

DOE/CH/10589--T1

FINAL REPORT:

DOE SPI-PHASE 1: TASK 1

HTS GENERATOR ASSESSMENT

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SPI - 1 Superconducting Generator Project

Final Report

Approach

A significant amount of work was done under a proprietary agreement between GE and DOE. Progress has adequately been reported through quarterly status reports. It is therefore felt that, rather than delivering a *composite final* report, it would be of greater value to write a brief report that refers to the work done, along with references to internal GE proprietary documentation. In the text, references indicate within parentheses the issuing organization, e.g. (GE-3)

The Basic Generator Design Concept

As expressed in the SPI-1 proposal (GE-1), the intention all along was to continue the superconducting generator work that GE terminated in the early eighties. The generator design concept, therefore, to be worked on was the one that has also been considered over the years by all researchers, universities, and industry, including Japan's Super GM program presently underway. This generator design concept employs a sc generator rotor winding and aims at capitalizing fully on the very high magnetic flux density in the generator air gap now possible through the use of superconductivity in the generator field. In other words, the sc generator design objectives were to obtain:

1. the maximum efficiency possible
2. considerable reduction in generator volume and weight
3. gains in power system stability

Such generators require the simultaneous development of not only sc rotor and winding, but of very challenging and novel stator windings as well, whose challenge, risk and development cost parallel those of the rotor!

sc Generator Work in a Nutshell

Work started immediately addressing the analytical techniques available for assessing such things as crushing forces on the rotors during generator terminal short circuit events, and generator stray losses. All the work necessary to develop generator design and power systems analysis tools was done with internal GE funding and much of it is documented, e.g. (GE-2), (GE-3), (GE-4). At the same time, recognizing the great challenge and need for a good stator winding design, a brain storming session took place in Schenectady, (GE-5) & (GE-6), (GE-7), and all known, plus additional novel stator winding design concepts were discussed.

ORNL's help was enlisted in suggesting and analyzing such a stator winding design. Their work and accomplishments are documented in (ORNL-1). Reference (GE-8) contains a description of much of the work and design thought process that went into the high power density superconducting generators. Reference (GE-9) is a typical record of frequent regular design meetings that took place during the execution of this contract.

Extensive work was performed on the interaction of the sc generator with the power system (GE-10).

Finally, the SPI - 1 effort culminated with the submission of a proprietary proposal for the SPI - 2 phase (GE-11) which contains many of the results found during the SPI- 1 work.

Summary of work accomplished

The enthusiasm generated during the execution of this contract had the effect of helping accomplish much more that could ever be anticipated within the allotted time and with the resources available. Nevertheless, to ensure that all expectations are indeed met, the following compares accomplishments *versus* the original contract statement of work.

Task 1: HTS Generator Assessment

Task 1(A): Define Application, Rationale and Requirements.

A specification was produced early in the design stage. Niagra Mohawk Power Corporation's withdrawal half way into the contract had no effect on the results.

Task 1(B): Establish Conceptual 100 MVA Generator Design

1 Using the specifications of Task 1(A), GE has employed standard and well as highly sophisticated design tools (developed concurrently with this projects with internal GE funding) to calculate values for electromagnetic parameters (e.g. dimensions and losses of the superconducting winding, electromagnetic shield and armature winding design; superconducting winding magnetomotive force; electromagnetic shield effects; armature reaction; synchronous, transient, subtransient reactances and time constants) of the generator and have produced practical and promising electromagnetic designs that could further be refined and developed into real machines.

2 GE has developed a conceptual thermal and mechanical design taking into account the generator electromagnetic parameters produced in 1. To achieve that, GE has satisfied the various demands placed on the mechanical system by the electromagnetic requirements (e.g., steady-state torque on the rotor, crushing loads on the rotor during faults, sc coil forces and support system) Similarly, GE has produced a thermal design which minimizes heat leaks into the cold rotor section.

3 GE has produced a proprietary conceptual design for a sc generator of the stator and stator winding including ventilation and electrical losses. Along with Oak Ridge, GE has considered several novel generator stator winding designs.

4 GE has produced a proprietary conceptual design for 600 MVA machines, for the purpose of calculating efficiency, and assessing design challenges that result from greater duties on the rotor components (e.g. coils, shields, et c).

5 Preliminary layout drawings have been produced for a sc generator.

6 Generator conceptual designs have been reviewed and reported

Task 1(C): Develop a Preliminary 100 MVA Generator sc Design.

Subtasks 1 through 4 below are the development of a more elaborate, preliminary engineering design of the conceptual design established in Tasks 1(B) 1 through 3 above. This more detailed design study was undertaken in order to potentially identify additional concerns to be addressed at a later development stage.

- 1 For the sc rotor section, GE has produced a preliminary design of cold mass field winding, support structure, quench controlling techniques, and instrumentation.
- 2 GE has also produced preliminary designs of the other non-sc rotor elements
- 3 GE has produced preliminary designs of armature winding and flux shield.
- 4 GE has produced preliminary design of all other generator stationary parts and components
- 5 GE has produced and specified a preliminary design of the auxiliary equipment, which are primarily the cryogenic refrigerator for the rotor.
- 6 GE has produced updated layout drawing depicting the generator and its auxiliaries
- 7 GE has been reporting the concepts and results of this work.

Task 1 (D) : Analyze Performance of Designed Generator -- System Interface Studies (Details included in Reference GE-10)

A preliminary design of a 100 MVA (nominal) superconducting (SC) rotor generator has been established by the GE-lead team under this Superconductivity Partnership Initiative. System interface studies for this superconducting generator were conducted to assess performance of the superconducting generator in order to help ensure the development of superconducting generators that may be successfully integrated with electric power grids.

The characteristics of superconducting generators affecting system performance may be quite different from those of conventional generators. In this study the performance of the SC generator was compared to that of a conventional generator that is normally employed by GE in a 105.7 MVA Frame 7 gas-turbine application. The superconducting generator in general has lower reactances, lower inertia, and longer time constants than a conventional generator.

These grid and prime-mover interface studies were undertaken to evaluate the interface implications of the superconducting generator in light of its different characteristics. The desire and ultimate design goal is a superconducting generator that meets all present and anticipated future requirements.

The following broad study categories were undertaken to evaluate unit performance and interface with the grid, as well as prime mover:

- Load rejection studies relative to both unit speed and voltage response.

- Voltage regulation/response studies for load and reactive switching.
- Stability studies, including steady-state, dynamic, and transient stability.
- Fault current studies, to determine generator-source fault current duties on equipment.
- Fault and switching studies to determine unit shaft torsional stress.
- Excitation requirements, identified in concert with an evaluation of study results.
- Protection requirements, identified in concert with an evaluation of study results.

The approach to this grid/prime mover interface studies was to evaluate performance by dynamic and transient simulation studies, supplemented with classical calculation procedures where appropriate, tailored to the specific performance aspect being investigated. The generator and bus-fed excitation system were modeled in detail in the simulation studies. Basic gas turbine/governor and power system models were incorporated in the study models.

Performance was determined, where practical and meaningful, for both the superconducting and conventional generators; aspects of performance were compared and judgments relative to adequacy of performance or suggestions for improvement were made. The superconducting generator has not necessarily been optimized during this preliminary design phase.

The studies verified that the superconducting generator preliminarily designed under the D.O.E. SPI-1 Program can be successfully integrated into the power grid. Specific areas of design analyses and tradeoffs that will further enhance system integration and performance were identified for pursuit during future detailed design stages of the program.

The system interface studies are reported in detail in a GE proprietary report on this task, "Superconducting Generator -- System Interface Studies", dated August 31, 1995.

Task 1(E): Quantify Energy and Economic Benefits of Program

- 1 GE has evaluated overall generator and system loss improvement compared to that of an equivalent-rated conventional generator.
- 2 GE has estimated generator cost and compared it to that of a conventional generator
- 3 GE has made net cost comparisons.

Task 1(F): Summarize Results of Study and Report

- 1 The SPI - 2 proprietary proposal submitted by GE constitutes a good summary of results and recommendations for future action.
- 2 A detailed review of the design was given to Richard Blausher on November 30, 1995 during his visit to GE's Power Generation Engineering group.

References:

GE

1. *Proposal for SPI-1 A 100 MVA Generator Utilizing High-Temperature Superconducting Windings - Design Assessment And Component Development, April 19, 1993.*
2. *Report - by Mark Runkle, TGE 94 - 19, Crushing Forces Under Balanced Three-Phase Sudden Short Circuit of a Superconducting Generator,*
3. *Report - by Jim Fogarty, TGE - 94-82 Axiperiodic Finite Element End Region Modeler, Part 1, User's Manual*
4. *Letter-Becky Nold, Feb. 16, 1994, Armature Bar Forces on Super Conducting Generators*
5. *Meeting Invitation by George Cotzas, Feb. 18, 1994 Brain Storming Session, Stator Winding Concepts of sc Generators (100-600MVA)*
6. *Letter Report, by Dave Willyoung, March 9, 1994, February 18, 1994 - Brainstorming Session and Revision of February 20 "After Glow" Report*
7. *Letter Report, by Dave Willyoung, Feb. 23, 1994, Revised List on Armature Winding Ideas*
8. *Report - by Jim Fogarty & CR&D, Conceptual Design of a 100 MVA Generator Utilizing High Temperature Superconducting Windings, May 6, 1994*
9. *Typical Records of Design Meetings, March 11, 1994, Invitation to a March 18, 1994 Meeting, sc Generators, Design of slot Support System, Needed Development Effort to Prove Design.*
10. *Report - Superconducting Generator System Interface Studies, August 31, 1995*
11. *Proposal for SPI II- Development and Test of a Prototype 100 MVA Superconducting Generator, June 9, 1995*

ORNL

1. *Report - Preliminary Conceptual Design of a Partial-Helical Stator for High-Temperature Superconducting, 100 - 600 MVA Generators.*