95$, the output power according to eqn (4) is $P_{out} = 1.5$ MW. The coefficient k_y estimated on the basis of eqn (5) is $k_y = 1.217$. Assuming the airg gap (mechanical clearance) as $g =$

[3]unpublished work

2.6 mm, the rotor surface linear speed is $v = \pi(D_{1in} - 2g)n_s = \pi(0.21 - 2 \times 0.0026) \times 250 = 160.85$ m/s. The allowable rotor surface linear speed for compact wound-field salient-pole synchronous machines with retaining sleeves is about 200 m/s.

The magnetic flux distribution in the cross section area of a salient pole multimegawatt generator is shown in Fig. 11. Rotor pole cores are highly saturated, because the volume envelope of an airborbne generator must be as small as possible.

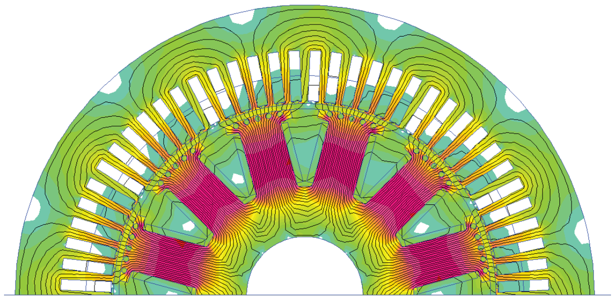

Fig. 11. Magnetic flux distribution in the cross section area of a 12-pole, 72-slot multimegawatt generator as obtained from the 2D FEM.

The stator slots are semi-closed trapezoidal or semi-closed oval slots. The number of stator slots per pole per phase is from 4 to 10. Large number of stator slots per pole per phase and double layer chorded windings allow for reducing the contents of higher space harmonics in the air gap magnetic flux density waveform. At high speeds (high frequencies) coils have a low number of turns and a large number of parallel wires. At speeds 15 000 rpm and higher, very often single turn coils must be designed in order to adjust the induced EMF to the terminal voltage. Parallel paths are common.

The outer surface of the stator core is sometimes corrugated to improve the heat transfer from the stator core surface to the stator enclosure or the liquid jacket.

The number of salient rotor poles is typically from 4 to 12. Pole shoes have round semi-closed slots to accommodate the damper. The rotor core is made of the same material as the stator core, i.e., iron-cobalt thin laminations. Rotor coils are protected against centrifugal forces with the aid of metal wedges between poles, which also participate in the cooling system of the rotor [17]. Sometimes, in addition to wedges, rotor retaining non-magnetic sleeves are used [8]. The rotor outer diameter and shaft diameter depend, amongst others, on the rotor critical speed. Problems of rotor dynamics are much more serious than in low speed synchronous machines [16].

Cooling techniques for high speed electric machines

High speed multimegawatt generators are cooled by the following media:

- air;
- oil;
- aircraft fuel;
- water/glycol mixture;
- refrigerant.

In a direct air cooling system the air enters through the housing or end bell and passes through the ducts between conductors, air gap and sometimes through rotor channels. The air is exhausted through a perforated screen around the periphery of the housing or special air outlet. Direct air cooling in high power density generators is rather insufficient.

Table 1. Heat transfer properties of some materials.

Material	Thermal conductivity W/(m °C)	Specific heat capacity J/(kg °C)	Specific density kg/m^3
Water at $20°$C	0.63	4184	997.4
Ethylene glycol	0.25	2380	1117
Engine oil at $20°$C	0.15	1880	888
Transformer oil at $25°$C	0.131	1870	879
Jet fuel (Jet A, Jet A1 and JP-8) at $50°$C	0.122	2050	784
Jet fuel (Jet A, Jet A1 and JP-8) at $100°$C	0.111	2300	735
Air at $20°$C	0.025	1005	1.177
Hydrogen	0.175	980	0.084

In most airborne multimegawatt generators liquid cooling must be employed. Heat transfer properties of liquids and gases are compared in Table 1. In general, liquids are much better coolants than air in terms of thermal conductivity and specific heat capacity.

Hollow conductors and direct liquid cooling seem to be economic solution for generators rated at 1 MW and above.

A typical liquid loop consists of an air-liquid heat exchanger, which is used to dump the heat load being carried by the liquid into the air conditioning system, a pump and resorvoir [13, 15]. Fig. 12 explains an oil cooling system for a multimegawatt wound-field synchronous generator with heat exchanger. The stator is cooled with the aid of an oil jacket and the rotor is cooled by pumping oil through the shaft. This hydraulic circuit employs a pressure sensing relief valve to regulate external circuit oil flow at minimum 38 liter/min $= 0.63$ liter/s.

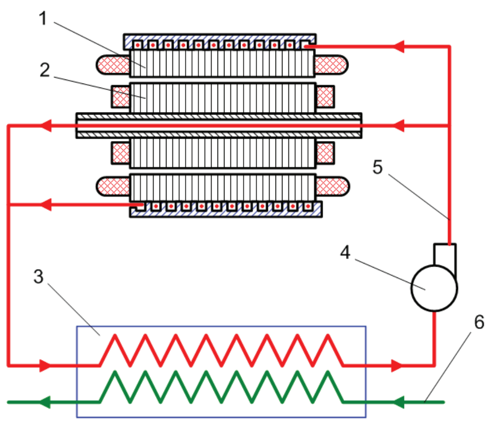

Fig. 12. Simplified diagram of oil cooling system for a multimegawatt aicraft synchronous generator with heat exchanger. 1 — stator of synchronous generator, 2 — rotor of synchronous generator, 3 — air-oil heat exchanger, 4 — pump, 5 — primary coolant (oil), 6 — secondary coolant (air). Oil reservoir is not shown.

The liquid coolant, i.e., oil or water is pumped through the stator jacket or through the stator hollow conductors (direct cooling system) and cooled by means of a *heat exchanger* system. Since the current density in the rotor field winding is high, the rotor also must be cooled by pumping the oil through the hollow shaft. The heat exchanger is a component that keeps two coolants separate, but allows transfer of heat energy between them. The *primary coolant* has lower temperature than machine parts. The *secondary coolant* has lower temperature than the primary coolant.

Table 2. Typical current densities for electrical machines with different cooling systems.

Cooling system	Current density, A/mm^2
Totally enclosed machine, natural ventilation	4.7 to 5.4
Totally enclosed machine, external blower	7.8 to 10.9
Through-cooled machine, external blower	14.0 to 15.5
Liquid-cooled machine	23.3 to 30.0

The cooling can be intensified by adding a fuel-oil heat echanger also called fuel-oil cooler (Fig. 13). A fuel is used to cool the generator oil and then the hot fuel can be pumped back to the wing fuel tanks, providing partially the wing de-icing. When the fuel flow is low, the fuel temperature will rise significantly, so recirculation lines are used to pipe the hot fuel back into the fuel tank [15]. Fuel is much better cooling medium than the air (Table 1).

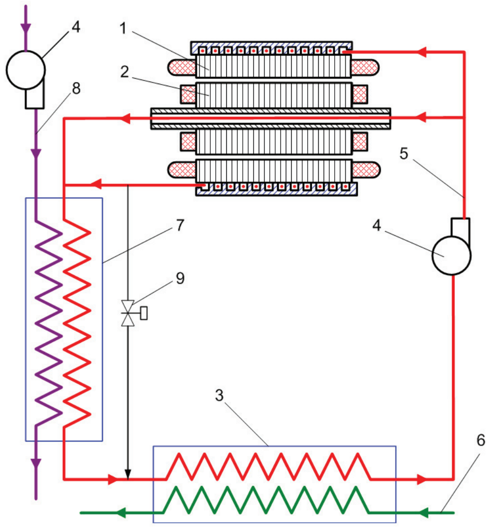

Fig. 13. Simplified diagram of oil cooling system for a multimegawatt aicraft synchronous generator with two heat exchangers. 1 — stator of synchronous generator, 2 — rotor of synchronous generator, 3 — oil-air heat exchanger, 4 — pump, 5 — primary coolant (oil), 6 — secondary coolant (air), 7 — fuel-oil heat exchanger, 8 — fuel (secondary coolant), 9 — fuel temperature control. Oil reservoir is not shown.

Similar to high-speed compressors and microturbines, a refrigerant, e.g., R-12 or R-134a can also be used for cooling multimegawatt generators. Refrigerant is directed to cool the stator core outer surface and/or stator core inner surface (air gap).

With increase in the output power, the rotor cooling problems become very difficult. One of methods is to use aluminum cold plates between the rotor coils and rotor pole core [14].

Typical current densities for electrical machines with different cooling systems are given in Table 2. Those values must be verified with calculation of internal temperature distribution using the thermal equivalent circuit or better – with the finite element method (FEM).

Table 3 shows a comparison of selected *cooling techniques* for high speed electric machines. The current density in the windings depends on the class of insulation, cooling system and duty cycle (continuous, short time or intermittent). The current density values given in Table 3 are for 220° C (maximum operating temperature of windings). The

Table 3. Selected techniques for enhancing heat dissipation in electric machines

Cooling system	Current density A/mm2	Advantages	Disadvantages
Fins and heat sinks	5 to 8	Simple method	Increase in weight and size
Water or oil jacket	10 to 15	Effective stator cooling	Increase in diameter and weight
Direct liquid cooling and hollow conductors	up to 30	Very intensive cooling of the stator winding	Increase in weight and size Too expensive for machines rated below 200 kW
Spray oil-cooled end turns of stator and rotor	over 28	Very intensive cooling of the rotor winding	Wet rotor; contamination of cooling medium (oil) with time
Liquid cooled wedges [17]	8 to 15 (estimated)	Intensive cooling of rotor winding	Does not effectively cool the rotor poles
Cold plates [14] between poles and rectangular wire rotor winding (IPS)	about 22 (estimated)	Intensive cooling of rotor winding	Requires installation of cold plates in rotor and cooling medium circulation

direct cooling system with hollow conductors is the most intensive cooling system (up to 30 A/mm^2). Spray-oil cooling (28 A/mm^2) is almost as intensive as direct cooling. Using cold plates between pole cores and coils, the estimated maximum current density should not exceed 22 A/mm^2. Thus, the spray oil-cooled rotor windings allows for maintaining higher current density than cold plates. Spray cooling of the rotor wire together with intensive cooling of the stator winding will theoretically lead to smaller size and weight than application of cold plates.

First prototypes

Air-cooled 2.5-MVA, 13 600-rpm synchronous generator

The first lightweight, high-speed, multimegawatt synchronous generator for helicopter application was built and tested in 1976 by *Aerojet Electrosystems Company*, Azusa, CA, USA, under contract with *Westinghouse Electric Corporation*, Lima, OH, USA [11]. It was a three-phase, 2.5-MVA, 13 600-rpm, 2887-5000-V, 6-pole, continuous-duty, air-cooled synchronous generator (Fig. 14). The generator was designed to be driven by the T64 GE turboshaft engine (prime mover). The architecture was the same as that of a conventional brushless aicraft synchronous generator, i.e., main generator, brushless exciter, and permanent magnet generator (PMG) – the so-called subexciter. The 650-mm long stator stack was made of 0.127-mm thick punchings. The 6-pole rotor was also laminated. The frequency was 680 Hz, full-load current 421/271 A, power factor 0.84/0.92, mass 680 kg, and power density 3.15 kW/kg.

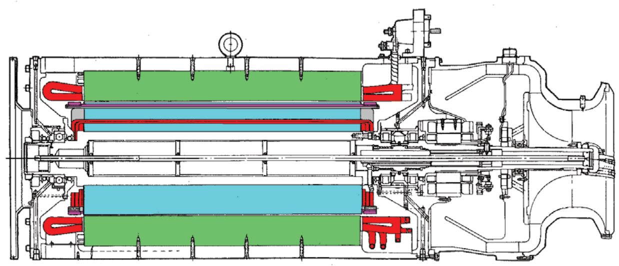

Fig. 14. 2.5-MW, 13 600-rpm, air cooled lightweight generator [11].

1-MW synchronous generator with cold plates

Innovative Power Solutions (IPS), Eatontown, NJ, USA has recently announced a lightweight megawatt-class airborne generator [6, 7]. Effective rotor cooling system with cold plates has been used to reduce the size of the generator [14].

The IPS megawatt airborne generator is a synchronous generator with salient-pole wound rotor (electromagnetic excitation) and conventional stator with laminated core and winding distributed in slots. A new patented method of cooling the rotor poles and conductors has been implemented [14]. This method uses cold plates disposed between each rotor pole and field coils. A cooling medium (liquid or gas) circulates in the rotor. Each cold plate serves to conduct heat from both the pole core and winding. The cooling medium enters the rotor through the shaft and is distributed between cold plates via manifolds, transfer tubes and plugs. The cooling medium after exiting the rotor (through the shaft) is then conducted to a heat sink or heat exchanger where its temperature is reduced.

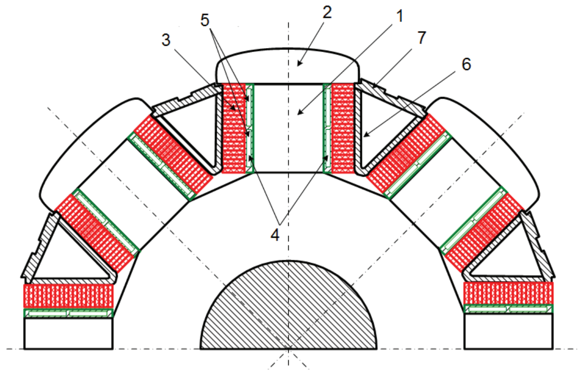

Fig. 15. Construction of rotor poles and winding. 1 — pole core, 2 — pole shoe, 3 — field winding, 4 — cold plate identical elements, 5 — cold plate passageways, 6 — V-shaped wedge, 7 — top wedge [14].

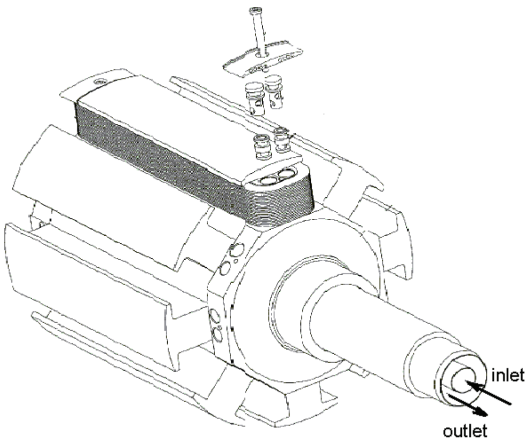

Fig. 16. Rotor of 1 MW IPS generator with cooling system [14].

According to IPS, the lightweight airborne 1 MW generator is 406 mm in diameter, 559 mm long and weighs 210 kg. The power density is 4.76 kW/kg.

To design the rotor field winding, IPS has used flat wires with rectangular cross section in an edge-winding fashion similar to how a slinky toy looks [6, 7]. The wire is in contact with cooling media along the entire perimeter of the coil. The smaller dimension of the wire is disposed toward the pole core lateral surface and the larger dimension is parallel to the pole shoe, as shown in Fig. 15. Since a rectangular cross section wire has bigger area of contact between adjacent wires than an equivalent round wire, the heat transfer characteristics for rectangular wires are better.

The rotor may have one or more *cold plates* surrounding each pole core. Fig. 15 shows a rotor with a pair of identical cold plates per pole. Each cold plate has passageways for conduction of a cooling medium (Fig. 16). Either liquid (oil) or gas cooling medium can be used. The end region of each cold plate matches the bend radius of the field excitation

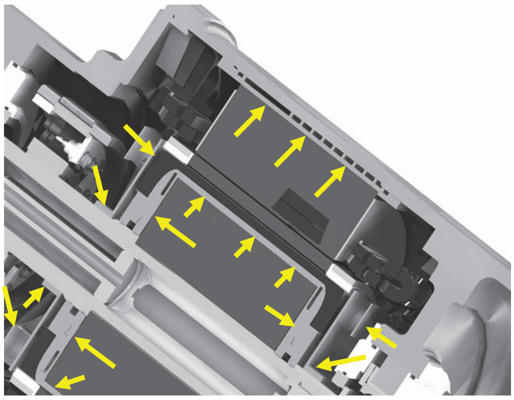

Fig. 17. Longitudinal section of IPS' lightweight megawatt generator. Arrows show cooling locations. Courtesy of *IPS*, Eatontown, NJ, USA.

coils. The proposed shape of cold plates does not increase the length and diameter of the rotor.

For fabrication of cold plates high thermal conductivity materials are used, i.e., aluminum, copper or brass [2]. The cold plate preferably includes its own insulating layer, e.g., in the case of aluminum, the insulating material is aluminum oxide with its thickness of 0.125 to 0.25 mm.

To provide adequate mechanical integrity of the rotor at high speeds and maintain good contact between the winding and cold plates, V-shaped wedges press the winding against cold plate surfaces (Fig. 15). Top wedges are used to secure V-shaped wedges in their positions (Fig. 15). Cooling locations fro rotor and stator are shown in Fig. 17.

Cold plates can be designed as two-part or single-part cold plates. In the first case both parts are identical. A pair of transfer tubes with plugs at each end of a cold plate provides hydraulic connection with manifolds located at opposite ends of the rotor [14]. This forms a closed system for circulation of cooling medium.

The overall cooling system can be improved by adding radial fans to the rotor and fins to the internal housing. Such a design, although increases windage and ventilation losses, can help to remove heat from the air within the generator and transfer heat to the aluminum housing (Fig. 17). The rotor and stator cooling technique implemented by IPS leads itself to compact generator design. However, the cold plate cooling system is less effective than spray oil-cooled end windings.

Oil-cooled 2.5 MW synchronous generator

Electrodynamics Associates, Inc., Oviedo, FL, has demonstrated in 2011 a 2.5-MW, 15 000-rpm, 1500-Hz, oil cooled multimegawatt synchronous generator (Fig. 18). The prime mover is planned to be a Rolls Royce T406 (AE 1107C-Liberty) turboshaft engine that would be capable of providing full power at altitude. The load would be a rectifier and ultimately some kind of DEW.

The generator is a conventional salient-pole $(2p = 12)$, wound-rotor synchronous machine with an exciter embedded in the rotor and oil-cooled rotor and stator. Details are given in Table 4 and Table 5. The power density claimed is 14.1 kW/kg for hogged aluminum housing and 16.7 kW/kg for magnesium housing.

The duty cycle is 6 min on and 12 min off. The generator is oil-cooled with maximum oil flow rate of 115.5 liter/min. The inlet oil temperature is 65.5° C. The oil cools the stator back iron with some incidental end turn wetting. The rotor field winding end turns are oil-sprayed.

Table 4. Mechanical specifications of 2.5-MW, 15,000-rpm synchronous generator.

Speed, rpm	10,000 to 15,000
Mass, kg	177 (Al housing, without oil)
Dimensions, mm	343 L × 559 W × 456 H
Rotor sleeve	welded inconel
Design life, h	1000
First critical speed, rpm	8000
Laminations	Hiperco Co alloy
Rotor damper	squeezed film damper

Table 5. Electrical specifications of 2.5-MW, 15,000-rpm synchronous generator.

Rated power, MW	0.5 to 2.5
Number of phases	3
Number of poles	$2p = 12$
Frequency, Hz	1000 to 1500
Line voltage, V	620/1240
Voltage regulation, %	± 1
Phase current, A	2500/1250
Power factor	0.95
Efficiency, %	85 to 95

Conclusion

High speed synchronous generators in the megawatt power range are necessary for new airborne missions as DEW and AR. Potential candidates are (a) wound-field, salient pole synchronous generators, (b) synchronous generators with HTS field excitation system, (c) homopolar generators with stationary HTS winding, and (d) all cryogenic generators. There are two difficult challenges in construction of high speed multimegawatt generators:

- high power density, low envelope volume and low mass;
- thermal management and heat dissipation.

Intensive oil cooling system of both the stator and rotor is required to minizmize the size and mass of the generator. Cooling systems with primary and secondary cooling media and heat exchangers are required. It is necessary to point out that high current density in the stator and rotor winding reduces the effciency. The desired efficiency should be at least 95%. At present time, classical rather than HTS airborne multimegawatt generators are preferred.

Fig. 18. Multimegawatt oil-cooled synchronous generator rated at 2.5 MW, 15,000 rpm, 1500 Hz. Photo courtesy of *Electrodynamics Associates, Inc.*, Oviedo, FL, USA.

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