Compact Superconducting Power Systems for Airborne Applications

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INTRODUCTION

In the development of future airborne megawatt-class power generation, it is important to minimize both the size and the weight of the system. The primary means of increasing the power density within the generator, as for all rotating machinery such as motors and alternators, is to maximize the magnetic flux density. This can be achieved by using a higher current-carrying capacity wire to increase the ampere-turns* in the windings without adding more turns via a longer length of wire. This has already been accomplished through the incorporation of superconducting wire in magnetic resonance imaging (MRI) magnets used in the medical field. In the case of MRI devices, the large size of the magnet is necessary to allow space for a human to fit inside. Without the availability of superconductors, MRI devices would require an extremely large magnet and a large room with a high ceiling. Another beneficial effect of incorporating superconductors into power systems is to increase the overall operation efficiency, thereby lowering parasitic heat losses, which can become substantial for higher power systems.

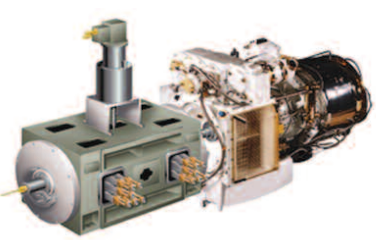
A **superconductor** is a material which, when cooled to less than a critical temperature, loses all electrical resistance.

A common misconception is that superconductor usage requires large amounts of cryogenic fluids in complicated coolant systems. Advancements in refrigeration systems eliminate this need, allowing for the use of more compact, higher-efficiency cryo-coolers. The cooling needs of a cryogenic system depend on the design of the system and, in particular, the heat losses of the insulation components and electrical devices. Cryogenic cooling is not a problem for most superconductor systems and should be considered the norm rather than the exception. Also, the reliability of the latest generation of cryo-coolers, which include new flexure mechanical bearings, is so high that the failure rates cannot even be measured after 5-10 years of operation. In addition to cryogenic systems, a new class of superconducting wire became available in 2008. The newer, high-temperature superconducting (HTS) wire, made from an yttrium barium copper oxide ($YBa_2Cu_3O_{7\text{-}Z}$ or YBCO) coated conductor, typically takes the form of a thin, flat tape, as opposed to a round wire. Two US companies† produce this new superconducting wire. The YBCO wire allows a much higher operating temperature than the previous generations of superconducting wire made from the bismuth strontium calcium copper oxide ($Bi_2Sr_2Ca_2Cu_3O_{10\text{-}Z}$ or BSCCO) family, thereby requiring a significantly smaller cryo-cooler to function. Depending on the magnetic field of the application, the operational temperature of YBCO is typically 20-40 K higher than for BSCCO wires.

There are several specific high-power applications being developed by the Air Force. These are described in the following sections.

MEGAWATT AIRBORNE GENERATOR

Recent efforts by the US Air Force (USAF) have been advancing power technologies using superconductors for airborne high-power applications (HPA). Large onboard demands for electrical power are projected for future military aircraft, making it necessary to develop not only suitable power generators but power distributors and conditioning technologies as well. To that end, the USAF initiated a new program for a Megawatt-level Electric Power System (MEPS) to develop and test superconducting power systems for airborne HPA. In 2004, the Air Force Research Laboratory (AFRL) initiated the design, building, and testing of the MEPS. The objective for the MEPS generator was to demonstrate HTS machine designs yielding power ratios in excess of the Air Force's initial (conservative) goal of 4.0 kW/lb (8.82 kW/kg). Using this figure as a starting point, future systems could be driven to much higher power ratios, since the initial machine configuration was a homopolar inductor alternator‡ (HIA). A prototype one-megawatt generator was completed in early 2007 and then a battery of tests were conducted to ensure a successful first full-power run of



Superconducting Generator MEPS Program

the HTS machine. During testing, the generator produced 1.3 MW output at its design speed of 10,000 rpm (10 krpm) and achieved 97% overall efficiency, even taking into account cryo-cooler losses. The MEPS demonstration validated the HIA concept as one viable alternative not only for HTS machines but also for a variety of advanced technologies for future HTS machine designs using the newer YBCO superconducting wire. The program included a conceptual design for a five MW HIA baselined to meet the above-noted specific power ratio goal.

GYROTRON MAGNET

Another superconductor candidate for HPA is the gyrotron magnet. A gyrotron is a high-field magnet necessary to generate high-power electromagnetic radiation. Similar to the MRI magnet, this can be accomplished with superconducting wire, but uses older, low-temperature superconductors (LTS). Developing

HTS Gyrotron

an HTS magnet with the newer HTS wire to replace the LTS windings could substantially reduce the refrigeration load. The new YBCO conductor operates at 60-77 K (as opposed to 4.2 K for LTS wire) and requires a cryo-cooler that is more than an order of magnitude smaller (by output) than that used for LTS materials. One company has already made an HTS gyrotron magnet out of an HTS conductor, they currently have a program to make a prototype YBCO gyrotron magnet.[§]

COMPACT POWER CABLES

With the development in the past 20 years of new electric conductors having up to 200 times higher power/volume capacity than standard copper conductors, the potential now exists to use these new conductors to improve the performance and efficiency of high-power current transmission systems. These new materials with higher conductivity include doped carbon graphite or nanotubes, hyperconducting metal alloys (e.g., aluminum) or BSCCO, and YBCO superconductor wires with operational temperatures up to 80 K.

The development of improved power density devices for specialized applications (including airborne applications) is ongoing; however, electrical power transmission between these devices is a problem that merits further investigation. For example, the weight of power cables running from advanced airborne high-power generators is likely to exceed the generator weight; and heat losses of wires, which are proportional to the increased device power levels, can reduce system performance. Improving the high power device operational temperatures from 50 K to 300 K would lead to the design of more optimal power transmission devices, further reducing system heat loss and weight. While there is significant focus on the development of higher performance power transmission devices for commercial power industries, there is relatively little activity ongoing to optimize power transmission systems for low voltage operation and low AC frequency or DC systems for airborne applications. Previously developed superconducting power lines for high voltage, high power operation (20-120 kV, 100-1500 MW) yielded four- to forty-fold reductions in total system heat loss (including cryogenic), and similarly transmission cable size and weight were reduced by a factor of ten, compared to copper, for commercially viable systems. Unfortunately, similar studies for airborne systems have thus far been very limited.

The basic principles required to design electrical power transmission systems for airborne applications are well understood; however, their specific design criteria have not yet been considered in detail. For airborne applications, operating voltages are typically fixed at 270 volts to minimize arc discharges at lower atmospheric pressures. However, this also causes problems with power supplies and power electronics. The output or operating power of a device is known from basic principles, specifically Ohm's law (P = IV, where I is the applied current, and V is the operating voltage). Thus, it is not practical to increase the operating voltage to increase the power output substantially for airborne applications, as would be typical for ground-based transmission systems. Consequently, it would only be practical to increase the operating current. Since voltage will not be increased, the device design may benefit by reducing the amount of electrical insulation needed. However, this also creates new design problems because of the need to accommodate much higher current levels.

A first study of this problem considered the design of high power transmission lines and cryogenic current leads for low voltage (<300 V) and DC, low-frequency AC (<1000 Hz), as well as for short line lengths (30 meters or less) which are typical for airborne applications. For any high-power application, developing refrigerated (or cryogenic) power transmission systems is considered when system size, weight, and total power losses, (including refrigeration) are projected to be lower than equivalent solid state components or materials (such as copper or aluminum) which operate at room temperature. An early study of transmission systems (using a 10-meter line at 5-10 MW DC power) demonstrated that by using a high-temperature superconductor system (HTS) instead of copper wire, transmission power densities could be increased three- to ten-fold, and the system heat loss and weight could be reduced by 10-15 kW and 1500-3000 lbs., respectively. The reason for the dramatic weight and heat loss differences between the superconductor and copper systems is the very high copper wire weight needed for these high power levels operating at 270 volt fixed level; and also because heat losses from the superconductor are almost zero, even for very high-power transmission. The only significant power losses for the superconductor transmission system are the cryo-cooler and vacuum component losses needed to maintain the cryogenic environment. Similarly, the cryo-cooler and vacuum components represent the only significant weight additions over conventional systems. The HTS wires experience almost no heat loss

A **hyperconductor** is a material which, when cooled to cryogenic temperature, loses most of its electrical resistance – unlike superconductors, which lose all resistance.

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and are very light and compact compared to copper wires. A similar system designed for AC power transmission also showed strong improvements, but this was limited to approximately 1 MW power transmission because superconductor cable designs to minimize AC losses are currently limited to operating conditions of no more than 3500 A or approximately 1 MW.

The energy densities afforded by superconductor power transmission devices over their copper counterparts are tremendous, which demonstrates how higher current density wires can be incorporated into power systems, thus greatly reducing the size and weight required for airborne applications. Also, heat losses can be substantially reduced. It should be noted that these improvements are realized for power transmission between devices operating at 50-77 K, such as superconducting generators and gyrotron magnets, as described above. If one of the devices was to operate at room temperature, a significant number of additional high-current power leads would be required to deliver the equivalent electrical power as at 77 K. Such high-current leads experience large heat losses (approximately 200 W/kA), which would increase the cryo-cooling requirements and reduce the benefits of the overall system. However, research on current leads operating in the 50-77 K regime has been limited, thus it may be a while before these problems are surmounted.

CONCLUSION

A major issue with superconducting wire has been overcome with the recent introduction of the YBCO coated conductor. It operates at a much higher temperature than the previous generations of superconducting wire. It also has much better stability than its predecessors, the low temperature superconductors. This article covered three examples of incorporating superconducting wire into advanced development components; two of these have been built and tested successfully, but all are YBCO conductor-ready. Although additional improvements are expected for the new YBCO conductor, it is now ready for advanced demonstrations. The future looks bright in this area, as the next generation of superconductors will dispel past misconceptions about this emerging technology and provide new opportunities for technologists with the vision and drive to seize upon them.

NOTES & REFERENCES

* An ampere-turn is the magnetomotive force of one ampere of current flowing through a closed loop of one turn.

† SuperPower, Inc., and American Superconductor Corporation

‡ Homopolar inductor alternator is an electrically symmetrical synchronous generator with a field winding that has a fixed magnetic position in relation to the conducting supports or armatures.

§ Cryomagnetics

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