

CRYOGENIC ALUMINUM-WOUND GENERATOR ROTOR CONCEPT

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ABSTRACT

The outline of a design for a liquid hydrogen cooled generator rotor that could be used to fabricate a 20 megawatt cryogenic generator is presented. The armature of an existing 20 megawatt superconducting generator¹ could be utilized in this new cryogenic generator concept without electrical modification and with minimum modification to its housing. A hydrogen cooled aluminum rotor would eliminate requirements for helium liquefiers/refrigerators, expensive superconductors and extra vacuum and magnetic shielding in superconducting generator rotors. Ideally the aluminum rotor could utilize the higher cryogenic temperatures of liquid hydrogen at 21K as conductor coolant and not require the fabrication techniques of a superconducting generator rotor. A most likely conductor candidate is high purity aluminum which has 1/500th its room temperature resistance² at liquid hydrogen temperatures. Recent research² has indicated the feasibility of fabricating high-purity aluminum conductors in a composite conductor form.

1. Introduction

High purity aluminum conductors cooled by liquid hydrogen have long been recognized as important to the development of lightweight, high power generators^{3,4}. There are two distinct advantages that the aluminum-wound rotor for use in aerospace applications would have over the superconductor-wound rotor. Foremost of these is conductor stability. The aluminum coil does not have the inherent risk of a superconducting coil going "normal", that is, suddenly becoming non-superconducting. When this happens, the liquid helium coolant in the rotor assembly suddenly changes to helium gas and causes a long delay in the recovery of superconductivity. However, cryogenic aluminum conductors have also been shown to exhibit a critical current below which equilibrium can exist between ohmic losses and cooling rate for a given cryogenic coolant⁵. The second advantage of the aluminum rotor is light weight. The mass of the alloying metals that constitute the superconducting wire used in a rotor coil is more than twice that of the equivalent aluminum wire.

To be competitive, the candidate aluminum wire for this alternative rotor design needs to be highly conductive in the temperature range around 21K. The most likely aluminum conductor would be a composite containing filaments of high-purity aluminum, which at the cryogenic temperature of liquid hydrogen has a resistivity of less than 1/500th the value of its room temperature resistivity. Hence, the best conductor candidate for this rotor design would be liquid hydrogen cooled aluminum. Several recent superconducting magnets^{6,7,8} have demonstrated a residual resistivity ratio in aluminum stabilizers of 1000-2000. These magnets were not operated at high magnetic fields and stresses so that the magnetoresistance and work hardening potential of the rotor application is not present. Ideally, the aluminum conductor would also have high yield and creep strength, e.g. the matrix material in the composite aluminum conductor discussed in references 2 and 9.

2. Rotor Design

Since this paper describes a conceptual design, only the significant characteristics of this candidate rotor design will be described. The emphasis will be on the electrical design of the rotor and a general description of its physical characteristics. Because of the physical constraints imposed by using the 20 megawatt generator armature and housing¹, the overall approach will be to substitute a highly conductive aluminum coil for the superconducting niobium-tin coil and utilize liquid hydrogen flow to cool the rotor windings instead of liquid helium coolant. Consequently, the overall dimensions of the aluminum rotor would be essentially the same as the superconducting rotor. Table 1 and Figure 1 illustrate these dimensions. Several comprehensive references exist on synchronous machine design^{10,11,12}.

Table 1

20 MW Superconductor Rotor Parameters

Number of coils (Poles)	4
Number of Turns/coil	980 turns
Amount of Current/coil	860 amps

Dimensions of Coil (Racetrack module):

Cross section	3" x 3"	7.62 cm x 7.62 cm
Active Length	6"	15.24 cm
Inside Width	3"	7.62 cm
Outside width	9"	22.86 cm
Inside bend radius	1.5"	3.81 cm
Outside bend radius	4.5"	11.43 cm

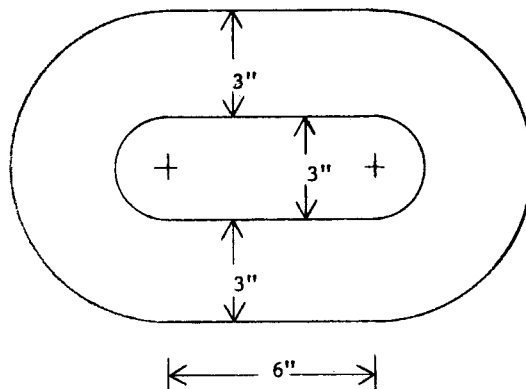


Figure 1. Racetrack Module Dimensions

3. Design of the Aluminum Wound Coils

Because of the physical constraints of the selected armature and housing, the overall physical dimensions of the aluminum rotor coils will have to be less than or equal to the overall physical dimensions of the superconducting rotor coils. Hence, an aluminum coil will have to be designed to fit in the conductor slot of the superconducting rotor coil. A cross section of one pole of this slot geometry is illustrated in Figure 2. The implication of this assumption is that

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1. REPORT DATE JUN 1985			2. REPORT TYPE N/A			3. DATES COVERED -		
4. TITLE AND SUBTITLE Cryogenic Aluminum-Wound Generator Rotor Concept						5a. CONTRACT NUMBER		
						5b. GRANT NUMBER		
						5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)						5d. PROJECT NUMBER		
						5e. TASK NUMBER		
						5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AF Weapons Laboratory Kirtland Air Force Base NM 87117						8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						10. SPONSOR/MONITOR'S ACRONYM(S)		
						11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited								
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.								
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15. SUBJECT TERMS								
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON		
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified						

the current density of the aluminum conductor will equal or exceed that of the superconductor.

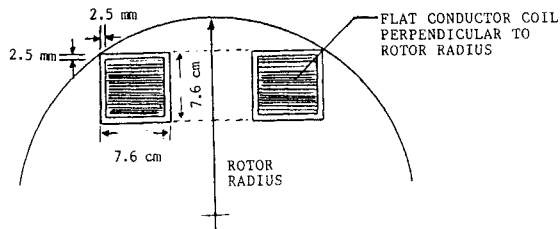


Figure 2. Cross Section of Selected Coil Geometry

To simplify coil design and construction, a twenty-turn coil of flat conductor is selected for this design. This provides maximum surface area for heat transfer of the ohmic heat to the liquid hydrogen coolant, as well as providing sufficient passageways for the hydrogen coolant. The maximum number of turns for a conductor with a large cross section that would still allow sufficient room for coolant is about 20. The flat conductor itself would consist of multiple filaments of small diameter pure aluminum bonded together to form the flat conductor geometry in an Al-Ce-Fe matrix⁹.

In determining the dimensions of the conductor, we conservatively assume that 35% of the coil module cross section must be allowed for structural support material and coolant passage space (see Figure 2). The high purity aluminum must be encased in a structural support material to maintain its conductive properties in order to prevent straggs in excess of 0.1% on the pure aluminum filaments¹³. Also, a gap of 2.5 mm is assumed to separate the coil module from the slot walls. This gap provides room for spacers, coolant passages, and side insulation. Thus we calculate the net conductor cross section per turn to be $37.74 \text{ cm}^2/20 \text{ turns} = 1.89 \text{ cm}^2/\text{turn}$. The conductor width is selected to be 7.12 cm with a thickness of 0.27 cm.

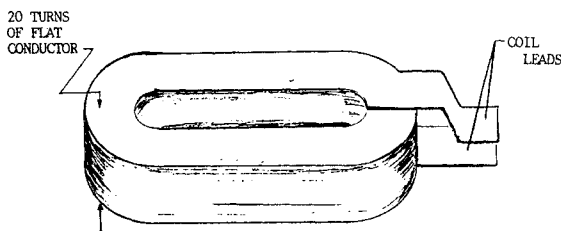


Figure 3. Three dimensional View of Coil Design

To determine the insulator separation which complies with the 0.1% strain criterion, simple structural analysis is applied to a beam supported at both ends under a distributed load. The formula for the maximum separation (S) between each of the insulating spacers, assuming the yield limit of the Al-Fe-Ce alloy, is:

$$S = \text{SQR}[(1.2 \times 10^6 \times R \times Y) / (2 \times W \times V^2)]$$

where R = rotor radius (in)
 Y = 1/2 thickness of the conductor (in)
 W = width of the conductor (in)
 V = rotor tip speed (in/sec)

Doing the necessary conversions provides us a value of (S) for the aluminum matrix of 0.14 cm. This may be too narrow to provide adequate coolant flow. However, if the structural support material consists of two thin bands of high-strength alloy sandwiching the flat conductor matrix, the separation could be increased to between 0.2 and 0.5 cm. The insulator strips would then have a width of between 0.2 and 0.5 cm. and a thickness of 0.1 cm., which corresponds to the size of the coolant channel.

4. Composite Aluminum Conductors

Except for its high conductivity at cryogenic temperatures, the other properties of high-purity aluminum render it wholly inadequate for use in the rotor coils of a high power alternator. In the annealed high-purity state, aluminum is mechanically too weak (typically 0.1 ksi yield strength) to withstand the internal mechanical stresses induced by the centrifugal forces of rotation and the back mmf of the stator under load. Furthermore, high-purity aluminum work hardens thereby lowering its conductivity. Embedding high-purity aluminum in a high strength matrix is a solution to these shortcomings.

Fabrication of a high-purity aluminum composite conductor requires that the matrix material have a workability that is compatible with aluminum and have practically a zero impurity diffusion from the matrix into the high purity aluminum filaments. A feasibility study and experiment completed at the Air Force Wright Aeronautical Laboratories indicates that such a composite can now be fabricated^{2,9}.

5. Determining Ohmic Losses

For this conceptual design, we assumed that pure aluminum would be used as the filaments in an aluminum composite conductor with properties which have just been determined^{2,9}. If we assume that the resistivity ratio of this composite at 21K is 500, then the estimated cryogenic electrical resistivity of the alloy is assumed to be $5.6 \times 10^{-9} \text{ ohm-cm}$.

Since our primary concern at this time is the steady state operation of the rotor coils, the following simple relation is used to calculate the net ohmic resistance of a single coil.

$$\text{Conductor Electrical Resistance} = L\rho/A$$

where L = conductor length
 ρ = electrical resistivity
 A = conductor cross section

Referring to Figure 1 as a guide, we calculate the net conductor length per turn to be 78.36 cm. Multiplying this result by 20 turns and adding 30.48 cm (12 inches) for the total length of the downleads provides us with the net conductor length for one coil which is 1598 cm. Having calculated the conductor length per coil and knowing the resistivity and the conductor cross section, we can now estimate the steady state ohmic resistance of a single coil to be 4.73×10^{-6} .

Since the basic magnetic geometry of the cryogenic aluminum rotor is to be the same as the superconductor rotor, the magnetomotive force (mmf) to generate the rotor magnetic field would be the same as in the superconductor rotor coils.

$$\begin{aligned} \text{mmf/coil (superconductor rotor)} &= 860 \text{ amps} \times 940 \text{ turns} \\ &= 808,400 \text{ ampere turns} \end{aligned}$$

Thus, the net current drawn per aluminum coil becomes:

$$808,400 \text{ ampere-turns} / 20 \text{ turns per coil} = 40,420 \text{ amps per coil}$$

Using the power relationship $P_c = I^2 R$ watts for steady state DC operation, we have the net power dissipated per coil.

$$P_c = (40,420 \text{ amps})^2 \times 4.73 \times 10^{-6} \text{ ohms} \\ = 7.73 \times 10^3 \text{ watts per coil}$$

Since there are four coils in the rotor, the net power dissipated in the rotor P_r becomes:

$$P_r = 4 \times 7.73 \times 10^3 \text{ watts per coil} \\ = 3.09 \times 10^4 \text{ watts}$$

Since the coils are to be connected in series and the downleads are relatively short compared to the coil conductor length, ohmic losses in the downleads were ignored. Ohmic losses in the excited circuit will be discussed later.

6. Determining the Conductor Heat Load

Because of its simplicity, we selected the arrangement outlined in Figure 4. Strips of insulating material are alternately laid across the width of the flat conductor between each turn to form a coolant channel for the cross-flow of liquid hydrogen. The width of the strips would depend upon the total number of strips and the total conductor area exposed to the liquid hydrogen. From our preliminary analysis and previous experience, at least one-half of the area on a given side of the flat conductor should be exposed directly to the hydrogen coolant cross-flow. Placing a coolant channel on the opposite side to an insulating strip will enhance the cooling process and minimize the possible occurrence of thermal hot spots under the insulating strips. Ultimately, the width of the insulating strips will be determined primarily by the results of mechanical analysis and fluid dynamics of the hydrogen flow rather than thermal analysis.

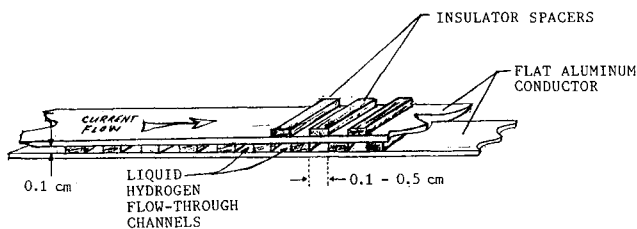


Figure 4. Simple Conductor-Insulator Matrix with Radial Flow-through Coolant Channels.

In performing the preliminary analysis, we assumed that there was negligible insulation on the conductor matrix except for the insulator strips separating the coil turns. As stated above, we assumed that one-half of the composite conductor outer surface is exposed to the cryogenic hydrogen coolant crossflow. With these assumptions, we calculate the thermal characteristics of the steady state behavior of rotor.

If we assume that 10% of the coil module cross section consisted of structural support material, then 25% of the cross section remains for the coolant cross

section separating the coil turns. The coolant cross sectional area is:

$$0.25 \times (7.62 \text{ cm} \times 7.62 \text{ cm}) = 14.52 \text{ cm}^2$$

Cross section of each coolant channel separating the coil turns:

$$14.52 \text{ cm}^2 / 19 \text{ turns} = 7.64 \text{ cm}^2$$

Width of each coolant channel between conductor turns:

$$7.64 \text{ cm}^2 / 7.62 \text{ cm} = 0.100 \text{ cm}$$

Coolant orifice between conductor turns:

$$\text{Orifice} = (\text{Length of turn} \times \text{channel width}) / 2 \\ = (78.36 \text{ cm} \times 0.100 \text{ cm}) / 2 \\ = 3.92 \text{ cm}^2$$

The effective orifice of the coolant cross sectional area depends on the fluid dynamic properties of the liquid hydrogen and its static pressure as it is forced between the coil turns. It is not the purpose of this paper to present a detailed thermal analysis of the rotor concept. Nevertheless, the orifice between each turn appears sufficient to permit effective coolant flow across the conductor surface.

The heat transfer surface available in each rotor coil is $11,581 \text{ cm}^2$. By dividing the ohmic power dissipated per coil by the heat transfer surface/coil, we arrive at a good approximation of the ohmic heat load per coil which is 0.667 watts/cm^2 . A heat load of less than 1 watt per square centimeter of surface area is readily manageable. The temperature rise in the worst case in the aluminum under these heat flux conditions would be 3mK. At this very low ΔT , the hydrogen flow requirements would be excessive, so a 3K temperature rise in the hydrogen would allow a more desirable cooling flow in the rotor of less than 1kg/sec.

Each coil has very low resistance so to minimize the current required from the exciter, all four coils are wired in series. Since the lengths of the rotor downleads are relatively short when compared to lengths of the windings in all four coils, the resistance of the downleads is ignored. The resistance of the rotor, R , thus becomes the sum of the individual resistances of each coil. The exciter current, I , becomes the same value in each coil.

$$R = 4 \text{ coils} \times 4.73 \times 10^{-6} \text{ ohms/coil} \\ = 1.89 \times 10^{-5} \text{ ohms/rotor}$$

Knowing the rotor resistance and the exciter current drawn by the rotor, we can now calculate the voltage, V_R , across the rotor downleads to be 0.76 volts.

Since the rotor is a low voltage, high current driven device, it seems suitable to consider utilizing a homopolar generator mounted on the same generator drive shaft as the exciter current source. Doing so would introduce an additional voltage drop due to the contact resistance of the homopolar generator current collector brushes. Typically, this is on the order of 300 millivolts or less. If we include brushes to transfer the exciter current from the homopolar generator to the rotor, there is an additional voltage drop of 300 millivolts. Consequently, a third to almost one-half of the losses in the rotor exciter circuit could be attributable to the contact resistance of the current collector brushes of the homopolar generator and of the downleads. Consequently, a worse case exciter circuit utilizing a homopolar generator

as the exciter current source would have the following ranges of characteristics.

Output Voltage: 1.1 to 1.4 volts

Output Current: 40,300 to 40,500 amps

Output Power Rating: 44,300 to 65,700 watts

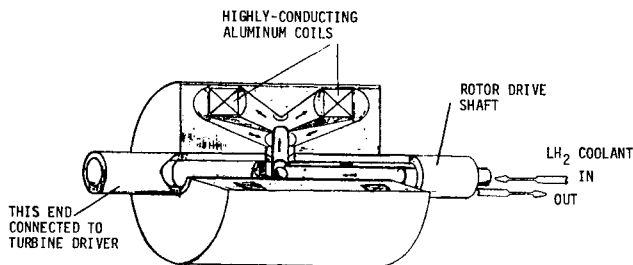


Figure 5. Cryogenic Rotor Concept

Depending on the efficiency of the exciter current source, the exciter power requirements could be as high as 100 kilowatts. In the case of the rotor shaft mounted homopolar type exciter, this loss would figure directly into the overall efficiency of the generator. Figure 5 illustrates the complete cryogenic rotor concept.

7. Generator System Concept

This generator rotor design was predicated upon the assumption that the generator would be part of a hydrogen fueled turboalternator prime power system. The hydrogen fuel, in its liquid state, would be stored in cryostats. Upon system startup, the liquid hydrogen at 21K would be pumped from the cryostats, through the generator rotor (perhaps including the stator) and then into the hydrogen combustor. The hot gases generated in the combustor would power the turbine assembly that would be turning the generator. Liquid oxygen would be combined in the combustor to sustain the combustion of the liquid hydrogen fuel. The concept of this system is illustrated in Figure 6.

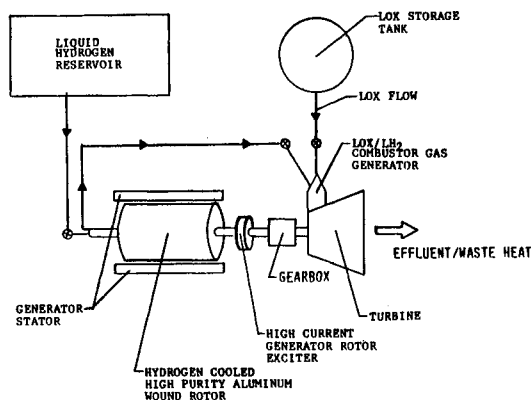


Figure 6. Cryogenic Generator System

8. Summary

Where a large reservoir of liquid hydrogen is stored as fuel, it appears feasible to utilize a hydrogen cooled aluminum generator rotor instead of a

superconducting rotor. This would eliminate the risk of thermal instability associated with a superconducting rotor should one of its coils unexpectedly go "normal". Any number of mechanical and thermal stress combinations could cause this to happen. Also, this would save weight by eliminating the need for a liquid helium reservoir and the associated liquid helium refrigeration and liquefaction equipment. Since preheating the liquid hydrogen prior to its entry into the combustor enhances the combustion process, passing the liquid hydrogen through the generator beforehand would be a plus. This would increase the overall thermodynamic efficiency of the power system.

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