SYSTEM CONSIDERATIONS FOR AIRBORNE, HIGH POWER SUPERCONDUCTING GENERATORS

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ABSTRACT

The design of rotating superconducting field windings in high power generators is greatly influenced by system considerations. Experience with two superconducting generators designed to produce 5 and 20 Megawatts has resulted in a number of design restrictions. The design restrictions imposed by system considerations have not prevented low weight and high voltage power generation capability. The application of multifilament Nb_3Sn has permitted a large thermal margin to be designed into the rotating field winding. This margin permits the field winding to remain superconducting under severe system operational requirements. System considerations include: fast rotational start-up, fast ramped magnetic fields, load induced transient fields and airborne cryogen logistics. Preliminary selection of a multifilament Nb_3Sn cable has resulted from these considerations. The cable will carry 864 amperes at 8.5K and 6.8 Tesla.

I. INTRODUCTION

Superconducting electrical generators have the potential for producing large amounts of power in a small volume with very low fixed weight. These features are extremely attractive for airborne, high power applications where volume and weight requirements are strict. Figure 1 illustrates a generalized airborne, high power system. Another attractive feature of the superconducting generator is that the rotational speed in the 20 to 30 MW power range allows direct coupling to the turbine which eliminates the gear box. Also, the high voltage capability of the ironless stator eliminates the need for a transformer. Since 1971, the U. S. Air Force has sponsored exploratory research and development programs in superconducting generators for airborne applications.[1] These high speed, synchronous machines utilize rotating, superconducting field coils. A prototype rotor and a 5 MVA generator have been designed and fabricated by Westinghouse Electric Corporation.[2,3,4] This machine uses a NbTi superconductor. A second generation machine using more advanced technology is being built by General Electric Co.[5] This 20 MW generator will use Nb_3Sn, with rotor fabrication scheduled to begin in Sep 1978. A drawing of this machine is shown in Fig. 2. The environmental shield is a conductive shield which keeps time varying magnetic fields produced within the generator from escaping into the aircraft environment. Torque is transmitted from the drive flange through the electromagnetic shield back through the torque tube extension to the torque tube which is shrunk onto the composite field winding support structure. The electromagnetic shield screens the superconducting field windings from any asynchronous magnetic fields produced by the stator (armature) winding currents. A thermal radiation shield at a cryogenic temperature intercepts thermal radiation from the warm electromagnetic shield. Power terminals are not indicated; however, they will be located near the coolant headers. The frame diameter is approximately 40 inches and the dry weight is approximately 1500 lbs.

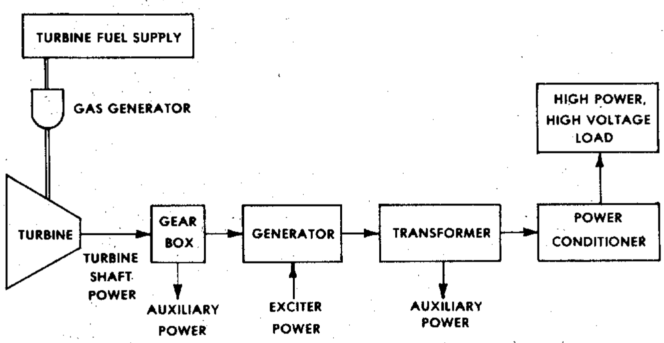

FIGURE 1 Generalized High Power, Airborne System

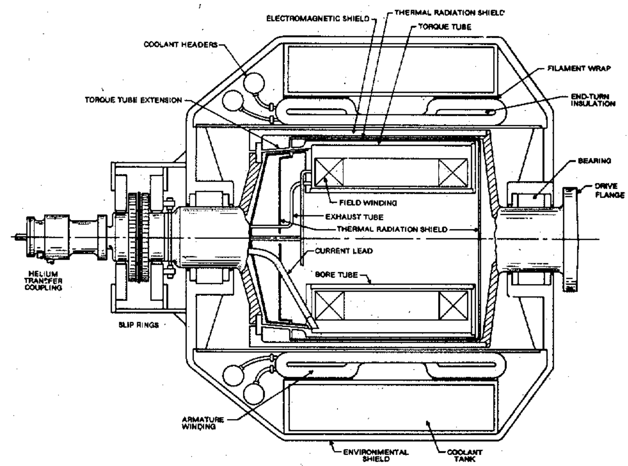

FIGURE 2 Advanced 20 MW Superconducting Generator (General Electric Co.)

Airborne high power systems have operational requirements which strongly influence superconducting generator design. Basically, the superconducting coil (field winding) likes to operate in a dc magnetic field with no relative mechanical motion which will generate heat and with no mechanical strain. As shown in Table I, system operational requirements are contrary to the above statement. These considerations are discussed below.

TABLE I

OPERATIONAL REQUIREMENTS

Requirement	Impact on Generator
Fast Start-Up	
One second excitation	Transient losses
One second spin-up	Hydrodynamic losses/ Mechanical movement
Sudden Load Application/Removal	Transient losses
High Efficiency	Higher weight/complexity
Rectified Output	Transient losses
High Voltage	Quality insulation system
Cryogen Logistics	Need low helium usage

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II. INFLUENCE OF OPERATIONAL REQUIREMENTS

Rapid Start Capability

Perhaps the most severe operational requirement is power generation within one second after demand. Figure 3 illustrates the possible sequences for attaining rated speed and excitation within one second. In Fig. 3(a), the rotor is simultaneously accelerated by the

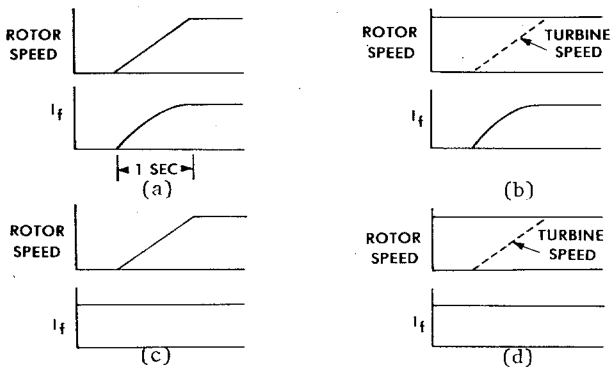

FIGURE 3 Possible Rapid Start-Up Methods

turbine and excited by an external power supply in one second. Fig. 3 (b) shows an idling system where the rotor is continuously rotated by means of an auxiliary motor and the turbine is brought up to speed in one second during the excitation ramp. When the turbine speed matches the rotor speed a clutch engages. Fig. 3(c) shows the rapid start concept of continuous field excitation and a one second spin up. Fig. 3(d) indicates continuous field excitation and rotor idling. Again, a clutch is used to connect the turbine to the rotor after the turbine is accelerated to speed in one second. It is desirable to avoid the complexity of an idling system and a clutch, therefore, the most attractive methods are 3(a) and 3(c). It has been determined that the lightest superconducting generator design[5] concept incorporates a conductive image shield. This requires that the rotor be spinning when the field is excited which rules out the method shown in Fig. 3(c). Therefore, the preferred method is the one illustrated in Fig. 3(a).

When this rapid start method is used, losses from both the one second ramp to rated field current and the one second spin-up must be accommodated by the field system without causing the superconductor to normalize. The one second current ramp results in a time varying magnetic field which produces heat within the field coils given by

$$P/V = a_1 \dot{B}^2 + a_2 \dot{B}, \text{ (watts/cm}^3\text{)} \qquad (1)$$

where $\dot{B}$ is the time rate of change of magnetic flux density and a_1 and a_2 are constants related to the properties and geometry of the superconductor which yield eddy current loss and hysteresis loss respectively. The advanced 20 MW superconducting generator (all characteristics discussed below refer to this machine) utilizes the large thermal margin, i.e., high critical temperature, of Nb_3Sn to operate under these severe transient conditions. A cabled, six strand, Nb_3Sn superconductor with a molybdenum central strand was selected for this application.[5,6] The operating current is 864 amps with a T_c of 8.5K at 6.8 Tesla and an overall current density in the epoxy impregnated winding module of 15,000 Amp/cm^2. Eddy current losses will also be generated in any conducting members of the rotor. A winding support structure made of a glass-epoxy composite material is used to reduce these losses in the cold region. However, the torque tube, bore tube and radiation shield will experience heating in the cold region.

During the excitation ramp the energy deposited in the winding is predicted to be 100 joules; torque tube, 340 joules; bore tube, 70 joules; and radiation shield, 3,700 joules. This will result in a loss of about 0.2 liters of liquid helium out of 4.5 liters stored in the rotor and is not expected to result in a quench since the first ramp will raise the winding temperature in the high field region to approximately 6K. For a continuous pulse train of 5 second pulses, the minimum off-time between pulses is estimated to be 5 seconds to allow sufficient cooling between pulses. Otherwise, the winding temperature would increase for successive pulses and eventually the winding would quench.

During tests of a prototype rotor developed by Westinghouse Electric Corp., moderate speed changes (2500 RPM/min or 42 RPM/sec) caused field normalization.[1] The goal for the advanced 20 MW generator is[1,5] 6000 RPM/sec. This speed change will cause approximately 0.6 liter of liquid helium to be boiled off. Rapid speed changes can also cause frictional heat due to relative movement between the winding module and support structure or between superconducting wires. The former will be eliminated by a special interface material and the latter by the monolithic nature of the epoxy impregnated coil module in this second generation machine.

Rectified Output

For DC operation, the generator output must be rectified and filtered. This presents problems which are not present when the load is balanced and passive. For a full wave, three phase bridge, the stator phase currents flow for 2/3 of a positive half cycle and 2/3 of a negative half cycle due to switching. This non-sinusoidal stator current waveform results in harmonic components of mmf in the air gap which move relative to the rotor, unlike the balanced condition where the resultant spatial mmf due to stator currents travels around the air gap at the same speed as the rotor and in the same direction. The predominant harmonics are the 5th and 7th, the former rotating counter to the rotor and the latter rotating with the rotor. Therefore, a resultant harmonic of 6 times the fundamental frequency produces eddy current losses in the electromagnetic shield. This shield cannot be cold since the losses are many kilowatts. Even though the time varying field which penetrates the shield is small (less than 1 gauss), the total winding loss is almost 1 watt resulting in a steady state temperature rise of 0.16K and an increase in helium consumption during operation of 1.4 liter/hr.

Pulsed Power Operation

As opposed to the continuous power generation of utility type generators, the load profile for high power airborne generators is pulsed. Pulse durations of several seconds to several minutes are considered. The sudden application or removal of load also results in time varying magnetic fields in the cold region of the rotor. Losses are estimated to be 15 joules for the winding, 13 joules for the torque tube, 0.3 joules for the bore tube and 152 joules for the radiation shield. Helium boil off is estimated to be 0.01 liters per application or removal of load. The limitation on the off-time between pulses was discussed under Rapid Start Capability.

Direct High Voltage Generation

Superconducting generators have the capability of directly generating the high voltages required for this application. The 20 MW generator is designed to produce 40 KV DC rectified. The direct impact upon the system is the elimination of the power transformer and consequently a reduction in weight and volume. The generator does not suffer a large weight penalty because the stator construction requires no iron teeth between stator bars (as in conventional iron core machines) and a relatively large amount of space can be used for insulation. An "air core" stator is possible because of the tremendous mmf capability of the superconducting field windings which can establish the required magnetic flux in the low permeability path of a large air gap.

Efficiency Considerations

Due to the importance of weight in this application, it is desirable to determine the effect of generator efficiency on system weight. Assuming that the output power and power quality are the same regardless of efficiency, the power conditioning subsystem and load are unaffected. For generators having different efficiencies, system weight is affected by the generator, generator cooling subsystem, turbine/gas generator and turbine fuel supply. In general, the weight of the generator increases as the efficiency increases; however, the turbine and gas generator weights decrease because prime mover power decreases for higher generator efficiency. Therefore, the weight effects on the system tend to cancel. The weights of the generator cooling subsystem and the turbine fuel supply depend upon the generator efficiency and run time and strongly affect the system weight as shown below.

The generator efficiency η, is the ratio of electrical power output to mechanical power input. If P_{LOSS} represents the heat generated within the generator due to i^2R, eddy current, windage and bearing losses, and P_{GEN} is the output power in megawatts, then

$$P_{LOSS} = P_{GEN} \frac{(1-\eta)}{\eta} . \quad \text{(Megawatts)} \qquad (2)$$

This heat must be removed to avoid damage due to excessive temperatures where long run times prohibit operation under adiabatic conditions. Cooling subsystem weight is given by

$$W_{COOL} = P_{LOSS} \dot{W}_{COOL} t_{on}, \text{ (lbs)} \qquad (3)$$

where $\dot{W}_{COOL}$ is in lbs/(Megawatt-second) and t_{on} is the run time in seconds. The other major system component weight is the fuel consumed by the turbine. For a turbine with a specific propellant consumption of SPC lbs/(Horsepower-hour), the fuel weight is given by

$$W_{FUEL} = \frac{.3724 \text{ SPC}}{\eta} P_{GEN} t_{on} . \quad \text{(lbs)} \qquad (4)$$

A system weight penalty of

$$\Delta W_{COOL} = P_{GEN} \dot{W}_{COOL} \left[\frac{1}{\eta-} - \frac{1}{\eta+} \right] t_{on}, \text{ (lbs)} \qquad (5)$$

is incurred when one uses a generator with an efficiency of $\eta-$ which is less than that for another generator with a higher efficiency, $\eta+$. The additional fuel weight is

$$\Delta W_{FUEL} = .3724 P_{GEN} \text{ SPC} \left[\frac{1}{\eta-} - \frac{1}{\eta+} \right] t_{on} . \text{ (lbs)} \qquad (6)$$

Consider two 20 MW generator designs with efficiencies of 95.4% and 92.6% with $\dot{W}_{COOL}$ = 1 lb/(MW-sec) for a hollow-conductor, water-cooled stator. Weight penalties associated with using the lower efficiency machine are plotted in Fig. 4 as a function of run time. The total system weight penalty is less for the turbine with the lower SPC since the cooling subsystem weight is independent of SPC. Also, note that the fuel weight penalty tends to dominate, especially for high SPC. The system weight penalty for both cases is only about 100 pounds for a 60 second run time; however, for long run times the weight penalty is significant, approaching 700 lbs for a run time of 5 minutes using the high SPC turbine.

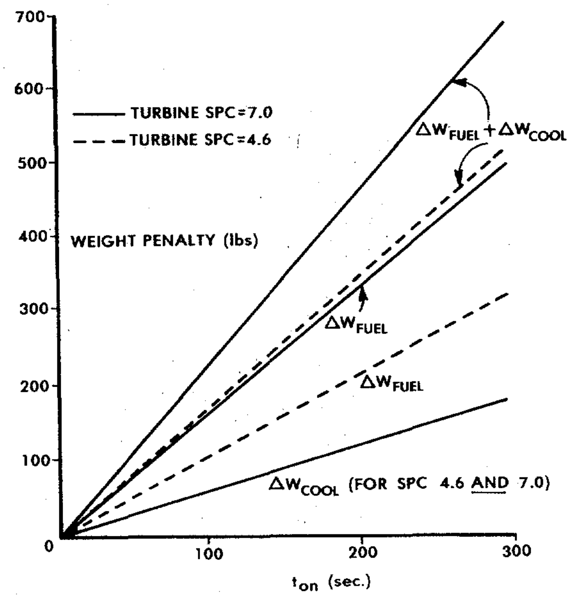

FIGURE 4 System Weight Penalties vs. Run Time

Cryogen Logistics

One of the more important system considerations is the large amount of liquid helium required on board an aircraft. A 20 MW generator will consume 20 liters/hour of liquid helium. For a 10 hour airborne mission assuming a 10% reserve, 220 liters of liquid helium will be required. System weight, volume and reliability will be adversely affected by the airborne helium supply and the great complexity and logistics problems of a cryogenic subsystem. Problems associated with the airborne cryogenic subsystem include: 1) supply from cryogen source to base, 2) base supply (filling and standby operations), 3) airborne supply, 4) helium reclamation and 5) reduced electrical breakdown potential when a helium overflow or leak is present in the confined space of the aircraft.

The most economical method of supplying helium to the base is direct transport of liquid from the source. The choice between using only liquid transported to the base or supplemental reliquefaction of boiloff will be an economic decision which is currently being studied.[8] Selection of a base supply system concept will be strongly dependent upon the liquid quantity required, the extent which reclamation of the helium gas is required and the undefined operational cryogenic lifetime of a superconducting generator in operational use. Cryogenic lifetime is defined as the length of time that the machine can be continuously maintained at standby (~80K) or operational (~4K) temperature.

Since cooldown from room temperature dominates helium consumption and more room temperature cooldowns are required for shorter cryogenic lifetimes, it is desirable to maximize the cryogenic lifetime of the superconducting generator. Operational lifetime for lightweight superconducting generators would ordinarily be determined by corona breakdown and high temperatures in the high voltage stator during power generation and is estimated to be 100 hours.

Since power generation at high voltage will occur for only one hundredth of the total mission time, the cryogenic lifetime should be at least 100 times the mission duration, i.e., 1000 hours for a typical ten hour mission. However, U.S. Air Force experience indicates that cryogenic subsystems are subject to handling and servicing lifetime limits due to the exigencies of flightline operational conditions. These limits appear to be hundreds of cryogenic operational hours.

Selection of a helium logistic system will also be strongly dependent upon the availability of liquid air, oxygen or nitrogen to eliminate excessive helium consumption during cooldown and standby operation. Aircrews already use oxygen at altitude and liquid oxygen which is already available should be more cost effective for cooldown of the superconducting generator than liquid helium.

Filling operations at the aircraft will probably be accomplished by portable Dewars which will be connected to individual aircraft after being filled at the liquid helium storage site on base. The aircraft cannot afford the weight and volume penalty of an airborne refrigeration system. A standby refrigeration system could be utilized on board the aircraft to maintain the superconducting generator at a temperature above the freezing point of air. The generator must always be kept cold (standby) because of the mechanical failure potential of the complex cryogenic rotor, long cooldown times (several hours) and excessive cryogen consumption for cooldown from room temperature. Standby cooling can also be accomplished on the ground by a mobile compressor and an on board refrigerator or by a portable, cryogenic heat exchanger using liquid oxygen or other available cryogenic fluids.

On board the aircraft, the standby cooling system must be augmented by a lightweight liquid helium storage Dewar capable of supplying the system mission requirement. Lightweight 220 liter Dewars are not yet available, but preliminary development effort funded by the Aero Propulsion Laboratory has demonstrated the capability of manufacturing large fiberglass reinforced epoxy Dewars at very low loss rates.[9] No attempt has been made to produce lightweight composite Dewars, but replacement of the fiberglass by Kevlar fibers would result in a Dewar subsystem weighing less than 100 pounds. Exhaust helium from the superconducting generator will be near ambient temperature to extract maximum enthalpy and will be vented overboard. A storage Dewar system is simplest, lightest weight and least expensive in terms of acquisition and developmemt cost; however, all of the helium is lost. The expense of replacing the vented helium is considerable, but the severe weight and volume penalty of an airborne helium recovery system is probably unwarranted at present. Estimated annual helium consumption based on highly optimistic projections of airborne generator applications is still only a small percentage of the 600 million cubic feet per year used for protective atmosphere use alone in 1990.[10] Beyond the year 2000, an impending helium shortage would motivate airborne helium reclamation.

Helium gas causes a significantly reduced breakdown potential because helium tends to diffuse through even the tiniest orifices. Careful consideration must be given to the on board helium supply and venting (or storage) system to eliminate the possibility of helium contamination of the environment surrounding high voltage components which must be located very close together on board an aircraft.

The expansion/compression sequence which an aircraft and all equipment in it goes through in a typical mission is a special problem for the Dewar subsystem. Appropriate check valves must be utilized to prevent severe losses of stored liquid. The low pressure ambient condition during the mission could provide a free source of subcooled helium for generator cooling should the need arise. Sloshing and high acceleration loads during the mission will cause special problems in Dewar design to prevent excessive losses.

III. CONCLUSIONS

System requirements for airborne high power applications strongly influence superconducting generator design. In particular, transient operational characteristics have dictated the use of the high critical temperature superconductor Nb_3Sn. Transient losses due to rectified output require an ambient temperature electromagnetic shield on the rotor. The advantages of high voltage generation, direct turbine coupling and high efficiency are offset, to some degree, by the additional weight and complexity of a cryogenic supply system.

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