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TEST RESULTS OF AC SUPERCONDUCTING CABLES*

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Summary

A superconducting power transmission system has been under development for nearly a decade. The early development, aimed at producing satisfactory cable conductor and insulation, has given way to the construction of a test facility designed to demonstrate and evaluate a 138 kV, 1000 MVA system.

The major components of the system are the cables themselves and the terminations. The last tests of the cable conductor have been in three cables about 37 ft long. The cables have been extensively tested at the rating of 4000 A and up to twice rated current. At 4000 A the losses are higher than expected by about 1 W, this is most likely due to end effects. The conductor is cryostable up to 6000 A. The cable insulation has been developed using coaxial geometry with samples up to 67 ft in length. The design operating stress is 10 MV/m, partial discharge inception levels of 13 MV/m are typical of the long cables tested. In an attempt to estimate the life of the insulation a series of 3 ft samples were subjected to high voltage, high frequency excitation. Based on these experiments the insulation life is well in excess of 30 years at the design stress. A full-size version of the cables for the 1000 MVA facility has been made at BNL. Some wrinkles developed during multiple passes through the taping machine but voltage withstand was acceptable.

The cable terminations permit the voltage and current interface across the temperature gradient necessitated by the low temperature environment of the cable. These components have required intensive development for several years. The termination consists of three distinct parts:

1) Cable joint with hand-applied stress cone

2) Helium space and cast epoxy bushing with forced-cooled leads

3) Ambient temperature elbow and air entrance bushing

All these components have been tested at the continuous rating of 4000 A and the intermittent rating of 6000 A. The epoxy bushing has been tested cold to 150 kV, 60 Hz and warm to 585 kV impulse level. The stress cone failed at 585 kV and is being slightly modified. The air entrance bushing has been energized to 6000 A with acceptable temperature rise. The 60 Hz voltage test of the bushing exceeded 240 kV and it has been impulse tested to 808 kV.

The ability to test two cables with simultaneous voltage and current excitation is provided by means of resonant test supplies. The parallel resonant current supply has been tested to 7000 A and the series resonant supply has been rested to 240 kV to ground. The current supply is required to float above ground potential; this unit has been tested to 100 kV.

The cryogenic system comprises a supercritical helium refrigerator, helium storage, transfer lines and 400 ft long cable enclosure. The system has been operated on several occasions for about a week at a time. The last test included the cooling of a simulated cable with built-in heat load. About 600 W of refrigeration was available at 8.5 K; a value well in excess of the expected load.

All the developmental testing is over and the project has entered the final demonstration phase of an ac superconducting power transmission system. A test facility designed to demonstrate and evaluate two 400 ft cables at 138 kV has been constructed. Virtually all the components have been built and tested. The cables themselves and four terminations are planned for installation in the late summer of 1981; this will permit testing at a level corresponding to a 1000 MVA, 3Ø rating.

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Abstract

All the major components of an ac superconducting power transmission system have been developed. A summary of test results during the developmental stages is given. A Test Facility designed to demonstrate and evaluate cables rated for 138 kV, 1000 MVA 3 Ø service is under construction. Most of the equipment has been installed and tested; results are presented.

Introduction

An ac superconducting power transmission system has been under development at Brookhaven National Laboratory since the early 1970's. The attractive technical features of the system are high power capability per circuit, ability to operate at the surge impedance load and low operating losses.[1] The cost of such a system is more difficult to estimate with accuracy at this stage of development; studies performed of actual electric utility company requirements indicate an ac superconducting system may be competitive with other underground technologies for high power circuits traversing many tens of miles of suburban routes.[2]

In 1975 construction started of a test facility which would take the cable development out of the laboratory stage and demonstrate cable performance with simultaneous voltage and current excitation.[3] Virtually all the components of the system are designed to meet normal utility company requirements for 138 kV equipment. The cables are designed for a maximum continuous line current of a little over 4,000 A, yielding a circuit rating of 1,000 MVA, the cables are about 400 ft in length.

The testing program has the goal of verifying the electrical, mechanical and thermal performance of all components comprising the 1,000 MVA Test Facility before they are installed; most of the work is complete. The last two components to be installed, namely the cables and terminations, are now in the process of construction and final testing.

Tests of AC Superconducting System Components

The components of the system comprise the cables, cable enclosure and terminations. In addition the Test Facility possesses a low-temperature supercritical helium cooling system and electrical excitation for 60 Hz voltage and current tests and for impulse testing.

Superconducting Cable Tests

The cables are of a flexible type with taped polymeric insulation and inner and outer conductors made with normal metal stabilizer (copper) and Nb_3Sn superconductor. The general construction of the cable is shown in Fig. 1. Both the conductor and dielectric insulation have been the subject of intensive development starting with the basic materials problem.

Conductor Testing. The Nb_3Sn conductor has been developed to the point that a low-loss tape with acceptable mechanical characteristics is available from commercial sources.[4] The conductor has been evaluated in

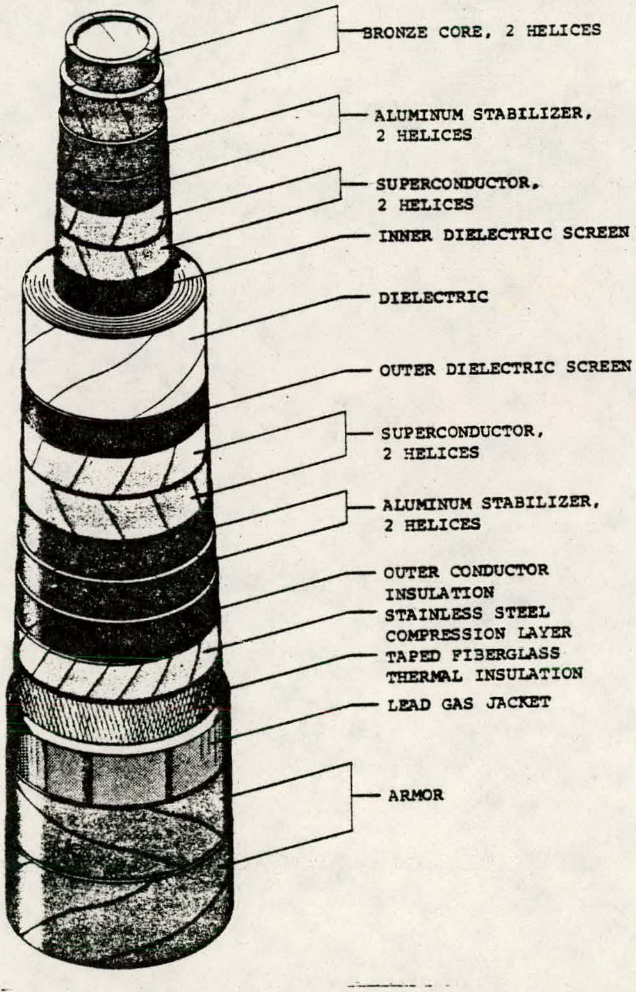

Fig. 1. Constructional details of a taped superconducting power transmission cable. The cable made at BNL has an O.D. of 2.3 in across the compression layer.

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the laboratory in three cables of about 30 ft in length. Comprehensive tests have demonstrated the performance, including effects of temperature, a quench to the normal state and momentary current overloads. This series of tests has been summarized in the literature.[5] In general the current-related performance of the cables has been very good. In all the cables tested the losses were higher than the expected value by about 1 W at the rated current of 4,000 A. There is some evidence the loss is due to end effects; this will be clarified by tests on the 100 m cables. The last cable tested in this series, designated # 103, was built with an insulation wall thickness of 0.25 in and was operated with gas-cooled, full-current leads. At a current of 4,000 A the total loss in the cable (≈ 37 ft in length) is about 3 W. The cable was tested up to 12 K. The cable was operated at 8 kA for about 30 minutes and recovered from a heat-induced quench while operating at 6 kA.

Insulation Tests. The insulation of the flexible superconducting cable consists of polymeric tape with the butt-gaps impregnated with supercritical helium. This is a composite insulation system in which the operating electrical stress is mainly determined by the dielectric characteristics of the helium. The main requirements of the polymeric tape are low-loss at the operating temperature and mechanical properties suitable for taping on conventional machines. This last requirement has resulted in extensive development work to obtain a significant increase in tensile modulus.[6] The topic of cable bending is covered below.

The properties of the cable insulation were first explored using 3 ft coaxial samples.[7] Based on the breakdown properties of helium and the dielectric constant of the insulation components a partial discharge inception stress of ∿ 20 MV/m may be expected for a well-made sample. An operating stress for the cable under 60 Hz excitation of 10 MV/m was chosen. Tests on long cables (up to 67 ft in length) have produced partial discharge inception levels in the range 13 MV/m.[8,9] Most of the long cables have visible imperfections in the insulation upon dissection. Nonetheless, a series of experiments with 3 ft long samples indicated the life of the insulation was quite acceptable even though partial discharge activity was heavy during accelerated life tests using high frequency excitation. A summary of the accelerated life testing is given in Fig. 2. Dielectric loss was measured on single sheets of insulation, coaxial short samples and 67 ft lengths of commercially produced cables. The recorded values varied from 5×10^{-6} for single sheets to 3.5×10^{-5} for 67 ft cables at helium temperatures.[8,9]

During impulse and surge voltage tests it is assumed the butt-gap is ionized and breakdown occurs due to puncture of the insulating tape or by step-wise discharge paths along the surfaces of the tapes. Tests performed on long cables with a total insulation thickness of 0.1 in indicated that breakdown stresses were about x 8 the operating stress. Impulse breakdown tests on small samples have demonstrated breakdown stresses in the range 130 to 207 MV/m.[8]

A full-size version of the cable to be used in the 1000 MVA tests was fabricated in order to evaluate construction techniques, bend performance and insulation performance; this cable is designated # 104. Due to the limited number of taping heads available on the Brookhaven machine the cable was made with multiple passes through the line. Ultimately the repeated bending resulted in typical collapse wrinkles appearing in the insulation. This cable was tested at room temperature using both N_2 and SF_6 impregnation. Partial discharge inception was only in the range 5 to 6.4 MV/m but the cable satisfactorily withstood 160 kV to ground (60 Hz) and 240 kV impulse tests. These levels were determined by the bushing used for the tests, which was not designed for higher voltages. No damage was apparent after the cable was dissected. Numerous changes in the details of cable construction were made in the light of our experience with cable 104 and a new version (# 105) is now being fabricated.

The various constraints imposed on the taping machine and materials for a bendable cable were derived empirically for kraft paper. In the 1960's the first analyses appeared which related cable bending performance to materials properties.[10] These analyses served as a guide in the development of polymeric tape.[6] Several experimental cables were taped with parametric variations and bend performance compared with theory.[11] The correlation was not good - clearly fudge factors are applied in practice when kraft paper cable is designed using the theory. These factors have still to be determined for polymeric tapes. In addition other mechanisms can lead to insulation damage on bending which were not considered in the original theory. Cable 105 has been manufactured with three distinct sections in which taping conditions were varied. The experience gained will be invaluable when the cable for the 1000 MVA Test Facility is made.

Cable Terminations

The design characteristics of the terminations are shown in Table I. These complicated devices have required extensive testing to achieve the present state of development. The general arrangement of the termination assembly is shown in Fig. 3. The cable is on the right side, the insulation is dressed with a hand-applied stress cone. This stress-cone permits the electric field to appear across the helium space in the center. A cast epoxy bushing then allows the temperature transition to room temperature.

Table 1

Characteristics of Cable Termination

Current kA, 60 Hz	:	4 continuous, 6 intermittent
Voltage, kV, 60 Hz	:	80 rated, to ground
Impulse withstand kV	:	650 rated, 850 qualification
Switching surge, kV	:	550 rated, 690 qualification
Cable stress MV/m	:	10 at rated voltage
Lead cooling, He g/s per cond'r	:	0.18 at 4 kA, 0.32 at 6 kA

The bushing has inner and outer gas-cooled leads and contains an internal shield. All the cryogenic portion of the termination is horizontal. A commercially-made SF_6 elbow and air entrance bushing connect on the left side.

The cast epoxy bushing has been tested up to 808 kV impulse and 240 kV 60 Hz. Full current tests up to 6 kA have been made. The heat load on the refrigerator has been somewhat higher than expected due to conduction of the epoxy itself. The bushing has been lengthened in the final version to counteract this effect.

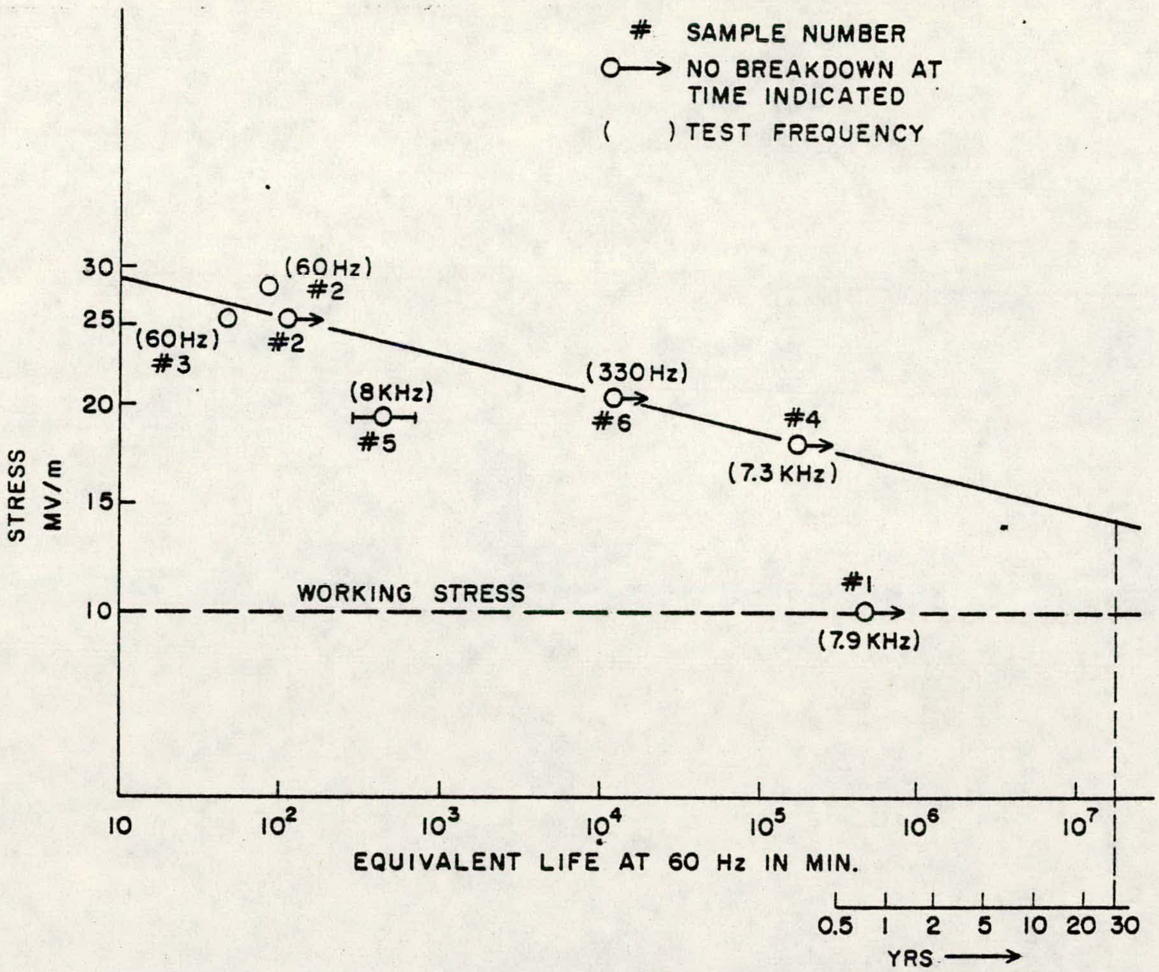

Fig. 2. Accelerated life test results for helium impregnated-polymeric tape insulation system. Number in parenthesis shows frequency of applied voltage waveform. Sample # 5 overheated at 8 kHz but when repeated at 330 Hz (point # 6) the life exceeded 10^4 min.

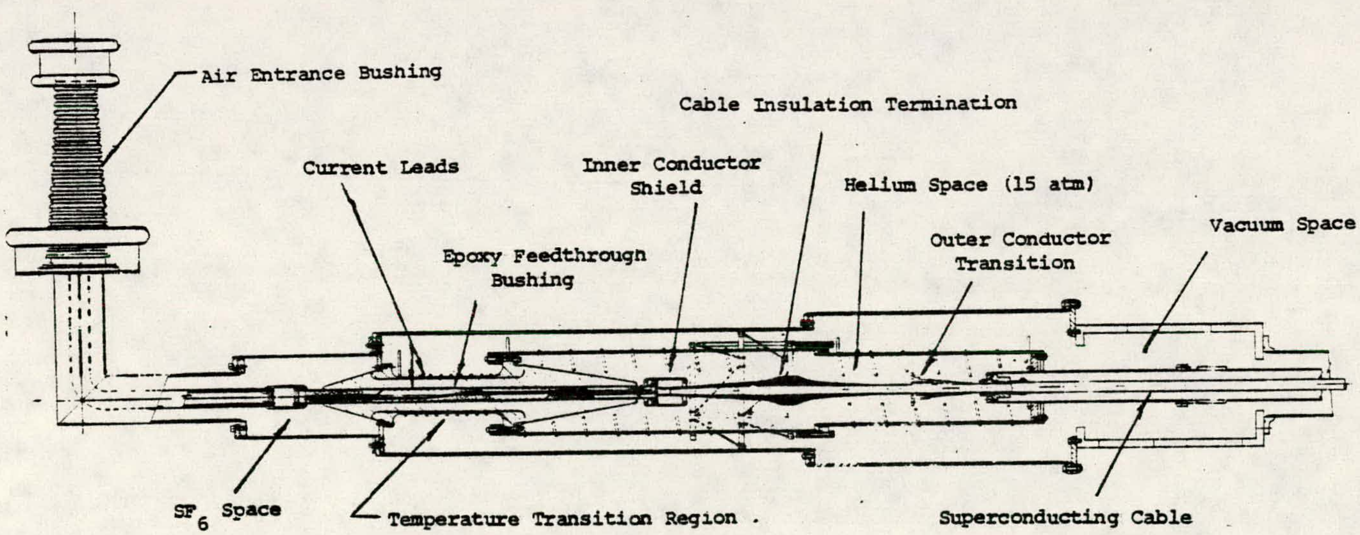

Fig. 3. General arrangement of terminations for 1000 MVA Test Facility. All the cryogenic equipment is horizontal, a conventional SF_6 field elbow and air-entrance bushing to the left of the temperature transition region provides adequate clearance to ground. The termination is rated for 80 kV to ground, 4000 A. BIL corresponds to 138 kV system operation.

A summary of the termination tests is given in Table 2.

Electrical System Tests

The purpose of the Test Facility is to evaluate the performance of superconducting cables with simultaneous voltage and current excitation at a level corresponding to 138 kV, 1000 MVA, 3 Ø rating. At the present time the electrical equipment is about 95% installed with all the major testing complete. A detailed description of the electrical system has been presented.[12] The circuit is shown in Fig. 4, it consists of two cables connected to terminations at both ends. For 60 Hz testing the terminations are connected to the three power supplies shown in Fig. 4. The current supply consists of a capacitor bank tuned to parallel resonance with the load presented by the terminations and cable inner conductors. The supply is designed to float above ground with a maximum potential of 100 kV rms. The voltage supply consists of an adjustable inductor tuned to series resonance with the combined shunt capacitance of both cables to ground. This raises the potential of both cable inner conductors and the current supply with respect to ground. A detailed computer simulation of the circuit indicated that slight differences existed between the currents in the inner and outer conductors. This effect is caused by unequal impedances in the inner and outer conductors of the termination; the unbalanced currents are an artifact of the test circuit and would not be encountered in an actual transmission system. The compensating supply is added to inject a small adjustable voltage which allows the cable conductor current to be balanced. It is planned to demonstrate impulse and switching surge withstand using a conventional Marx generator. The only unusual feature of this supply is the large stored energy necessitated by the capacitance of a 400 ft test cable.

All the supplies have been installed and tested except the compensating supply, which is under construction. The design features of the cable system are given in Table 3. The test results of the electrical equipment are summarized in Table 4.

Cryogenic System Tests

The cryogenic system of the Test Facility consists of a 500 W (nominal) supercritical helium refrigerator, helium storage, transfer lines and a cable enclosure about 400 ft in length. An aerial view of the facility during construction is shown in Fig. 5. Numerous tests of the various components have been performed.[3,13] The cable enclosures have maintained vacuum for three years; the average vacuum space is now ≈ 40 μmHg at room temperature.

The last test to be performed was a cool-down of the cable enclosure which contained a dummy cable with a heater to simulate cable losses. A "far-end" turbine expander was tried for the first time. The use of expanders at both ends of the cooling loop is the best way to cool a transmission line.[14]

The complete system was operated continuously from 17 November 1980 to 22 November 1980. On 20 November all the line was below 8.5°K and the heaters were energized. The power in the heaters was slowly increased to 600 W by 22 November. At no time did the load exceed 8.5°K. Some heat leaks which exceeded design expectations were discovered and will be corrected for the next run. The refrigerator output was calculated to be 700 - 800 W for twenty four hours and 1000 W for short-term periods.

Conclusion

All the major components of a 138 kV, 1000 MVA superconducting transmission system have been built and tested except a field splice. All components have required extensive developmental testing during the past few years. The electrical tests have always been performed with separate voltage and current excitation; simultaneous excitation will be possible when the Test Facility is complete.

The cryogenic testing of the Test Facility is complete and final assembly of the four terminations is proceeding. Electrical equipment for full power tests of the cables have been installed and tested. Full size versions of the superconducting cable have been

Table 2

Summary of Termination Tests

Component	Test	Comment
Epoxy bushing	Short circuit test to 6000 A	Electrical losses at 4 kA ≈ 300 W (close to design value)
	60 Hz ac test to 240 kV	3 x line to ground stress
	Impulse test to 808 kV	Exceeds required 650 kV for 138 kV system
Pressure vessel outer conductor	Current test to 6000 A	Losses at 4 kA ≈ 2.5 W (design value)
Stress cone	60 Hz ac test to 150 kV	
	Impulse test to 585 kV	Breakdown - some redesign in hand
Air Entrance bushing	Tested up to 6000 A	Temperature rise stabilizes to 136°F at 4000 A
	60 Hz ac test to 240 kV	
	Impulse test to 808 kV	

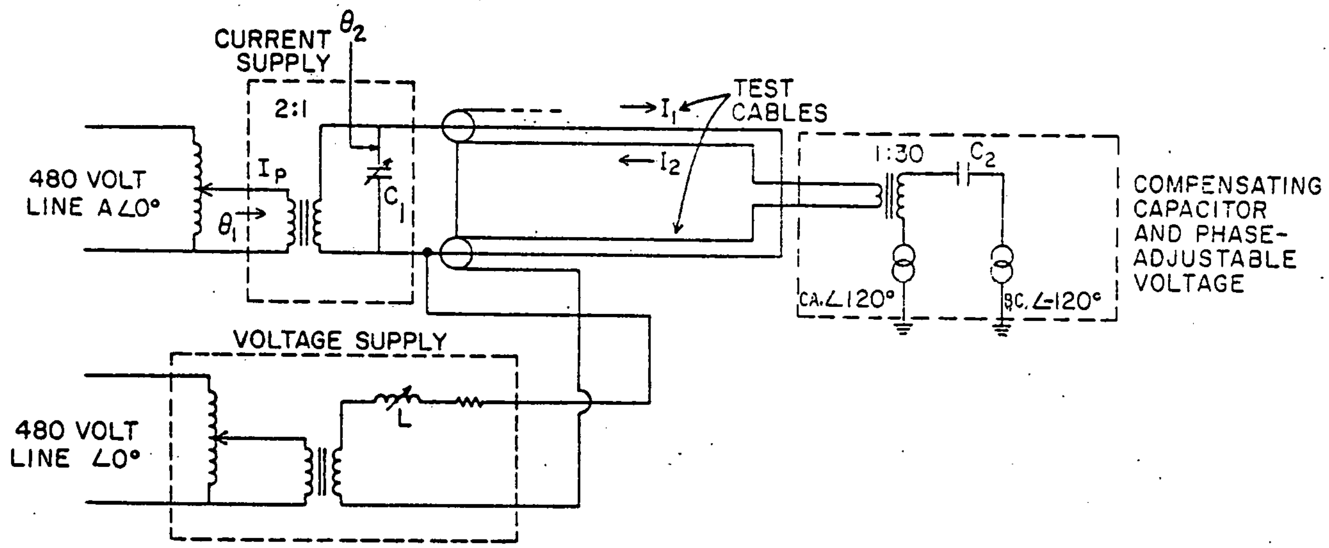

Fig. 4. Simplified circuit diagram of equipment to excite two superconducting cables at 4000 A, 80 kV to ground. The current supply is a capacitor bank in parallel resonance with the cable inductance. The voltage supply is an adjustable inductor in series resonance with the cable capacitance. The compensating supply permits the cable inner and outer conductor currents to be exactly matched.

Table 3

Cable System Characteristics

No. of cables	: 2
Length	: ≈400 ft (each)
Rated voltage	: 138 kV (L-L)
Rated current	: 400 A (continuous)
	: 6000 A (intermittent)
Impulse withstand	: 650 kV (impulse)
	: 550 (switching surge)
Rated power	: 960 MVA (3 Ø basis)
Maximum stress at rated voltage	: 10 MV/m
Linear current density	: 455 A/cm
Cable capacitance	: 0.044 μf
Cable inductance	: 25 μH
Cable impedance	: 23 Ω

fabricated and construction of 1000 ft of cable for the Test Facility is expected to be complete by the summer of 1981. The final testing of this phase of development will begin in late 1981 with simultaneous voltage and current excitation, overvoltage and overcurrent tests, measurements of losses and finally testing of impulse and surge withstand of a full-scale system.

Acknowledgement

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Table 4

Test of Electrical Excitation Equipment

Test Supply	Tests Performed	Comments
60 Hz resonant voltage supply 0-240 kV at 13 amps	240 kV at 8.47 amperes (0.1 μF load)	measured Q = 51.6
	160 kV at 9.04 amperes (0.15 μF load)	measured Q = 69.0
	240 kV at 0.013 μF load	partial discharge less than 5 pC; tunes easily; no gap chatter
	400 Hz overvoltage test	withstood 311 kV overvoltage
60 Hz high current power supply 0-6000 amps at 240 V rms at 100 kV floating potential	7250 amperes at 240 volts	Q = 28.5
	isolation insulation test: 120 kV	partial discharge free at 100 kV
150 kJ impulse generator 0-1000 kV charging voltage	impulse tested to 850 kV	waveform: 1.5 x 50 μs
	switching surge tested to 650 kV	waveform 200 x 2000 μs

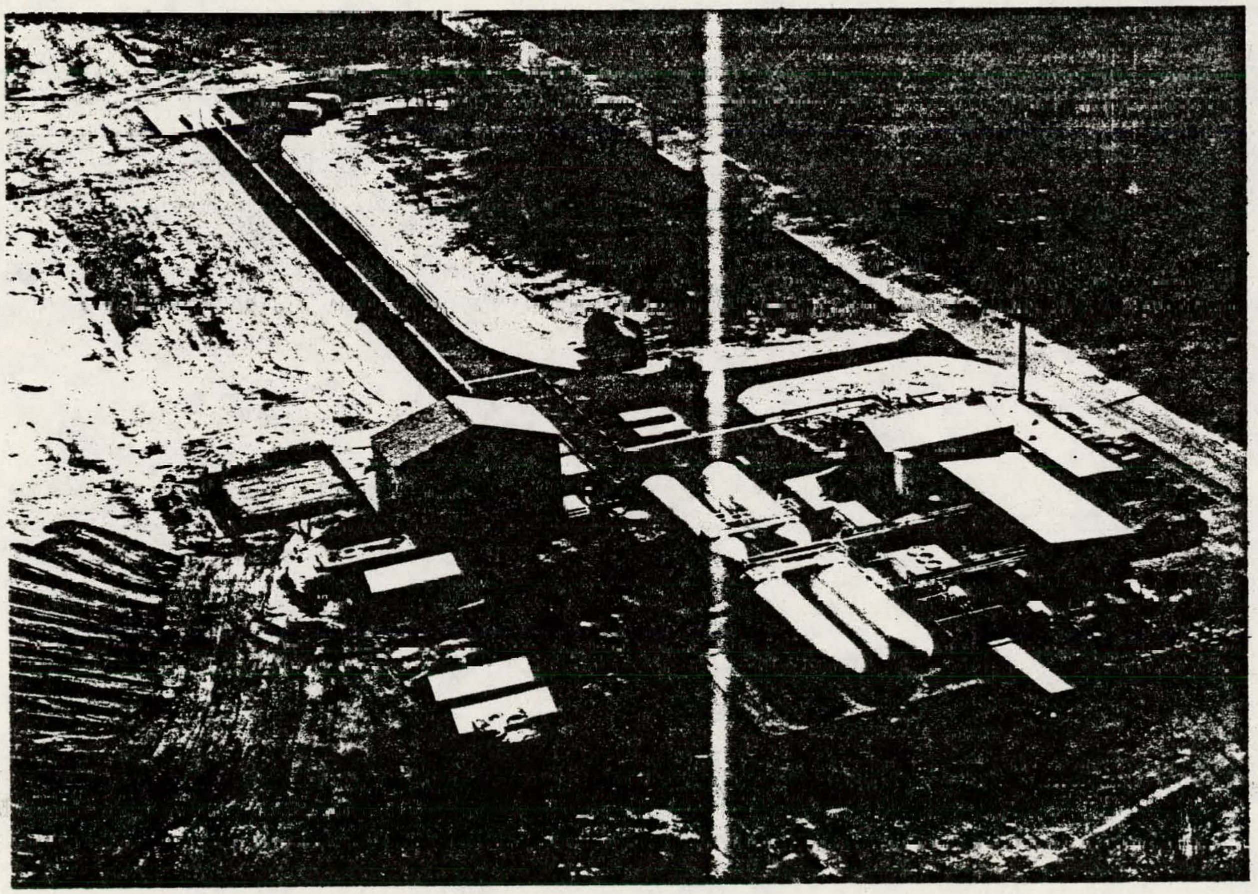

Fig. 5. 1000 MVA Test Facility during construction. The refrigerator and control room are in the buildings on the lower right side. The cable enclosure is the pipe leading to the top left side.

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