

M2Or2A-01 [Invited]



# Design of MW-Class Industrial Motors by AMSC

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# List of Published Reference

## THIS PRESENTATION IS BASED ON THE FOLLOWING AMSC (A FEW OTHERS) PUBLIC INFORMATION

- Kalsi, S.S., "Applications of High Temperature Superconductors to Electric Power Equipment", IEEE/Wiley, ISBN 978-0-470-16768-7, 2011
- S.S. Kalsi, D. Madura, G. Snitchler, M. Ross, J. Voccio and M. Ingram, "Discussion of Test Results of a Superconductor Synchronous Condenser on a Utility Grid", [Applied Superconductivity, IEEE Transactions on](#), Volume: 17, [Issue: 2](#), Year 2007
- S. S. Kalsi, D. Madura, M. Ross, M. Ingram, R. Belhomme, P. Bousseau and J-Y. Roger, 'Operating Experience of a Superconducting Dynamic Synchronous Compensator', Paper No. A1-108, CIGRE Session 2006 in Paris
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- Kalsi, S.S.; Henderson, N.; Gritter, D.; Nayak, O.; Gallagher, C.; "Benefits of HTS technology to ship systems", [Electric Ship Technologies Symposium, 2005 IEEE](#), 25-27 July 2005 Page(s):437 – 443, Digital Object Identifier 10.1109/ESTS.2005.1524712
- Snitchler, G.; Gamble, B.; Kalsi, S.S.; "The performance of a 5 MW high temperature superconductor ship propulsion motor", [Applied Superconductivity, IEEE Transactions on](#), Volume 15, Issue 2, Part 2, June 2005 Page(s):2206 – 2209, Digital Object Identifier 10.1109/TASC.2005.849613
- Haran, K.; Kalsi, S.S.; Arndt, T.; Karmaker, H.; Badcock, R.; Buckley, R.; Haugan, T.; Izumi, M.; Loder, D.; Bray, J.; Masson, P.; Stautner, W.; "High Power Density Superconducting Rotating Machines – Development Status and Technology Roadmap", Supercond. Sci. Technol. 30, (2017) 123002 (41pp)
- Kalsi, S.S., Hamilton, K.A. and Badcock, R.A., "Superconducting rotating machines for aerospace applications", Presented at AIAA Conference, Cincinnati, OH, 2018

# Superconducting Rotating Machines

## OUTLINE

- Possible applications
- Superconductors
- SC Machine Configurations
- High Speed SC Machines
- Low Speed SC Machines
- Ultra High-Speed SC Machines
- Outlook

*Conventional motor*



# POSSIBLE SUPERCONDUCTORS FOR APPLICATIONS

# Types of Superconductors

- **LTS** – NbTi and Nb<sub>3</sub>Sn
- Operate at ~ 5 K
- Cooled with liquid helium
- Moderate field
- Low cost conductors



*LTS are used in MRI and High Field Magnets*

- **HTS** – BSCCO and ReBCO
- Operate at ~ 20 – 77 K
- Cooled with LH<sub>2</sub>, LNe, LN<sub>2</sub> and Refrigerators
- Very high fields
- High cost conductors



*HTS have still to find a niche application*



Conventional



Superconducting

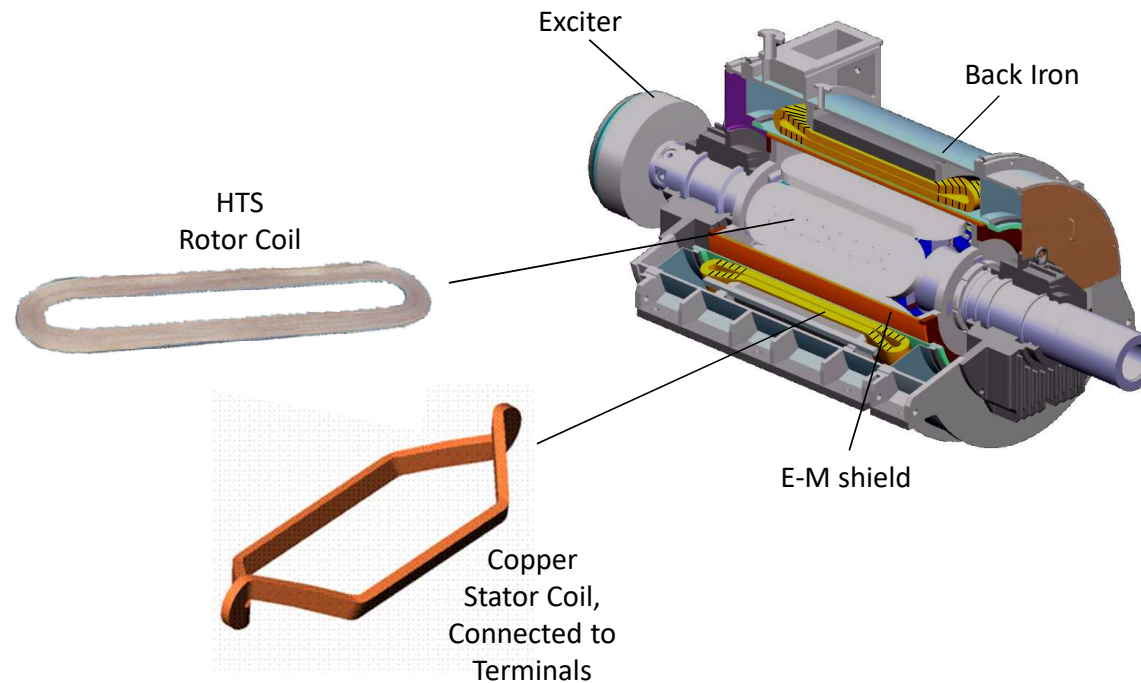
## SC MACHINE CONFIGURATIONS

# Superconducting (SC) Machine Configuration

- Majority of machines are synchronous type employing SC for the DC field winding
- Until the nineties, most machines were built with NbTi (low temperature superconductors – LTS)
- Nineties onwards, High Temperature Superconductors (HTS) became favorite
- Majority of the SC machines have DC excitation winding on the rotor
- In a few applications, DC excitation winding is on the stator and rotor carries AC armature winding
- Homopolar synchronous machines are most suited for very high-speed applications

*Only HTS based machines are discussed in this presentation*

# Key Components of HTS Rotating Machines



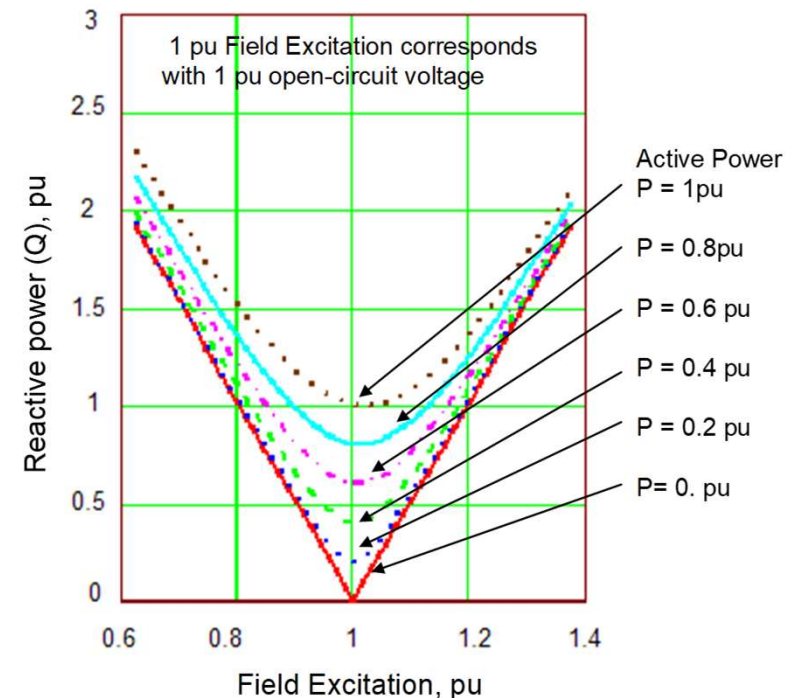
*Most commonly used configurations: HTS field winding and Copper armature winding*



# What makes HTS Machines attractive?

Features making such machines attractive are;

- Compact size
- Light weight
- Ability to supply reactive power (MVARs) up to full MVA rating (both leading and lagging)
- Virtually no harmonics in the terminal voltage
- Improved rotor life – elimination of thermal load cycling of field winding current changes
- Higher efficiency – under partial and full-load operations
- Lower vibrations and noise



*Ability to operate over the whole dynamic range of P and Q powers enhances dynamic stability of the machine and the system*

# What makes HTS Machines attractive?

Harmonics generated inside an HTS synchronous machine are extremely small as shown below;

Harmonic Order	Fraction of Fundamental	Harmonic Order	Fraction of Fundamental	
			Radial	Tangential
1	1	1	1	1
3	0	3	-0.057	0.116
5	$5.977 \cdot 10^{-4}$	5	$3.869 \cdot 10^{-4}$	$7.097 \cdot 10^{-3}$
7	$7.394 \cdot 10^{-6}$	7	$4.567 \cdot 10^{-5}$	$-1.153 \cdot 10^{-3}$
9	0	9	$-7.546 \cdot 10^{-5}$	$-4.378 \cdot 10^{-4}$
11	$6.074 \cdot 10^{-8}$	11	$4.55 \cdot 10^{-6}$	$-4.586 \cdot 10^{-5}$
13	$1.542 \cdot 10^{-10}$	13	$-8.935 \cdot 10^{-7}$	$1.027 \cdot 10^{-5}$
15	0	15	$5.559 \cdot 10^{-7}$	$4.827 \cdot 10^{-6}$
17	$1.032 \cdot 10^{-11}$	17	$-1.149 \cdot 10^{-8}$	$5.882 \cdot 10^{-7}$
19	$-3.381 \cdot 10^{-14}$	19	$-2.729 \cdot 10^{-9}$	$-1.475 \cdot 10^{-7}$

Harmonics generated by field winding in stator

Harmonics generated by stator AC winding on the rotor surface

*Lower harmonic content eases machine component design and simplifies external control systems*

Examples of High-Speed Machines Built and Tested at AMSC

- 1000 hp, 1800 rpm synchronous motor
- 5000 hp, 1800 rpm synchronous motor
- 8 MVAR, 1800 rpm synchronous condenser

## HIGH SPEED SC MACHINES

# AMSC INDUSTRIAL MOTORS HIGH SPEED MACHINES

# 1000 HP, 1800 RPM Synchronous Motor

- First motor jointly built by AMSC and Baldor/Rockwell Automation
- 1000 HP, 1800-RPM, 4-pole
- Field Winding - Employed BSCCO-2223 conductor @25 K
- Armature Winding – Dimond type copper coils
- HTS Cooled with liquid neon
- Tested in the Summer 2000
- Met performance expectations



Field Winding on the Rotor



AC Winding  
on the Stator

*Encouraging progress on this motor motivated AMSC to build 5000 HP motor*

# AMSC 5000 HP Motor Features

- 5000 HP, 1800-RPM, 60 Hz motor
- Line voltage 6.6 kV
- HTS field operating at 30 K
- Field winding cooled with Gifford-McMahon (G-M) cryogenic refrigerators
- Stator winding cooled with fresh water
- Frame dimensions:  
1.1 m dia x 1.6 m long
- Weight – 6.8 ton
- Efficiency – 97.7%

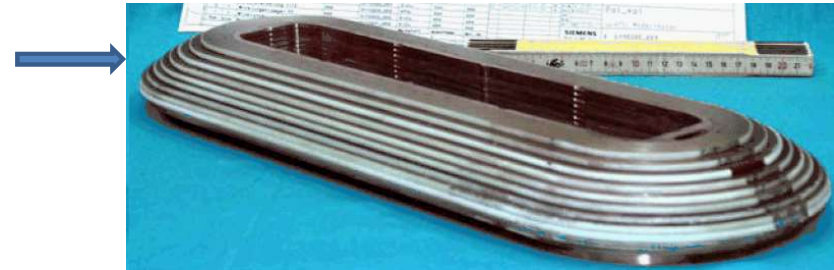


5000 HP Motor – No-load Testing  
June 2001

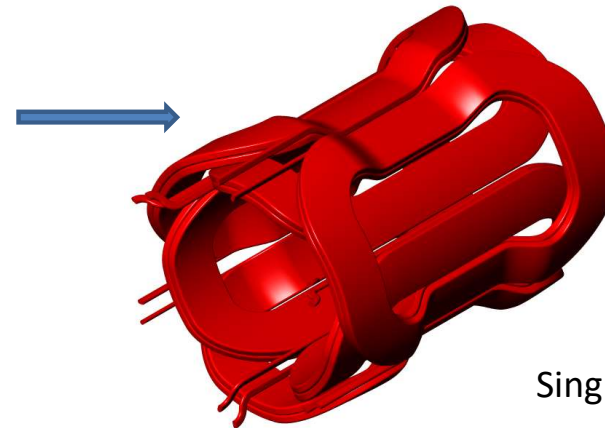
*World's most powerful HTS industrial motor to date*

# 5000 HP Motor Rotor and Stator Details

- Field Winding - pancake BSCCO-2223 coils
- Field Coils - Conduction cooled with liquid neon
- Closed-loop cooling system used G-M cryocooler cooler
- Armature Winding – Innovative Single layer copper coils
- Copper coils cooled with fresh water
- Met all performance expectations



Field Coil



Single Layer Stator

*Success of this project led to the US Navy Propulsion motor projects*

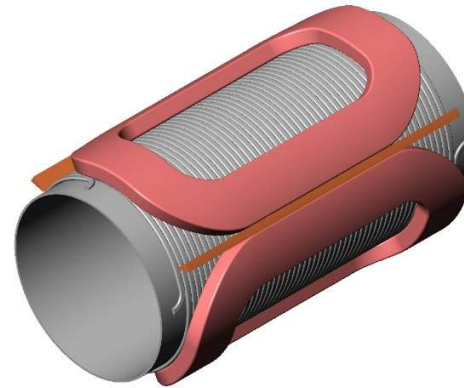


# Design Features - 5,000 HP Motor

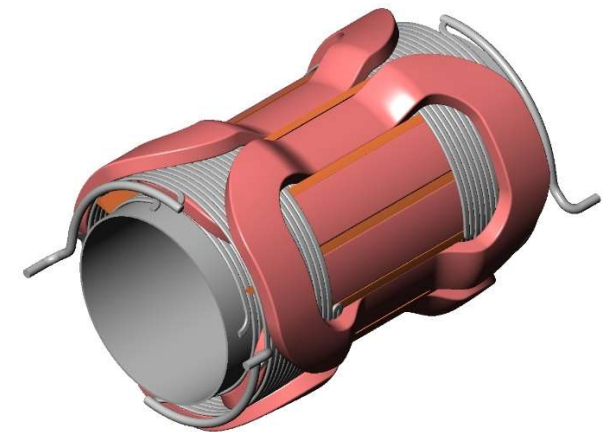
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Voltage	6.6	kV L-L
Number of phases	3	
field inner radius	6.9	in
field outer radius	8.16	in
em shield thickness	1.0	in
em shield outer radius	9.60	in
armature inner radius	11.7	in
armature outer radius	13.6	in
iron yoke inner radius	14.05	in
iron yoke outer radius	18.46	in
field current density	10000	amp/cm2
armature current density	232	amp/cm2
straight length	20	in
length over end turns	39.25	in
number of poles	4	
speed	1800	rpm
power factor	0.99	
field inductance	2.78	henry
field operating current	309	amp
armature phase current	349	amp
Angle at Full Load	14.70	deg
synchronous reactance	0.25	pu
transient reactance	0.22	pu
subtransient reactance	0.15	pu
Efficiency	98	%



Stator coil details

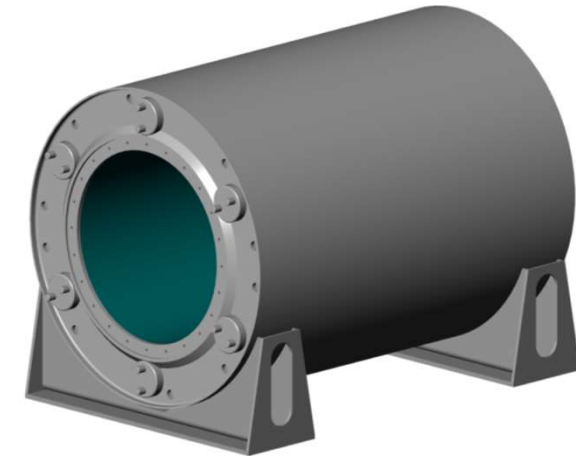
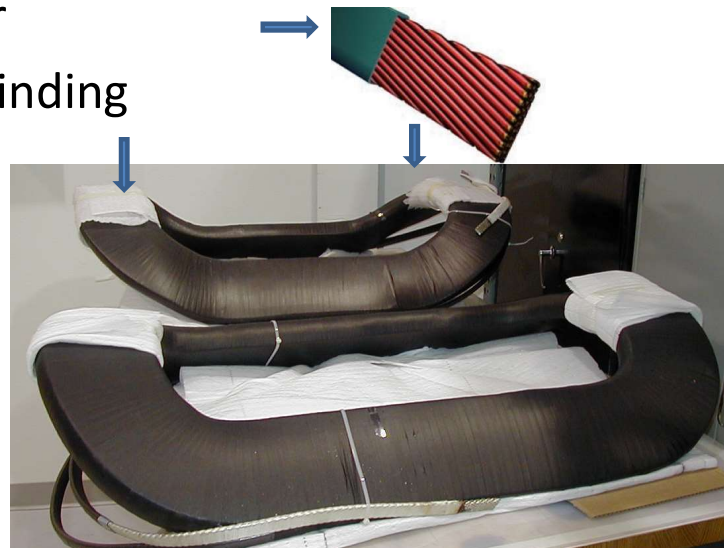


*Showing layout of unique single layer armature coils cooled with fresh water in cooling tubes*



# As Built Stator Components

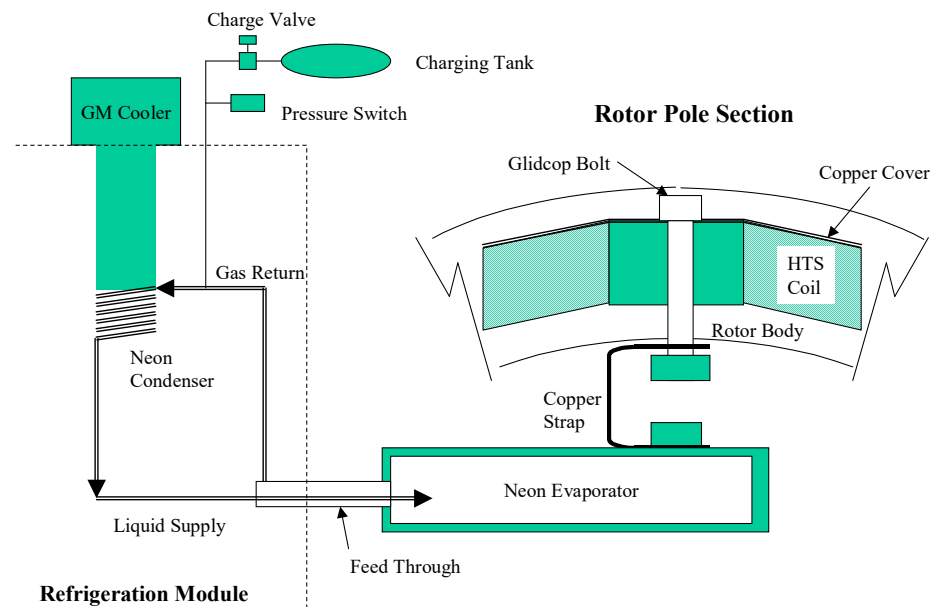
- Conventional iron core
- Coils and cooling tubes epoxy impregnated
- Water cooled stator windings
- Litz conductor
- Single layer winding



*First stator built using such coils cooled with fresh water*  
*- Built by Everson Tesla – Nazareth, PA*

# As Built Field Coils and Cooling System

- Condensing neon heat transport
- Cryomech AL330 G-M cryocooler
- Conduction cooled HTS winding

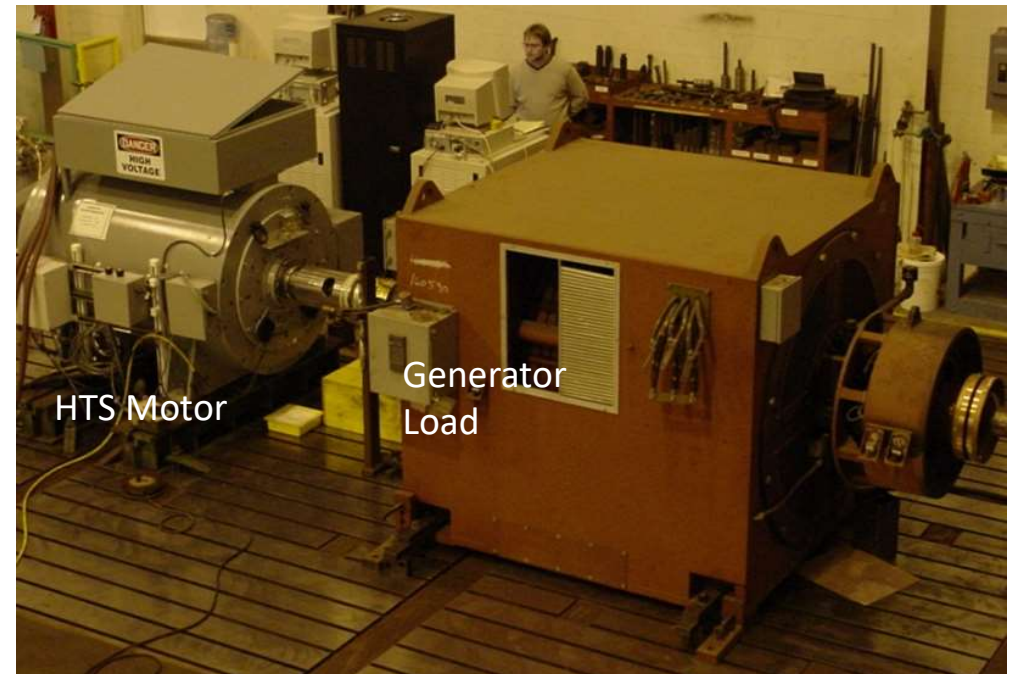


*Field coils were conduction cooled using a closed cycle neon interface medium*

# 5000 HP Motor - Load Testing in June 2001

## Summary of Test Results

- Factory and load testing completed per IEEE 115
- Motor efficiency: 97.7%
- 1/3 reduction in volume compared to the industry standard
- 40% reduction in losses compared to the industry standard



*Achieved successful demonstration of the first powerful HTS motor in 2001*

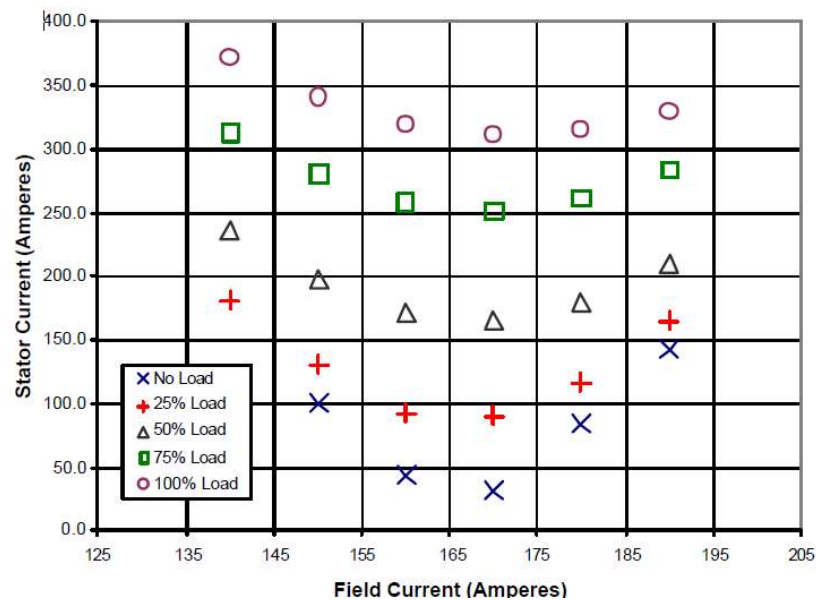
# Comparison of Design and Measurements

Parameter	Design	Measured	Units
Line Voltage	6.6	6.6	kV
Phase Current	329	330	A
Rating	5000	5000	hp
$X_d$	0.32	0.30	pu
$X_d'$	0.28	0.23	pu
$X_d''$	0.16	0.17	pu
Back EMF	1.043	1.035	pu
Ampere-turns	261	279	kA/pole
Power factor	Unity	Unity	

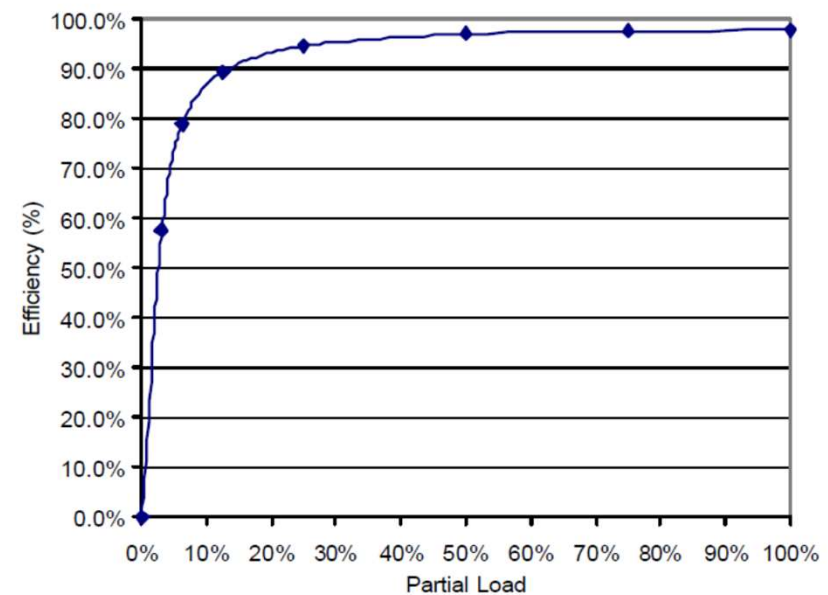
*Excellent comparison between calculated and measured parameters  
validated design codes*

# 5000 HP Motor Test Results

Test measurement conducted per IEEE-115



Measured V-curves



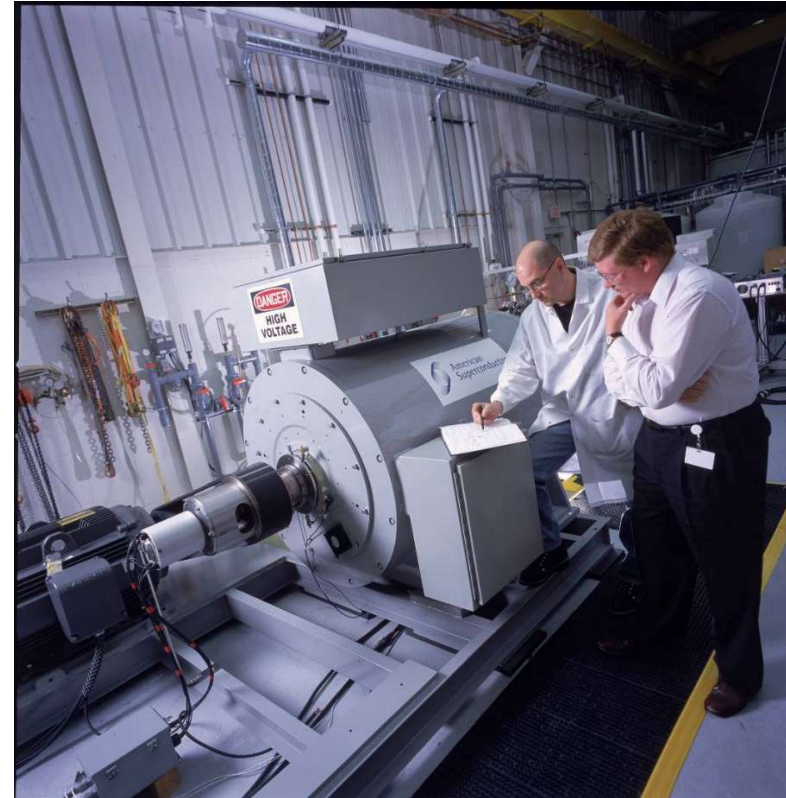
Motor efficiency based on the test data

*Excellent performance exhibited by measured V-curves and Efficiency*



# Lessons Learned from 5000 HP Motor

- Dominant losses are;
  - Stator Copper
  - Iron Core
  - Cryogenic power is small
- Validated machine design algorithms
- Demonstrated;
  - vacuum system over several months
  - thermal insulation system on the rotor
  - cooling systems for Rotor and Stator



*Design algorithms and component validation with the 5000 HP motor were later used for designing future machines – this motor still exists at AMSC*

*SuperVAR<sup>®</sup>*  
*Dynamic Synchronous Condenser*

**AMSC – SuperVAR**

**HIGH SPEED SC MACHINES**



Hoeganaes, Tennessee

# SuperVAR<sup>®</sup> Prototype Project Description

Similar to a conventional synchronous machine but with better performance

- 8 MVA prototype SuperVAR machine for testing on TVA grid
- TVA had partially supported the prototype development
- TVA had planned to order 5 production units following the successful testing of the prototype
  - rated 12 MVA at 13.8kV



Rating	8 MVAR
Voltage	13.8 kV line to line
Ambient Temp	-30° to +40°C
Losses	1.5% rating at 8MVA
	Including 30kW 480V auxiliary power

*AMSC was offering 12 MVA production units for delivery in early 2006*



# Characteristics of a SuperVAR<sup>®</sup> Condenser

- Fast reacting transient dynamic voltage support and stability (leading and lagging VARS) at a multiple of the machine rating
  - Applicable to a range of voltage regulation, power quality and voltage collapse problems
- Reduced operating costs over conventional condensers
  - Low losses even at partial load
  - No rotor rewind costs due to eliminated thermal cycling
- Generates very low levels of harmonics - requiring no filters
- Simplified installation
  - Pre-packaged, self-contained units
- Operates at line voltage on low side of transmission to distribution transformer
  - Stator may be provided for distribution level voltages (up to 13.8kV)
  - No additional transformer needed in most applications

*SuperVAR Condenser had very attractive features*

# Component Fabrication for $\pm 8$ MVAR Unit



Field Winding Assembly



Complete Rotor Assembly



Stator SEP 25 2003



Refrigerator

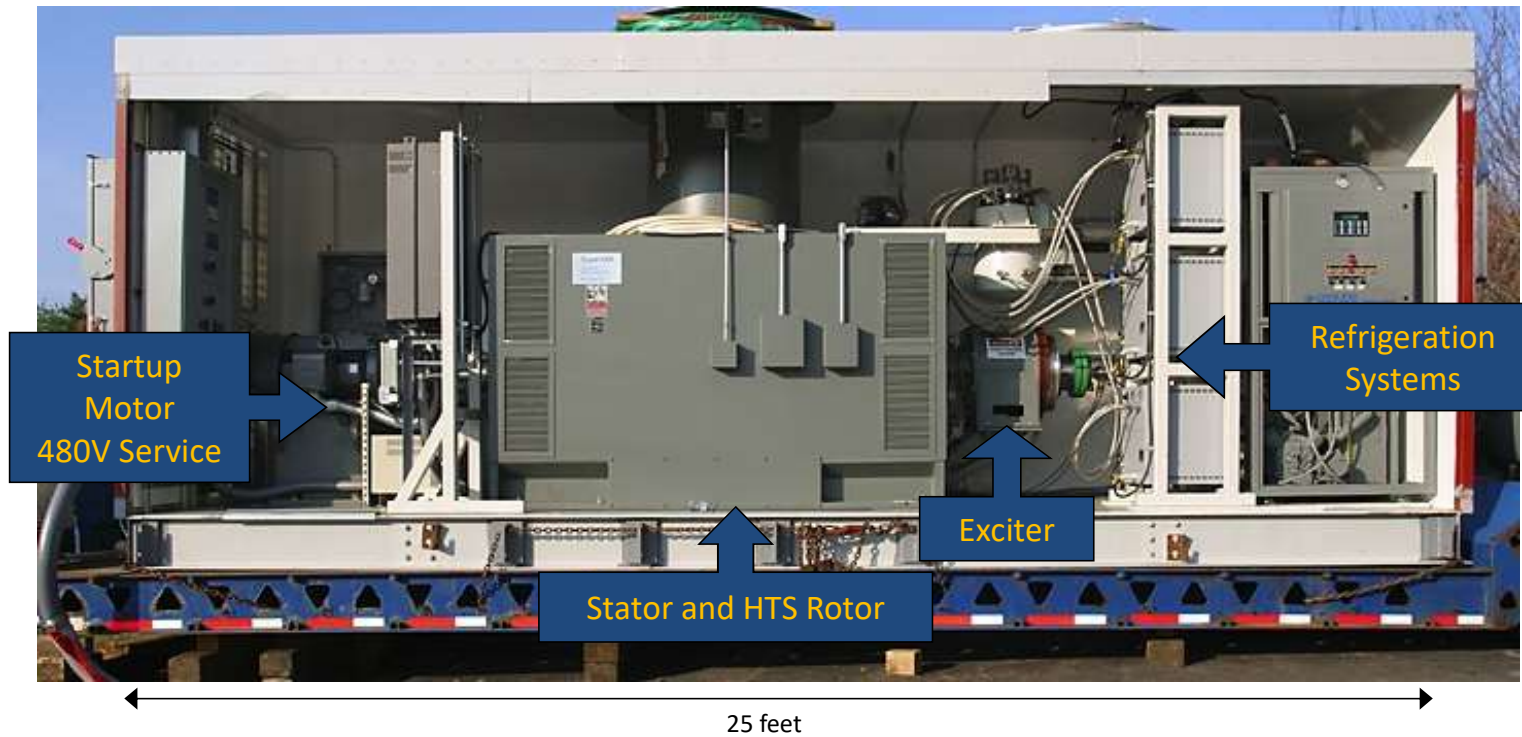


Exciter under test

*Superconducting rotor in a conventional stator*

# $\pm 8$ MVAR Unit at TVA Site

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*SuperVAR condenser and its supporting equipment mounted in a container for ease of mobility*

# Test Results

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## 8 MVAR SuperVAR™ Performance Parameters

<u>Parameters</u>	<u>Measured</u>
Synchronous reactance ( $x_d$ ), pu	0.37
Transient reactance ( $x_d'$ ), pu	0.21
Sub-transient reactance ( $x_d''$ ), pu	0.13
Sub-transient reactance ( $x_q''$ ), pu	0.13
Armature short-circuit time constant ( $\tau_{sc}$ ), s	0.05
D-axis Transient open-circuit time constant ( $\tau_{do}'$ ), s	860
D-axis Sub-transient open-circuit time constant ( $\tau_{do}''$ ), s	0.02
Q-axis Sub-transient open-circuit time constant ( $\tau_{qo}''$ ), s	0.04
Armature resistance ( $r_a$ ), pu	0.007
Inertial constant, s	1.4

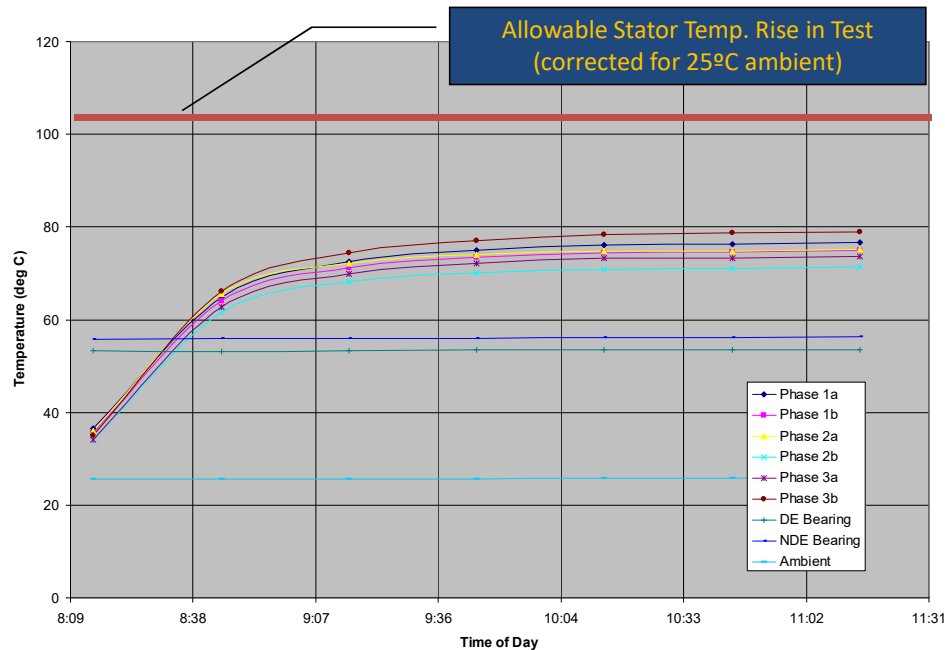
*Machine parameters were measured – Low  $X_d$  is the key to machine's excellent performance*

# Test Results

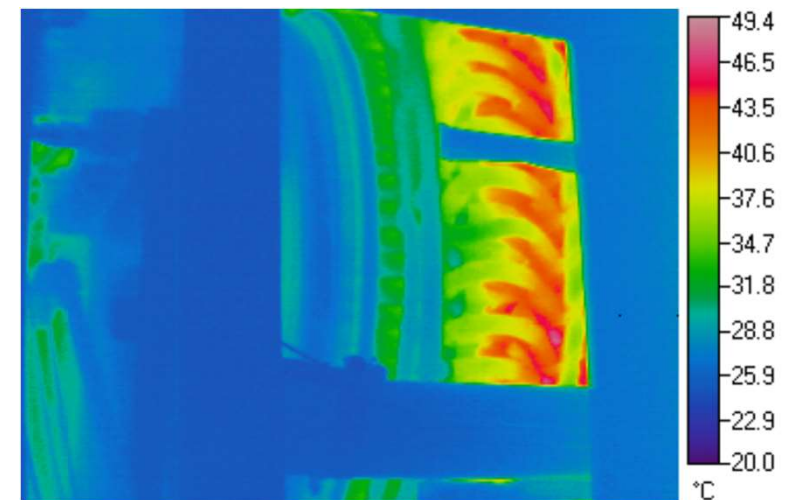
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## Zero Power Factor Heat Run at 8MVAR



Temperature of stator end turns after 3 hours operation at 8MVA



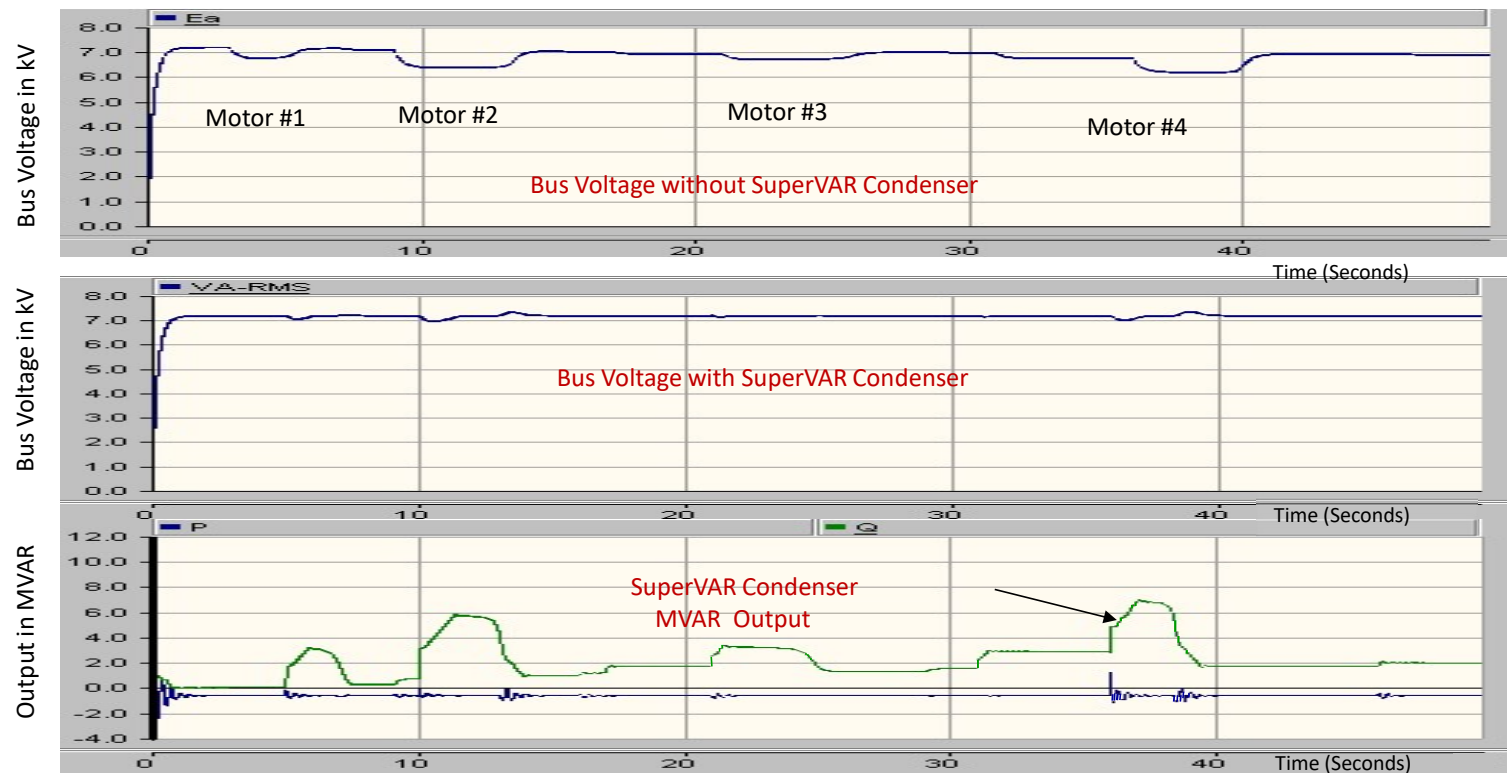
- Temperature rise must be  $\leq 120^{\circ}\text{C}$  at  $40^{\circ}\text{C}$  ambient temperature
- Stator end turn temperature monitored using infrared camera

*All temperatures were within design limits*



# Mitigating Multiple Motor Starts: Simulation

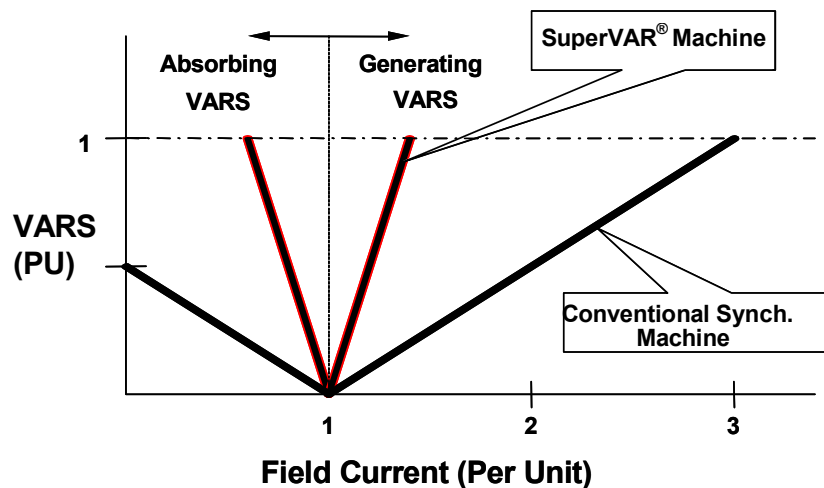
M. Ross, AMSC PES, using Power Technologies Inc. PSS/E simulation software



*SuperVAR: an excellent solution for solving flicker problems due to switching in of large loads*

# Electric Utility Applications

## V-Curves -- Conventional Vs. SuperVAR Condensers

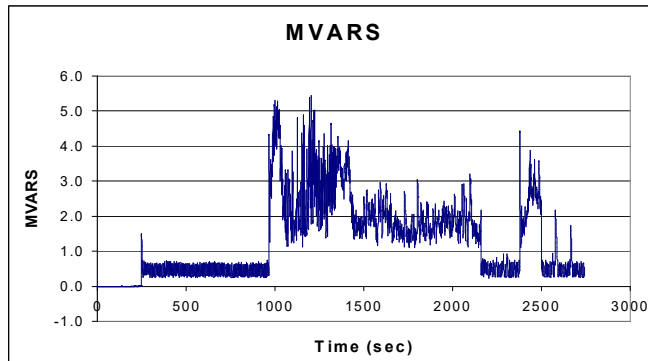


*SuperVAR machine leveraged proven features of Conventional stator combined with HTS rotor*

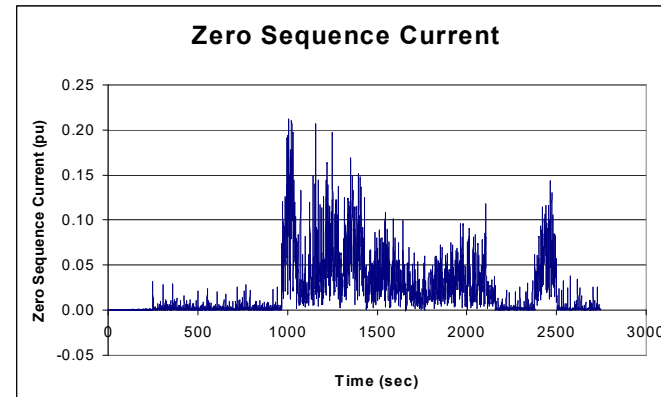
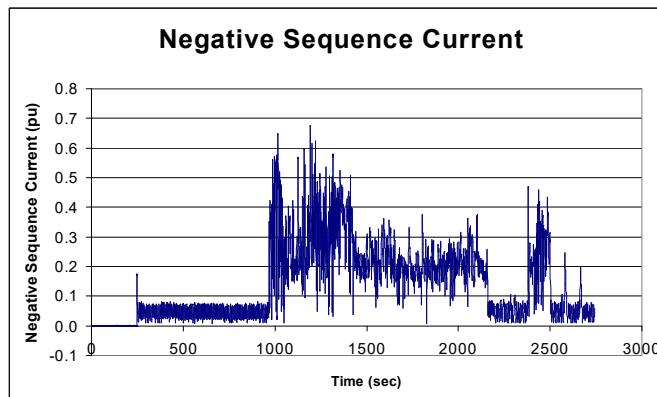
## SuperVAR Machine Advantages

- **Fast reacting transient dynamic voltage support and stability (leading and lagging VARS) at a multiple of the machine rating**
  - Applicable to a range of voltage regulation, power quality and voltage collapse problems
- **Reduced operating costs over conventional condensers**
  - Low losses even at partial load
  - No rotor rewind costs due to eliminated thermal cycling
- **Generates very low levels of harmonics so requires no filters**
- **Simplified installation**
  - Pre-packaged, self-contained units
- **Operates at line voltage on low side of transmission to distribution transformer**
  - Stator may be provided for distribution level voltages (up to 13.8kV)
  - No additional transformer needed in most applications

# Machine Performance on TVA Grid



- Machine was first synchronized on Tennessee Valley Authority (TVA) grid in Gallatin, TN on 10 October 2004
- Operated on regular basis between November 2004 and November 2005
- Experienced millions of transients due to the arc furnace operations
- A typical 1-hr burn cycle is shown here

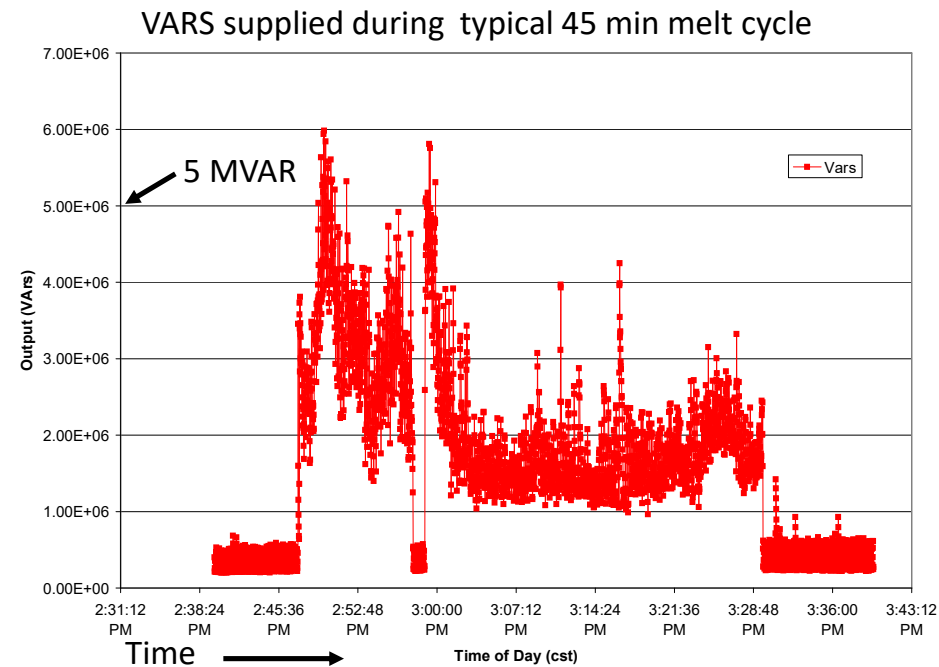


*SuperVAR machine operated without a single problem while experiencing high level of negative and zero sequence currents*



# Real Life Operation on TVA Grid - I

- Machine installed on TVA grid in Gallatin, TN
- Synchronized 10 October 2004
- $\pm 8$  MVAR capability verified
- Machine reacted quasi-instantaneously to transients due to arc furnace operations



Courtesy of TVA

VARs supplied during a typical melt cycle

*SuperVAR™ machine successfully supporting arc furnace, reducing grid disturbance*

# SuperVAR<sup>®</sup> Conclusions

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- SuperVAR<sup>®</sup> synchronous condenser was built and tested
  - Extensive testing in the factory with > 3 hour on-grid operation
  - Operated on TVA grid in Hoeganaes, TN. -- November 2004 to November 2005 – Regular operation lasting 1 year

*SuperVAR<sup>®</sup> Condensers have applications for a wide variety of grid related problems*

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# ULTRA HIGH-SPEED SC MACHINES



NSWC-Philly-  
20180822

Superconducting Rotating Machines

# 4MW, 15000-RPM AC Generator

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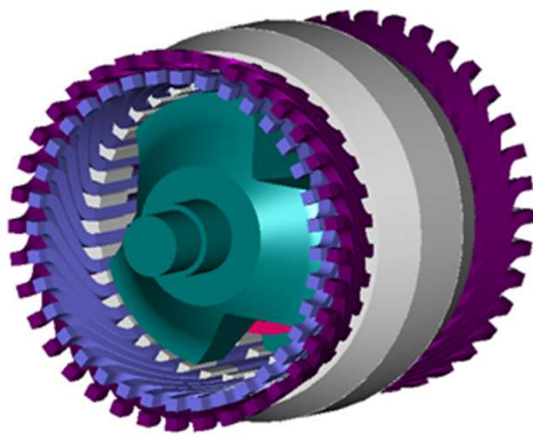


- MW Class Power System Integration in Aircraft
- Two generator programs in progress
  - Synchronous generator utilizing HTS wire
  - Inductor (homopolar) generator with both armature and field windings stationary

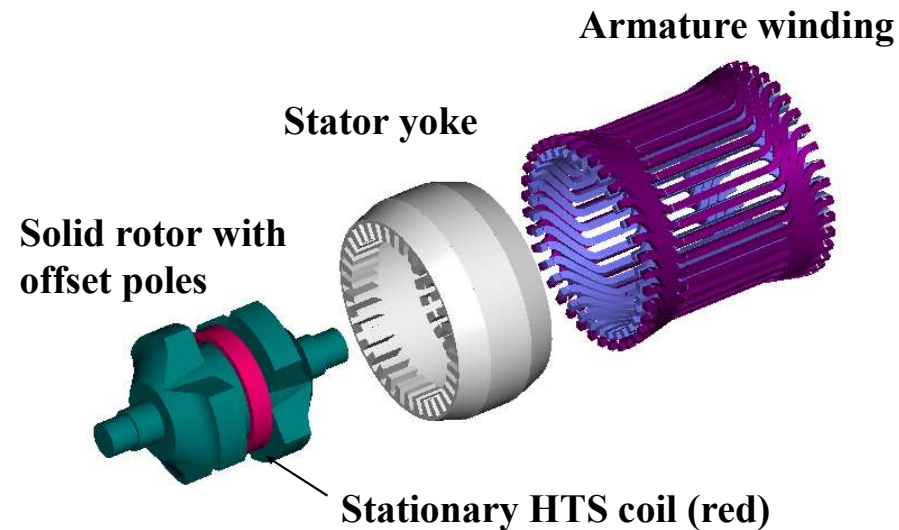
*Challenge: Transferring current and coolant to the rotor at very high speed*

# High Speed AC Inductor Generator Concept

Inductor Alternator with Stationary Superconducting Coil, Solid Rotor Forging, and Conventional Air Core Stator



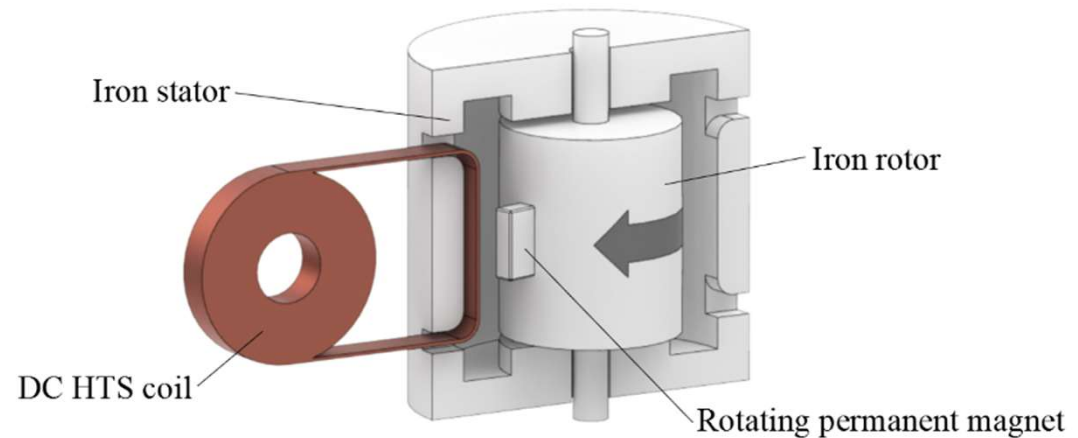
Courtesy GE



*Rotor has no active components*

# HTS Dynamo Concept

- Field coils excited wirelessly for minimizing thermal conduction into cold environment
- Brushless exciter (Dynamo) shown here accomplishes this
- Dynamo exciter could operate at currents  $> 1$  kA
- Plans are to integrate it with the coolant transfer coupling



*This dynamo concept has been successfully built and demonstrated by RRI-VUW*

# What's will make HTS Machines Attractive

- HTS technology amply demonstrated – need for economic viability:
  - Low-cost HTS wire and
  - Reliable and affordable cooling system
- **MUST:** Improve wire performance (e.g., extended window of operation in terms of higher temperature and magnetic field and lower cost)
- Building HTS machines by leveraging synergies of off-the-shelf-components
- Designing machines by including dynamic variation of operating parameters (e.g., temperature, excitation, amount of fuel and environment)
- HTS machines may have sweet applications where other technologies are not feasible; Example: > 20 MW wind power generators and Motors/Generators for aerospace
- An affordable and reliable HTS technology may extend its applications to central power stations, wind turbine generators, ship propulsion and industrial motors

*Future of the HTS technology looks very promising*

# Questions

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