Design and Operational Testing of a 5/10-MVA HTS Utility Power Transformer

C. S. Weber, C. T. Reis, D. W. Hazelton, S.W. Schwenterly, M.J. Cole, J.A. Demko, E.A. Pleva, S. Mehta, T. Golner, N. Aversa

Abstract— **High temperature superconducting transformers offer many economic, operational, and environmental benefits over conventional power transformers for utility applications. To establish the technical and economic feasibility and benefits of HTS transformers of medium-to-large (>10MVA) ratings, a team that includes Waukesha Electric Systems (transformer manufacturer), SuperPower, Inc. (HTS systems manufacturer), Oak Ridge National Lab, and Energy East has designed, built and tested a prototype 5/10MVA superconducting transformer. The transformer's 4.5-ton cold mass has been successfully maintained at temperatures of 30-50 K for several months, without full-time operator attendance. The transformer has reached its full three-phase operating current, and has been tested to 1.4 times operating current (limited by available power supplies) in single-phase mode. It is now undergoing long-term tests at various current levels, high-voltage tests, and transient overcurrent tests at the Waukesha site. This paper summarizes the manufacturing, cooldown, and the test results achieved to date.**

Index Terms— **Superconducting device testing, High-temperature superconductors, Superconducting transformers**

I. INTRODUCTION

HIGH temperature superconducting (HTS) transformers offer a varied set of benefits which make them very attractive for utilities, and are now being demonstrated as prototype devices. This is the second phase of a three phase program to build increasingly larger superconducting transformers, culminating in a 30/60 MVA unit in the final phase. The benefits and fabrication choices made by this team for the 5/10 MVA transformer are described in greater detail in [1] and [2]. Assembly of the prototype 5/10-MVA transformer is complete and tests have been completed. Further details of the assembly and test can be found in [3].

TABLE I
SPECIFICATIONS OF THE 5/10 MVA TRANSFORMER

Connection	3 phase, Δ/Y
Primary/Secondary Voltage (kV)	24.9/4.2
coil Voltage (kV)	24.9/2.4
Primary/Secondary BIL (kV)	100/50
Primary/Secondary Current (A)	116/694
coil Current (A)	67/694
peak coil Current for WES plant(A)	40/416
Overload Ratings	2 sec-10X, 48hr-2x
Cooling System	Cryocoolers
Instrumentation	Local

II. MANUFACTURE AND TEST

A. Technical Challenges

In the 5/10 MVA transformer, new ground was broken in terms of handling higher voltage and heat load levels (mainly derived from ac loss considerations) than were encountered in the prior 1MVA effort. Additional challenges were encountered in creating a three phase device where the connections between the phases were contained within the vacuum tank. Each team member was responsible for specific components of the design, development, and construction of the HTS transformer.

B. Phase Set Assembly

Each electrical phase consists of an assembly of multiple vacuum impregnated epoxied coil windings, with integrated cooling, encapsulated into one package. Downleads for the primary and secondary windings are included in the phase set assembly. The design and fabrication of the phase sets comprised a balance between the sometimes conflicting needs of a cryogenic system to maintain superconductivity, the high voltages present on the windings and downleads, and the use of vacuum as a thermal insulation. Voltage standoff is handled by the included insulation and the composition of the epoxy. The phase sets were then mounted on a frame (Fig. 1a) which also supported the thermal shields (Fig. 1c).

C. Cooling Module

The cooling module consists of the cryocoolers and heat exchangers for the Helium gas loop to cool the phase sets. A second module consisting of a cryocooler, heat exchanger, and tank for the liquid Nitrogen system was used to cool the thermal shields. Both modules are shown in Figs. 1b & c above the phase set assembly. The cooling concepts are

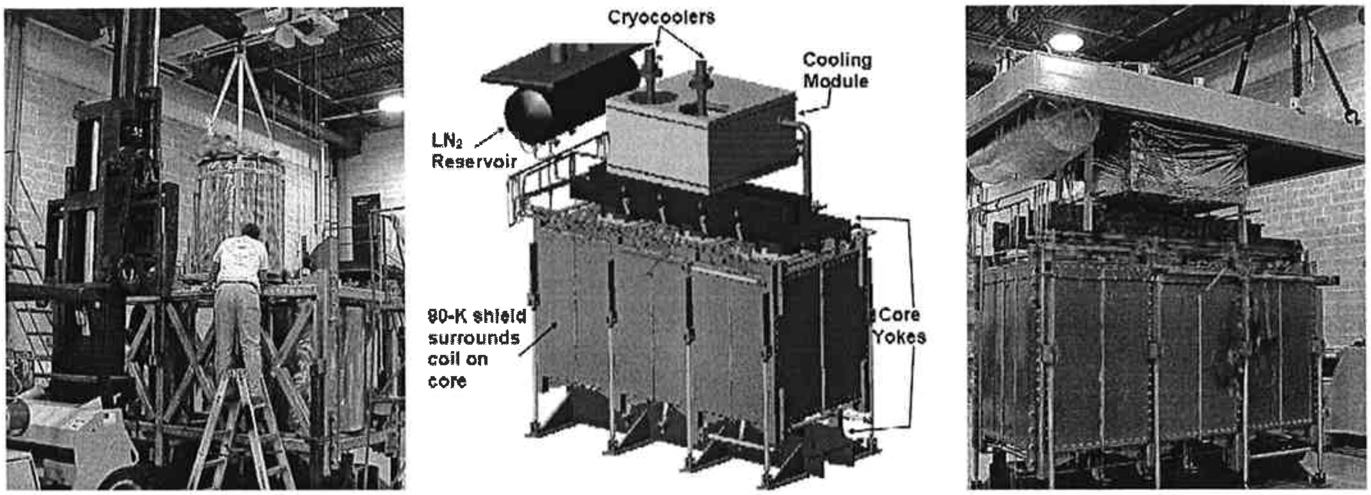
---

Manuscript received October 5, 2004. This work was supported in part by the U.S. Department of Energy under Contract #DE-FC36-98GO10282, and by NYSERDA under Contract #4460-IABR-IA-98.

C. S. Weber, C. T. Reis, and D. W. Hazelton are with SuperPower, Inc, Schenectady NY 12304 USA.

S. W. Schwenterly, M. J. Cole and J. A. Demko are with Oak Ridge National Laboratory, Oak Ridge TN 37831 USA.

E. F. Pleva, S. Mehta, N. Aversa and T. Golner are with Waukesha Electric Systems, Waukesha WI 53186 USA.



(a) (b) (c)

Fig. 1. (a) Assembling coils into frame, (b) Sketch of components in 5/10MVA transformer, (c) Pre-fit of cover assembly

described in greater detail in [4].

D. Final Assembly

The various participants in the project each were responsible for the manufacture of a subsection of the 5/10 MVA transformer; these were then assembled at Waukesha. With this approach to the manufacture, the transformer was very modular in design. Final assembly of the unit commenced in December, 2002 with the integration of the phase sets onto the frame/core assembly. All systems were vacuum leak-checked to 10^{-9}atm-cc/sec before installation in the tank.

Next, the 80K thermal shields were attached to the frame and the shield plumbing was completed. Finally, multi-layer insulation (MLI) was applied over the thermal shields. This core and coil assembly was lowered into the vacuum tank first, and then the cover assembly was mounted.

III. PRELIMINARY TESTS

A. Testing of a Single Phase

Phase set #2 was cooled in Waukesha Electric System's (WES) vacuum test tank. To cool the phase set, LN_2/cold N_2 gas was used from LN_2 dewars. During the cooldown, radial gradients across the phase set were maintained at about 5 K and below. Axial temperature gradients were maintained at 10K and below during the initial stages of cooling, and typically 5K and below.

Partial discharge testing was carried out using both analog and digital test equipment. Very high values of pd were present. Tests were taken over the full range of temperatures that were available from 293K to 79K. The general trend was for the PD onset voltage to increase slightly at colder temperatures. Once the final temperature was achieved, the phase set was held for 38 min at full operating voltage without breakdown. There was no change in the pd patterns taken before this withstand test and those taken after, indicating no damage to the phase set. More details on the results of single phase voltage and PD testing are available in [3]. Even though there was pd present in the phase sets, the team decided to continue with the project. It was felt that the pd presented a lifetime problem if the device were to operate for many years, but it would not impact the characterization tests and the short term operation planned.

B. Initial Testing of Assembled Transformer

Global leak check in the evacuated tank showed that total leak rates in both the LN_2 and Helium systems were in range of 10^{-6}atm-cc/sec. Preliminary electrical tests at room temperature included the industry standard tests consisting of ratio between the primary windings and the secondary windings, winding resistance measurements, insulation capacitance and dissipation measurements, insulation resistance measurements, and measurements of core to ground insulation resistance (Megger test). This set of tests was repeated periodically to monitor for any damage. Results are discussed in greater detail in [3].

1) Cooldown: The 350–W helium loop and the liquid nitrogen shields cooled the 4.5-ton cold mass to less than 30K in about 10 days, which was comparable to the time estimated. After the initial cooldown of the frame and thermal shields, the LN2 tank was filled, all cryogenic systems ran close cycled. The system reliably maintained stable operating temperatures near 29K and ran unattended with no problems.

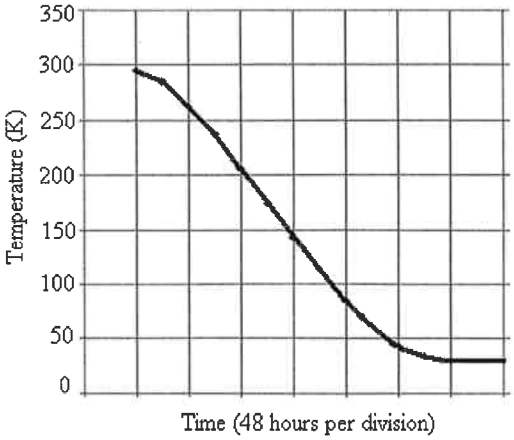


Fig. 3. Initial cooldown profile of three phase transformer

2) *Preliminary Electrical Tests:* The initial testing was intended to address the normal operation test. Both the LN2 and He gas cooling systems experienced higher than expected leaks into the vacuum space due to minor assembly issues resulting in higher background vacuum. Preliminary thermal and electrical test results matched the performance expected in the coils, once calculations were modified to take into consideration the higher heat leak.

Winding resistances were monitored during cooldown. The superconducting portion of the coils achieved zero resistance around 90K. All room temperature (RT) resistances in Table 2 were measured using 1 Amp applied current. All cold temperature resistances were measured using 5A applied current to minimize the effect of contact voltages.

TABLE 2
WINDING RESISTANCE

Resistance, mΩ	Temp	A Phase		B Phase		C Phase	
		L-L	L-N	L-L	L-N	L-L	L-N
LV	Cold	0.59	1.2	0.61	1.2	0.50	1.1
	RT	56.9	29.8	54.9	27.7	54.9	27.6
HV	Cold	2.02		2.03		1.85	
	RT	1791.6		1790.0		1787.7	

As expected, the LV line to line (L-L) resistance is greater than the LV line to neutral (L-N) resistance when warm. When cold, the opposite is true due to the length of the resistive X0 (neutral) lead.

3) *Electrical Tests (June, 2003):* Short-term single-phase tests were carried out with the LV winding shorted. This caused current to flow in both the primary and secondary windings without applying a large ac voltage. The measured impedance matched design calculation; at 210V all phases carried about 67A on the primary, corresponding to an impedance of 0.84%.

Three-phase tests were carried out with all 3 LV bushings shorted together. All phase sets were energized to rated current for a few hours, as shown in Table 3 for June 2003. Initial test results show that heating occurs within the phase sets during operation at currents of $63A_{rms}$. Calculations show that this is primarily due to a poorer than expected vacuum level, leading to a higher than expected background heat leak. At the end of the initial testing, the transformer was warmed up. After warm-up, the gas leaks were found and addressed. The repaired unit passed room temperature ratio and capacitance tests.

C. *Transport of Cold Unit*

The transformer was recooled. The cooldown profile the second time was substantively the same as the first time. The unit was then subjected to the same set of preliminary electrical tests, including the ratio between the primary windings and the secondary windings, winding resistance, and capacitance measurements. The transformer was loaded onto a low ride truck used for the transport of conventional transformers and driven ¼ mile down the road to another testing facility. Here the transformer was moved by standard crane arrangement to the test facility, as shown in Fig. 3. The phase sets remained superconducting over the entire duration of the transport and re-evacuation process.

After transport, the transformer was subjected to the same set of preliminary electrical tests. Results were acceptable, and correspond to previous warm and cold data, showing that no damage occurred in the transport.

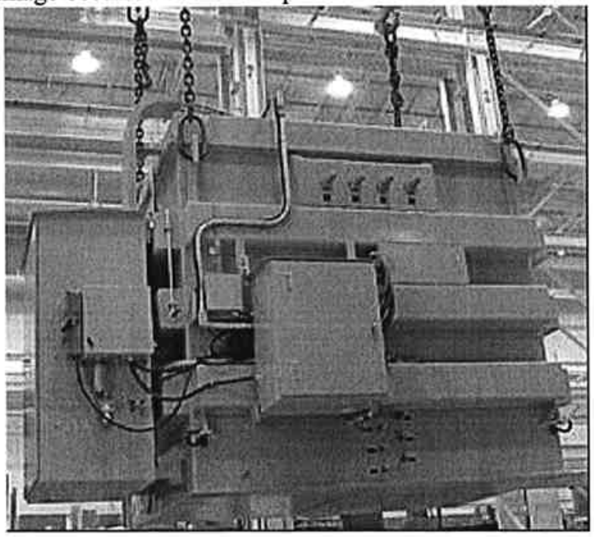


Fig. 3. Transporting the HTS transformer by crane through the WES plant.

D. *Test Results of Repaired Transformer (December, 2003 – April, 2004)*

A summary of the key tests performed is shown Table 3.

1) *Current Testing:* Initial tests showed that Phase A was operating at a higher heat load than the rest of the phases. Since a single cooling circuit was used for all three phases, the additional heat generated in Phase A had an impact on the other phases. Without auxiliary cooling the transformer was able to run unattended at current levels that correspond to those necessary for the diurnal load cycle of the WES manufacturing plant. This test was performed three times, each at least two days. The durations of long term tests were limited by the needs of the manufacturing facility.

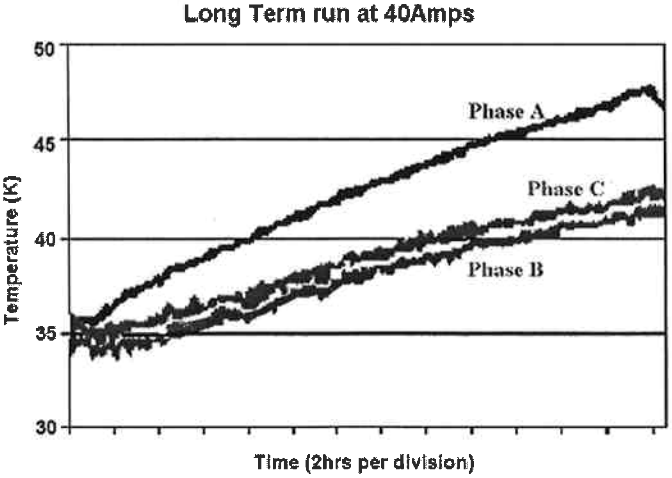


Fig. 4: Temperature of coils during long term run, showing effect of damaged phase heating other phases.

Using liquid Helium in the auxiliary cooling circuit provided sufficient additional cooling to enable operation at twice rated current, even in the damaged phase, as shown in Fig. 5. The undamaged phases showed a maximum increase in temperature of less than 10 degrees, which was approximately as calculated. Longer term overcurrent testing was not conducted due to the ability of the damaged phase to heat up the good phases.

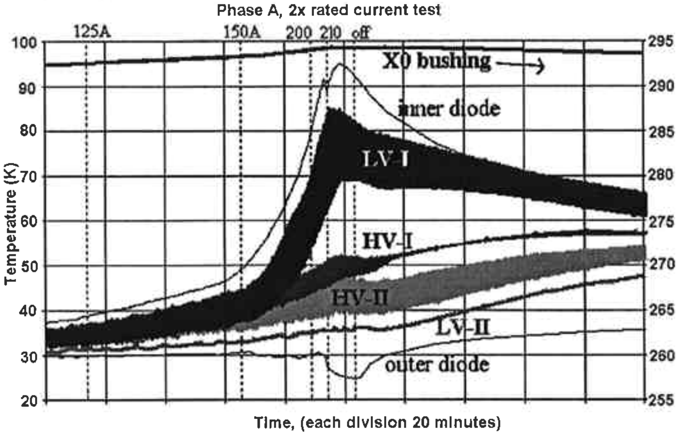


Fig. 5: Thermal profile of damaged phase during high current testing

Unfortunately, damage to some LV leads also occurred during the overcurrent testing. The leads were undersized, causing excess heating, which resulted in the insulation burning off of the leads. This damage occurred prior to any voltage testing.

TABLE 3

PARTIAL TEST SCHEDULE, ALL VALUES RMS

Date	Test
	Unit cooled down
6/23-25/03	**Three-Phase Short Circuit Tests** - (representative selection) 67A for 1 hr. 46.2A for 6 hr 34.6A for 7 hr
6/26/03	**Two Phase HV & PD Tests**-A& B phases- PD Inception at 5 kV; raise to 12 kV; no trip.
6/27/03	**Single-Phase Short Circuit Overload Tests**: A-phase: 94A B-phase: 97A C-phase: 98A
	Warm-up, repair leaks, cooldown
12/11/03	**Three-Phase Short Circuit Tests** - (representative selection) 38.6A for 6 hr. 48.5A for 9.5 hr. then 67A (100%) for 69 min. 49.6A for 10.5 hr.
1/13 - 3/11/04	**Three-Phase Short Circuit Tests** - unattended 23.1A to 35.8A for 48hr, three steps 24.2A to 37A for 56 hr, two steps 23.7A for 18hr, between 35A & 51A for 38 hr
3/20/04	**Three-Phase Short Circuit Tests** - LHe auxiliary cooling 46A to 67A for 7.3 hr, three steps 43A to 133A for 2hr, five steps
3/22/04	**Three-Phase Short Circuit Tests** 34.6A for 1 hr.
3/23/04	**Three-Phase Open-Circuit High Voltage Tests** Ramp to HV-8.2kV, hold 3min BREAKDOWN
4/5/04	**Single-Phase Short Circuit Tests** A Phase-60A for 1hr C Phase-60A for 30min
4/7/04	**Two-Phase Open-Circuit HV Tests** -A & C Phases B Phase shorted out. BREAKDOWN going from 13 kV to 15 kV.
4/8/03	Final Warm-up

Note that 116A into the bushings (line current) corresponds to 67A in the HV coils, due to the delta connection of the primary side of the transformer. All values above are **coil** current or voltage.

2) *Voltage Testing:* Three phase voltage testing was performed by energizing the LV bushings through a variable voltage source, with the HV bushings open circuited. During ramping up to rated voltage, a flashover occurred at 8.2kV (HV) damaging Phase B. Subsequent diagnostic testing revealed that this was most likely a flashover from the low voltage coils to ground. The lead suspect is the damaged insulation from the LV leads.

Two phase voltage testing was then performed on the remaining phases (A & C). A flashover occurred when ramping from 13kV to 15kV (HV) causing a short between the HV and LV windings.

3) *Next Steps:* These faults led to the termination of testing. A failure mode analysis and root cause study is being performed. Besides the thermal coupling of the leads which has already been identified, prime suspects are the substantial decrease in dielectric properties of the epoxy used, the possibility for the inclusion of voids during the manufacturing process, and the impact of a very low impedance transformer (such as this) when internal shorts occur.

IV. REFERENCES

[1] Reis, C.T.; Mehta, S.P.; McConnell, B.W.; Jones, R.H. "Development of high temperature superconducting power transformers" Power Engineering Society Winter Meeting, 2001 IEEE , Volume: 2 , 2001 p.432 -437

[2] Reis, C.T.; Mehta, S.P.; McConnell, B.W.; Jones, R.H. "Development of high temperature superconducting power transformers" Power Engineering Society Winter Meeting, 2002 IEEE , Volume: 1 , 2002 p.151-156

[3] E. F. Pleva,, S. W. Schwenterly, C. T. Reis, "Assembly and test of 5/10MVA transformer " IEEE PES General Meeting, 2004, , June, 2004

[4] Schwenterly, S.W.; Cole, M.J.; Demko, J.A.; Pleva, E.F.; Hazelton, D.W. "Design and Operating Performance of Cryocooled Helium Thermosiphon Loops for HTS Transformers" Advances in Cryogenics Engineering, Vol. 49, 2004 to be published