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FINAL REPORT:

A 100 MVA Generator Utilizing High Temperature Superconducting Windings -- Design Assessment & Component Development

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Program Goals

The operation of a high temperature superconducting generator rotor using closed-cycle refrigeration to indirectly cool the field windings was considered to be the best choice for an HTS application. The SPI program proposed to achieve the following goals:

- In Task 1 a 100 MVA generator with a HTS rotor field winding would be designed. An energy and economic benefits analysis was to be a key part of the program. In addition, the generator/grid interactions were to be modeled.
- Concurrently, Task 2 was to include further development of Bi-2223 silver-clad tape as well as an alternate Tl-1223 conductor, manufacture of 3,000 meters of tape, and development and fabrication of a prototype field coil.

Summary of Results

Details of progess have been reported in the quarterly status reports and summarized in the final reports on the tasks. Therefore this report will give a review of the original goals of each task and summary of results for each.

Task 1 - HTS Generator Assessment

The objective of this task was the development of a preliminary design for a 100 MVA HTS generator. The principal design effort was shared by groups from GE's Power Generation Engineering and Corporate Research and Development, with inputs on armature design from Oak Ridge National Laboratory. The key topics studied were: generator mechanical design, generator producibility, superconductor coil design, cryocooler requirements, rotor and superconducting coil cooling, conceptual EM rotor shield design and performance, generator steady-state performance, generator losses, and preliminary generator cost.

The results from these studies were incorporated into a preliminary generator design which includes the superconducting coil electromagnetic and structural design, the cold mass support components, the EM shielding design, and the cryogenic refrigeration system design.

The performance of the HTS generator interacting with the utility grid was modeled in detail. This modeling was jointly undertaken by groups from GE's Power Systems Engineering Department and Power Generation Engineering. Transient modeling of the HTS generator interactions with the power system grid, fault event evaluations, and system stability have been considered. This modeling has included the development of rotor equivalent circuits for power system studies, transient system faults such as generator load shedding from full load operation, power system stabilizer modeling, and preliminary excitation system specifications. The results have shown that in all cases the HTS generator meets or exceeds the performance of the conventional generator designs.

Task 2 - HTS Wire and Coil Development

Bi-2223 PIT Tape Development and Fabrication

The objective of this task has been to further improve the processing and properties of the Bi-2223 silver-clad powder in tube conductor to be used for the prototype coil. The Bi-2223 PIT conductor development effort has been the responsibility of Intermagnetics General Corporation with inputs from Argonne National Laboratory. Examples of items considered were: mono- and multi-filament conductors, conductor uniformity, both along the length of a conductor and batch-to batch, and optimization of conductor critical current. The multi-filament conductor has been chosen for the 3000 meter coil winding due to its superior production yield and its reduced strain sensitivity as compared to the mono-filament conductor.

Some of the accomplishments toward improving the processing and properties of silver-clad Bi-2223 will be listed here. The fabrication of >100 meter lengths of mono-filament tape that carried over 20 A at 77 K zero field was demonstrated. Multi-filament tapes were fabricated 20 meters long carrying over 42 A (J_c = 21,000 A/cm^2) and 90 meters long carrying over 35 A (J_c =17,500 A/cm^2) at 77 K and zero field. The capability to manufacture 200 meter lengths of multi-filament tapes was demonstrated. The superconductor fraction of multi-filament tapes was increased from 20 to 35%. Mono-filament tapes with dispersion strengthened silver were fabricated. Techniques were developed for application of ceramic and epoxy insulation on the HTS tapes. A single piece length of conductor was fabricated that was >1,250 meters long and carried over 18 A (J_c =12,000 A/cm^2) at 77 K zero field.

IGC manufactured and delivered over 3,000 meters of Bi-2223 mono- and multi-filament HTS tape to GE for the fabrication of a small test coil and the large prototype coil.

Alternative Conductors

This task addressed the development of two cuprate superconductors which could replace the Bi-2223 material as the material of choice for future superconducting applications. A group at New York State Institute for Superconductivity worked on improvements in processing and properties of $Bi_2Sr_2CaCu_2O_Y$ (Bi-2212). This material can be processed in shorter times than Bi-2223 which could lead to possible cost advantages over Bi-2223. A second alternate conductor material is $TlBa_2Ca_2Cu_3O_Y$ (Tl-1223). It can be utilized at higher temperatures than Bi-2223. Coil operational temperatures could be increased to 40 Kelvin or higher if an economical process can be developed for fabrication of Tl-1223 conductors. Two teams looked at this promising alternate material: IGC and Los Alamos National Laboratory worked together while GE was teamed with Oak Ridge National Laboratory.

Powder-in-tube processing was used as one route for manufacturing the Tl-based superconductor. Variables considered were thermomechanical treatment, powder precursor type, composition, and heat treating atmosphere. With optimization of the process, critical currents as high as 25 A (J_c =19,000 A/cm^2), at 77 K zero field were achieved. Multi-filament PIT-derived tapes had J_c values up to 15 A under the same test conditions.

Another Tl-conductor processing route considered was the use of magnetic alignment of powders in a conductor precursor. This method did not prove feasible. Good C-axis alignment could be attained, but low densities in the sintered parts kept the J_c values too low. As a result, work on this processing technique was discontinued early in the program.

The final Tl-conductor processing route considered in the program was the use of thick films of Tl-1223. Multi-zone furnaces were used to heat treat precursor films in thallium-containing atmospheres. Dip coating was evaluated as a coating process for depositing the precursor film on silver tapes. Precursor powders were purchased and prepared in-house. Process variables considered were: starting phase assemblage, coating thickness, pressing pressures and thallination conditions — time, temperature and thallium vapor pressure. Although the final Tl-1223 films were mainly c-axis oriented, there were always some non-aligned grains present. The final Tl-1223 film properties from powder precursors were not as good as with spray pyrolyzed precursors. Further development is needed to obtain a long Tl-1223 conductor using the thick film route. Even better J_c values could be attained if the thick film technique could be used in conjunction with bi-axially aligned substrates.

HTS Coil Development and Fabrication

The objective of this task was to develop HTS coil technology aimed specifically at the superconducting generator application. Bi-2223 tape produced by Intermagnetics General Corporation under a previously described task was to be used. Elements of the coil development and fabrication were to be: Development of winding techniques, Development of mechanical reinforcing and insulation techniques, Devise joining techniques, Fabricate a prototype coil, and Test and characterize the performance of the coil.

The first coil made was a small, layer-wound circular coil which was fabricated to evaluate handling and performance of the Bi-2223 tape. This showed the need for a stronger conductor. GE then developed procedures for laminating the silver-clad superconductor between to layers of copper. In addition, a "cigarette-wrap" paper insulation provides good dielectric insulation between turns and layers with a minimum of additional coil build.

The prototype racetrack coil was fabricated from about 2000 meters consisting of 23 discrete lengths of Bi-2223 tape from IGC. The tapes were laminated, insulated and joined together with solder overlap joints. The layer-wound finished coil consists of 51 layers with 23 turns per layer with a total of 1165 turns. A heat exchanger was placed around the coil and the assembly epoxy impregnated. The finished outer dimensions were 67 cm long, 30 cm wide and 10 cm thick.

The coil assembly was cooled to temperatures as low as 16 Kelvin using a prototype closed-cycle helium gas refrigeration system. The maximum stable current level in the test coil/cooler configuration was 34 amperes (39.6 KA-turns) at a coil temperature of 25 K. Transient ramping tests were performed over a range of operating temperatures to explore coil performance under conditions analogous to those experienced by a superconducting generator field coil. Good performance is predicted for a typical 3-phase fault condition.

In summary, all of the program objectives were met. The test results and analysis gives a high level of confidence that the satisfactory preformance of a full-scale generator field coil can be achieved.