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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21274385
Report (National Research Council of Canada. Radio and Electrical Engineering Division : ERB), 1963-03

ERB-627

UNCLASSIFIED

NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION

CANADIAN PARTICIPATION IN AN INTERNATIONAL COMPARISON OF VOLTAGE TRANSFORMER CALIBRATIONS - 1962

N. L. KUSTERS AND O. PETERSONS

OTTAWA

MARCH 1963

ABSTRACT

A voltage transformer rated at 350 kv and having a maximum ratio of 4000/1 has been calibrated by both the National Research Council of Canada and the National Bureau of Standards of the United States. The results obtained by the two laboratories are presented, and a comparison indicates that agreement to 20 parts per million has been achieved. The calibration methods used by the National Research Council are described briefly.

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CANADIAN PARTICIPATION IN AN INTERNATIONAL COMPARISON OF VOLTAGE TRANSFORMER CALIBRATIONS - 1962

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INTRODUCTION

In 1962 a comparison was made between voltage transformer calibrations performed by the National Research Council of Canada (NRC) and the National Bureau of Standards of the United States (NBS). For this purpose a transformer owned by the Hydro-Electric Power Commission of Ontario was calibrated at both national laboratories.

This report presents the calibration results which were obtained by NRC. A comparison with the corresponding results obtained by NBS is made. In addition, the calibration methods used by NRC are described briefly, and the features of the transformer which are pertinent to its ratio stability are discussed.

DESCRIPTION OF THE TRANSFORMER

The transformer was a cascade type [1] manufactured by the Canadian General Electric Company. It consisted of three identical sections, each of which was essentially a separate transformer with its own core. The primary voltage is distributed equally among the series-connected primary windings of the three sections. The secondary winding of the entire transformer is wound on the section which is at the lowest potential. To ensure equal voltage distribution between each primary section and to provide a low-impedance path for the load current, the three cores are linked together with low-voltage windings.

In this transformer, voltage ratios of 4000/1, 3000/1, and 2000/1 are available at the rated primary voltage of 350 kv. These ratios are obtained by using the full number of turns in the primary winding and by changing the number of turns in the secondary winding. In addition, ratios of 1200/1 and 1000/1 are obtained by connecting the primary voltage across the two lowest sections of the transformer.

SHIELDING

In a transformer of the type described the windings are not electrically shielded from nearby surfaces, and therefore capacitive currents resulting from potential differences between the transformer and surrounding objects will flow in the windings. Since the internal impedance (winding resistance and leakage inductance) of a high-voltage transformer is not negligible relative to that of the stray capacitances, the voltage drops resulting from the capacitive currents may be appreciable. This is an undesirable effect, since the voltage ratio of the transformer then depends on the environment.

To reduce this proximity effect the transformer was equipped with two shields (Plate I), one of which was connected to the high-voltage terminal and the other to the ground terminal. For the three highest ratios, both shields were used, while for the 1000/1 and 1200/1 ratios only the lower shield was used. These shields reduce the capacitances between the windings and the objects external to the transformer, thus making the ratio of the transformer less dependent on its environment. The shields, however, also alter the internal capacitances of the transformer, and because of this, the voltage ratio in the shielded condition is substantially different.

CALIBRATION METHODS

The transformer was calibrated at NRC by using a new high-voltage capacitance ratio bridge [2] in conjunction with gas-dielectric capacitors. This bridge was built on the current comparator [3] principle and its accuracy is 10 parts per million (ppm). The high-voltage capacitor was a commercial 50 pf compressed-gas unit rated at 500 kv rms, while the low-voltage capacitors were of the parallel-plate air-dielectric type.

The calibrating procedure using this bridge is a two-step operation. First, the ratio of capacitances of two capacitors is determined by applying the same voltage to both capacitors. The ratio of currents in the capacitors is then measured by a current comparator, this measured ratio being equal to the ratio of capacitances. Next, the primary voltage is applied to one capacitor, the secondary voltage to the other, and the ratio of the currents in the capacitors is again determined. This ratio is the product of the voltage ratio of the transformer and the capacitance ratio which was determined in the previous step.

In the first measurement the voltage applied to the capacitors may be considerably different from that of the second measurement. Therefore, the sta-

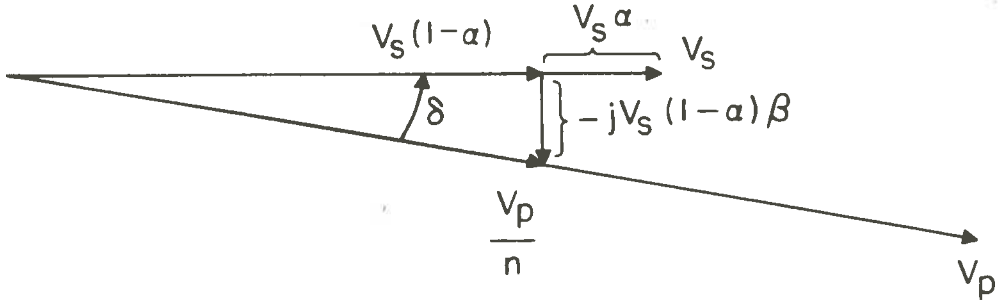

Fig. 1 Transformer errors as measured by high-voltage capacitance bridge

bility of the capacitor characteristics with the applied voltage must be known. An investigation covering this aspect of capacitors was carried out previously [4].

The bridge is direct-reading in transformer errors (α and β) as defined by the vector diagram of Fig. 1 and eq. (1)

$$\frac{V_p}{n} = V_s\,(1-\alpha)\,(1-j\beta)\,, \tag{1}$$

where V_p is the primary voltage

V_s is the secondary voltage

n is the nominal ratio of the transformer

α is the in-phase error

β is the quadrature error.

The ratio correction factor (RCF) and phase angle (δ) may be obtained as follows:

$$\mathrm{RCF} = \frac{\left|\dfrac{V_p}{V_s}\right|}{n} = (1-\alpha)\,(1+\beta^2)^{\frac{1}{2}} \simeq 1-\alpha\,, \tag{2}$$

$$\delta = \tan^{-1}\beta \simeq \beta\ (\text{radians})\,. \tag{3}$$

At NRC a capacitive voltage divider of the type described by Clothier and Medina [5] was also available for calibration of voltage transformers. The ratio of capacitances comprising the arms of this divider must be equal to the nominal voltage ratio of the transformer. If capacitors with gaseous dielectric are to be used exclusively, the highest capacitance of the low-voltage arm must be limited to several thousand pf. For calibration of a transformer with a voltage ratio of the order of 1000, a high-voltage capacitor having a capacitance of approximately one pf is required. Such a capacitor, having a nominal capacitance of one pf and rated at 80 kv was available. Consequently, calibration of the transformer up to this voltage could be, and was performed by two methods.

The balancing circuitry associated with the capacitive divider is direct-reading in transformer errors, α and β, defined by the equation

$$\frac{V_p}{n} = V_s\,\frac{(1-j\beta)}{(1+\alpha)}\,, \tag{4}$$

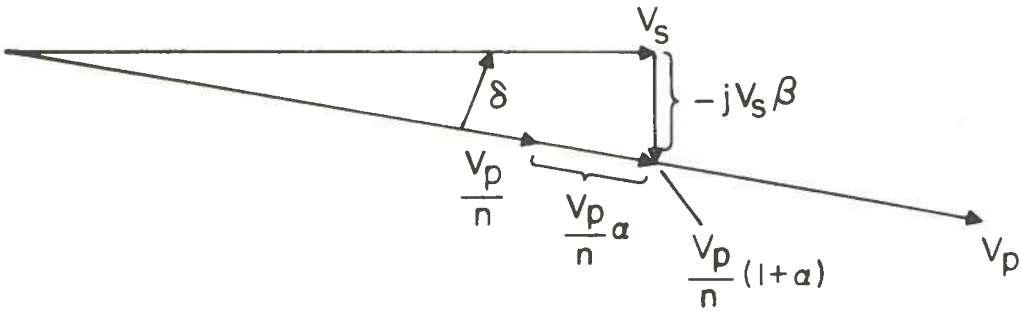

Fig. 2 Transformer errors as measured by capacitive voltage divider

which is represented vectorially in Fig. 2. Equation (4) when expanded becomes

$$\frac{V_p}{n} = V_s\,(1 - j\beta)\,(1 - \alpha + \alpha^2 - \ldots\ldots) \quad . \qquad (5)$$

If the second and higher order terms of α are neglected, eq. (5) is equivalent to eq. (1).

The accuracy of the voltage divider method is the same as that of the capacitance bridge method. The stability of the capacitor characteristics with voltage is equally important in both methods.

CALIBRATION RESULTS

The transformer was fully calibrated at NRC in March 1962, at all nominal ratios for a range of voltages, with, and without the prescribed burden. Subsequently the transformer was transported to the NBS laboratory in Washington, D.C., where the same calibrations were performed. Finally it was returned to NRC and checked for any changes in its ratio which might have occurred during transit.

Complete NRC calibration results are given in Tables I to V. For comparison, NBS results are included in the same tables. Table VI is a comparison of results which were obtained using the two calibration methods available at NRC.

The measurements yielding the results of Table VI were performed before and after the tests at NBS. The data in this table thus provide information about the transformer stability. Although the calibration results in Table VI are for the primary voltages of 80 kv only, additional tests indicated that the differences between measured values obtained before and after the NBS test were constant over the whole voltage range of the transformer.

ADDITIONAL MEASUREMENTS

1) Variations in Transformer Errors with Temperature

At the ratios of 4000/1, 3000/1, and 2000/1, the quadrature error varies in the negative direction by approximately 0.2% of the measured value per °F. The calibration results presented in this report were obtained with the transformer at an ambient temperature of 70°F (±2°).

2) Changes in Transformer Errors Resulting from Addition of Shields

At the three highest ratios the addition of shields shifts the in-phase error in the negative direction by 1500 ppm and the quadrature error in the positive direction by 730 ppm. The calibration results in Tables I to VI are thus applicable only if the transformer is equipped with shields.

3) Variations in Transformer Errors Due to Changes in Environment

As was mentioned before, the ratio of the transformer is susceptible to changes in environment. To some extent this susceptibility or proximity effect was reduced by the addition of shields. Also, ample clearance was provided in the laboratory space around the transformer.

The order of magnitude of the proximity effect can be estimated by performing measurements of the type described in Ref. 6. In these, the voltage at the secondary winding of the transformer is measured while the primary winding is short-circuited and a potential difference between the transformer and the surrounding objects is applied. The resultant capacitive currents which flow in the primary winding of the transformer magnetize the core, thus inducing a voltage in the secondary winding.

To illustrate the severity of the proximity effect, the variations in transformer errors, corresponding to the introduction of certain objects in the vicinity of the transformer, were measured. One of the objects was a piece of 3-inch tubing 8 feet long which was suspended from the high-voltage busbar at a point approximately 4 feet from the transformer. The other was a high-voltage capacitor located approximately 8 feet from the transformer. The outer part of this capacitor is the high-voltage electrode, and thus it could be excited from the high-voltage busbar or, alternatively, grounded. Both of these objects are shown in Plate II. The variations in transformer errors ($\Delta\alpha$, $\Delta\beta$) at a ratio of 2000/1 are recorded below. The variations are defined as the transformer error with the object present, minus the error with the object removed.

VARIATIONS IN TRANSFORMER ERRORS RESULTING FROM PROXIMITY EFFECTS

	Transformer Without Shields		Transformer With Shields	
	$\Delta\alpha$ (ppm)	$\Delta\beta$ (ppm)	$\Delta\alpha$ (ppm)	$\Delta\beta$ (ppm)
Tubing suspended from bus	- 187	+ 95	- 53	+ 29
Capacitor energized from bus	- 273	+ 123	- 86	+ 36
Capacitor grounded	+ 24	- 10	+ 14	- 9

From these measurements certain conclusions can be drawn:

a) The largest variation results from the proximity of the objects at high voltage, and the shields reduce this effect by approximately a factor of three.

b) The shift in the transformer errors which results from the proximity of objects at ground potential is much smaller, but for these the shields are not as effective.

COMPARISON OF NRC AND NBS RESULTS

In Tables I to V a comparison is made between the calibration results which were obtained by NRC and NBS. From these tables it is noted that the maximum deviation at the ratios 2000/1, 3000/1, and 4000/1 is less than 20 ppm. At the ratio of 1000/1 this is slightly in excess of 20 ppm, but at 1200/1 the deviation approaches 140 ppm for the in-phase component and 30 ppm for the quadrature component.

At this point it is of interest to consider the ratio stability of the transformer, since any discrepancies in calibration results of the two laboratories must be viewed in relation to this stability. The comparison of NRC results of March and November, 1962, (Table VI) indicates that shifts have occurred in transformer ratios during the intermediate period in which the transformer was transported to NBS and back to NRC. The shifts in general are of the same order of magnitude as the discrepancies between the results of the two laboratories. A particularly large shift of 175 ppm in the in-phase component and 23 ppm in the quadrature component occurs at the 1200/1 ratio. Since this ratio is obtained by using a non-integer number of turns in the secondary winding, that is, by making one turn link only part of the magnetic material, it is probable that this ratio would be affected more than the others.

At ratios of 2000/1, 3000/1 and 4000/1 the variations of in-phase errors with voltage differ by a small amount for the two laboratories. This could be attributed to an undiscovered voltage coefficient in the capacitors of either laboratory. For the 1000/1 ratio, a similar difference is observed for the quadrature error. No explanation can be suggested for this.

CONCLUSIONS

Within the past three years NRC has participated in two international comparisons of transformer calibrations. In the previous comparison [7] the agreement between the NRC and NBS results at ratios of 1000/1 and higher was between 100 and 300 ppm. In the present comparison the results agree to within 20 ppm at all ratios for which the transformer had adequate stability. Thus an improvement of one order of magnitude has been achieved.

When the ratio stability of this transformer and its susceptibility to the proximity of external objects is considered, it appears that any closer agreement would be difficult to achieve with this particular transformer.

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TABLE I

CALIBRATION RESULTS — NOMINAL RATIO 1000/1

FREQUENCY 60 CPS

Primary Voltage (kv)	Secondary Voltage (volts)	Burden (ohms resistive)	α* (ppm)			β* (ppm)		
			NRC	NBS	NRC-NBS	NRC	NBS	NRC-NBS
50	50	Infinite	+ 1208	+ 1227	- 19	+ 373	+ 386	- 13
60	60		+ 1201	+ 1222	- 21	+ 358	+ 371	- 13
69	69		+ 1196	+ 1218	- 22	+ 349	+ 360	- 11
80	80		+ 1192	+ 1214	- 22	+ 340	+ 348	- 8
100	100		+ 1186	+ 1208	- 22	+ 330	+ 334	- 4
120	120		+ 1184	+ 1206	- 22	+ 325	+ 326	- 1
130	130		+ 1185	+ 1206	- 21	+ 326	+ 323	+ 3
50	50	882	+ 1110	+ 1131	- 21	+ 55	+ 67	- 12
60	60		+ 1106	+ 1123	- 17	+ 42	+ 51	- 9
69	69		+ 1100	+ 1121	- 21	+ 33	+ 43	- 10
80	80		+ 1098	+ 1115	- 17	+ 23	+ 29	- 6
100	100		+ 1091	+ 1109	- 18	+ 13	+ 18	- 5
120	120		+ 1089	+ 1107	- 18	+ 8	+ 8	0
130	130		+ 1088	+ 1109	- 21	+ 9	+ 5	+ 4

* The transformer errors (α and β) are defined by the equation $\frac{V_p}{n} = V_s\,(1 - \alpha)\,(1 - j\beta)$

TABLE II

CALIBRATION RESULTS — NOMINAL RATIO 1200/1

FREQUENCY 60 CPS

Primary Voltage (kv)	Secondary Voltage (volts)	Burden (ohms resistive)	α* (ppm)			β* (ppm)		
			NRC	NBS	NRC-NBS	NRC	NBS	NRC-NBS
60	50	Infinite	- 1108	- 1236	+ 128	+ 241	+ 270	- 29
72	60		- 1118	- 1248	+ 130	+ 235	+ 263	- 28
82.8	69		- 1124	- 1256	+ 132	+ 231	+ 260	- 29
96	80		- 1130	- 1265	+ 135	+ 229	+ 255	- 26
120	100		- 1138	- 1274	+ 136	+ 231	+ 252	- 21
144	120		- 1140	- 1278	+ 138	+ 241	+ 251	- 10
156	130		- 1140	- 1279	+ 139	+ 249	+ 250	- 1
60	50	882	- 1212	- 1338	+ 126	- 15	+ 10	- 25
72	60		- 1224	- 1354	+ 130	- 20	+ 2	- 22
82.8	69		- 1232	- 1365	+ 133	- 24	0	- 24
96	80		- 1241	- 1374	+ 133	- 25	- 3	- 22
120	100		- 1249	- 1385	+ 136	- 23	- 7	- 16
144	120		- 1252	- 1390	+ 138	- 14	- 10	- 4
156	130		- 1252	- 1390	+ 138	- 9	- 12	+ 3

*The transformer errors (α and β) are defined by the equation $\frac{V_p}{n} = V_s\,(1 - \alpha)\,(1 - j\beta)$

TABLE III

CALIBRATION RESULTS — NOMINAL RATIO 2000/1

FREQUENCY 60 CPS

Primary Voltage (kv)	Secondary Voltage (volts)	Burden (ohms resistive)	α* (ppm)			β* (ppm)		
			NRC	NBS	NRC-NBS	NRC	NBS	NRC-NBS
100	50	Infinite	- 845	- 848	+ 3	- 1174	- 1178	+ 4
150	75		- 785	- 788	+ 3	- 1170	- 1175	+ 5
200	100		- 749	- 754	+ 5	- 1164	- 1171	+ 7
250	125		- 726	- 731	+ 5	- 1160	- 1169	+ 9
300	150		- 715	- 724	+ 9	- 1158	- 1165	+ 7
350	175		- 714	--	--	- 1159	--	--
100	50	882	- 959	- 968	+ 9	- 1495	- 1505	+ 10
150	75		- 898	- 909	+ 11	- 1492	- 1505	+ 13
200	100		- 862	- 872	+ 10	- 1488	- 1501	+ 13
250	125		- 838	- 852	+ 14	- 1484	- 1498	+ 14
300	150		- 826	- 842	+ 16	- 1482	- 1495	+ 13
350	175		- 826	--	--	- 1479	--	--

* The transformer errors (α and β) are defined by the equation $\frac{V_p}{n} = V_s (1 - \alpha)(1 - j\beta)$

TABLE IV

CALIBRATION RESULTS — NOMINAL RATIO 3000/1

FREQUENCY 60 CPS

Primary Voltage (kv)	Secondary Voltage (volts)	Burden (ohms resistive)	α^* (ppm)			β^* (ppm)		
			NRC	NBS	NRC-NBS	NRC	NBS	NRC-NBS
100	33.3	Infinite	- 897	- 906	+ 9	- 1142	- 1142	0
150	50		- 840	- 851	+ 11	- 1138	- 1142	+ 4
200	66.7		- 805	- 818	+ 13	- 1135	- 1135	0
250	83.3		- 783	- 798	+ 15	- 1130	- 1132	+ 2
300	100		- 773	- 789	+ 16	- 1128	- 1129	+ 1
350	116.7		- 773	- 790	+ 17	- 1128	- 1127	- 1
100	33.3	882	- 948	- 960	+ 12	- 1276	- 1276	0
150	50		- 892	- 903	+ 11	- 1272	- 1276	+ 4
200	66.7		- 857	- 869	+ 12	- 1268	- 1272	+ 4
250	83.3		- 833	- 850	+ 17	- 1264	- 1268	+ 4
300	100		- 822	- 839	+ 17	- 1262	- 1265	+ 3
350	116.7		- 822	- 840	+ 18	- 1262	- 1261	- 1

* The transformer errors (α and β) are defined by the equation $\frac{V_p}{n} = V_s\,(1 - \alpha)\,(1 - j\beta)$

TABLE V

CALIBRATION RESULTS — NOMINAL RATIO 4000/1

FREQUENCY 60 CPS

Primary Voltage (kv)	Secondary Voltage (volts)	Burden (ohms resistive)	α* (ppm)			β* (ppm)		
			NRC	NBS	NRC-NBS	NRC	NBS	NRC-NBS
100	25	Infinite	- 955	- 954	- 1	- 1062	- 1060	- 2
150	37.5		- 910	- 913	+ 3	- 1061	- 1060	- 1
200	50		- 882	- 885	+ 3	- 1058	- 1059	+ 1
250	62.5		- 863	- 867	+ 4	- 1054	- 1057	+ 3
300	75		- 850	- 858	+ 8	- 1056	- 1055	- 1
350	87.5		- 850	- 859	+ 9	- 1056	- 1051	- 5
100	25	882	- 994	- 993	- 1	- 1157	- 1154	- 3
150	37.5		- 946	- 953	+ 7	- 1155	- 1154	- 1
200	50		- 920	- 925	+ 5	- 1152	- 1154	+ 2
250	62.5		- 898	- 907	+ 9	- 1150	- 1151	+ 1
300	75		- 889	- 898	+ 9	- 1150	- 1148	- 2
350	87.5		- 888	- 898	+ 10	- 1149	- 1147	- 2

*The transformer errors (α and β) are defined by the equation $\frac{V_p}{n} = V_s (1 - \alpha)(1 - j\beta)$

TABLE VI

COMPARISON OF TRANSFORMER ERRORS AS MEASURED BY TWO BRIDGES DURING MARCH AND NOVEMBER OF 1962

(BEFORE AND AFTER THE SHIPMENT OF THE TRANSFORMER TO NBS)

FREQUENCY 60 CPS, PRIMARY VOLTAGE 80 KV, BURDEN ∞ OHMS

Nominal Ratio	Secondary Voltage (volts)	α (ppm)					β (ppm)				
		BRIDGE I*			BRIDGE II †	BR. I - BR. II	BRIDGE I			BRIDGE II	BR. I - BR. II
		Mar.	Nov.	Mar. - Nov.	Mar.	Mar.	Mar.	Nov.	Mar. - Nov.	Mar.	Mar.
1000/1	80	+ 1202	+ 1195	+ 7	+ 1206	- 4	+ 340	+ 341	- 1	+ 344	- 4
1200/1	66.7	- 1114	- 1289	+ 175	- 1111	- 3	+ 231	+ 254	- 23	+ 235	- 4
2000/1	40	- 893	- 912	+ 19	- 894	+ 1	- 1177	- 1175	- 2	- 1177	0
3000/1	26.7	- 942	- 962	+ 20	- 944	+ 2	- 1145	- 1141	- 4	- 1141	- 4
4000/1	20.0	- 992	- 1010	+ 18	- 992	0	- 1061	- 1056	- 5	- 1059	- 2

* BRIDGE I — NRC High-voltage Capacitance Bridge. This bridge measures transformer errors defined by the equation $\frac{V_p}{n} = V_s\,(1 - \alpha)\,(1 - j\beta)$.

† BRIDGE II — Transformer Calibrating Bridge of the Clothier and Medina Type. This bridge measures transformer errors defined by the equation

$$\frac{V_p}{n} = V_s\,\frac{(1 - j\beta)}{(1 + \alpha)}$$

ADDENDUM

On March 12, after completion of this report, word was received from NBS that, through an oversight, some rather significant corrections to NBS results had been omitted. These corrections eliminate the discrepancy in the variations of in-phase errors with voltage, as discussed on page 7, and thus improve the interlaboratory agreement. The corrected calibration results will be made available in a joint NBS-NRC paper which is planned for presentation during the Summer General Meeting of the Institute of Electrical and Electronic Engineers in Toronto, Ont., June 16-21, 1963. It is expected that this paper will be published in the Transactions of the Institute.

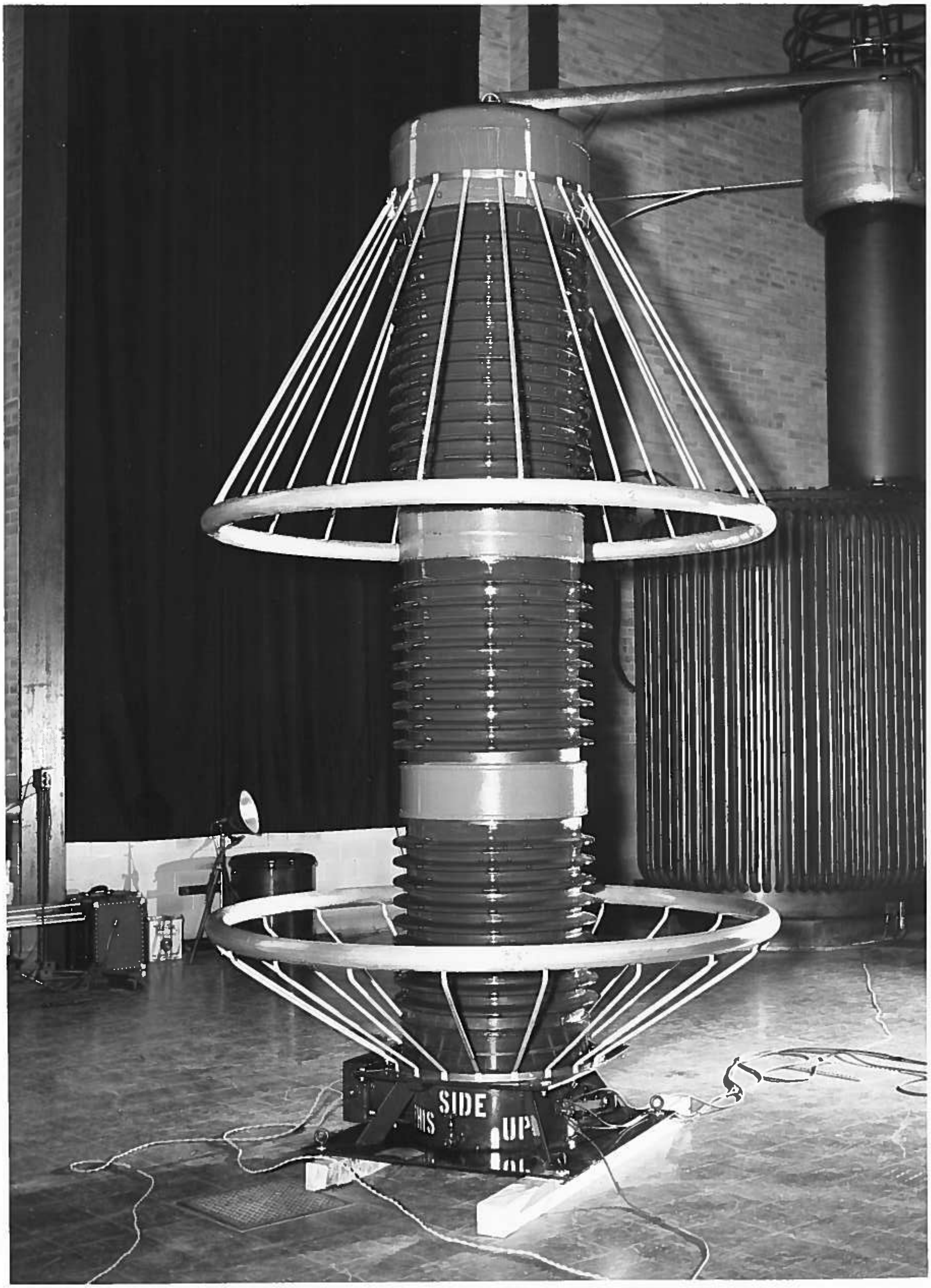

Plate I — Transformer equipped with shields

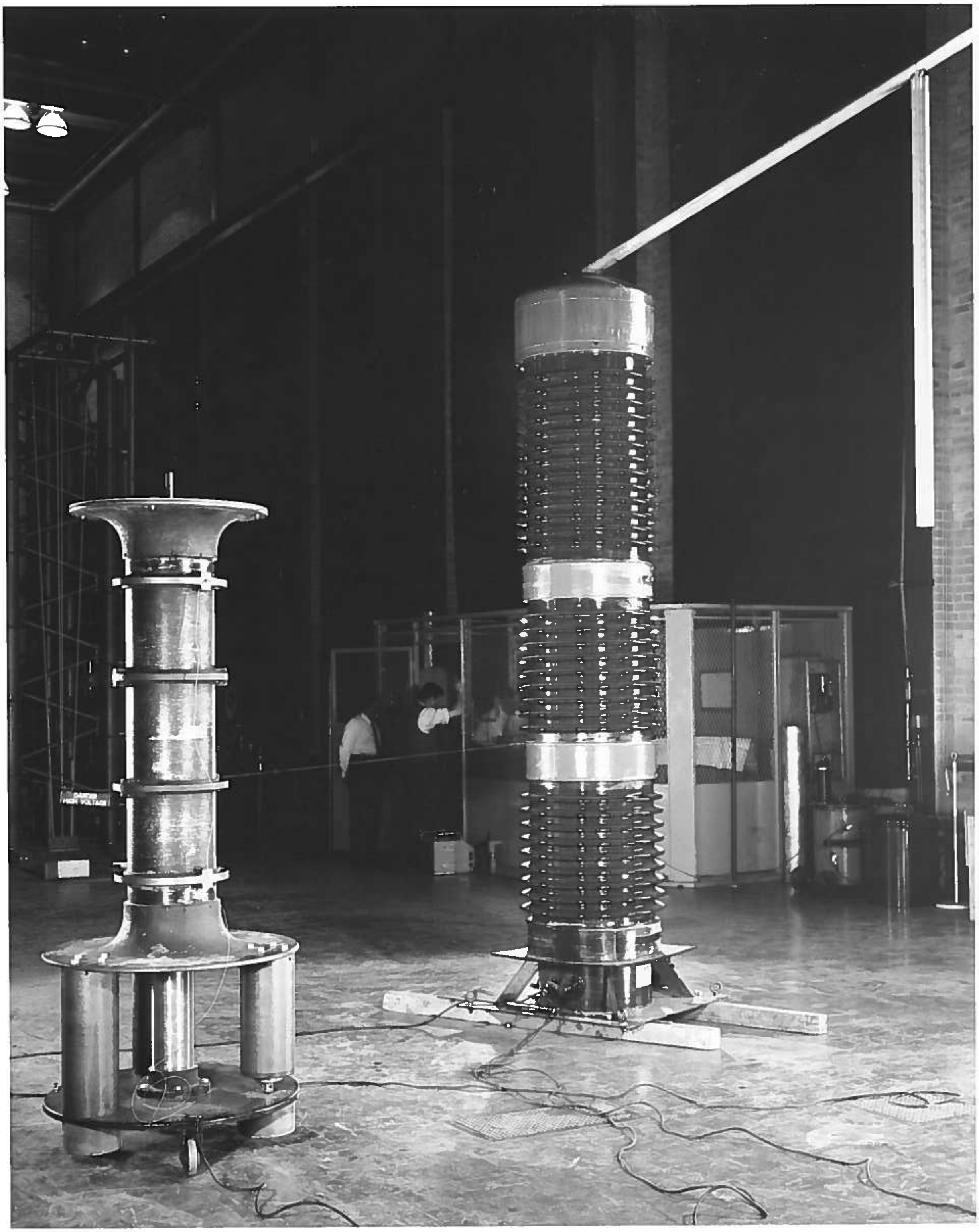

Plate II — Transformer and objects for which proximity effects were recorded
Top Right: Tubing suspended from busbar Left: High-voltage capacitor