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LOAD EXCITATION AT THE SUPERCONDUCTING CABLE TEST FACILITY*

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Introduction

The Test facility has been constructed to evaluate and demonstrate flexible superconducting power transmission cables under realistic conditions. The general design of the site and the cryogenic equipment has been described.[1] Power supplies are installed to excite two superconducting cables either separately or simultaneously. The cables form a straight run of 100 m with a pair of terminations rated for full current and voltage located at the east and west ends of the cable enclosure. A view of the site during construction is shown in Fig. 1. The general operating conditions of the cables are shown in Table I.

Table I

Cable Characteristics

Length	:	≈ 100 m
Rated voltage	:	138 kV (L-L)
Rated current	:	4000 A (continuous)
		6000 A (intermittent)
Impulse withstand	:	650 kV (switching surge)
Rated power	:	960 MVA (3Ø 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

General Arrangement

The simplified circuit of the cables and test equipment is shown in Fig.2. The voltage of the inner conductors is raised in a series resonant mode using the cable shunt capacitance in resonance with an adjustable inductor in the exciting supply. The supply is rated for 3X rated line to ground voltage (240 kV).

The quality factor of the series circuit is about 50. The supply is shown in Fig. 3.

The load current is established by means of a source driving the inner conductors connected in series and tuned to resonance by a capacitor bank. The supply transformer and capacitor bank are suitably insulated so that the inner conductor circuit can be raised in voltage as described above.

Impulse Testing

The conventional impulse testing requirements for a 138 kV system voltage cable and accessories are a routine lightning impulse test to 650 kV and type testing to 813 kV. To meet these requirements a 150 kJ impulse generator has been purchased from Haefeley in Basal, Switzerland. A summary of the impulse generator's specifications is as follows:

Stored Energy	:	150 kJ
State Voltage	:	200 kV
No. of Stages	:	5
Construction	:	Modular
Output	:	815 kV lightning impulse (1.5 × 50 μs) into 0.07 μf
		650 kV switching surface (250 × 2500 μs) into 0.07 μf
Duty Cycle	:	One pulse every 30 seconds maximum

Figure 4 is a photo of the impulse generator being erected in the high voltage building. The generator output waveshapes are specified for a lumped capacitive load. The cable does not behave as a lumped element and modifications must be made to permit impulse testing in a predictable fashion. The circuit has been simulated using computer analysis and an optimized series R.C. load will be used during impulse testing.

The grounding system covers the west end 53 ft × 56 ft concrete switchyard immediately adjacent to the high voltage building, the high voltage building, 40 ft × 20 ft, which is constructed on a concrete slab and the 53 ft × 32 ft concrete termination yard located 320 ft east of the switchyard. A 6" steel wire mesh of 5/16" diameter wires is embedded in the concrete flooring and pads 2" below the surface. The wire mesh provides an equipotential surface for the switchyard, the termination yard and the high voltage building. Connection to the equipotential surface is made through 250,000 CM (copper conductor) pig-tails. The wire mesh at the switchyard and the termination yard is connected by the jacket of the cables under test.

Grounding of the equipotential surfaces is accomplished by driving eleven 3/4" diameter steel rods 70 feet into the ground. The ground rods penetrate 15 feet into the watertable; the watertable is 55 feet below the earth's surface.

The high voltage building (934) and the outer concrete switchyards must be electrically isolated from both the refrigerator and instrumentation service area (Building 933) and from the general laboratory complex. Ground faults during the high voltage impulse testing of the power cable are coupled through the earth, fluid pipes and electrical wiring from the high voltage test area to the service building and can induce harmful transient voltages to both personnel and equipment if suitable protection is not provided. All wiring required for power and control functions and all fluid pipes, such as the vacuum-insulated pipe required for refrigerant transport, must be electrically isolated from the high voltage test area. Each isolation gap must be designed for a voltage stress that is dependent on the resistivity of earth, the grounding arrangement about the high voltage test area, and the maximum impulse voltage.

Operating Considerations

Using only the series and parallel resonant power supplies described above the currents in the cable inner and outer conductors will not be equal. If this condition arises the external magnetic field will increase the refrigeration load due to eddy current losses. A third power supply is required so that the currents may be balanced. This compensating supply is shown in Fig. 2. It consists of a capacitor to tune out the leakage inductance of the terminations and an injected voltage to compensate for real losses in the normal metal parts of the termination conductors.

The complete circuit has been analyzed using computer simulation. Table II shows the power required when the system is operating with two cables each excited to 320 MVAR.

In order to design the ground break in the wiring and pipes it was necessary to investigate ground transients using a worse-case failure, namely, a flashover from the termination to ground at the maximum value of impulse waveform. The results of this computation are given in Table III.

Table III

Summary of Worse Case Ground Fault; Preliminary Design

Peak fault current through switch yard pad	62,000 amperes
Peak voltage across switch yard pad	50,000 volts
Peak ground-neutral voltage across cable	45,000 volts
Peak ground-neutral current through the cable	50,000 amperes
Voltage overshoot across switch yard pad	10,000 volts
Peak voltage across helium transfer line	32,500 volts
Duration of major transient spike	2 μsec
Duration of fault current	8 μsec
Duration of ground-neutral voltage across the cable	0.05 sec

Table II

Input Power Requirements for Rated Load VA

Current Supply (1Ø - 480 volt, Phase A-B)	
Primary voltage	215 volts
Primary current	35.46 A
Primary power factor	0.88
Primary VA	7.63 kVA
Primary power	6.72 kW
Secondary voltage	95 volts
Secondary current	68.9 A
Secondary power factor	0.996
Secondary VA	6.545 kVA
Secondary power	6.52 kW
Voltage Supply (1Ø - 480 volts, Phase A-B)	
Secondary voltage	1570
Secondary current	2.69 A
Secondary power factor	0.998
Secondary VA	4223 VA
Secondary power	4215 W
Compensating Voltage	
Phase CA Secondary voltage	3.58 volts
Secondary current	134.0 A
Secondary power factor	0.64
Secondary VA	480 VA
Secondary power	307 watts
Phase BC Secondary voltage	15.18 volts
Secondary current	134 A
Secondary power factor	0.985
Secondary VA	2034 VA
Secondary power	2004 watts
Total Compensating Requirements	
Secondary VA	2514 VA
Secondary power	2307 watts
Total Input Power	
Volt-Ampere	14.367 kVA
Power	13.242 kW

The voltage across the ground break of 32.5 kV was considered excessive and three extra ground rods 150 ft long were sunk, these penetrated 100 ft into the watertable. It is believed the break voltage will not exceed 10 kV with the ground system now in service.

Measurements

Measurements of the dielectric loss angle (tan δ) will be made using a high voltage capacitance bridge manufactured by Guildline Instruments Inc., Smith Falls, Ontario, Canada. The Guildline Bridge is a current comparator capacitance bridge which employs a transformer ratio arm in place of resistance network of the standard Schering Bridge. It has a permanent accuracy of $\pm$ 10 ppm and the bridge used at BNL has been calibrated to $\pm$ 5 ppm. The standard capacitor has a value of 150 pf at 335 kV rms and was built by Micafil (ASEA) Inc. The loss measurement system described has been used to measure 20 meter foot lengths of polyethylene cables with dissipation factors less than 3.5×10^{-5} radians.

The electrical measurement of conductor loss will be difficult with a sample which is so large; several methods are under review. It is expected that losses will be measured calorimetrically; a temperature measuring system has been installed using a small computer for data processing and logging. The thermal and flow instrumentation is based on equipment now installed in the laboratory horizontal cryogenic enclosures, an accuracy of about 20 mK is expected at the operating temperature of 7 K but this does not include possible thermal gradients between the cable and the sensors.

References

1) Forsyth, E.B. and Gibbs, R.J., The Brookhaven Superconducting Cable Test Facility, IEEE Trans. on Mag., MAG 13, No. 1, 172, Jan. 1977.

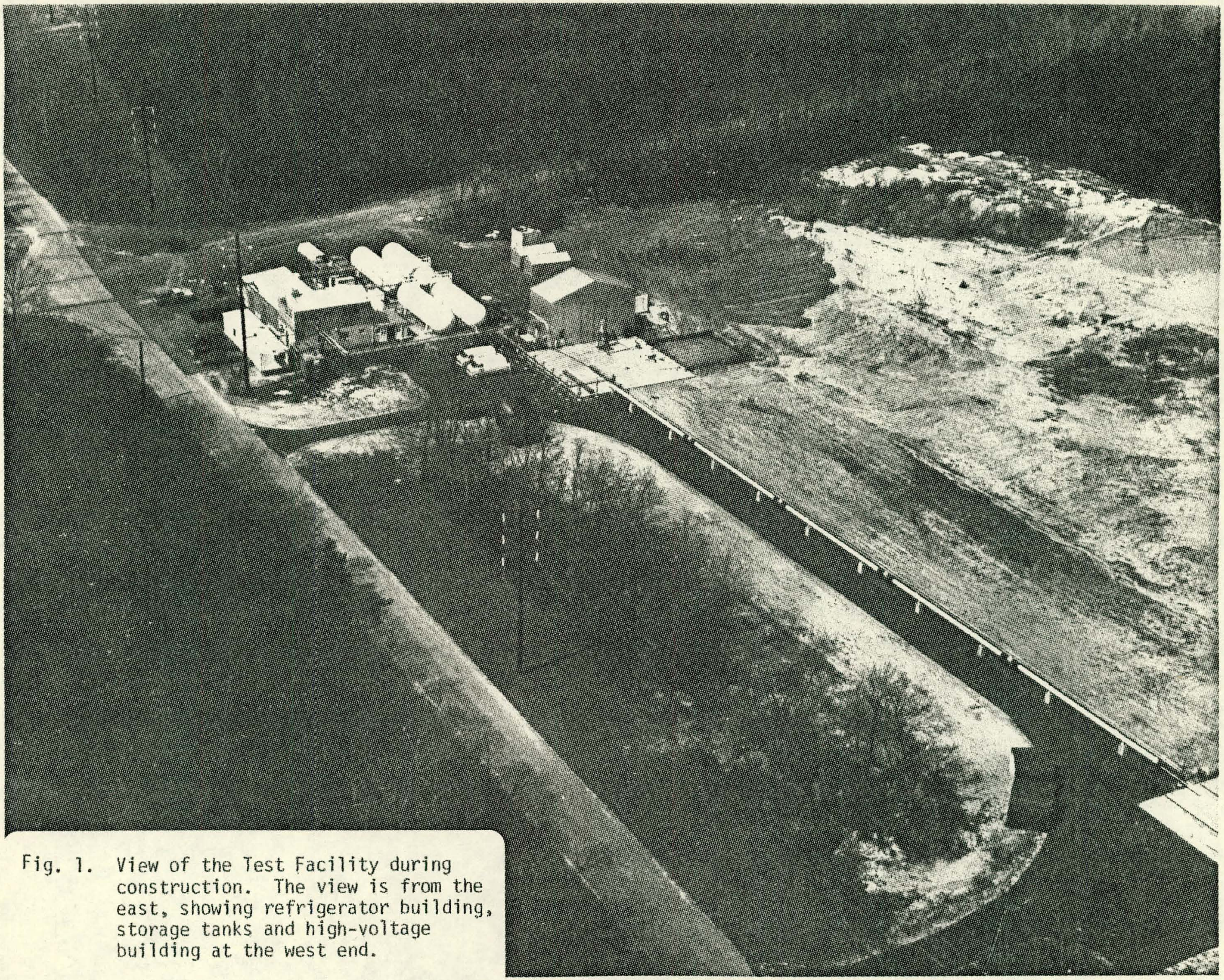

Fig. 1. View of the Test Facility during construction. The view is from the east, showing refrigerator building, storage tanks and high-voltage building at the west end.

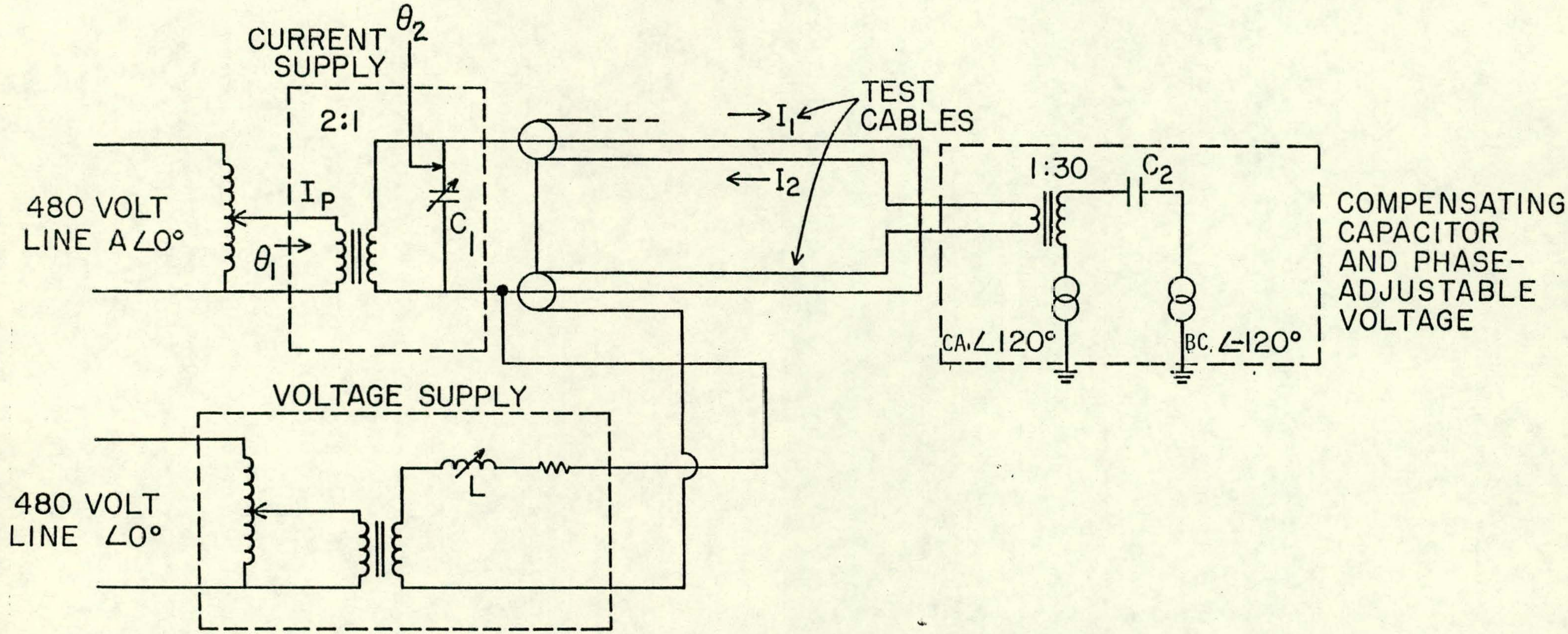

Fig. 2. Simplified model of cables and power supplies at the Test Facility.

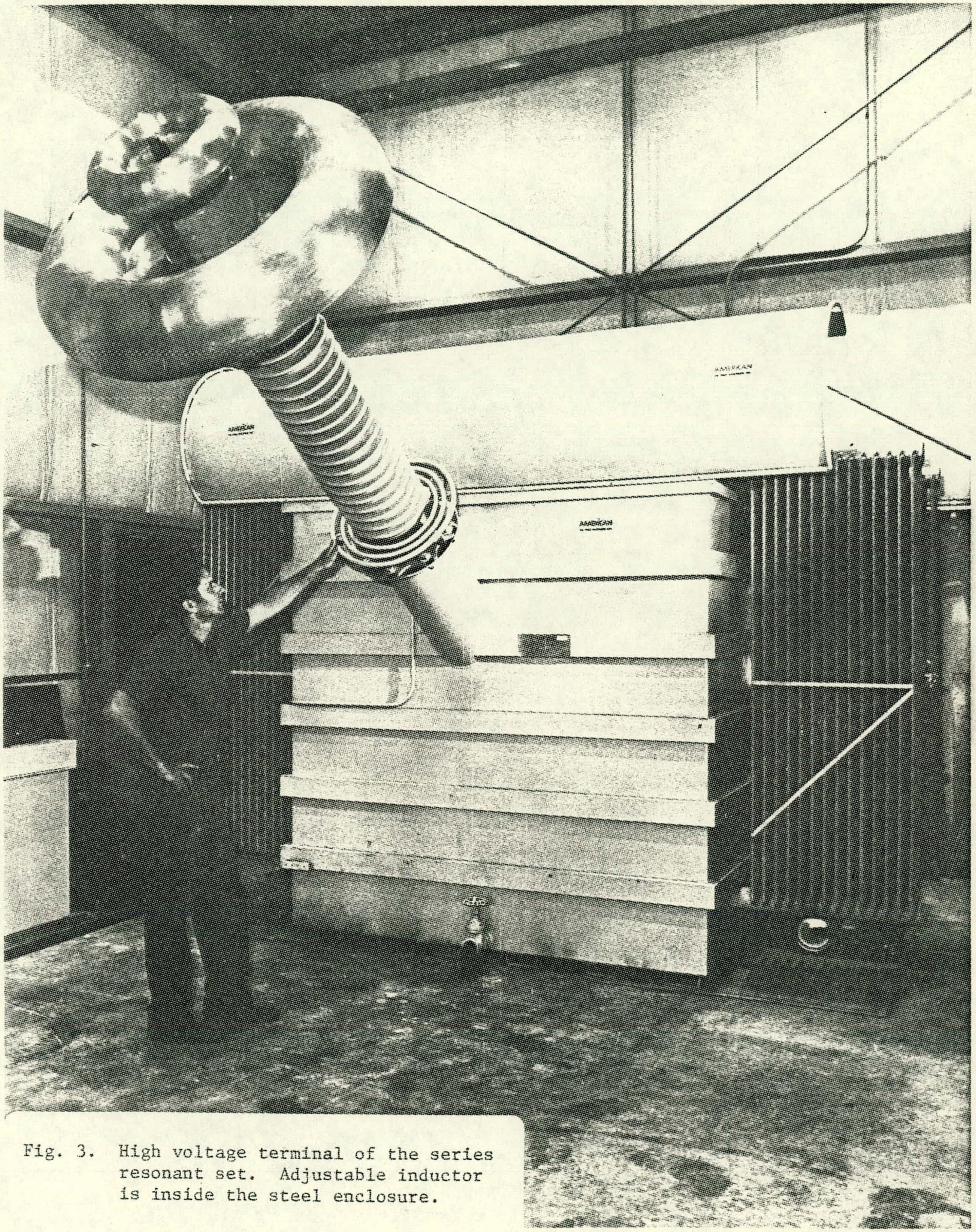

Fig. 3. High voltage terminal of the series resonant set. Adjustable inductor is inside the steel enclosure.

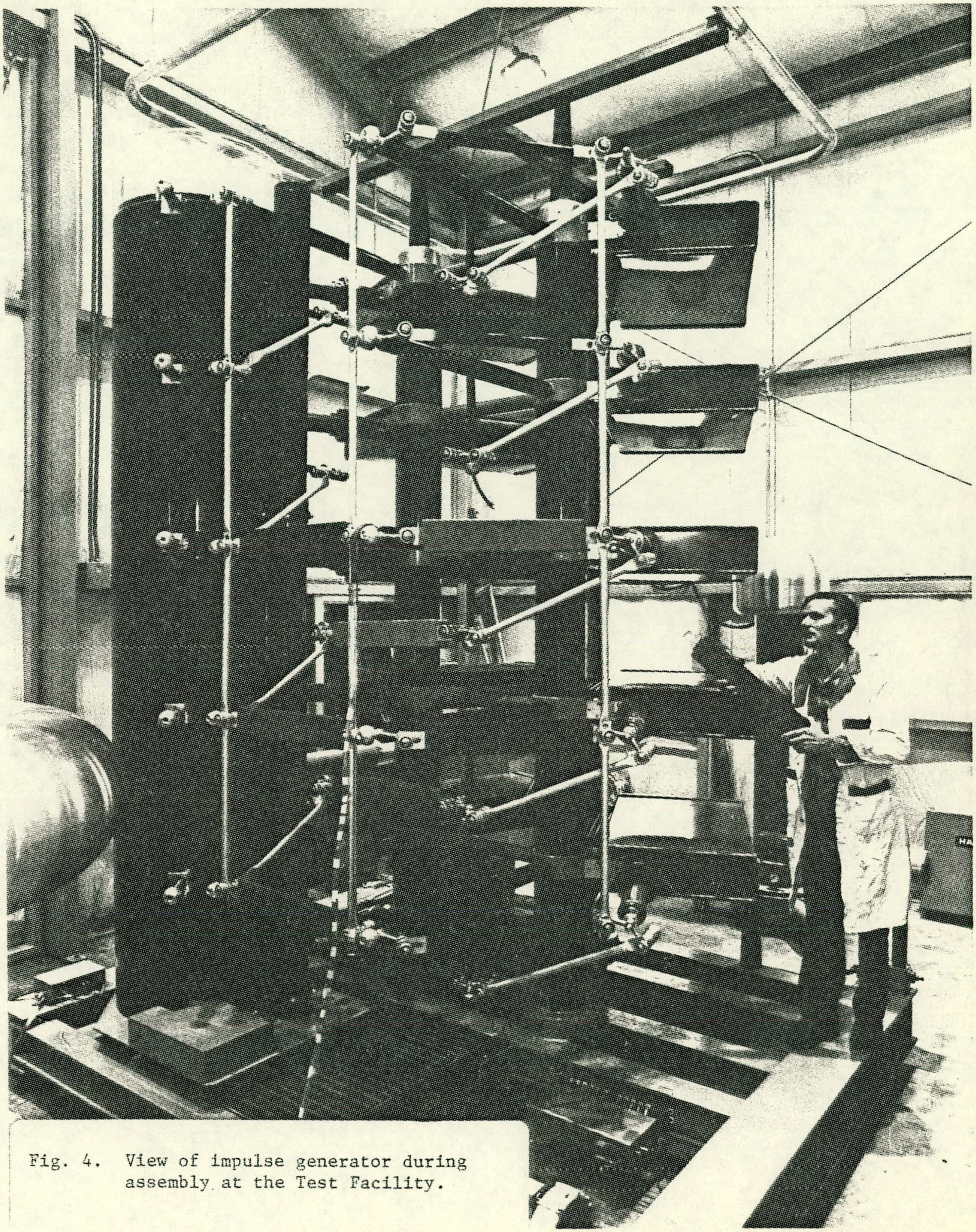

Fig. 4. View of impulse generator during assembly at the Test Facility.