# Multimegawatt Synchronous Generators for Airborne Applications: a Review

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*Abstract*—Airborne high-speed synchronous generators rated in the power range of megawatts have been discussed. These generators are nowadays necessary for new aerospace missions, such as directed energy weapon (DEW) and airborne radar (AR). Requirements, ferromagnetic materials for magnetic circuits, electromagnetic design and cooling techniques for highspeed multimegawatt generators have been discussed. New sizing procedure has been proposed. First prototypes (1 MW and 2.5 MW) have been outlined.

*Index Terms*—Synchronous generators, airborne, multimegawatt, aerospace, high speed, magnetic circuits, sizing procedure, cooling systems.

#### I. 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 volume and mass of electrical machines and increase their power density.

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], [8], [11], [16]. 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], [8]–[10], [15], [16]:

- 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).

#### **II. REQUIREMENTS**

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

- high power density (output power-to-mass);
- brushless design;

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- compact design;
- minimum number of components;
- ability to withstand high temperature;
- low subtransient time constant (pulse operation);
- need to drive a rectifier without significant impact on the efficiency;
- high reliability (the failure rate < 5% within 80,000 h);
- high efficiency over the whole range of variable speed;
- low total harmonics distortion (THD);
- minimum cost-to-output power ratio and cost-toefficiency ratio.

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 [15].

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) [7]. 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. A good materials for retaining sleeves have high permissible stresses, very low electric conductivity, high thermal conductivity, and low specific density.

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.

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*).

#### **III. 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<sup>1</sup> 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 highpowered microwaves (HPMs), high-energy lasers (HEL), and particle beams (PBs) [8]. 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.,

$$E = \frac{P_{dout}\Delta tS}{A} \qquad J/m^2 \qquad (1)$$

where  $P_{dout}$  is the DEW output power,  $\Delta t$  is the duration of the DEW pulse,  $0 \leq S \leq 1.0$  is the dimensionless transmission number, also called Strehl<sup>2</sup> ratio, and A is the spot area on the target. To destroy soft targets, i.e., fabrics, plastics, etc., approximately  $1000 \times 10^4$  J/m<sup>2</sup> are required, but extremely hard targets, i.e., tanks, mine resistant vehicles, armored trucks, etc., might require  $100\ 000 \times 10^4$  J/m<sup>2</sup> [11]. Once the target has absorbed this energy, it will begin to heat up and even burn out.

The only difference between HELs and HPMs, which are both made up of photons, is their energy level. The photon energy

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

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  $\lambda$  is the length of wave.

The power generation capabilities of microwave tubes (MTs) operating at 300 MHz to 300 GHz range from watts to megawatts. MTs include klystrons, gyrotrons, gridded tubes and cross field tubes. *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*.

#### A. High power microwave

HPM weapons produce either beams or short pulses of highfrequency 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* [11].

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. 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

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}} \qquad \text{m} \tag{3}$$

where f is the frequency,  $\mu_0 = 0.4\pi \times 10^{-6}$  H/m,  $\mu_r$  is the relative magnetic permeability and  $\sigma$  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 equalent 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.

## B. Particle beam weapon

A 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 an 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.

#### C. 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. 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 multimegawatt 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.

The Beriev A-60 Russian research program which started in the 1970s was aimed to demonstrate an airborne HEL DEW capability and provide 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. 1). A large bulge on the upper back of A-60 is a sliding port for a 1-MW laser turret [3]. For feeding the

<sup>&</sup>lt;sup>1</sup>Scottish physicist Robert A. Watson-Watt (1892-1973), inventor of radiolocators (British equivalent of radar) to detect airplanes.

<sup>&</sup>lt;sup>2</sup>named after German physicist and mathematician Karl Strehl (1864-1940).



Fig. 1. 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.

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 [3].

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 aircraft to conduct counterair warfare is greatly enhanced by a HEL weapon<sup>3</sup>. A HEL weapon can automatically identify, acquire, target, and engage an enemy missile or aircraft.

# IV. 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 miltary applications include but are not restricted to:

- accurate terrain measurements for assisting in lowaltitude 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;
- nose-mounted fighter radars;
- side-looking airborne radar (SLAR) for ground reconnaissance and surveillance.

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 Xband radar that can see from about 100 km away.

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



Fig. 2. System block diagram for a generic electrically powered airborne DEW system.

# V. 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. 2. So far, the electrical power and thermal management systems for airborne DEWs are in early development.

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], [16]. Large power, high speed HTS generators, if available, would be lighter and more compact than conventional copper wire-wound or permanentmagnet 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.

## VI. ELECTROMAGNETIC DESIGN

Multimegawatt generators are typically three-phase salientpole 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.

## A. Ferromagnetic materials

To minimize the overall dimensions of airborne multimegawatt 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, transformers and magnetic bearings, 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

<sup>&</sup>lt;sup>3</sup>For example, the GBU-54 laser joint direct attack munition under F/A-18 *Hornet* wing [1].

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<sup>3</sup>, modulus of elasticity 207 GPa, electric conductivity  $2.5 \times 10^6$  S/m at room temperature, 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 poleshoes of synchronous generators.

## B. Sizing equations

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

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

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,  $\epsilon$  is the EMF-to-voltage ratio,  $\eta$  is the efficiency, and  $\cos \phi$  is the power factor. For  $1 \le p \le 20$  the coefficient  $k_y$  can be estimated as  $k_y \approx 1.05 + 1/(1.5p)$ .

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<sup>2</sup>,  $B_{mg} = 0.9$  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  $k_y = 1.217$ . Assuming the airg gap (mechanical clearance) as g = 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.

Eqn (4) can be derived using the definition of the pole pitch  $\tau = \pi D_{1in}/(2p)$  and fundamental relationships between the EMF,  $E_f$ , magnetic flux,  $|phi_f$ , and effective number of turns,  $N_1k_{w1}$ , i.e.,

- rms value of the EMF  $E_f = \pi \sqrt{2} f N_1 k_{w1} \Phi_f$  induced by the rotor magnetic flux  $\Phi_f$
- rotor magnetic flux  $\Phi_f \approx \Phi_{f1} = \frac{2}{\pi} \tau L_i B_{mq1}$

Thus, the apparent electromagnetic power can be expressed as

$$S_{elm} = m_1 E_f I_a = m_1 \pi \sqrt{2} n_s N_1 k_{w1} B_{mg} D_{1in} L_i I_a \quad (5)$$

where  $n_s = f/p$  is the synchronous speed,  $N_1$  is the number of turns per phase,  $k_{w1}$  is the stator winding factor and  $B_{mg}$  is the peak value of the air gap magnetic flux density approximately equal to the peak value of its first harmonic  $B_{mg1}$ . Putting the armature current density  $j_a = I_a/s'_a$  and the slot area

$$A_{slot} = \frac{2m_1 N_1 s_a'}{a_p k_{fill}} \tag{6}$$

in which  $a_p$  is the number of parallel paths,  $s'_a$  is he conductor cross section including parallel wires and  $k_{fill} < 1$  is the slot fill factor, the apparent electromagnetic power (5) becomes

$$S_{elm} = \frac{\pi}{\sqrt{2}} n_s k_{w1} D_{1in} L_i j_a B_{mg} A_{slot} a_p k_{fill} \tag{7}$$

Typical values of current densities  $j_a$  for wound-field highspeed synchronous generators with forced air cooling system are up to 10 A/mm<sup>2</sup>, for liquid cooling system liquid jacket)  $10 \le j_a \le 15$  A/mm<sup>2</sup>, and for direct liquid cooling system up to 30 A/mm<sup>2</sup>. The slot-tooth zone area is

$$A_{st} = \pi \frac{D_{1y}^2 - D_{1in}^2}{4} = \frac{\pi}{4} D_{1in}^2 (k_y^2 - 1)$$
(8)

where the inner diameter of the stator yoke is the sum of the stator inner diameter  $D_{1in}$  and the double the stator slot depth  $h_{sl}$ , i.e.,  $D_{1y} = D_{1in} + 2h_{sl}$ . The coefficient

$$k_y = \frac{D_{1y}}{D_{1in}} \tag{9}$$

depends on the number of poles. In the slot-tooth area approximately 2/3 of the area is occupied by the slots and about 1/3 of the area is occupied by the teeth, so that the slot area is

$$A_{slot} \approx \frac{2}{3} A_{st} = \frac{\pi}{6} D_{1in}^2 (k_y^2 - 1) \tag{10}$$

Putting eqn (10) into eqn (7) the apparent electromagnetic power takes the following form

$$S_{elm} = m_1 E_f I_a = \frac{\pi^2}{6\sqrt{2}} n_s k_{w1} D_{1in}^3 L_i J_a B_{mg} a_p k_{fill} (k_y^2 - 1)$$
(11)

On the other hand

$$S_{elm} = m_1 \epsilon V_1 I_a = \epsilon \frac{P_{out}}{\eta \cos \phi} \tag{12}$$

where  $\eta$  is the efficiency,  $\cos \phi$  is the power factor, the EMF coefficient  $\epsilon = E_f/V_1$  ( $\epsilon > 1$  for generator,  $\epsilon < 1$  for motor) and the true (active) output power  $P_{out} = m_1 V_1 I_a \eta \cos \phi$ . Thus

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

where

$$k_D = \frac{D_{1out}}{D_{1in}} = \frac{D_{1out}}{D_{2out} + 2g} \approx \frac{D_{1out}}{D_{2out}}$$
 (13)



Fig. 3. Magnetic flux distribution in the cross section area of a 12-pole, 72-slot multimegawatt generator as obtained from the 2D FEM.

Since the volume of the machine

$$V = \frac{\pi}{4} \left(\frac{D_{1out}}{k_D}\right)^2 L_i = \frac{\pi}{4} D_{1out}^2 L_i$$
(14)

the product  $V \times D_{1out}$  is

$$VD_{1out} = \frac{m_1 \epsilon k_D^3 P_{out}}{\pi \sqrt{2} n_s k_{w1} J_a B_{mg} k_{fill} a_p (k_y^2 - 1) \eta \cos \phi} \quad (15)$$

The radial height of the stator yoke is inversely proportional to the number of poles. Thus, the output-to-input diameter ratio (13) and the ratio  $k_y$  given by eqn (9) can be estimated as:

$$k_D \approx 1.75$$
 if  $p = 1$ 

$$k_D \approx 1.05 + \frac{1}{p}$$
 if  $1 \le p \le 20$  (16)

$$k_y \approx 1.05 + \frac{1}{1.5p} \tag{17}$$

The length of the stator stack for a given stator outer diameter  $D_{1out}$  is

$$L_i = \frac{4V}{\pi D_{1out}} \tag{18}$$

The length of the single-sided stator end turn can be approximately calculated as

$$l_{1e} \approx (0.05p + 1.2) \frac{\pi (D_{1in} + h_{sl})}{2p} k_{w1} + (0.002 \dots 0.005)$$
(19)

The axial length of the stator one-sided overhang

$$h_{ov} = \frac{l_{1e} - \tau k_{w1}}{2} + 0.005 \tag{20}$$

The length of stack with overhangs  $L = L_i + 2h_{ov}$ .

The magnetic flux distribution in the cross section area of a salient pole multimegawatt generator is shown in Fig. 3.

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 frequency) coils have low number of turns and 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.

# D. Rotor

Rotor pole cores are highly saturated (Fig. 3), because the volume envelope of an airborne generator must be as small as possible.

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 [14]. Sometimes, in addition to wedges, rotor retaining non-magnetic sleeves are used [7]. 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.

# VII. COOLING TECHNIQUES FOR HIGH SPEED ELECTRIC MACHINES

High speed multimegawatt generators can be cooled by the following media:

- air,
- oil,
- aircraft fuel,
- water/glycol mixture,
- refrigerant [6].

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.

In most airborne multimegawatt generators a liquid cooling must be employed. Heat transfer properties of liquids and gases are compared in Table I. 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

Thermal Specific heat Specific Material conductivity capacity density  $W/(m \circ C)$ J/(kg °C) kg/m<sup>3</sup> Water at 20°C 4184 997.4 0.63 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  $100^{\circ}C$ 0.111 2300 735 0.025 1005 Air at 20°C 1.177 0.175 0.084 Hydrogen 980

 TABLE I

 HEAT TRANSFER PROPERTIES OF SOME MATERIALS.

TABLE II Typical current densities for electrical machines with different cooling systems.

Cooling system	Current density, A/mm <sup>2</sup>
Totally enclosed machine, natural ventilation	4.5 to 5.5
Totally enclosed machine, external blower	7.5 to 11.0
Through-cooled machine, external blower	14.0 to 15.5
Liquid-cooled machine	23.0 to 30.0

by the liquid into the air conditioning system, a pump and reservoir [13]. The stator is cooled with the aid of an oil jacket and the rotor is cooled by pumping oil through the shaft (Fig. 4). This hydraulic circuit employs a pressure sensing relief valve to regulate external circuit oil flow at minimum 40 liter/min = 0.67 liter/s. The oil flow is proportional to the power losses.

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.

The cooling can be intensified by adding a fuel-oil heat exchanger also called fuel-oil cooler (Fig. 4). 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 deicing. 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 [13]. Fuel is much better cooling medium than the air (Table I).

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 difficult. One of the methods is to use aluminum cold plates between the field coils and rotor pole core [5].



Fig. 4. 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.

 TABLE III

 Selected techniques for enhancing heat dissipation in electric machines

			Nº 1 i
Cooling system	Current density	Advantages	Disadvantages
	A/mm2		
Fins		Simple	Increase
and heat sinks	5 to 8	method	in weight and size
Water or oil		Effective	Increase in diameter
jacket	10 to 15	stator cooling	and weight
Direct liquid		Very intensive	Increase
cooling		cooling	in weight and size
and hollow	up to 30	of the	Too expensive for machines
conductors		stator winding	rated below 200 kW
Spray oil-cooled		Very intensive	Wet rotor;
end turns of stator	over 28	cooling of the	contamination of cooling
and rotor		rotor winding	medium (oil) with time
Liquid cooled	8 to 15	Intensive cooling	Does not effectively
wedges	(estimated)	of rotor winding	cool the rotor poles
Cold plates		Intensive	Requires
between poles	about 22	cooling of	installation of cold
and rectangular wire	(estimated)	rotor winding	plates in rotor and
rotor winding (IPS)			cooling medium circulation

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

Table III 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 III are for 220° C (maximum operating temperature of windings). The direct cooling system with hollow conductors is the most intensive cooling system (up to 30 A/mm<sup>2</sup>). Spray-oil cooling (28 A/mm<sup>2</sup>) 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<sup>2</sup>. Thus, the spray oil-cooled rotor windings allows for maintaining higher current



Fig. 5. 2.5-MW, 13 600-rpm, air cooled lightweight generator [10].

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.

# VIII. FIRST PROTOTYPES

### A. 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 [10]. It was a three-phase, 2.5-MVA, 13 600-rpm, 2887-5000-V, 6-pole, continuous-duty, air-cooled synchronous generator (Fig. 5). 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.

# B. 1-MW synchronous generator with cold plates

Innovative Power Solutions (IPS), Eatontown, NJ, USA announced in the mid 2000s a lightweight megawatt-class airborne generator [4], [5]. Effective rotor cooling system with cold plates has been used to reduce the size of the generator [12].

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 [12]. 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.

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.



Fig. 6. 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 [12].

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 [4], [5]. 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. 6. 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 6 shows a rotor with a pair of identical cold plates per pole. Each cold plate has passageways for conduction of a cooling medium. 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 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. 6). Top wedges are used to secure V-shaped wedges in their positions (Fig. 6).

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 [12]. It 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 it increases windage and ventilation losses, can help to remove heat from the air within the generator and transfer heat to the aluminum housing. 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.

 TABLE IV

 Specifications of 2.5-MW, 15,000-rpm synchronous generator.

Rated power, MW	0.5 to 2.5
Speed, rpm	10,000 to 15,000
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
Mass,	177 (Al housing)
kg	150 (Mg housing)
Dimensions, mm	$343 \text{ L} \times 559 \text{ W} \times 456 \text{ H}$
Rotor sleeve	welded inconel
Design life, h	1000
First critical speed, rpm	8000
Laminations	Hiperco Co alloy
Rotor damper	squeezed film damper



Fig. 7. Multimegawatt oil-cooled synchronous generator rated at 2.5 MW, 15,000 rpm, 1500 Hz. Photo courtesy of *Electrodynamics Associates, Inc.*, Oviedo, FL, USA

## C. Oil-cooled 2.5 MW synchronous generator

*Electrodynamics Associates, Inc.*, Oviedo, FL, demonstrated, in 2011, a 2.5-MW, 15 000-rpm, 1500-Hz, oil cooled multimegawatt synchronous generator (Fig. 7). 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 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 IV. The power density 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  $65.5^{\circ}$  C. The oil cools the stator back iron with some incidental end turn wetting. The rotor field winding end turns are oil-sprayed.

# IX. 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 minimize 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.

The presented new seizing procedure (Section VI.B) can be used for the design of all synchronous and induction machines.

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