

# Performance of Superconductor Dynamic Synchronous Condenser on an Electric Grid

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**Abstract** — High-temperature superconductor (HTS) dynamic synchronous condensers have been developed for applications in an electric grid. The HTS dynamic synchronous condensers, also called SuperVAR®, are similar to conventional synchronous condensers, but the copper field winding has been replaced with an HTS field winding. The HTS dynamic synchronous condensers have some very attractive features, such as a small footprint, transportability, high reliability, and peak and dynamic reactive compensation capability for leading or lagging VARs. These HTS dynamic synchronous condenser machines are also inherently stable to close-in faults and can provide up to twice the nominal rating for about one minute (peak rating) during depressed voltage events. These machines also use about one-half of the energy of a conventional synchronous condenser because the HTS field winding losses are essentially zero. In October 2004, the first HTS dynamic synchronous condenser was installed on the Tennessee Valley Authority (TVA) grid serving an arc furnace where it is being exposed to a large number of transients, providing an excellent accelerated age test of the device. TVA has ordered five HTS dynamic synchronous condensers rated at 12 MVAR, and successful operation of the first prototype machine is expected to lead to release of these orders to production by TVA, making HTS dynamic synchronous condensers the first HTS commercial product for enhancing power grid reliability. This dynamic synchronous condenser machine will also be very attractive for dispersed generation applications (such as wind farms), for providing voltage regulation, and for improving the low voltage ride-through (LVRT) capability and for the decommissioning of older, less efficient “Reliability Must Run” generators.

**Index Terms**—capacitor, dynamic synchronous condenser, FACTS (Flexible AC Transmission System), reactive power, reactors (inductors), STATCOM (Static Shunt Compensator), SuperVAR®, SVC (Static VAR Compensator), VAR (Volt-Ampere-reactive), low voltage ride through (LVRT)

## I. NOMENCLATURE

HTS – High-temperature superconductors  
LTS – Low-temperature superconductors  
BSCCO – HTS material used in first generation wire  
FACTS – Flexible AC transmission systems  
LVRT – Low voltage ride through  
VAR – Volt-ampere-reactive power  
SVC – Static VAR compensators

## II. INTRODUCTION

While conventional dynamic synchronous condensers based on copper field coils have been widely used in the power grid, their relatively low efficiency has limited their potential applications, and their lifetime has been limited by insulation degradation caused by field current heating during cyclic operation. They have been replaced by electronic solutions such as Static VAR Compensators (SVCs), and Flexible AC Transmission System (FACTS) devices. Although other reactive compensation devices, such as SVC are capable of boosting system voltage, during a voltage collapse situation their output varies in proportion to the square of the voltage - thus making such devices less effective at the point in time when their functionality is most needed to boost voltage.

The HTS dynamic synchronous condenser machine eliminates many problems associated with conventional condensers and FACTS electronic devices. The HTS dynamic synchronous condenser employs an HTS field winding that always operates at a constant cryogenic temperature and field current excursions are quite small between no-load and full-load conditions. This inherent feature of the dynamic synchronous condenser machine significantly reduces the need for maintenance as compared to a conventional synchronous condenser, which experiences significant thermal cycling within the rotor.

Heavy filters are normally used to attenuate undesirable harmonics produced by many FACTS devices. Since the dynamic synchronous condenser machine produces essentially no harmonics, large filtering equipment is avoided. The HTS dynamic synchronous condenser current output is independent of system voltage – the output current can be increased several times its continuous rating using a fast exciter [1]-[3]. This over-load current can be maintained for a time duration constrained by the  $I^2t$  limit of 120 seconds.

## III. HTS DYNAMIC SYNCHRONOUS CONDENSER FEATURES

While conventional synchronous condensers have been widely used in the power grid, their relatively low efficiency has limited their potential applications, and their useful lifetime has been limited by field winding insulation degradation caused by field current heating during cyclic operation [4]. As shown in Figure 1, the field current of a conventional machine must be increased by three times between no-load and full-load and this increase causes significant field winding heating that leads to premature failure. Dynamic synchronous condenser design based on

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HTS wire in the rotor field winding requires only a small change in field current between no-load and full-load, and it always operates at a constant temperature. Because the superconductor wire has dramatically reduced losses, the HTS dynamic synchronous condenser is estimated to be 98.8% efficient, typically 1% more efficient than copper-based conventional units. The HTS dynamic synchronous condenser machine retains its high efficiency down to partial loads of 25%, whereas the efficiency of conventional machines drops more rapidly due to its field winding losses, which are caused by the high field current. Thus, the net impact of HTS dynamic synchronous condensers on system losses and operating costs is very favorable.

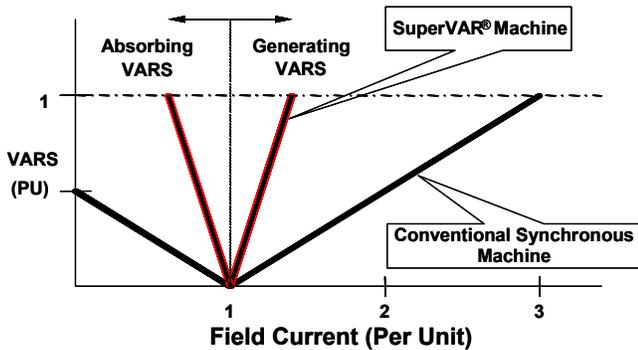


Figure 1: V-curves for Conventional Synchronous and HTS Synchronous Condenser Machines

Because of its compact size and low-cost design, the new HTS dynamic synchronous condenser will also be a very economic option for providing peak and dynamic reactive compensation to a power system. It has a small footprint and is readily transportable for easy placement in distribution substations. It has been shown to be inherently stable to transient faults, and can provide up to twice its nominal current for about one minute (peak rating) during depressed voltage events. Because the large temperature excursions (characteristic of copper-field windings) are eliminated, and because large VAR output is possible with very small variations in excitation current, the HTS dynamic synchronous condenser machine is expected to be highly reliable.

To demonstrate these attractive features of the HTS dynamic synchronous condenser, the first prototype unit is operating in the TVA grid near an arc furnace [5]. At this site, the testing is intended to show not only that the HTS dynamic synchronous condenser machine is a new, preferred option for handling arc furnace flicker, but that it will also handle hundreds of thousands of transients in less than a year. The as-delivered picture of the  $\pm 8$  MVAR HTS dynamic synchronous condenser machine (trailerized) with key components highlighted is shown in Figure 2. The specifications for the prototype and planned production versions of the HTS dynamic synchronous condenser machine are provided in Table I. This HTS dynamic synchronous condenser machine can be built for any voltage between 4.16

kV and 20 kV. Total losses (including refrigeration system) are  $\sim 1.2\%$  of the rating. These losses are equivalent to losses in an electronics FACTS device.

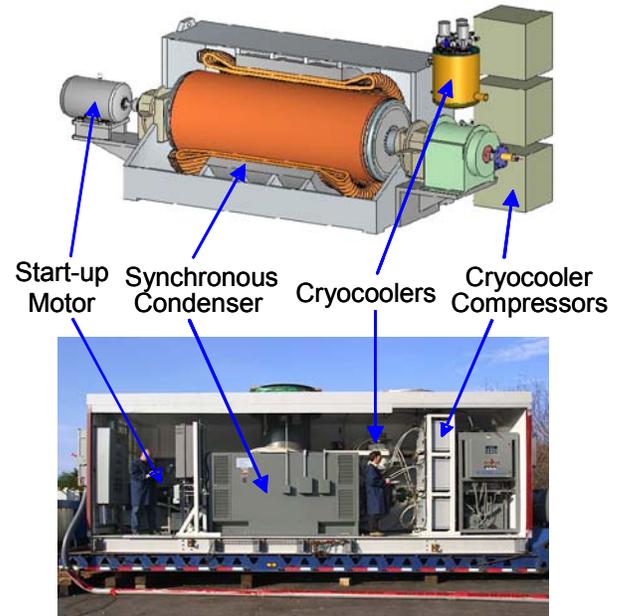


Figure 2: AMSC's +/- 8 MVAR HTS Synchronous Condenser Machine with Key Characteristics Highlighted

Table I: HTS Synchronous Condenser Specifications

Rating	$\pm 8$ MVAR (prototype unit) $\pm 12$ MVAR (production unit)
Voltage	4.16 to 20 kV line to line
Ambient Temp	$-30^{\circ}$ to $+40^{\circ}$ C
Losses	1.5% rating at 8MVA, including 30kW 480V auxiliary power

The HTS dynamic synchronous condenser support system consisting of the following subsystems is shown in Figure 3:

- HTS rotor
- Stator lubrication and cooling system
- Refrigeration
- Exciter, control and communication system
- Auxiliary power system
- Startup motor and controller

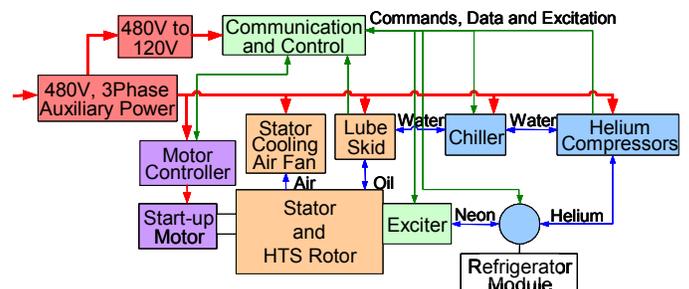


Figure 3: HTS Synchronous Condenser Support Systems

TVA will release to manufacture five production units previously ordered (each rated 12 MVAR), contingent on the successful testing of the 8-MVAR prototype. With this first commercial order, the HTS dynamic synchronous condenser will be the first commercialized HTS application for the electric power grid.

The open-circuit and short-circuit test measurements are shown in Figure 4. The machine does not exhibit any saturation effect over the operating range (1.3 pu voltage). Parameters measured from these tests are summarized in Table II. These parameters can be utilized for simulation of this machine with commercial codes such as PSS/E, EMTF and PSCAD.

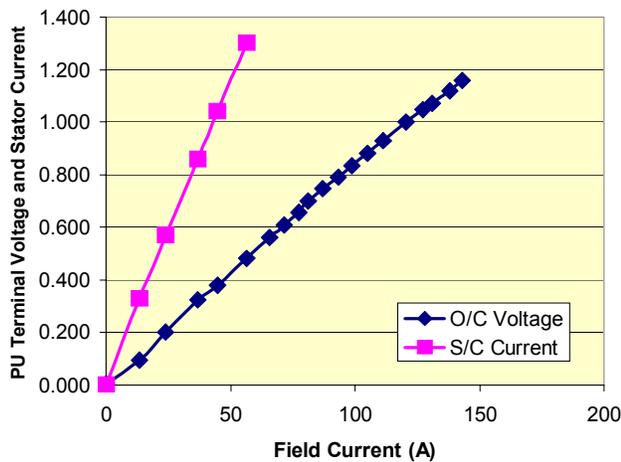


Figure 4: Open-Circuit and Short-circuit Measurements on the HTS Dynamic Synchronous Condenser

Table II: Measured Parameters for the 8 MVAR HTS Dynamic Synchronous Condenser

Parameters	Measured
Synchronous reactance ( $x_d$ ), pu	0.36
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 O/C time constant ( $\tau_{do}'$ ), s	860
D-axis Sub-transient O/C time constant ( $\tau_{do}''$ ), s	0.02
Q-axis Sub-transient O/C time constant ( $\tau_{qo}''$ ), s	0.04
Armature resistance ( $r_a$ ), pu	0.007
Inertia constant, s	1.4

#### IV. TEST RESULTS ON GRID

After factory testing, the machine was installed at an electric arc furnace and began grid operation on October 10, 2004. It was gradually brought to regular operation in January 2005. Since then the machine has been operating to help reduce flicker caused by the arc furnace. MVARs supplied by the machine during a typical melt cycle are shown in Figure 5. The figure shows MVAR contributions at 1-second

intervals, though the peak instantaneous contribution could be significantly higher. The machine has been absorbing transient disturbances with very high negative (>30%) and zero sequence (>15%) current components as shown in Figure 6 and Figure 7. The rotor with a continuous damper winding, in the form of a copper shell, absorbs heating created by negative and zero sequence currents very effectively with an insignificant temperature rise in cryogenic components. The stator winding has also withstood these currents while staying within the peak allowable temperature.

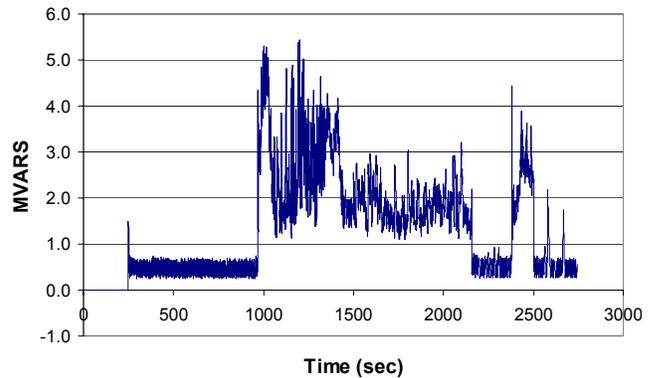


Fig. 5: MVARs Supplied by HTS Synchronous Condenser during an Arc Furnace Burn Cycle

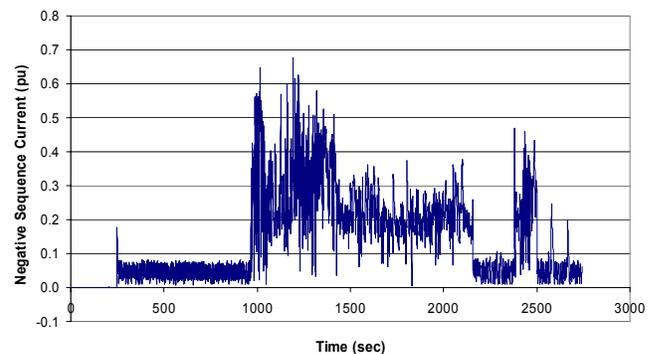


Figure 6: Negative Sequence Currents Experienced by HTS Dynamic Synchronous Condenser during an Arc Furnace Burn Cycle

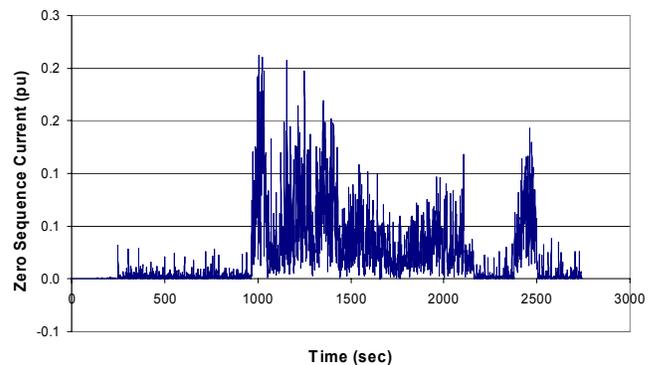


Figure 7: Zero Sequence Currents Experienced by HTS Dynamic Synchronous Condenser during an Arc Furnace Burn Cycle

#### V. WIND FARM APPLICATION (SIMULATION)

Simulations show that an HTS dynamic synchronous condenser can provide benefit to an existing 78 MW

Midwestern (U.S.) wind farm, as shown in Figure 8. Studies have shown that this wind farm would have inadequate voltage regulation and low voltage ride through capabilities unless additional equipment was installed to mitigate this situation. Approximately 40 MVAR of additional capacitive reactive support was required in order to meet the voltage regulation and power factor requirements. Simulations also showed that the wind farm would not be capable of surviving a number of three-phase and single-line to ground transmission faults without tripping at least a portion of the wind turbines.

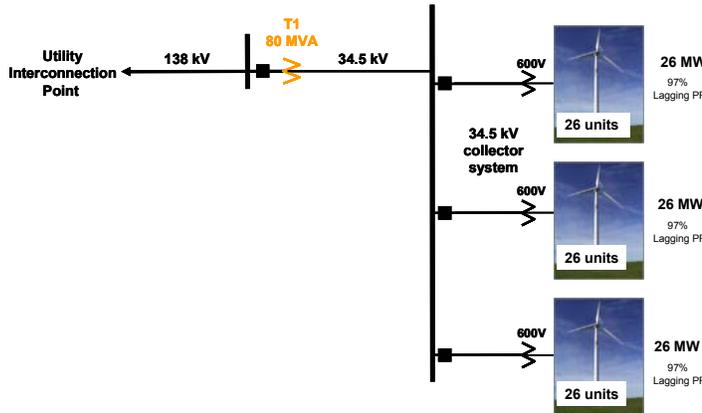


Figure 8: 78 MW Existing Wind Farm, No Compensation Equipment

To improve the low-voltage ride through (LVRT) capability of the wind farm, two 12 MVA HTS dynamic synchronous condenser units were used in the simulation. The HTS dynamic synchronous condenser units were used (see Figure 9) on the 34.5 kV main collector bus of the wind farm via two 12 MVA transformers to step the 13.8 kV output of the units up to 34.5 kV.

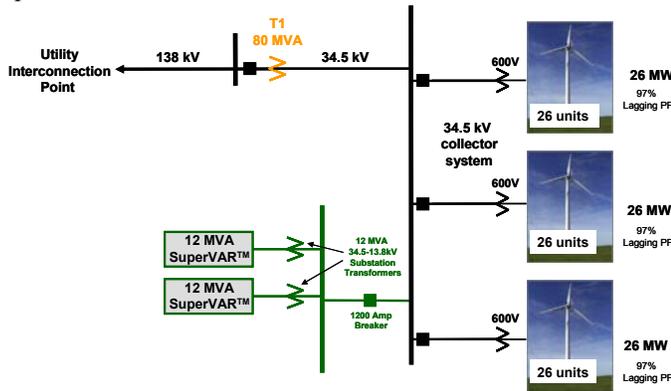


Figure 9: Wind Farm with Two HTS Dynamic Synchronous Condenser Units Installed to Improve LVRT

With the HTS dynamic synchronous condenser units installed, the LVRT capability of the solution was significantly improved. A comparison, with and without the HTS dynamic synchronous condenser machine installation, of the wind farm voltage and real power output in response to a low voltage fault described in the interconnection agreement is shown in Figure 10.

Without the HTS dynamic synchronous condenser units installed, the fault event causes all the turbines in the wind

farm to trip on low voltage, as is demonstrated in Figure 10. With the HTS dynamic synchronous condenser solution installed, the 34.5 kV bus voltage is kept high enough so that no turbines trip and the wind farm successfully rides through the event. Thus, the LVRT issue can be solved by the two HTS dynamic synchronous condenser units.

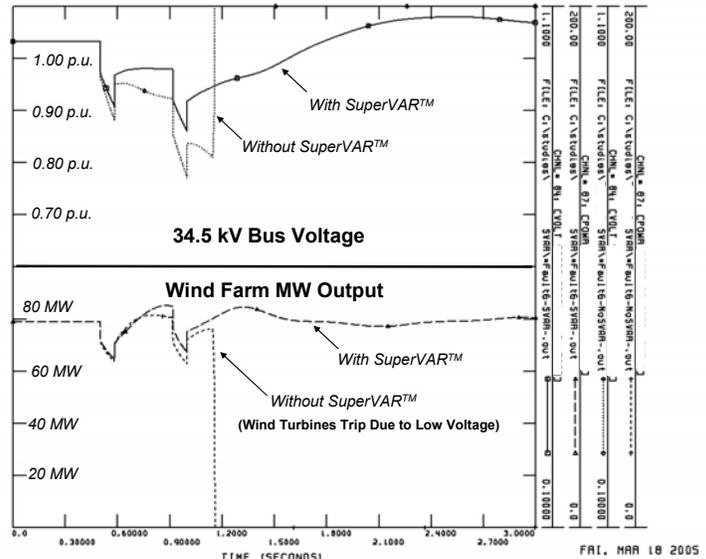


Figure 10: Wind Farm Bus Voltage and MW Output with and without SuperVAR®

## VI. CONCLUSIONS

A SuperVAR® dynamic synchronous condenser machine was installed on the grid in October 2004 and gradually brought to regular operation in January 2005. The machine is improving power factor and reducing flicker caused by the arc furnace. The HTS dynamic synchronous condenser can solve a variety of utility problems without the operational and performance limitations of conventional machines and electronic FACTS devices. Simulation studies have shown that HTS dynamic synchronous condenser machines installed at the collector bus of a wind farm system will mitigate voltage regulations and LVRT problems. With a combination of steady voltage regulating output and fast reacting transient capability, the HTS dynamic synchronous condenser can address a number of additional problems associated with integration of wind farms with the grid. This machine will provide outstanding value to transmission system operators beginning in 2006.

## VII. ACKNOWLEDGEMENTS

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