Voltage Testing of Cables

Middleton and Dawes

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SIMPLEX WIRE & CABLE Co
MANUFACTURERS
201 DEVONSHIRE ST. BOSTON
CHICAGO SAN FRANCISCO

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By W. I. Middleton and
Chester L. Dawes

A paper read June 25, 1914,
before the American Institute
of Electrical Engineers

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Voltage Testing of Cables

We are pleased to present the following reprint of "Voltage Testing of Cables," because it contains three features of general interest to engineers:

(1) A technical discussion indicating a rational method of standardizing voltage tests on insulated conductors.

(2) A consideration of some difficulties encountered in making voltage tests, and methods of overcoming them.

(3) A description of an instrument based on the oscillograph principle, with which the maximum voltage may be determined regardless of wave form.

Mr. Middleton, as electrical engineer in charge of our Testing Department for twelve years, has made a careful scientific study of this subject, in addition to becoming thoroughly familiar with its practical side. Mr. Dawes, an instructor at Harvard University and at the United States Naval Academy, Annapolis, has aided greatly by his knowledge of the theory and mathematics of the subject.

The experiments described in the paper were made in our factory. The voltmeter has been developed by us, owing to the lack of any simple instrument available for reading peak voltages.

SIMPLEX WIRE & CABLE CO.

Boston, September, 1914

VOLTAGE TESTING OF CABLES

BY W. I. MIDDLETON AND CHESTER L. DAWES

Abstract of Paper

In this country rubber compound, paper, and cambric are generally used for cable insulation. From the formula $S = \frac{0.868\,V}{d \log_{10} \frac{D}{d}}$, the stress at any point in a homogeneous insulation may be determined. The minimum stress and the maximum allowable voltage occur when the conductor is 10/27 of the sheath diameter. The present irrational practise of testing cables should be standardized to conform to this formula or a modification of it.

Over-stressing of the insulation is accompanied by a change of insulation resistance and electrostatic capacity.

No one factor of safety is applicable to every cable system, but one must consider the conditions of operation as well.

In testing, the voltage may be applied: (1) by submersion; (2) between the conductor and metallic sheath; (3) between wires. The submersion test is the most severe. A sine wave is desirable for testing purposes, but rarely occurs in a commercial generator under these severe conditions of load. Reactance cannot always be used successfully to reduce the volt-ampere load on the generator.

With a distorted wave an a-c. voltmeter gives only a poor indication of the maximum voltage. The writers have devised an instrument based on the oscillograph principle, with which the maximum voltage may be determined, regardless of wave form.

THE design of cables is largely dependent on data obtained from voltage tests made on commercial lengths. Such tests are usually conducted in the testing-room but are frequently made after the cable has been installed. The importance of this subject has led the writers to present such data as may seem either useful or of interest in connection with the design or testing of cables, and further, to enumerate some of the difficulties encountered in making such voltage tests, together with the methods adopted to eliminate these difficulties.

Insulating Materials

In this country, three materials are in general use for the insulation of wires and cables; rubber compound, varnished cambric, and paper.

Rubber compound is the oldest, and is the only one that can be used under all conditions without the aid of a lead sheath. Its composition is more complex than that of the others, involving pure rubber, certain mineral ingredients, and hydrocarbons. The number of such ingredients and the proportion of each that can be used has allowed a great number of compounds to be made and has led to considerable discussion as to the value of some of these as insulating materials.

Paper as an insulation for wires and cables is used in two ways: wrapped on loosely and kept dry, as in telephone cables, or put on tightly and saturated with some good insulating oil or compound. The insulating properties of this class of cable depend absolutely on the soundness of the lead sheath.

Varnished cambric is the most recent material used for cable insulation and stands between rubber and paper; it has a number of good qualities. Being a cotton fabric coated on both sides with several films of insulating varnish, it is almost water proof, and may be submerged in water for a considerable length of time without undue deterioration. In the process of manufacture, the varnished cloth is applied spirally in the form of tape, a viscous insulating compound being simultaneously applied between layers.

VOLTAGE AND STRESS FORMULAS

Theoretically, the stress at any point on a homogeneous cylindrical insulation may be determined from the following formula:

$$S = \frac{0.434\ V}{X \log_{10} \frac{R}{r}} \tag{1}$$

where V = volts impressed between conductor and sheath,
r = radius of the conductor,
R = radius of the insulation,
X = distance from the axis to the point in question,
S = stress in volts per unit thickness of insulation at this point.

The stress will be a maximum at the surface of the conductor. Therefore letting $X = r$, $r = d/2$, and $R = D/2$, the stress at the surface of the conductor becomes

$$S = \frac{0.434\ V}{\frac{d}{2} \log_{10} \frac{D}{d}} = \frac{0.868\ V}{d \log_{10} \frac{D}{d}} \tag{2}$$

where d = diameter of the conductor,
D = diameter of the insulation.

This relation is shown in Fig. 1.

With D and V fixed, the maximum stress at the surface of any insulated wire will be inversely proportional to $d \log_{10} \frac{D}{d}$. It will therefore diminish with an increase in the diameter of the conductor, until a minimum is reached, after which the stress will increase with further increase of conductor diameter. This minimum may be found by differentiating formula (**2**), and equating to zero, and the value of d corresponding thereto is found to be $D/\epsilon = D/2.72$ where ϵ is the Napierian base. This relation plotted with volts per mil as ordinates and conductor diameter as abscissas, is shown in Fig. 1. Point A shows the point of minimum stress. The wire diameter for minimum stress is about $10/27$ of the diameter of the insulation.

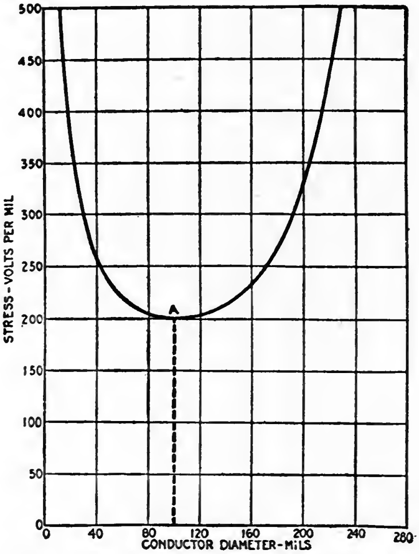

FIG. 1—CURVE OF STRESS AND CONDUCTOR DIAMETER.
Voltage (V) constant at 10,000. Diameter over insulation (D) constant at 272 mils.

If in formula (**2**), D and the maximum allowable stress S are kept constant, and the voltage is allowed to vary with the conductor diameter, we have

$$V = \frac{Sd}{0.868} \log_{10} \frac{D}{d} \qquad (3)$$

This relation is shown in Fig. 2. Under these conditions the maximum voltage that we may impress between the conductor and the outside, without exceeding the allowable stress, occurs when $d = D/2.72$.

This does not mean, however, that if this maximum voltage were impressed upon the cable when d is less than $D/2.72$ the insulation would break down, but rather that the wall of insulation between the diameter $D/2.72$ and the conductor would be stressed beyond the allowable limit. The layer nearest the conductor is under the maximum stress, and the stress in any other layer is inversely proportional to its distance from the center if the electrical characteristics of the insulation remain unchanged. Theoretically, then, all cables having d less than $D/2.72$ should break down at the same voltage, hence follow the line ABC, if it be assumed that the voltage drop across the over-stressed layer is practically zero.

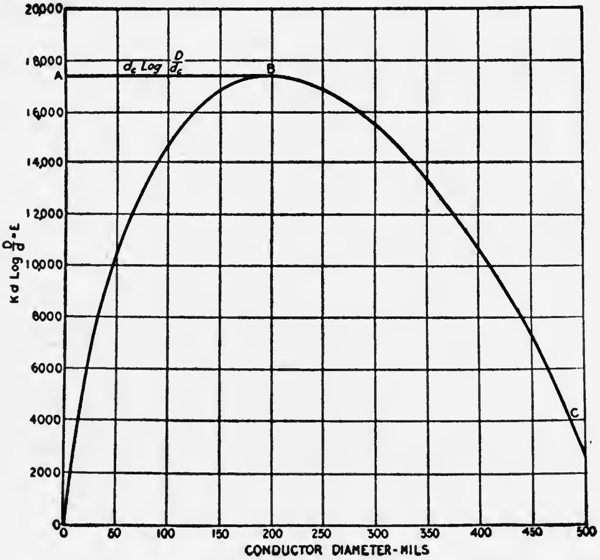

Fig. 2—Relation between Test Pressure and Conductor Diameter
E = $K d \log D / d$. $K = 200$. D = 544 mils. Stress constant.

All wires having the same outside diameter whose conductor diameter is equal to or less than D/2.72 (= *dc*) should have the same breakdown voltage.

Although there has been no evidence, so far as the writers know, that these inside layers are actually broken down under these conditions, it is a well-known fact that the dielectric constant of an over-stressed dielectric is greater than the normal constant before breakdown, and this tends to reduce the voltage drop across the inner layers and throw more stress on the outer wall. Whether or not this be true, experience indicates that the breakdown occurs along the line AB, Fig. 2, and little or nothing is gained in making d less than $D/2.72$.

TABLE I

Values of $d \log_{10} \frac{D}{d}$. D and d in mils

	Size Wire B. & S.								
Wall (in.)	No. 14	No. 12	No. 10	No. 8	No. 6	No. 4	No. 1 Std.	4/0 Std.	1,000,000 Cir. Mils
1/32	19.1	20.0	21.3	21.9	22.8	23.9	24.8	25.6	26.2
3/64	25.2	27.1	28.9	30.7	33.0	33.7	36.0	37.6	38.8
2/32	30.3	33.0	36.4	38.0	40.5	42.4	46.0	49.4	51.6
5/64	34.5	38.0	41.1	44.2	47.6	50.4	55.5	59.5	64.0
3/32	38.4	42.2	46.3	50.4	54.4	58.0	64.5	70.0	75.5
7/64	41.6	46.0	50.8	55.6	60.0	65.1	73.0	79.6	87.1
4/32	44.6	49.5	54.9	60.4	65.9	71.0	80.7	89.0	98.4
9/64	47.2	52.7	58.6	64.8	70.9	76.9	88.1	97.6	108.9
5/32	49.7	55.5	62.2	69.0	75.6	82.5	95.5	107.0	119.2
6/32	54.0	60.8	68.3	76.3	84.5	92.5	108.5	123.2	141.1
7/32	57.7	65.3	73.8	82.9	92.2	102.0	121.0	138.9	161.2
8/32	61.0	69.3	78.6	88.8	99.1	110.0	132.0	153.0	180.4
9/32	64.0	72.9	83.0	94.1	105.3	117.3	141.0	166.2	198.8
10/32	66.3	76.2	87.0	98.9	111.3	124.5	150.5	179.3	217.0

The following formula has therefore been adopted as most nearly representing the breakdown stress for small conductors with a heavy wall of insulation.*

$$S = \frac{0.868\ V}{d_c \log_{10} \frac{D}{d_c}} \tag{4}$$

where $d_c = D/2.72$.

**Potential Stresses in Dielectrics*, by H. S. Osborne, TRANS. A. I. E. E., Vol. XXIX, part 2, p. 1553.

Discussions, by W. I. Middleton, p. 1587; Henry A. Morss, p. 1589; Wm. A. Del Mar, p. 1614.

The maximum voltage that may be safely impressed upon a cable of a given insulating material is proportional to $d \log_{10} \frac{D}{d}$ and to a constant K, depending on the quality of material (formula **3**).

Values of $d \log_{10} \frac{D}{d}$ are given in Table I, for walls from 1/32 in. (0.794 mm.) to 10/32 in. (7.94 mm.) thick on various wires from No. 14 B. & S. to 1,000,000 cir. mil cable, and these values are plotted in Fig. 3. These tables and curves are very useful in the application of the formula to cable testing, for the value of K only needs to be known to determine the allowable voltage test or proper diameter. When d is expressed in mils, K varies from 100 to 250 for rubber compounds, is about 250 for cambric, and for paper with thin walls is much less than 250 but is greater than this for walls exceeding 10/32 in. (7.95 mm.)

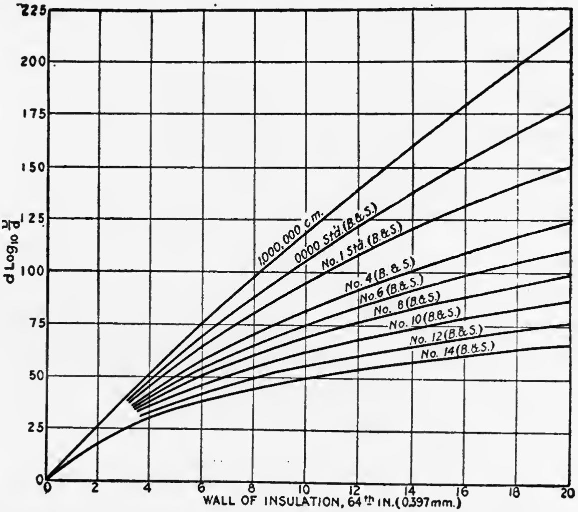

FIG. 3—RELATION BETWEEN d LOG$_{10}$ D/d AND WALL OF INSULATION. "d" AND "D" IN MILS

STANDARDIZATION OF VOLTAGE TESTS

Until recently no attempt has been made to standardize voltage tests on insulated wires and cables with reference to the theoretical stress. The result is a chaotic condition of affairs. A very common rule has been to specify a test of 2½ times the working pressure, the feeling being that this allows a good factor of safety. This rule might be satisfactory if the wires were all of one size and the same wall of insulation used for each working pressure. As such is not the case, the only rational way to test all cables is by the $d \log_{10} \frac{D}{d}$ rule or a modification of it.

On October 1, 1905, the Underwriters' Laboratories specified that all Code wires for voltages between 0 and 600 volts should be tested after ten hours immersion in water, with 1500 volts (alternating current) for not less than five seconds. That specification showed the influence exerted on most engineers at that time by the factor of 2½ times the working pressure.

A little study of Fig. 3 together with the sizes of wires and walls of insulation made under the code specifications shows how absurd this test was. The conductors varied from No. 14 to 1,000,000 cir. mils and larger (0.064 to 1.156 in. or 1.63 to 29.4 mm.) in diameter; the wall of insulation from 3/64 in. (1.19 mm.) to 7/64 in. (2.78 mm.), (0.0469 to 0.109 in.). If the 3/64 in. (1.19 mm.) wall of insulation on the No. 14 would stand 1500 volts, it should surely stand much more than this on the 1,000,000 cir. mil. It would therefore be possible for the 1,000,000 cir. mil cable to meet this test even were the wall of insulation defective or actually less than 3/64 in. (1.19 mm.) in places, whereas the main object of the voltage test is to break down any such faults.

The 1911 Code specifications for 0 to 600 volts have, in part, remedied this defect by calling for a test of the 1,000,000 cir. mil at 3500 volts, but at the higher voltages they still hold to 2½ times the working pressure. The specifications of some of the largest buyers in the country to-day are equally inconsistent.

This is a lamentable condition. It allows too much variation in the dielectric strength of the insulating materials. Some of this variation may be due to ignorance, and some may be intentional. When a cable is tested at only one-half the voltage to which it should be subjected, there results in many instances a carelessness in its manufacture. The writers believe that too little has thus far been accomplished in the line of the standardization of cable testing, when compared with other branches of engineering.

The following tests, in Tables II and III, are recommended

TABLE II

Recommended Voltage Tests for High-Voltage Cables.

30 percent Para Rubber

Wall of insulation (inch)	3/64	2/32	5/64	3/32	7/64	4/32	5/32	6/32	7/32	8/32
550,000 cir. mil and larger					14,000	16,000	19,000	22,000	25,000	28,000
500,000 cir. mil to 250,000 cir. mil					13,500	15,000	18,000	20,500	23,000	26,000
4/0 to 1 B. & S.			11,000	12,000	13,000	14,000	17,000	19,000	21,000	24,000
2 to 4 B. & S.			10,000	11,500	12,500	13,500	16,000	18,000	20,000	22,000
6 B. & S.		8,000	9,500	11,000	12,000	13,000	15,000	17,000	19,000	21,000
8 "	6,000	7,500	9,000	10,000	11,000	12,000	14,000	15,500		
10 "	6,000	7,500	8,000	9,500	10,000	11,000	12,500	13,500		
12 "	5,500	6,500	7,500	8,500	9,000	10,000	11,000	12,000		
14 "	5,000	6,000	7,000	7,500	8,000	9,000	10,000	11,000		

for high-and medium-voltage cables, respectively. Table IV, on the other hand, is the specification as called for by a purchaser for the cables listed in Table III. It will be seen that the testing pressure recommended is from 1½ to 2½ times that called for by the purchaser. As far as working pressure is concerned, the factor of safety demanded by the purchaser in Table IV is, without doubt, sufficient. Yet the tests called for by this table would not begin to show up any but the most serious defects in the insulation of the respective cables.

The *A. R. E. E. committee on "Wire and Cable Specifications" has taken the most important step thus far in the standardization of voltage tests for cables, in its recent recommendations for tests on rubber, cambric and paper insulation.

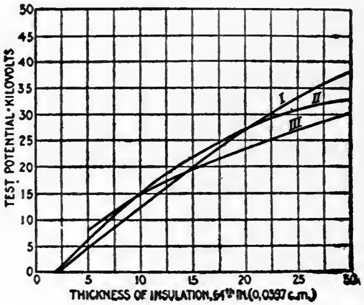

FIG. 4—POTENTIAL TESTS ON CONDUCTORS, RECOMMENDED BY A. R. E. E. NO. 1 TO NO. 4/0 A. W. G.

I. Paper or varnished cambric.
II. Rubber.
III. 155 $d \log_{10} D/d$ for No. 1 A. W. G.

From Fig. 3 it will be noted that there is but a relatively small difference in the values of $d \log_{10} \frac{D}{d}$ for diameters corresponding to No. 1 and No. 4/0 B. & S. gage, consequently one set of values covering these ranges has been recommended, and is plotted in Fig. 4.

Curve I is recommended for paper and varnished cambric, curve II for rubber, and curve III is the value of $Kd \log_{10} \frac{D}{d}$ when $K = 155$ and d and D are given in mils. Up to a 20/64-in. (7.95-mm.) wall the paper and cambric are rated at a lower working pressure than the rubber, for mechanical reasons, but above this they should test even better than the rubber.

OVER-STRESSING CABLES

Much has been said in the past relative to unduly severe testing conditions in that the insulation, initially sound mechanically, becomes stressed beyond the electric elastic limit when tested. Although the short duration of the test may not develop any faults, the cable is nevertheless permanently injured, hence less able to withstand the shocks incidental to service conditions.

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*Association of Railway Electrical Engineers.

TABLE III

Recommended Voltage Tests for Low-Voltage Cables.

INSULATED WITH LOW-TENSION RUBBER COMPOUND. VOLTAGE TEST AT FACTORY FIVE MINUTES AS PER TABLE; VOLTAGE TEST AFTER INSTALLATION 30 MINUTES AT 50 PERCENT OF TABLE VALUE.

Size conductor	Minimum thickness insulation, inch.	Test pressure, volts.
Stranded		
1,000,000 cir. mils	4/32	10,000
750,000 "	4/32	10,000
500,000 "	4/32	9,000
350,000 "	4/32	9,000
4/0 A. W. G.	3/32	7,000
2/0 "	3/32	6,500
1/0 "	3/32	6,500
2 "	3/32	6,000
Solid		
4 A. W. G.	3/32	5,500
6 "	3/32	5,500
8 "	3/32	5,000
10 "	3/32	4,500
12 "	3/32	4,000
14 "	5/64	3,500
14 (3) " conductor	5/64	3,500

TABLE IV

Voltage Tests as Specified by a Purchaser.

TESTS ON CABLES INSULATED WITH LOW-TENSION RUBBER COMPOUND. VOLTAGE TEST AT FACTORY FIVE MINUTES AS PER TABLE; VOLTAGE TEST AFTER INSTALLATION 30 MINUTES AT 80 PERCENT OF TABLE VALUE

Size conductor	Strands	Wall.	Volts working pressure	Volts test pressure
Stranded				
1,000,000 cir. mils	61	4/32	1000	4000
750,000 "	61	4/32	"	4000
500,000 "	37	4/32	"	4000
350,000 "	37	4/32	"	3000
4/0 A. W. G.	19	3/32	"	3000
2/0 "	19	3/32	"	3000
1/0 "	19	3/32	"	3000
2 "	7	3/32	"	3000
Solid				
4 A. W. G.		3/32	1000	3000
6 "		3/32	"	3000
8 "		3/32	"	3000
10 "		3/32	"	3000
12 "		3/32	"	3000
14 "		5/64	"	2000
14 "	3-Cond.	5/64 (no belt)	"	2000

This may be the case, but fortunately the insulation resistance and the electrostatic capacity enable us to determine the degree to which the insulation has been over-stressed.

Immediately after the stress is applied, the insulation resistance, measured with direct current, may drop considerably below its initial value as obtained a few moments previous to the application of voltage. This change may be as great as 50 per cent. If further readings of insulation resistance are taken, they will show a gradual increase and will approach their initial value if the cable has not been over-stressed, whereas, if it has been over-stressed, the resistance recovers but little. Care must be taken to keep the temperature constant during these tests, for insulation has a very large resistance temperature coefficient. Table V shows some typical data taken from tests made on long lengths of wire as they were passing through the testing room.

TABLE V

WIRES SHOWING RESULTS OF STRESS.

Megohms in 1000 ft.

Test No.	Feet	Before voltage	2500 volts 1 min.	5000 volts 1 min.	After 2 hours	5000 volts 5 min.	After 2 hours	
1	1562	14,500	14,500	7,500	11,500			
2	1547	22,000	22,000	16,000	18,000			
3	3150	7,500	7,500	6,000	7,000	5,000	5,000	
4	1740	15,000	15,000	6,500	10,000	750	2,500	
5	2402	15,000	15,000	7,500	10,000	2,500	3,500	
							Break-down voltage	Megohms in 1000 ft. after repair. 4000 volts, one min.
6	3560	4,800				4,620	13,000	4,400
7	1425	3,500				3,440	12,000	4,470
8	2350	9,000				9,015	15,000	8,425
9	2750	7,660				7,660	15,000	9,150
10	2400	2,950				2,740	7,500	2,810

The insulation resistances in tests (1) and (2) were affected considerably after the 5000-volt one-minute test, but practically recovered after two hours. It is possible that they would have completely regained their initial resistance if allowed sufficient time.

Tests (3), (4) and (5) were first made under the same conditions and, except in the case of (3), the recovery was much poorer than in the former cases. They were then subjected to 5000 volts for five minutes, with a noticeable reduction in the resistances of (3) and a very large and permanent reduction in that of (4) and (5). These last two were permanently injured.

In tests (6) to (10) inclusive, there was no marked decrease in resistance after the 5000-volt test, so they were broken down, repaired by patching the faults, tested at 4000 volts for one minute, and the insulation resistance measured again, with the results shown in the table. Tests (7) and (9) gave even better results than the initial resistances, due no doubt to patching a localized fault.

TABLE VI

WIRES SHOWING THE RESULTS OF STRESS.

Microfarads per 1000 ft.

Feet	Before voltage test	After 5000 volts for 1 min.
3150	0.126	0.130
2176	0.146	0.150
2470	0.130	0.134
2925	0.130	0.133
2775	0.120	0.124

Unfortunately, the electrostatic capacity of these cables was not measured after every application of voltage, but Table VI shows in a general way the increase of capacity due to stress in the dielectric. For a given stress the change in capacity is much smaller than the change in resistance.

These results show that it is possible to make a rubber compound which is not easily stressed beyond the electric elastic limit, and further, that if a compound is so stressed it is possible by means of the insulation resistance to determine if the test has been too severe.

FACTOR OF SAFETY

It is not the intention of the writers to tell the operating engineers what should be the factor of safety in a cable system. Great fear has been expressed now and then, that engineers, knowing that cables will stand these high-voltage tests, will be tempted to use them on higher working pressures than they should. In this connection it is well to bear in mind that a factor of 2½ times the working pressure is not applicable to all conditions.

(1) *In two systems of the same kilowatt capacity the cables on that system having the lower voltage should have the greater factor of safety.* This is because the surge voltage on the lower-voltage system will be greater because of the greater current, and the maximum possible rise in voltage is $e = i\sqrt{\frac{L}{C}}$, where i is the amperes current transient, and L and C the system inductance and capacity, expressed in henrys and farads respectively.

(2) *In two systems having the same voltage, those cables operating on the system having the greater kilowatt capacity should have the greater factor of safety.* The reason for this is obvious. As has been frequently observed, transients that are practically unimportant in a small system become dangerous if allowed to take place in a large system. The writers have in mind a case where 2300-volt distributing cables, when connected to a relatively small plant, gave practically no trouble, but later, when this smaller system received its energy from a large transmission network, these same cables, though *normally* operating at the same voltage as before, gave so much trouble that they had to be replaced by cables better suited to the conditions.

METHOD OF TESTING

The voltage test can be applied to wires and cables in several different ways; by submerging the cables in water; testing them against a metallic covering on the outside such as a lead sheath or tin foil; and testing one wire against another when there is more than one wire in the cable. The submersion test is the most severe as the water makes very close contact with the outside of the cable regardless of any surface irregularities that may be present. The water also has a tendency to penetrate into any foreign substance that may be in the insulating material, provided this substance has any affinity for water.

All of these tests may be, and generally are, made on rubber insulated cables. The cambric cables to be braided are generally submerged before and after braiding; cambric cables to be lead-covered are not submerged, as considerable trouble in drying them is experienced, and as they are to be tested after the lead covering has been applied, the submersion test is not necessary. Paper cables are not submerged, and all tests are made after leading.

The voltage test, as applied to cables, is practically the same whether it is made submerged, against the lead, or against the contiguous wires, the object being to break down any weakness that may exist in the insulation. How much pressure, and for how long it shall be applied, are questions that have long been the subject of much discussion.

For several reasons, it is necessary to apply the voltage test to the finished cable and not to a short sample. (1) It is desirable to break down any weak places that may occur in the cable, it being quite impossible to avoid entirely such places in manufacture; (2) to satisfy inspectors and purchasers that the cable meets specifications as regards dielectric strength; (3) to obtain data and information as to the dielectric strength of the material; (4) constants obtained in laboratories from tests of short lengths are not applicable to commercial lengths and are usually misleading.

TESTING APPARATUS*

Recommendations have appeared at different times regarding the type of generator and transformer that it is advisable to use for testing purposes, and the consensus of opinion seems to be that a smooth-core generator with field control, and a variable-ratio transformer, are most satisfactory. As will be shown later, it is doubtful if the generator of ordinary design can maintain its wave form under the severe conditions imposed by cable testing.

Where cables of some length are to be tested, a frequency of 25 cycles is preferable to one of 60 cycles, for the necessary generator and transformer capacities are practically proportional to the frequency, and according to the best information the writers can obtain there is no appreciable difference in severity of cable tests whether made at 25 or 60 cycles.

In the following tests, made in the testing laboratory of a wire manufacturer, the generator used was a motor-driven 25-kv-a., 220-volt, four-pole, 25-cycle, single-phase alternator, having 10 slots per pole, and a conductor belt ⅝ the pole pitch. The transformer capacity was 50 kv-a., 220-50,000 volts. The secondary consisted of four separate 12,500-volt coils, capable of being con-

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* *High-Tension Testing of Insulating Materials,* A. B. Hendricks, TRANS. A. I. E. E., Vol. XXX, part I, page 167.

nected either in parallel, in series-parallel, or in series. The high-tension winding had a total of 12,512 turns, and the low-tension 55 turns. The reactance voltage was about 6 percent.

Fig. 5 shows the generator voltage on open circuit, and except for the tooth harmonics, the e.m.f. wave is practically sinusoidal. For testing purposes, this wave is perfectly satisfactory if it could be maintained under all load conditions. In Fig. 6 is shown the generator voltage wave taken at 220 volts when the transformer is connected, and also the exciting current wave of the transformer.

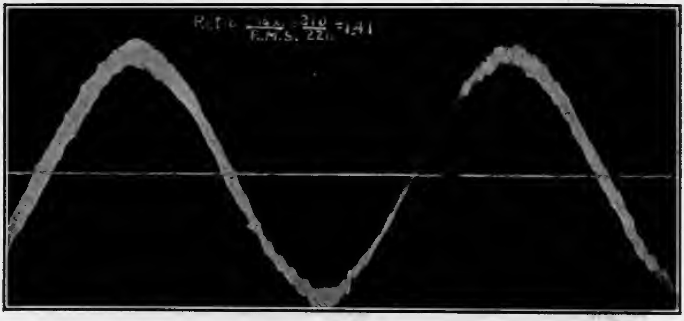

Fig. 5

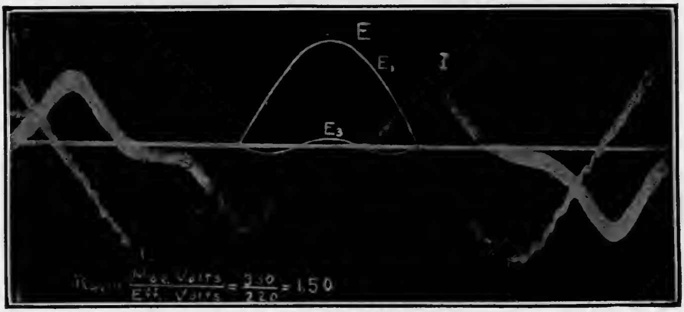

Fig. 6

This transformer exciting current is about 17 percent of the rated load current of the transformer, but is 34 percent of the rated load current of the generator. This is rather high, and further, Fig. 6 and other experiments showed that the transformer iron was being operated at unusually high saturation. It might well be argued that a large transformer magnetizing current is desirable, as it tends to offset the leading component of cable charging current, but it should be remembered that beyond a certain core density the additional exciting current is made up almost entirely of harmonics which do not neutralize the fundamental. Experience has shown this to be undesirable for other reasons. Examination of the current wave in Fig. 6 shows that the transformer takes a pronounced third harmonic current, and this current reacting on the generator flux tends to start wave distortion, producing a third harmonic in the e.m.f. wave as shown. If a cable, like most other electrical apparatus, took a comparatively small charging current, most of the following difficulties, due to wave distortion, would disappear.

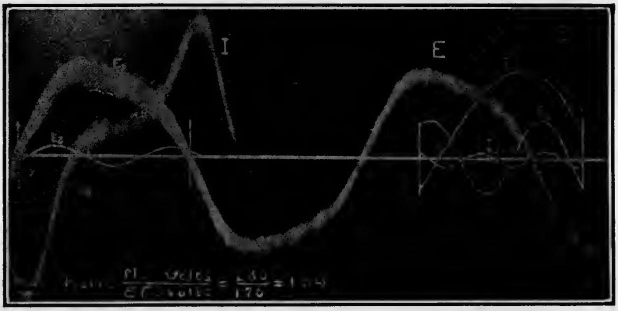

Fig. 7

Figs. 7, 8 and 9 show various voltage waves actually obtained under different conditions of test. The voltages on the cables, given in connection with all the following oscillograms are according to the ratio of transformation, hence, are not strictly correct. In actual practise this voltage is determined directly from the high tension side by means of a potential transformer.

The reasons for this distortion are obvious. The generator may have, inherently, a sine wave voltage, but the transformer exciting current has a prominent third harmonic. This current and the single-phase pulsating armature reaction produced on the flux wave, will usually introduce harmonics in the voltage wave as shown in Fig. 6. This wave is communicated to the transformer secondary where the cable intensifies it in its charging current, and it is reflected back in the generator current, and increased wave distortion results. These reactions are cumulative and will continue to increase until counter-reactions, set up in the magnetic and electric circuits become sufficiently great to balance them. Generator saturation, generator and transformer series leakage reactance and the phase relations of the harmonics may tend to counteract distortion. The value of series reactance may be such as to produce resonance for one harmonic and not for the others.

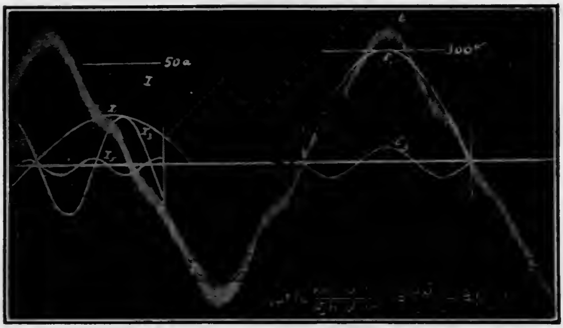

Fig. 8

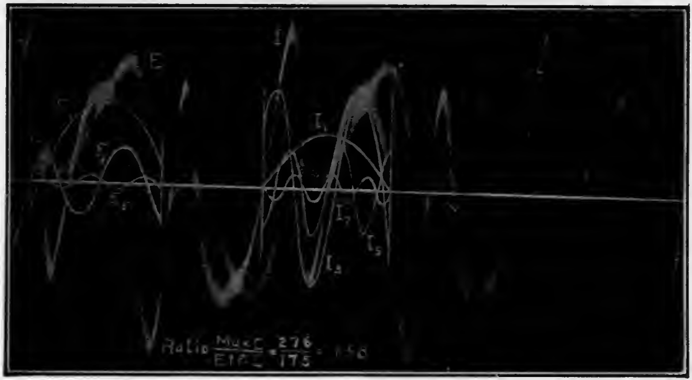

Fig. 9

The generator may be represented by a coil that is a source of voltage and having reactance and resistance; the transformer may be replaced by a shunt impedance of a value equal to the open-circuit impedance of the transformer, and by two series impedances, one representing the equivalent resistance and leak-

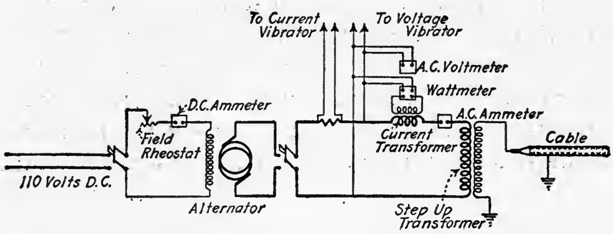

FIG. 10—DIAGRAM OF CONNECTIONS

age reactance of the primary side, and the other the impedance of the secondary reduced to the primary side; the cable represents a condenser referred to the primary side and having a very high effective resistance. Fig. 11 shows this condition.

The shunt impedance *b d* has a decided effect on the generator wave form, in that its current wave, especially at the higher voltages, is mostly made up of harmonics, and these, reacting on the generator flux, are responsible for the initial distortion to which reference has been already made. The series circuit *a b c d e*, consisting of the transformer primary and secondary resistances and leakage reactances and the condenser, all in series with the generator armature, exerts some influence on the generator wave form. The magnitude and shape of the generator current wave, may be dependent on the relation of inductance to capacity in this circuit. Therefore, harmonics may be intensified or diminished depending on their frequency, on the transformer

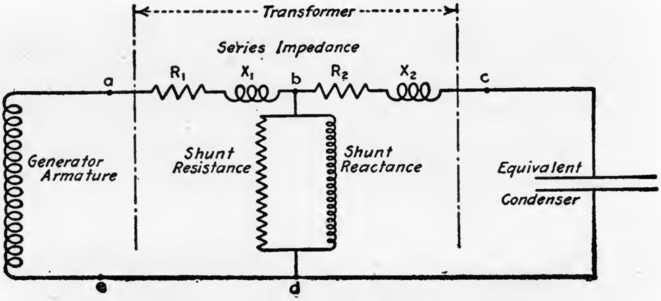

FIG. 11—EQUIVALENT CIRCUIT DIAGRAM

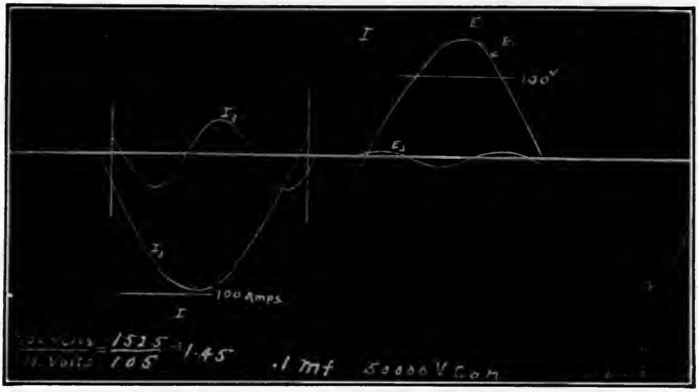

Fig. 12

inductance and the cable capacity. These effects are illustrated in Figs. 12 to 15 inclusive.

The oscillograms shown in Figs. 12 and 13 were taken when a cable having a capacity of 0.1 microfarad was connected to the transformer secondary, and those shown in Figs. 14 and 15 were taken with another cable having a capacity of 0.13 microfarad, connected to the transformer secondary. Two tests were made with each cable; one in which all four of the transformer secondary coils were connected is series (50,000-volt) connection, the other in which the series-parallel (25,000-volt) connection was used. In order to compensate for the change in transformer

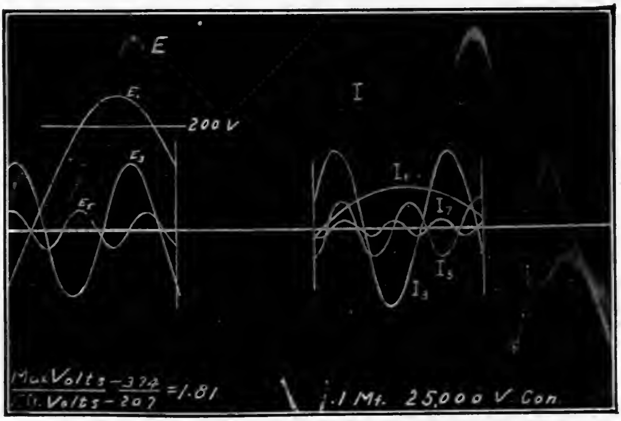

Fig. 13

ratio so that the effective voltage on the cable should remain approximately unchanged, the generator voltage was practically doubled when the change was made from the 50,000-volt to the 25,000-volt connection.

Figs. 12 and 14 show the results obtained with the 50,000-volt connection, and in each case the e.m.f. wave is very nearly sinusoidal, and no appreciable harmonics above the third, appear in the current wave. In each of these cases the generator was operated at low saturation, a condition in which it would be less able successfully to oppose severe reactions on the flux wave. The natural frequency of the transformer and cable circuit in the case of Fig. 12 is 110 cycles, and of Fig. 14, 96.6 cycles. The shunt circuit *b d*, owing to the variable nature of its inductance, would be difficult to take into consideration, except in a very general way and was consequently neglected in this frequency determination.

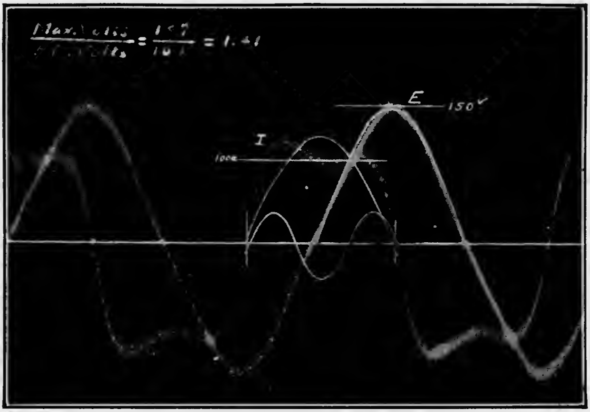

Fig. 14

In Figs. 13 and 15, the approximate sinusoidal e.m.f. waves shown in Figs. 12 and 14 are distorted, containing fair-size fifth harmonics, and third harmonics about 50 percent of the fundamental. In each case the current wave is even more distorted than the e.m.f. wave showing a seventh harmonic, a fifth equal in magnitude to the fundamental and a third about twice as great as the fundamental. In these cases, the natural frequency of the circuit was 215 and 192 cycles respectively.

Thus in each case, with the same generator, the same transformer, the same frequency and the same cable, an approximate sine wave is converted into a complex wave by simply changing the transformer ratio and the generator voltage. These phenomena cannot be explained on the basis of a resonant series circuit for the best wave shapes were obtained when the circuit constants were more conducive to the flow of the troublesome third and fifth harmonics. However, in these two latter cases the transformer exciting current contains harmonics of very appreciable magnitude as shown in Fig. 6, and in the writers' opinion, these harmonics are practically responsible for the results that were obtained.

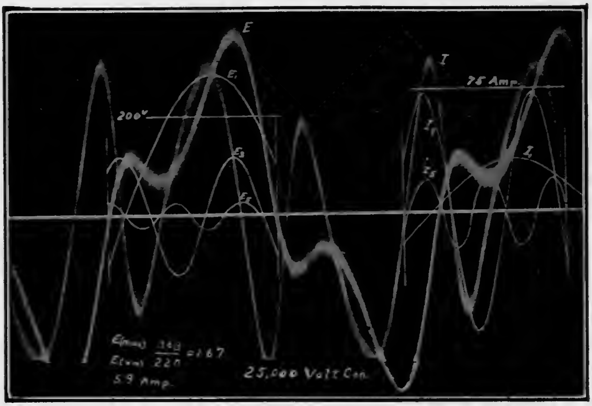

Fig. 15

It might also be added, referring to Fig. 11, that in the circuit *a b c d*, the resistance is very small, thus offering excellent opportunities for oscillations to take place during the transient or building up condition. Great care must be exercised in raising and lowering the voltage, as the possiblity of building up an abnormal potential across the cable is always present, and this may result in a puncture.

Specific illustrations of this have come to the writers' attention on several occasions. When the voltage across a cable was being gradually raised, the spark-gap, connected in parallel, would discharge light sparks, momentarily, when the switchboard voltmeter indicated that the potential across the gap was only half that at which the gap was set. If the voltage was held constant for an instant, the sparking would discontinue, and the voltage could then be raised cautiously without further disturbance. The fact that the gap was not ruptured showed that a transient rise of voltage occurred, but that there was insufficient energy to cause a dynamic arc.

USE OF REACTANCE

It occurred to the writers that the generator current might be considerably reduced by using a shunt reactance to neutralize the leading component of the cable-charging current, thus securing a better wave form by reducing the ampere load on the generator. This has been tried abroad* and also by the Edison Electric Illuminating Co. of Boston.†

We made nine tests, and in every case the same cable was used, namely 1000 ft. (305 m.) No. 1/0, 7/32 in. (5.56 mm.) wall, rubber insulation, having a capacity of 0.175 microfarad. Three different tests were made at each of three different voltages. At each voltage; first, the oscillogram was taken without the reactance; second, the reactance was adjusted until the line current was a minimum; and third, the reactance was adjusted for the best voltage wave form. The results of these tests are shown in Figs. 16A to 18C inclusive.

The following conclusions are to be drawn from the above tests.

(1) The point of minimum current does not necessarily correspond to the best wave shape.

(2) The best wave shape may occur at an abnormally large value of lagging current.

(3) The wave can not be made sinusoidal in every case.

(4) At the point of minimum current (usually denoting resonance for a parallel circuit) the power factor is below 50 percent in two cases, and 70 percent in the third, and the waves are not necessarily in phase.

Further, in Figs. 18A, 18B and 18C, when the generator voltage was low, there was but slight distortion in the e.m.f. wave, which tends to confirm the previous theories as to the effect of the transformer exciting current on the e.m.f. wave.

Thus with a commercial generator and transformer, the e.m.f. wave, by the use of reactance, could not always be made sinusoidal, and when this was accomplished, it was at the expense of greater generator capacity. This is undoubtedly due to the

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Electrotechnischer Zeitschrift, Feb. 27, 1908

†"High-Potential Cable Testing at Boston," by C. L. Kasson, *Electrical World*, Vol. 60, p. 354.

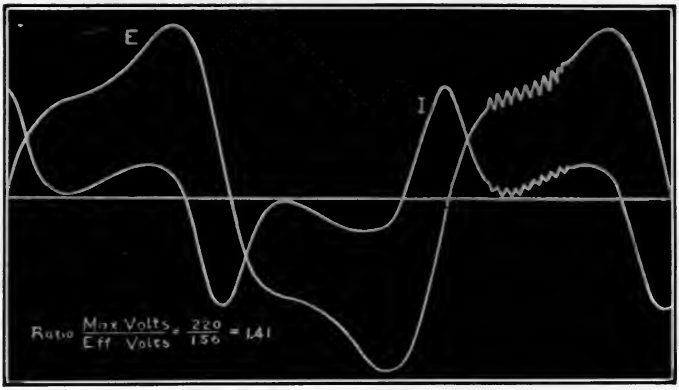

Fig. 16 A

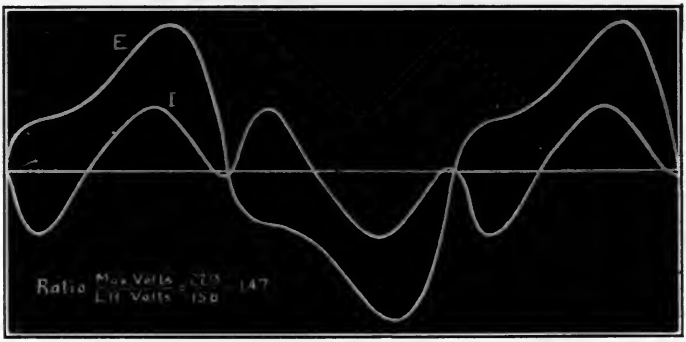

Fig. 16 B

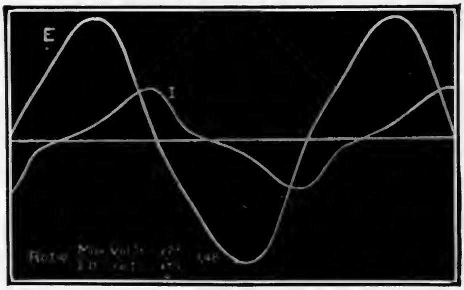

Fig. 16 C

Fig. 17 A

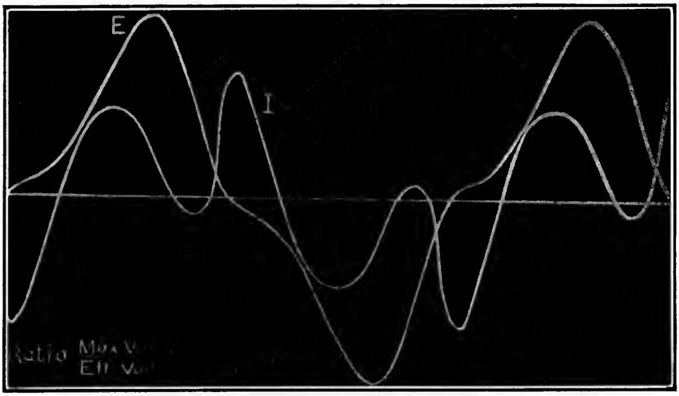

Fig. 17 B

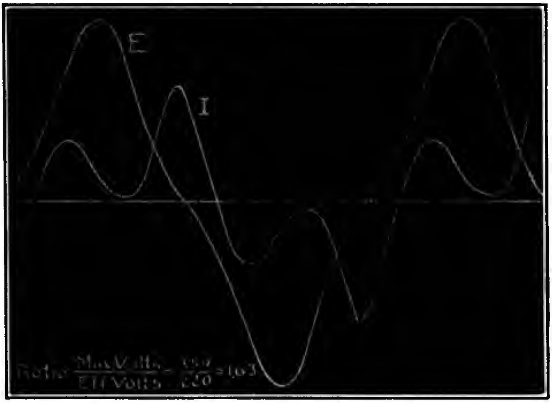

Fig. 17 C

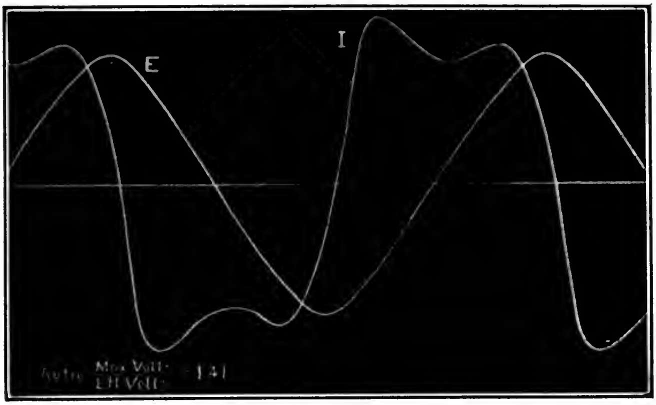

Fig. 18 A

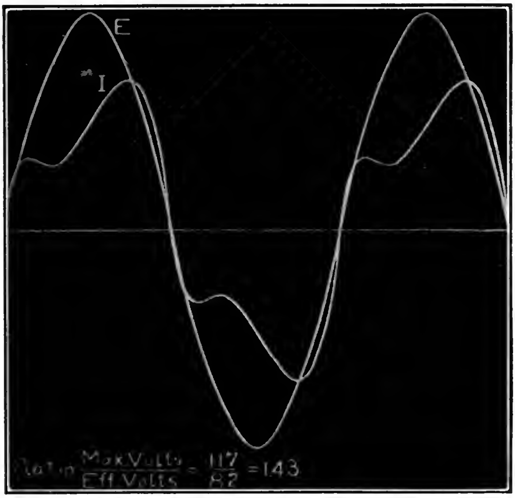

Fig. 18 B

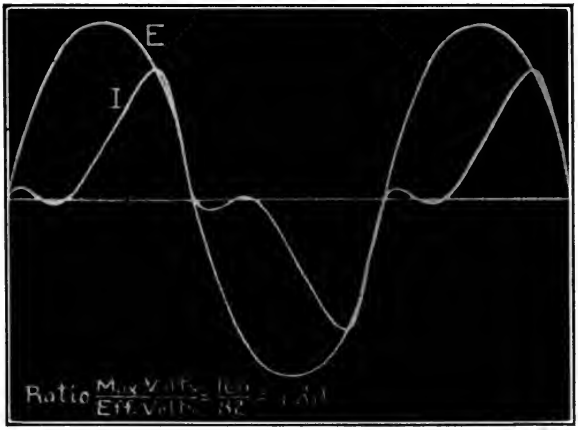

Fig. 18 C

fact that a circuit can be tuned to but one fequency at a time, and when the third harmonic current was neutralized, the reactance allowed a very arge fundamental to pass. The power-factor is explained by the fact that the harmonic currents in cable tests predominate in the current wave, whereas the voltage is largely fundamental. The harmonics in the current wave contribute no power with respect to the fundamental voltage, yet all add up in quadrature, contributing to the volt-amperes.

These results show that in our particular case, at least, a shunt reactance would be of but very little value in improving the generator wave form, and reducing the volt-ampere load of the generator.

Sine-Wave Generator

As a result of our tests, the wire manufacturer came to the conclusion that a generator of the ordinary design was wholly unsuited for reliable testing of wires and cables. Moreover, no manufacturer would guarantee a generator to produce an approximate sine wave under these severe conditions of test. The services of Prof. C. A. Adams of Harvard University were secured, and under his specifications such a generator was built and installed, rated at 85 kv-a. All oscillograph records, taken up to the present time and under various conditions of test, have failed to show any departure from a sine wave.

The 50-kv-a. transformer has been replaced by one rated at 75 kv-a., 75,000 volts, operating at a much lower core-density than the former, and taking a much less distorted exciting current. Hence the distorting influence of this current on the generator wave is much less than it was in the case of the 50-kv-a. transformer.

Method of Measuring Voltage

It is essential to obtain reliable knowledge of the maximum voltage to which the cable may be stressed under the preceding conditions of distorted wave form, if the tests are to be of any great value. Where the wave varies from a peaked to a flat-topped wave, the effective value is only a poor indication of what the maximum voltage may be. The circuit conditions are a function of so many variables that only a wide experience with his apparatus enables an operator to know what wave form may be expected under any given set of conditions.

The spark gap immediately suggests itself, as a means of determining these peak values. Although the needle gap is not conceded to be a device of high accuracy yet it is accurate enough for the work in hand. There are objections to its use, however. The voltage can only be determined by connecting the gap in parallel with the cable to be tested, and noting the transformer primary voltage when the gap breaks down at the predetermined value at which it is set. This is a very dangerous practise, as a disturbance is created in the highly oscillatory circuit already described, and cables have often been known to puncture at a voltage apparently much less than their rating, and after the gap had actually broken down. The spark gap can therefore be used only with considerable care, and the danger of a surge is always present. Furthermore, it is not a piece of apparatus that is easily or quickly manipulated, and is wholly unsuited for a testing room where a large number of tests must be completed in a short time.

The oscillograph in its ordinary form is a very satisfactory piece of apparatus for experimental work, but it requires considerable attention, is clumsy to handle, requires skill to manipulate, and it does not hold its calibration for any considerable time.

Prof. F. A. Laws of the Massachusetts Institute of Technology, and the writers, have, however, adapted the oscillograph principle to an instrument which may be placed directly on the switchboard, and from which the peak value of any voltage wave may be quickly and accurately determined. A sectional view of this instrument is shown in Fig. 19, and is almost self-explanatory.

The lamp, having a straight tungsten filament, is mounted so that its distance from the vibrator may be adjusted to suit the optical requirements of the system. The light then passes through suitable spherical lenses to the vibrator, from which it is reflected through a cylindrical lens to the ground glass screen, where the peak of the voltage wave may be determined from the extremity of the band of light.

The necessary vertical and horizontal adjustment of the beam of light can be made from the front of the switchboard by means of two milled heads which actuate the two adjusting rods. To compensate for changes in the amplitude of vibration due to variations of temperature and other causes, an adjustable rheostat is connected in series with the vibrator, and by throwing the vibrator circuit on direct current, with a double-throw switch, the calibration can be quickly and accurately made. A double scale is also provided. The magnets are operated at high saturation so that fluctuations in exciting current affect the instrument but slightly. The instrument as used, is connected to the secondary of a potential transformer, whose primary is connected directly to the high-tension circuit. Other views of the instrument are shown in Figs. 20 and 21.

To the manufacturer the importance of this type of instrument is evident. He is aware of the maximum stress at which his cables are being tested at all times, regardless of generator and transformer wave-form. No additional factor of safety is necessary in the cable due to uncertainty on this point. Furthermore, purchasers and inspectors can be quickly and convincingly shown that their cables are being tested at the specified voltage, without employing a troublesome oscillograph or a spark-gap, and without exposing the cable to the dangers accompanying the use of this latter device.

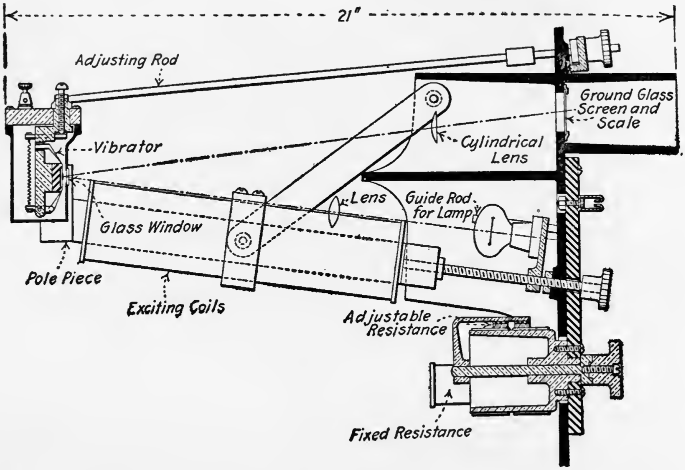

FIG. 19—SECTIONAL VIEW OF SIMPLEX VIBRATING VOLTMETER

This instrument is not only useful for cable-testing, but can be employed to advantage where apparatus other than cables must undergo potential tests. The e.m.f. waves of all testing-generators are not sinusoidal, even at light loads, and their wave-form may change with the field excitation.

When the e.m.f. is taken directly from a commercial circuit supplying other loads, this voltage wave may vary with the load and the number of generators on the system, as well as through the compensators and other control devices employed.

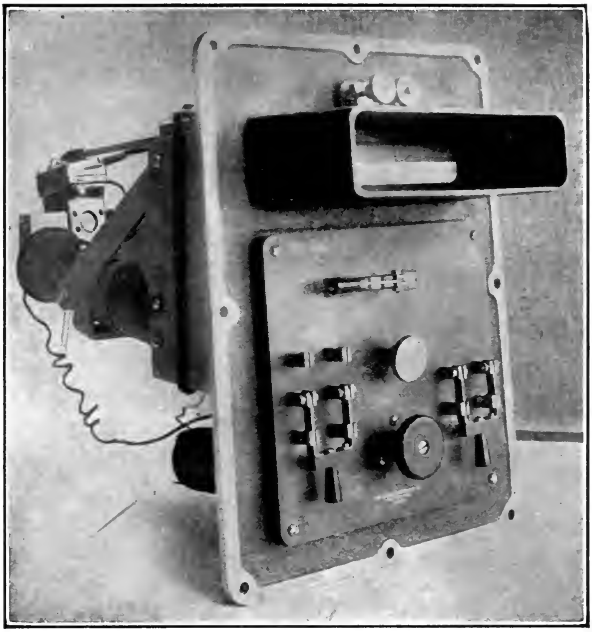

FIG. 20

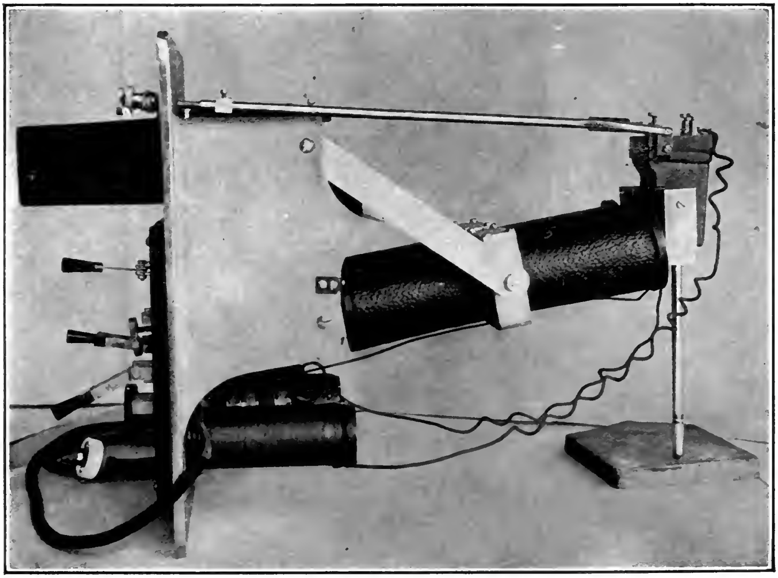

FIG. 21

This voltmeter is also capable of indicating slow-period transients which the ordinary type of meter owing to its inertia cannot follow. Instances of this have come to the writers' attention in the cases already cited, when the voltage was being raised on a cable. In a certain power system, it was found necessary to change the lightning arresters from 2300 to 3300 volts owing to the fact that continual discharges were taking place due to a considerable length of submarine cable having been added to the system. Whether this was due to a change in wave-form or to surges, the writers are not prepared to say, but such an instrument would have quickly given the required information.

In closing, the writers wish to express their thanks to Prof. F. A. Laws, of the Massachusetts Institute of Technology, for his part in the development of this instrument; to Mr. W. G. Wolfe, of Boston, for his assistance in developing the optical system; to Professors C. A. Adams, H. E. Clifford, and A. E. Kennelly of Harvard University, for their helpful suggestions and criticisms during the preparation of this paper.