Copyright 1911. By A. I. E. E.
(Subject to final revision for the Transactions.)

ELECTRIC LINE OSCILLATIONS

BY G. FACCIOLI

In the summer of 1910 some tests were performed on the lines of the Great Western Power Company, which are operated at 100,000 volts, to obtain information on oscillations and rises of potential, due to switching operations. In these experiments the oscillograph was extensively used and this paper deals

with some of the most important and representative records.

Since it was necessary to conduct the investigation without interrupting the operation of the system, the study of switching phenomena is rather incomplete and limited to no-load conditions.

Mr. W. W. Lewis, who assisted in these experiments, gives a description of the methods and apparatus employed, in an appendix to this paper.

FIG. 1

Fig. 1 is a map of the system of the Great Western Power Company. Two three-phase lines run on the same towers (Fig. 2) the conductors of each line being situated on a vertical plane. Each conductor consists of a copper cable No. 000, B. & S. gauge (seven strands, outside diameter $\frac{1}{2}$ in. approximately). The vertical

NOTE:—This paper is to be presented at the 28th Annual Convention of the A. I. E. E., Chicago, June 26-30, 1911. Notice of oral discussion or any written discussion should be mailed to reach the Secretary before the date of the meeting. Written discussion received within 30 days thereafter will be treated as if presented at the meeting.

distance between conductors is ten feet, and the horizontal distance between lines is 14 ft.

The following tests were performed:

1. Switching in and out an open three-phase line at the generating station by high-tension switches.
2. Switching in and out an open three-phase line and step-up three phase transformer at the generating station by low-tension switches.

FIG. 2.—Transmission line of Great Western Pr. Co. at Brighton

3. Switching in and out a three-phase line, connected at the end to an unloaded three-phase step-down transformer, by high-tension switches, at the generating station.

4. Switching in and out a three-phase step-down transformer at the end of an unloaded three-phase line by high-tension switches.

5. Switching, by high-tension switches, one of the three-phase lines unloaded, on and off the end of the other three-phase line, carrying normal load.

Before entering into the discussion of the oscillographic records, it is advisable to study the constants of the line which, as we said before, consist of three No. 000 B. & S. copper cables situated on a vertical plane. The distance between conductors is 10 ft. and the length of the line is 154 miles.

Line Inductance. The total inductance of each conductor is 0.323 henry.

Line Capacity. The total capacity of each conductor to the neutral is figured as 2.2 microfarads. It is interesting to compare this figure obtained by calculation, with the figure derived from actual test.

From a series of experiments, which it is superfluous to enumerate, we find that when the voltage at the generator end of the line is 51,700 volts from conductor to neutral, the voltage at the far end of the open line is 64,000 volts from conductor to neutral. In this case, the charging current per phase is 48 amperes.

Assuming the capacity of the line concentrated in two identical condensers, one at the beginning of the line, and the other at the end of the line, we have

$$48 = 2 \pi f c (51,700 + 64,000)$$

where f is the frequency, 60 cycles.

c is the capacity of each of the two condensers into which the line capacity was divided.

We find $c = 1.1$ microfarads.

This gives for the total line capacity from each conductor to neutral the value of 2.2 microfarads, which is identical to the value obtained by calculation.

Line Resistance. The ohmic resistance of each conductor is 50 ohms.

Generator Reactance. In all the experiments, the source of power is a 10,000 kv-a. three-phase generator. The windings of the generator are Y-connected, and the neutral is not grounded. The speed of the alternator is 400 rev. per min., its normal voltage is 11,000 volts. The machine has 18 poles and three slots per pole per phase.

In later calculations, we will frequently have occasion to use the value of the synchronous reactance, and of the leakage reactance of the generator.

The value of the synchronous reactance may be deduced by test, as follows:

Referring to Fig. 3, when the line is disconnected (high-tension switches open) the voltage of the generator is 4,430 volts between phase conductors.

When the line is connected (high-tension switches closed) the voltage of the generator for the same exciting current is 8,730 volts, and the current supplied by the generator is 400 amperes.

Neglecting the ohmic resistance and the exciting current of the step up transformer, we have

$$2 \pi f L_g 400 = \frac{8730 - 4430}{1.73}$$

where L_g is the synchronous inductance per leg and f is the frequency, 60 cycles.

FIG. 3

$$L_g = 0.01645 \text{ henry}$$

If we refer the synchronous inductance to the high-tension side of the step-up transformer, whose ratio of transformation is 9.56, we obtain a value of $L_g = 1.52$ henry.

The leakage inductance of the generator deduced by calculation is 0.00276 henry, and referred to the high tension side of the step up transformer is 0.253 henry.

Transformer Reactance. The transformers used in all the tests—step-up or step-down transformers—are 10,000 kv-a. three-phase transformers, delta connected on both primary and secondary sides.

The leakage inductance of the transformer referred to its high tension side (L_t) is 0.088 henry, from each conductor to neutral.

Electrostatic Capacity of the Apparatus. The capacity of the generator windings, and of the transformer windings plays an important role in some of the oscillations, as we will see later. However, no attempt is made to determine the value of these capacities.

The theory of the phenomena involved in this investigation is well understood, and will, therefore, be omitted with the exception of a few instances. All the calculations and theoretical considerations in this paper had their origin or inspiration from Dr. Steinmetz's treatise on "Transient Electric Phenomena and Oscillations."

TEST No. 1

Fig. 3 shows the arrangement of the apparatus. The potential was recorded across one phase of the low-tension side of the step-up transformer.

The current was taken either across the secondary of the current transformer connected in the low-tension circuit, or across

FIG. 4

the secondary of the current transformer connected in the high-tension circuit. All the switches in this and the following tests were of the oil type.

The low-tension switches were closed, and the generator and step-up transformer excited at a certain voltage. Then the 154 miles of three-phase line were switched in or out by means of the high-tension switches and the waves of e.m.f. and current were recorded at the moment of closing or opening the high tension switches.

The line under test was open at the far end.

Fig. 4 represents a simplified diagram of the connections.

L_g is the reactance of the generator.

L_t is the leakage reactance of the step-up transformer.

L_l is the reactance of the line.

c is one-half of the line capacity.

We neglect ohmic resistances and assume the susceptance of

the step up transformer equal to infinity. We neglect also the electrostatic capacity of the apparatus.

If, for a first approximation, we consider L_l as negligible, the closing and opening of the high-tension switches connects and disconnects the condenser given by the line capacity on and from the inductance of the generating system.

It is known that in a circuit consisting of a condenser in series with an inductance, the general expression of the e.m.f. across the condenser and of the current contains three terms.

The e.m.f. across the condenser is

$$e = e_1 + e_2 + e_3$$

And the current is

$$i = i_1 + i_2 + i_3$$

i_1 and e_1 are the values corresponding to stationary conditions of charging current and condenser potential at fundamental impressed frequency. The current leads the e.m.f. by 90 deg. and the effective value of the current is equal to the effective value of the e.m.f. divided by the line condensive reactance.

i_2 and e_2 represent a damped oscillation at a frequency independent of the impressed frequency but depending on the constants of the circuit, as follows:

$$\text{Frequency} = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \left(\frac{r}{2L}\right)^2}$$

Where L is the inductance of the circuit, C the capacity, and r the resistance.

This term depends mainly upon the point of the impressed e.m.f. at which the oscillation starts. There is no point at which this term is absent, and it reaches its maximum value when the oscillation starts at the maximum of the impressed e.m.f.

i_3 and e_3 depend on the constants of the circuit and upon the instantaneous values of current and of difference of potential in the circuit at the moment the oscillation starts.

A. SWITCHING IN OPEN LINE BY HIGH-TENSION SWITCHES

In the special case of switching in a line, if the operation is instantaneous and no secondary phenomena occur, the third term disappears since the e.m.f. and current in the line are zero at the moment the switches are closed.

The complex oscillation produced by closing the high-tension switches, thereby connecting suddenly the line condenser to the inductance of the generating system, will then consist in our case of a fundamental wave at 60 cycles on which is superimposed a damped oscillation whose frequency is—neglecting ohmic

$$\text{resistance—}f = \frac{1}{2\pi\sqrt{LC}}.$$

Referring to Figs. 3 and 4, $L = L_g + L_t$ (line inductance neglected).

C = total line capacity.

For L_g we must take the value of the true self-inductance of the armature of the generator, and not the value of the synchronous inductance, as the latter includes the effect of armature reaction which must act on the field circuit where any change in flux is retarded by a change in field current.

If, however, the oscillation lasts a comparatively long time, then the armature reaction may enter in the phenomenon.

$L = 0.253 + 0.088 = 0.341$ henry.

$C = 2.2$ microfarads.

Frequency of oscillation = 139 cycles.

If L_t is not neglected and the circuit is treated as represented in Fig. 4, the frequency of oscillation is 167 cycles. Finally, by taking the total synchronous inductance of the generator in the circuit represented in Fig. 4, the frequency of oscillation is 83 cycles.

In these calculations we have neglected the ohmic resistances, which are actually very low, so that they not only allow the occurrence of a free oscillation (r^2 less than $4L/C$) but do not practically affect the value of the frequency of oscillation.

This frequency is then comparatively low, and is between 83 and 167 cycles.

In Fig. 5, a 60-cycle wave is superimposed on a 120-cycle damped oscillation, and the resultant wave is almost identical to those obtained in the oscillograms, showing that the frequency of free oscillation found by test is of the same order of magnitude as calculated and approximately equal to 120 cycles.

However, the oscillograms show that closing the high-tension switches (Fig. 3) produces a more complicated phenomenon than theoretically assumed, as the switches do not close the circuit at once and permanently. Several secondary phenomena occur, as follows:

First: The three switches may not close the circuit at the same instant.

If one switch only closes its circuit, then one wire only of the three phase line is energized, and the potential of the system to ground is unbalanced (the system has no point permanently grounded). A charging current from this wire returns to the generator through the line capacity in series with the capacity to ground of the generating apparatus (transformer included) giving rise to a high frequency oscillation.

If two switches close and the third remains open, single-phase unbalanced load is thrown on the generator, giving rise to odd harmonics of the generated e.m.f. (third, fifth, etc.,) as shown clearly in some of the records.

FIG. 5

Since the first closing of a high-tension switch is generally due to an arc before the metallic contact is established, it is natural to expect that the three switches of a three-phase system will not begin to close the circuit at the same instant.

Second. Arcs strike between contacts and die out before the metallic circuit is permanently established. It follows that instead of one starting oscillation, we obtain a series of oscillations, due to the successive closing and opening of the circuit.

We should then expect to find in the records a number of successive oscillations, which consist of a fundamental 60-cycle wave superimposed on a damped oscillation of 120 cycles, when all the three phases of the line are being connected to the generating system. Other frequencies will appear when the three phases are not connected simultaneously, and at the instant

when the line and the generating system become disconnected, the line on one side and the generating system on the other side will oscillate at their own natural frequency. Since the oscillograms of the electromotive force are taken on the low-tension side of the generating system, our records do not show the free oscillations of the line, and, likewise, do not show some of the oscillations which occur at high-frequency between the high-tension side of the transformer and the line and which do not go through the iron of the apparatus.

Record No. 1. Referring to Fig. 3, this record is taken at the moment of switching in 154 miles of unloaded three-phase line onto the high tension winding of the step-up transformer by closing the high-tension switches.

Before the switches are closed the wave of e.m.f. gives the generator e.m.f. (4,500 volts, 60 cycles), which shows the harmonic due to the teeth of the machine, while the current—taken in the high-tension circuit—is obviously zero.

After a high frequency impulse in the e.m.f. and current, due probably to an arc in one of the switches, the circuit is closed and the oscillation has the appearance of the resultant wave of Fig. 5 (120 cycles superimposed on 60 cycles).

The current has two long zeros before the metallic contact is permanently established, due to arcs in the switch, and finally the last oscillation occurs, which is damped in less than three fundamental cycles.

The new conditions of equilibrium are now reached, and the record shows an e.m.f. of 9,300 volts and a charging current of 48 amperes.

It must be remembered that the e.m.f. is taken across two conductors of the low-tension circuit, while the current is taken in one conductor of the high-tension circuit. Therefore, if the current leads the corresponding e.m.f. by 90 deg., the record should show the high-tension current leading the e.m.f. by 60 deg. or lagging 120 deg. behind the e.m.f. In many of the records either the current or the e.m.f. should be reversed to obtain the proper phase relation.

After the complex oscillation has occurred, the e.m.f. is smooth and does not contain the harmonic due to the teeth of the alternator, because of the very high impedance offered by the generator reactance to the flow of this harmonic (17th harmonic), which *lags*, the inductive reactance of the generator being several times the condensive reactance of the line at that frequency.

RECORD No. 1

It is interesting to note that the first oscillation differs from the last in the wave of e.m.f. The first oscillation of e.m.f. shows a higher degree of distortion and contains odd harmonics (3rd and 5th) in addition to the natural frequency at which energy is exchanged between inductance and capacity. As pointed out above, this is due to the fact that all the three switches were closed at the last oscillation, while, very probably, all the three switches were not closed when the first oscillation started. Furthermore, while the first oscillation began with zero volts across the condenser, the successive oscillations started under different conditions. In fact, when the current is zero and the circuit is opened by the dying out of an arc in the switch, the e.m.f. across the condenser is near its maximum value and the energy thus stored in the line is dissipated at the natural frequency of the line, but this oscillation may not have died out entirely before the circuit is reestablished. This introduces a third term in the expression of the e.m.f. and current, as mentioned above.

FIG. 6

The record shows also high frequency impulses in the e.m.f., due mainly to a change of energy from leading to lagging or vice versa. For instance, high frequency appears in the e.m.f. whenever the current goes to zero and the arc in the switch dies out. This occurs especially when the current maintains a low value for a comparatively long time due to the interference between the 60-cycle and the 120-cycle waves.

Referring to Fig. 6. Let us assume that the line is disconnected when the charging current, which is leading, is passing through zero.

At this instant the impressed e.m.f. E is maximum. On E is superimposed the e.m.f. e , which is generated by the flow of the charging current i through the reactance of the generating system, so that $E + e$ is active across the condenser. At the next instant the high tension current remains zero, because the arc in the high tension switch has died out, but the generator must excite the transformer, which is still connected. Hence, lagging energy is supplied, and a current j flows. The current j produces an e.m.f. e' across the reactance of the generating system.

It follows that a sudden change of difference of potential has occurred with the corresponding change of energy stored in

the capacity of the generating system. The new equilibrium is reached through an oscillation at the natural frequency of the apparatus.

This high-frequency appears in the e.m.f. of the low tension circuit and obviously not in the high tension current, but we must expect to find it in the low tension current, as we will see later.

The *switching-in* is then complicated by arcs and by the irregular closing of the three switches.

The record shows only the phenomena occurring in one particular conductor and phase, and does not show—as stated before—the free oscillations of the line. This line—154 miles long—oscillates at a frequency of 300 cycles when the length of the line corresponds to a quarter wave length.

The records also do not show, or show incompletely, what happens at the very first establishing of the circuit, as only the oscillations passing through the iron of the step-up transformer and of the measuring transformer are recorded. At the very first establishing of the circuit, the energy stored in the high-tension winding of the step-up transformer is thrown into the line, and a direct record of the high-tension e.m.f. would show this phenomenon and the process by which the potential is established on the line.

Finally, the records do not show what happens at the open end of the line, where the wave of e.m.f. undergoes a total deflection.

Record 1 gives as maximum over-tension 60 per cent above final maximum voltage. The current reaches a maximum of 160 per cent above final maximum value. The total complex oscillation lasts for a length of 10 fundamental cycles, or one-sixth of a second.

Record No. 2. This record is taken under the same conditions as the preceding record, but it gives the current in the low-tension circuit instead of the current in the high-tension circuit.

We start again with an e.m.f. of 4,500 volts and the exciting current of the transformer, which is so small that it does not show in the record. Then an oscillation similar to the one of Record 1 occurs, and finally we have 9,300 volts and 450 amperes.

All the remarks concerning the preceding record apply to this record, and the low-tension current shows, as expected, high frequency impulses when the arcs in the high-tension switches die out.

The maximum over-tension is 55 per cent above the final

RECORD No. 2

RECORD No. 3

maximum value, while the current reaches a maximum of 175 per cent above the final maximum value.

The complex oscillation lasts nine fundamental cycles, or three-twentieths of a second.

B. SWITCHING OFF OPEN LINE BY HIGH-TENSION SWITCHES

Fig. 3 shows the connections used, and the records are taken at the moment of opening the high-tension switches, thereby disconnecting the line from the high-tension winding of the step-up transformer.

If the switching is instantaneous, then the sudden falling of the current I to zero gives an increase of potential E , such that

$$\frac{C E^2}{2} = \frac{L I^2}{2} \text{ where } C \text{ is the capacity and } L \text{ the inductance of the}$$

line. In other words, the electromagnetic energy stored in the system is transformed into electrostatic energy, and will be gradually dissipated.

Let us consider now the other limit case where the switch opens the circuit very gradually through a continuous arc, which increases slowly in length and resistance, so that the successive adjustments in value and phase of current and e.m.f. follow the progressive change in the conditions of the circuit. In this case, the disturbance is reduced to a minimum, but it is evident that the gradual modification of the circuit and of its constants occurs in the switch, where the most active consumption of the energy stored in the system takes place. It follows that, generally speaking, the opening of the circuit imposes severe conditions on the switch.

Between these two limit cases, approaching one or the other, according to the constants of the circuit and the characteristics of the switch, lies the actual opening of the circuit in practice.

The phenomenon is complicated, however, by the fact that the arc in the switch is apt to rupture and reestablish itself several times before the circuit is permanently opened.

From this point of view we see that the phenomena and oscillations which accompany the opening of the circuit are very similar to those met with in closing the circuit. Two main differences exist, however. First, in opening the circuit the movable contact of the switch travels away from the other contact, while in closing the circuit, the movable contact travels toward the other contact.

In the latter case, then, the first arcs which strike are long,

and there may be long intervals between arcs, while there is little or no probability of rupturing small arcs near the end of the stroke. In the former case short arcs may die out at the zero points of the wave of current, but will be at once reestablished owing to the short distance between contacts, while the striking of long arcs at the end of the stroke appears improbable when the movable contact is rapidly moving away from the fixed contact.

Second, in opening the circuit, if the interval between successive arcs is short, then the oscillation produced when the circuit is reestablished finds the potential across the condenser very nearly equal to the impressed e.m.f. while in closing the circuit, at the first instant, the e.m.f. across the condenser is zero, and in the successive starting oscillations the difference between the impressed e.m.f. and the condenser e.m.f. may be considerable owing to the comparatively long time during which the circuit was left open.

Record No. 3. This record starts with an e.m.f. of 9,300 volts and 49 high-tension amperes.

The high-tension line is disconnected from the generating system through an oscillation which lasts four fundamental cycles, or one-fifteenth of a second, and then the e.m.f. falls to 4,500 volts and the high-tension current to zero amperes.

Before the oscillation of current begins the peaks of the waves of e.m.f. for five half-cycles show an almost instantaneous break apparently due to arcs which occur near the maximum value of the e.m.f. on the rising side.

This shows that the switch started to open the circuit $\frac{5}{2 \times 60}$
 $= 1/24$ th of a second before the current in this particular conductor starts its oscillation.

Here again we note the absence of long zeros between arcs and the absence of high frequency impulses, except at the moment of final opening when the energy supplied by the generator changes from leading to lagging.

It is also remarkable that the wave of e.m.f. is hardly affected and that only a slight over-tension is produced, while the current reaches very high values. This oscillation of the current is similar to that obtained in closing the circuit and has the usual frequency of 120 cycles superimposed on the fundamental.

An inspection of the current wave shows, however, that the 120 cycles oscillating current does not start opposite in phase to

the fundamental current as seen in the previous records, but its starting zero is shifted 60 deg. from the zero of the fundamental, showing that this oscillation of current is started by an arc opening the circuit and re-closing it in one of the two switches other than that in series with the current transformer from which the record is taken.

This may explain also why the e.m.f., which is the e.m.f. of one phase of the delta, is not distorted.

We must remember, however, that the record gives the e.m.f. in the low-tension circuit and therefore does not show the phenomena which occur in the line and in the high-tension winding of the transformer, where the sudden change of conditions may produce high frequency impulses interesting the capacity of the line and the air reactance only of the high-tension winding of the transformer.

Record No. 4 is similar to record No. 3. It starts with 9400 volts and 450 low-tension amperes. After the line is disconnected the volts fall to 4400 and the current becomes the exciting current of the step-up transformer. In Record No. 4 the oscillation is limited again to the current and shows two successive arcs, the first, quickly reestablished, in the switch in series with the current transformer, originating high frequency in the e.m.f.; the other probably in one of the other switches.

Here again the over-tension is small (30 per cent above normal maximum value), while the current reaches a very high maximum value. The total time of the oscillation is $3\frac{1}{2}$ fundamental cycles, or a little more than one-twentieth of a second.

TEST No. 2

A. SWITCHING IN OPEN LINE AND STEP-UP TRANSFORMER BY LOW-TENSION SWITCHES

Fig. 3 gives the diagram of connections.

The low-tension switches are left open and the generator excited to a certain voltage. The high-tension winding of the transformer is connected to the line (high-tension switches closed). The records are taken at the moment of closing the low-tension switches, thereby energizing step-up transformer and line.

The switching by low-tension switches differs from the switching by high-tension switches mainly in the following points: First, the switches are of the oil type but of different design. Second the energy must go through the transformer before reaching the line and therefore there will be no steep wave fronts

RECORD No. 4

RECORD No. 5

entering the line. Third, the magnetization of the transformer calls for an oscillation of magnetizing current depending on the point of the wave of e.m.f. at which the switching occurs. Generally speaking, if the switches are closed at the maximum of the wave of e.m.f. no rush of current will occur provided the residual magnetism is zero. If the switching occurs at the zero point of the e.m.f. then in the first half-cycle the induction in the iron must grow to twice the normal maximum value and a rush of current follows, etc.

These oscillations of magnetizing current will appear, of course, in the waves of low-tension current only.

Fourth, owing to the small voltage and the small distance between contacts the arcs in the low-tension switch are less severe and less frequent.

Substantially, however, the oscillations will present the same character as in the high-tension switching.

Record No. 5 gives the low-tension volts and high-tension amperes when the low-tension switches are closed. (Fig. 3).

For this record the potential transformer through which the wave of e.m.f. is taken is connected on the generator side of the low-tension switches (instead of on the line side as shown in Fig. 3). The record, therefore, starts with the no-load e.m.f. of the generator (4400 volts) and zero high-tension current.

After the oscillation is completed, the e.m.f. is 9300 volts, and the high-tension current is 48 amperes. The conditions are therefore identical to those of Record 1. The maximum over-tension is 50 per cent above the final maximum value, and the current reaches a maximum value of 108 per cent higher than the final maximum value.

The oscillation lasts three fundamental cycles, or one-twentieth of a second.

The oscillation consists of two parts: First, a very short high frequency impulse in the e.m.f. due very likely to only one switch closing the circuit, then the usual oscillation of e.m.f. and current resulting from the 120 cycles damped wave superimposed on the fundamental.

It must be noted that in this case there is practically *one* fundamental oscillation, that is to say, the switches did not produce arcs which opened and closed the circuit several times before establishing permanent contact. As mentioned above, the oscillation of current due to the magnetization of the transformer does not show in this record, which gives high-tension current.

RECORD No. 6

RECORD No. 7

Another interesting point shown by the record is the rapidity with which the oscillation is damped.

Record No. 6. This is taken under conditions identical to those of Record 5. Since the potential transformer through which the wave of e.m.f. is taken is connected in this case on the line side of the switches this record starts with zero e.m.f. However, the idle line experimented upon runs parallel to the other three-phase line, which was carrying normal load during the test, and, therefore, the small e.m.f. due to the mutual induction between the two lines appears before the switches are closed.

The oscillation is very similar to that shown in the preceding record, and it is apparent that the switches did not close simultaneously, as the wave of e.m.f. starts ahead of the wave of current.

The maximum over-tension is 55 per cent above the final maximum value of the e.m.f. and the maximum value reached by the current is 165 per cent higher than the final maximum value of the current. The oscillation lasts $4\frac{1}{2}$ cycles, or a little less than one-fourteenth of a second.

Record No. 7 gives the low-tension e.m.f. and low-tension current under conditions similar to those of the two preceding records.

The potential transformer through which the wave of e.m.f. is taken is on the generator side of the switches, and the record starts with the no-load e.m.f. of the generator (4450 volts) and zero low-tension current.

After the oscillation is completed, the e.m.f. is 9400 volts and the current is 450 amperes.

The maximum over-tension is 40 per cent above the final maximum value of the e.m.f. and the maximum value reached by the current is 125 per cent higher than the final maximum value of the current. The total oscillation lasts $8\frac{1}{2}$ fundamental cycles, or seven-fiftieths of a second.

This record shows clearly how the switches may not close the circuit at the same instant. In fact, before the current has started the e.m.f. is distorted for $4\frac{1}{2}$ cycles. This distortion of the e.m.f. shows the existence of a single-phase load, and the dissymmetry between the positive and negative waves of the e.m.f. reveal the presence of a considerable rush of magnetizing current. Then the third switch closes and the oscillation is similar to those obtained in the two previous records.

RECORD No. 8

RECORD No. 9

B. SWITCHING OFF OPEN LINE AND STEP-UP TRANSFORMER BY LOW-TENSION SWITCHES

Fig. 3 gives the diagram of connections. The generator excites the line through the step-up transformer, and the oscillation is recorded at the moment of opening the low-tension switches.

Record No. 8 gives the low-tension e.m.f. and low-tension current. It starts with 9300 volts and 450 amperes. After the oscillation is completed, the voltage and current fall to zero, since the potential transformer through which the wave of e.m.f. is taken is connected on the line side of the switch.

The maximum over-tension is 43 per cent above the normal maximum value of the e.m.f. and the maximum value reached by the current is 56 per cent higher than the normal maximum value.

The oscillation lasts a comparatively long time and is not completed in the record.

After the secondary current has entirely died out and the low-tension switches have disconnected permanently the transformer and line from the generating system, the e.m.f. across the secondary winding of the transformer still continues and reaches the zero value through a long, slow oscillation.

When the low-tension switches are entirely open, the high-tension winding of the transformer is still connected to the line and the presence of the e.m.f. on the low-tension side of the transformer is explained by an exchange of energy between the capacity of the line and the open-circuited inductance of the transformer.

Record No. 9 shows this very clearly. This record gives the low tension e.m.f. and high tension current under conditions similar to those of *Record 8*.

The record starts with 8650 volts and 44 amperes. In this case both current and e.m.f. do not rise above their normal maximum value. The oscillation lasts for 15 cycles, or one-quarter of a second.

After the secondary switches are opened the line and the transformer slowly synchronize. The high-tension current (which obviously has no image in the open secondary) consists of impulses having the characteristic shape of currents exciting iron circuits, and shows a strong decrement due to losses. The frequency of oscillation is very low, as the oscillating circuit is composed of the line capacity and of the total open-circuited

inductance of the transformer. The frequency also decreases gradually because the e.m.f. and flux density decrease and therefore the inductance of the transformer increases, lowering the frequency.

TEST No. 3

A. SWITCHING IN BY HIGH-TENSION SWITCHES UNLOADED LINE CONNECTED AT THE FAR END TO STEP-DOWN TRANSFORMERS

Fig. 7 is the diagram of connections used in this test. The end of the line is connected to an unloaded 10,000 kv-a. step-down transformer, delta-connected on both primary and secondary sides.

The generator excites the step-up transformer and the oscillation is recorded at the moment of closing the high-tension switches at the power house.

This test is similar to test 1-A, with the difference that the

FIG. 7

three-phase line is not open at the far end, but closed by an unloaded three-phase step-down transformer.

Fig. 8 gives the equivalent circuits corresponding to the connections of Fig. 7. If we compare Fig. 8 with Fig. 4, we find that in the case of Fig. 4 the oscillations occur between the line capacity (neglecting line inductance) and the inductance of the generating system, while in the case of Fig. 8 the oscillations occur between the same line capacity and the inductance of the generating system connected in parallel to the open-circuit inductance of the step-down transformer. Since this open-circuit inductance of the transformer is exceedingly high in comparison with the inductance of the generating system, we conclude that the frequency of oscillation and in general all the phenomena met with in Test 1-A will be reproduced in Test 3-A. The switches used in both tests are the same.

Record No. 10 gives the low-tension e.m.f. and high-tension current when the high-tension switches connect the unloaded line and step-down transformer to the generating system.

The record starts with 4400 volts and zero current. After the oscillation is completed, the volts are 8700 and the high-tension current 43 amperes.

This record shows all the features pointed out in Test 1-A, namely, irregular closing of the switches, long zero of current, e.m.f. distorted by single-phase load, and oscillations due to a damped 120 cycles wave superimposed on the fundamental.

A new feature, however, which was not given by Record 1, is the distortion of the line current due to the magnetization of the step-down transformer. The line current assumes regular form after approximately 20 cycles following the completion of the main oscillation.

The maximum over-tension is 50 per cent above the final maximum value of the e.m.f. and the maximum value of the

FIG. 8

current is 200 per cent higher than the final maximum value of the current.

The total oscillation (disregarding the distortion due to the magnetization of the step-down transformer) lasts about 8 cycles, or a little less than fourteen-hundredths of a second.

In conclusion, the phenomena are substantially the same whether the line is open or closed on an unloaded transformer.

Record No. 11 is taken across one of the low-tension windings of the step-down transformer and shows the establishing of the electromotive force on the low-tension side when the high-tension switches are closed at the power house 154 miles away. The record starts showing a small e.m.f., due to the mutual inductance on the line under experiment from the parallel loaded line, and the final voltage is 12,000 volts. This corresponds to a voltage of 87,500 volts on the high-tension side of the step-down transformer, while the voltage on the high-

RECORD NO. 10

RECORD NO. 11

tension side of the step-up transformer at the power house is 81,400 volts. Of course, the record does not show what occurs on the high tension side of the step-down transformer, where the incoming wave of electromotive force is partially reflected.

B. SWITCHING OUT BY HIGH-TENSION SWITCHES UNLOADED LINE CONNECTED AT THE FAR END TO STEP-DOWN TRANSFORMER

Fig. 7 gives the diagram of connections used in this test. The oscillation is recorded at the moment of opening the high tension switches at the power house, thereby disconnecting the line and step-down transformer from the generating system.

This test is similar to Test 1-B, with the difference that the three-phase line is not open at the far end, but connected to a step-down transformer.

Record No. 12 gives the low-tension electromotive force and the high-tension current at the moment of opening the high-tension switches (see Fig. 7).

The record starts with 8700 volts and 43 amperes. After the oscillation is completed, the current falls to zero and the e.m.f. becomes the no-load voltage of the generating system, 4400 volts.

All the considerations mentioned in connection with Tests 1-A, 1-B and 3-A apply to this case, since the high-tension switches are the same in the four experiments.

The wave of e.m.f. shows that an arc dies out and is immediately reestablished in one of the switches, then—after less than half a cycle—a similar phenomenon is repeated, and the oscillation proper begins. At this moment the arcs in the switches are of such nature as to modify the conditions of the circuit, and the current shows the characteristic resultant wave due to a 120 cycle damped oscillation superimposed on the fundamental wave.

Here, again, the oscillation is damped very quickly, a considerable part of the energy being dissipated in the long arcs of the switches.

Record No. 13 is the complement of the preceding record, and gives the potential across one phase of the low-tension winding of the step-down transformer at the end of the line when the switches are opened at the power house under conditions similar to those of Record 12.

Record 13 starts with 12,000 volts, corresponding to 87,500 volts between line conductors at the receiving end of the line, the voltage at the power house being 81,400 volts.

RECORD No. 12

RECORD No. 13

Record 13 shows that the dying out of the electromotive force across the secondary of the step-down transformer consists of two distinct periods.

First, the high-tension switches at the power house are opening the circuit and modify the conditions of the circuit for the length of about one fundamental cycle. Second, the high-tension switches at the power house are permanently opened, and the typical low-frequency oscillation takes place between the capacity of the line and the open-circuited inductance of the step-down transformer, as in the case of Test 2-B.

In Record No. 12 the maximum over-tension is 20 per cent above the maximum value with line connected, and the current reaches a value 116 per cent higher than the maximum value of the charging current. The oscillation lasts three cycles, or one-twentieth of a second.

In Record No. 13 the maximum over-tension is 26 per cent above the maximum normal value.

TEST No. 4

A. SWITCHING IN BY HIGH-TENSION SWITCHES THE STEP-DOWN TRANSFORMER (10,000 KV-A.) AT THE RECEIVING END OF THE LINE

Referring to Fig. 7, the line is energized by the generator through the step-up transformer, and the records are taken at the moment of closing the high-tension switches at the far end of the line, thereby energizing the step-down transformer.

The high-tension oil type switches used in this test are different in design from the high-tension switches used in Tests 1 and 3.

However, the remarks made before on the irregular closing of the switches hold in this case also.

From a theoretical point of view, the most convenient way to picture the phenomenon consists, perhaps, in considering the winding of the transformer as a high-tension line, closed at the far end and under peculiar conditions of electrostatic capacity and inductance. Since the high-tension winding of this step-down transformer has a total length of approximately ten miles, this view of the phenomenon is plausible.

The records are taken on the low-tension side of the step-down transformer, therefore they reveal the establishing of the difference of potential across the low-tension windings, but fail to show the phenomena connected with the first instant of closing the circuit, when the line is, so to speak, drained by the high-tension winding of the transformer.

RECORD No 14

RECORD No. 15

Record No. 14 gives the low-tension e.m.f. across one phase of the low-tension delta of the step-down transformer (which is delta-connected on both primary and secondary sides.)

The record starts, obviously, with zero electromotive force, and after the oscillation is completed the e.m.f. is 12,000 volts, corresponding to 87,500 volts across line conductors.

Record 14 shows an oscillation consisting of three distinct periods: First, a difference of potential is established across the phase of the secondary winding under investigation, and this difference of potential falls to zero through an oscillation, due very probably to the striking of an arc in one of the switches only. Second, another switch closes the circuit, and a normal wave of e.m.f. of small value is established across the secondary winding. In this connection it must be noted that if two switches close the circuit, the full potential is applied at the terminals of the wind-

FIG. 9

ing connected across the two switches, while each of the other two windings of the delta receive one-half of the full difference of potential. This explains the low value of the e.m.f. in the second period of the oscillation. Third, all the three switches have closed the circuit, and the oscillation proper begins, showing an asymmetrical wave of e.m.f. due to the rush of current exciting the step-down transformer.

Record No. 15 shows these phenomena more clearly and gives the high-tension current as well as the low-tension e.m.f. at the moment of switching in the step-down transformers at the end of the line.

Record 15 was taken on the system of the Sierra & San Francisco Power Company, when three 3,750 kv.-a. transformers, unloaded, were switched in at the end of 135 miles of three-phase line.

Fig. 9 gives the connections used in this case, the step-down

transformers being Y-connected, with grounded neutral, on the high-tension side, and delta-connected on the low-tension side.

The e.m.f. was taken across one phase of the low-tension delta and the current is the current flowing to ground through one of the high-tension windings.

Record 15 shows again the three periods in the oscillation of the e.m.f. and the rush of exciting current. The final voltage is 12,000 volts, corresponding to 104,000 volts across phase conductors.

The oscillation of e.m.f. in Record 14 lasts 10 cycles, or one-sixth of a second, and apparently no over-tension occurs.

A record of the generator e.m.f. and current taken at the power house at the moment of switching in the step-down transformer at the end of the line, under conditions described in connection with Record 14, shows no distortion whatever of the e.m.f. of the generator, but a distortion of the wave of current, due to the magnetization of the transformer.

B. SWITCHING OUT BY HIGH-TENSION SWITCHES THE STEP-DOWN TRANSFORMER (10,000 KV-A.) AT THE RECEIVING END OF THE LINE

Fig. 7 gives the connections used in this test.

The records are taken at the moment of opening the high-tension switches at the end of the line, thereby disconnecting the 10,000 kv-a. step-down transformer from the line.

All the apparatus and connections are the same as those used in Test No. 4-A.

Record No. 16 gives the electromotive force across one phase of the secondary delta at the moment of opening the high-tension switches, which disconnect the step-down transformer from the line.

The record starts with an e.m.f. of 12,000 volts, corresponding to 87,500 volts across line conductors, and after the oscillation is completed the voltage is obviously zero. The main oscillation lasts 4 cycles, or one-fifteenth of a second, and the maximum over-tension is 20 per cent above the normal maximum value.

The most important frequency in this oscillation is the natural frequency of the transformer, which appears more and more prominent the more elastic and unstable is the connection between the transformer and the line, *i.e.*, when the switches begin to open the circuit their arcs are short and steady and the fundamental frequency applied to the transformer is but little

RECORD No. 16

RECORD No. 17

disturbed by the oscillation of the transformer. As the arcs become longer and the supply of energy to the transformer becomes more difficult, the natural frequency of the apparatus asserts itself more and more until, at the very end, the transformer is free to oscillate at its natural frequency. This natural frequency of the transformer is approximately 1700 cycles.

After the main oscillation is completed another short oscillation occurs, due probably to an arc in one of the switches. This last oscillation recalls in its character the beginning of the oscillation of Record 14, when the transformer was switched onto the line.

Record No. 17 is taken under identical conditions to Record No. 15, with the difference that the three step-down transformers (see Fig. 9) are switched off the end of the line of the Sierra & San Francisco Power Co. The apparatus, connections and conditions of Record 17 are identical with those of Record 15.

Record 17 confirms entirely the results obtained by Record 16.

A wave of generator e.m.f. and current taken at the power house at the moment of switching out the step-down transformer under the conditions of Record 16, does not show any distortion in the waves of current and e.m.f. of the generator.

TEST No. 5

A. SWITCHING BY HIGH-TENSION SWITCHES ONE OF THE THREE-PHASE LINES, UNLOADED AND CONNECTED AT THE FAR END TO A STEP-DOWN TRANSFORMER, ONTO THE END OF THE OTHER THREE-PHASE LINE CARRYING NORMAL LOAD

Fig. 10 gives the diagram of connections used in this test.

Line No. 2, excited by three 10,000-kv-a. three-phase alternators and three 10,000-kv-a. three-phase step-up transformers, carries a load of approximately 20,000 kilowatts, the majority of which is delivered at the end of the line—Oakland substation—154 miles away from the power house.

Line No. 1 is unloaded and connected at the power house to an idle 10,000 kv-a. step-down transformer.

Records are taken when the beginning of Line No. 1 is thrown at the Oakland substation by high-tension switches onto the high-tension bus bars, energized by Line No. 2. The high-tension switches are of the same type as those used in Test No. 4.

As stated before, the two lines are identical and run on the same towers for the whole length—154 miles. Therefore, when the high-tension switches are closed at the Oakland substation

the circuit consists of a loop 308 miles long, whose beginning and end are both at the power house.

Record No. 18 gives the electromotive force on the low-tension side of the generator end of the loop, and the electromotive force on the low-tension side of the step-down transformer at the receiving end of the loop. One of the electromotive forces is reversed in phase to avoid confusion.

It being necessary to maintain the load of Line No. 2 in operation and in consequence to avoid great variation in voltage, the voltage at the generator end of the loop was regulated by hand at the moment the switching occurred at the Oakland substation. The records, therefore, do not give the true oscillation in voltage and over-tension, which would have occurred if the fields of the generators had been kept constant.

FIG. 10

When one line is connected to the other, the most prominent frequencies which appear are the full-wave oscillations of the total loop and of each line. Since the total loop is 308 miles long, its full-wave oscillation has a frequency of 600 cycles, while each line—154 miles long—has a full-wave oscillation of 1200 cycles, neglecting ohmic resistance.

Record No. 18 starts with 11,100 volts at the generator end of Line No. 2 and zero volts at the receiving end of Line No. 1. After the oscillation is completed, the regulated voltage at the generator end of Line No. 2 is 11,225 volts, while the voltage at the receiving end of Line No. 1 is 9,850 volts.

These last voltages correspond to 107,500 volts between line conductors at the generator end of the loop and 94,300 volts between conductors at the receiving end of the loop.

RECORD No. 18

RECORD No. 19

All the remarks made before on the performance of high-tension switches apply, obviously, to this case and are not repeated.

The oscillation lasts 3 cycles, or one-twentieth of a second. The main frequency superimposed on the fundamental is approximately 1200 cycles.

Record No. 19 covers the same experiment as *Record No. 18*, but is taken at the switching point--the Oakland substation--on the low-tension side of the transformers carrying the load.

The record starts with a voltage of 11,300 volts and after the oscillation is completed, the voltage is 11,900 volts. This last voltage corresponds to 86,800 volts between line conductors at Oakland, while the voltage at the power house, at the generator end of the loop, is 105,200 volts.

The oscillation lasts nine cycles, or less than one-sixth of a second. A frequency of about 1200 cycles is superimposed on the fundamental.

No conclusion can be drawn as to the over-tension because the voltage was regulated at the power house, as explained above.

B. SWITCHING BY HIGH-TENSION SWITCHES ONE OF THE THREE-PHASE LINES, UNLOADED AND CONNECTED AT THE FAR END TO A STEP-DOWN TRANSFORMER OFF THE END OF THE OTHER THREE-PHASE LINE CARRYING NORMAL LOAD

Fig. 10 gives again the diagram of connections.

Record No. 20 is taken under conditions similar to those of *Record 18*, but it gives the low-tension voltages at the generator end and at the receiving end of the loop when the high-tension switches are opened at the Oakland substation and the idle Line No. 1 is disconnected from the loaded Line No. 2.

The record starts with 11,225 volts (107,500 volts between line conductors) at the generator end of the loop, and 9,850 volts (94,300 volts between line conductors) at the receiving end of the loop. After the oscillation is completed, the volts at the generator end of the loop are 11,100 (106,000 volts between line conductors) and the voltage at the receiving end of the loop is zero.

The oscillation of voltage at the beginning of the loop lasts six cycles, or one-tenth of a second. At the receiving end the oscillation is composed of two parts: The first part covers the period during which the high-tension switches are opening the circuit. The second part occurs after the switches are entirely opened and shows the characteristic exchange of energy be-

RECORD No. 20

RECORD No. 21

tween the disconnected line and the step-down transformer at low frequency.

The two parts of the oscillation over-lap, and a frequency of 600 cycles (half-wave length oscillation of 154 miles of line) is superimposed on the low frequency surge between line and transformer.

The first part of the oscillation shows a frequency of about 1200 cycles, increasing in magnitude and superimposed on the fundamental.

Record No. 21 covers the same experiment as *Record No. 20*, but is taken at the switching point—at the Oakland substation—and gives the voltage on the low-tension side of the transformers carrying the load.

The record starts with a potential of 11,900 (86,800 volts between line conductors) and ends with 11,300 volts (82,500 volts between line conductors).

Before the switches are opened, the voltage at the power house, at the generator end of the loop, is 102,500 volts.

The oscillation lasts eight cycles, or a little less than one-seventh of a second, and shows the usual frequency of about 1200 cycles superimposed on the fundamental.

In the last two records, at the moment of opening the high-tension switches the field of the energizing generators was strengthened in order to compensate for the drop in the line due to the disappearance of the charging current required by the idle Line No. 1. Under these conditions *Record No. 20* shows a maximum over-tension of 22 per cent above the final maximum voltage of the loaded Line No. 2, and a maximum over-tension of 21 per cent above the final maximum voltage of the idle Line No. 1. In *Record No. 21* the maximum over-tension is 27 per cent above the final maximum voltage.

These records, as repeatedly mentioned above, show only the potentials on the low-tension side of the step-up or step-down transformer, and in order to form an idea of the phenomena occurring on the high-tension line these tests were supplemented by measuring—at the instant of performing the different switching operations—the maximum sparking distance across a choke-coil inserted in series with a line conductor. Figs. 3, 7 and 10 show the exact location of the choke-coils shunted by spark gap.

Each choke-coil consists of 34 turns of half-inch copper rod. The inside diameter is $5\frac{1}{2}$ in., the outside diameter $6\frac{1}{2}$ in., the total height 32 in.

The inductance of each coil is 0.0326 millihenry, so that 100 amperes at 60 cycles would give across the choke-coil a drop of 1.26 volts.

Each of the different switching operations was repeated several times, and the following table gives the maximum sparking distances obtained across the coil.

Test No.	Diagram	Record No.	Sparking distances
1-A	3	1 and 2	$\frac{1}{2}$ in. at switching point.
1-B	3	3 and 4	$\frac{1}{2}$ " " " "
2-A	3	5, 6 and 7	Less than $\frac{1}{2}$ in.
2-B	3	8 and 9	Less than $\frac{1}{2}$ in.
3-A	7	10	$\frac{1}{2}$ in. at generating station—switching point.
		11	Less than $\frac{1}{2}$ in. at receiving end.
3-B	7	12	$\frac{1}{2}$ in. at generating station—switching point.
		13	Less than $\frac{1}{2}$ in. at receiving end.
4-A	7	—	Less than $\frac{1}{2}$ in. at generating station.
		14	$1\frac{1}{2}$ in. at receiving end—switching point.
4-B	7	—	Less than $\frac{1}{2}$ in. at generating station.
		16	$\frac{1}{2}$ in. at receiving end—switching point.
5-A	10	18	Less than $\frac{1}{2}$ in. at generating station.
		19	$\frac{1}{2}$ in. at switching point.
5-B	10	20	Less than $\frac{1}{2}$ in. at generating station.
		21	$\frac{1}{2}$ in. at switching point.

These sparking distances represent the product of the intensity of the current times the steepness of its wave front. In Test 1-A, for instance, the maximum instantaneous value reached by the current is 130 amperes. A sine-wave current whose maximum value is 130 amperes would give across the choke-coil at 60 cycles a drop whose maximum value is 1.63 volts. In our test, the maximum difference of potential across the choke-coil rose to 5,500 volts, from which value we can form an idea of the steepness of the wave front. In the case of Test 4-A the difference of potential reached the value of 24,000 volts.

These results, supplemented by a general inspection of the records, allow us to draw the following conclusions:

In the class of phenomena which we have investigated, abnormally high potentials to ground or between line conductors, or across windings of apparatus, are not to be feared. The maximum over-tension which the records show is 60 per cent above normal operating value. This corroborates the theory of these phenomena, whereby the maximum possible over-tension is equal to the normal tension when the damping effects are neglected.

On the other hand, a glance at the records impresses one with the fact that, if high potential is absent, high frequency is a common occurrence. The spark gap tests tabulated above confirm this impression and point out the danger resulting to the end turns of apparatus from these switching operations.

It seems, therefore, that our common method of protecting transmission systems by lightning arresters connected in series with a spark gap does not answer the purpose effectively in all cases.

Of course, atmospheric disturbances, arcing grounds, switch-

FIG. 11.—Oscillograph

ing heavy loads, etc., constitute a class of disturbances which may be taken care of by our present protecting system, since they may give origin to high differences of potential across conductors or to ground; but the switching phenomena with which this paper deals call mainly for protection against high frequency impulses, whose existence has been repeatedly shown by theoretical considerations, but perhaps has not been properly realized in practical operation.

The fact remains, however, that these tests were performed for a long period of time—several months—on systems operated

at the highest voltages in use to-day. The switching operations performed, for instance, on the system of the Great Western Power Company during this investigation were more numerous and more severe than the system will experience in a long time of normal operation, and yet no damage whatever resulted to the line or to the apparatus, showing that the confidence of the engineers in high-voltage installations is justified.

The only danger, perhaps, consists in the possibility that some of the frequencies, at which inductances and capacities exchange energy, will coincide with the frequency of the generating system or its harmonics. A simple calculation of the constants of the circuits is, however, sufficient to obtain the value of these frequencies and to ascertain the absence of resonance.

The high frequency impulses, which originate at the point where the switching is performed, extend over a short length of the circuit only. The steepness of such impulses is quickly reduced and smoothed over and their effect is localized.

The oil high-tension switches open the circuit, as generally admitted, at the zero point of the wave of current, and since the establishing of the circuit is generally due to an arc, they close the circuit at the maximum point of the wave of e.m.f. or in its neighborhood. No attempt was made in these experiments to close the switches at different points of the wave of e.m.f., but it was preferred to obtain information as to the point of the wave at which the switches would naturally close the circuit.

Low-tension switching is preferable—when possible—to high-tension switching. In this connection, it is interesting to note that high-tension switching may be undesirable when transformers are near the switching point, in which case low-tension switching may be generally arranged for.

In energizing a line two methods of procedure may be followed (a) the open line is connected to the generating system, and the step-down transformer is thrown onto the end of the live line: (b) the step down transformer is connected to the dead line and then line and transformer are connected to the generating system.

Our records show that the second method is the best, as it produces one oscillation only and this oscillation is of the same character as the less severe of the two oscillations which take place in the first procedure.

This paper discusses, naturally, only a small number of the numerous oscillograms taken. For each switching operation several records were obtained, and the ones published are representative.

APPENDIX

BY W. W. LEWIS

The method of recording the waves shown in the foregoing paper is described in this appendix.

Apparatus Used. The oscillograph used was of the three-element electromagnetic type illustrated in exterior view in Fig. 11 and previously described in papers before the Institute.

This is regularly equipped with the film holder, shown in Fig. 12*a* and 12*b*, which consists of three parts; a cylindrical drum to which the film is fastened, by means of spring-clips, a light-tight hollow semi-cylindrical holder in which the drum revolves, and a cover which fits over the end of the holder after the drum is in place. The holder is provided with a rectangular aperture and shutter, and a suitable arrangement for holding

FIG. 12A.—Standard film holder

in place on the oscillograph. The standard film for which this holder is adapted is $3\frac{7}{8}$ in. wide by $12\frac{3}{4}$ in. long.

An auxiliary arrangement was devised for films longer than

FIG. 12B.—Standard film holder

the standard. This is illustrated in Figs. 13*a* and 13*b*. The following modification in the regular holder was necessary. The clips for holding the regulation film to the drum were removed and a slot $\frac{1}{8}$ in. wide by 2 in. long cut in the drum parallel to its axis. An aperture was cut in the lower part of the holder

$\frac{3}{4}$ in. wide by $3\frac{1}{8}$ in. long. A small wooden box with open top and inside dimensions $1\frac{1}{2}$ in. by $3\frac{3}{4}$ in. was made. This fitted over dowel pins and was fastened to the holder by small hooks. The box was made for a No. 2 Bull's Eye Kodak spool, as this was a convenient size and permitted of ready means of holding

FIG. 13A.—Film holder with attachment for long films

in place. These spools have a hole bored throughout their length, and a brass rod with a knurled head served to hold them in place and forms an axis on which they could revolve. A piece of spring brass pressed a small brass cylinder, through a hole in the side of the box, against the end of the spool and served to act as a brake. This was later found to be unnecessary.

Method of Operation. The method of operation with the regulation film will first be described, assuming that all the preliminary steps have been taken and there remains only the exposure of the film. The procedure in making the exposure is

FIG. 13B.—Film holder with attachment for long films

ordinarily as follows: First, start motor which revolves the film; second, open aperture in the film holder; third, operate electromagnetic shutter.

The oscillograph shutter may be operated in two different ways, first by a worm contact, which opens the shutter and

commences the exposure at the beginning of the film, stopping the exposure at the end of one revolution; after the lever is pulled the film holder makes about one revolution before the shutter opens. Second, by the instantaneous or disk contact, which opens the shutter instantaneously when the releasing lever is pulled and keeps it open during one revolution of the film.

FIG. 14

For ordinary normal waves of 60 cycles frequency the film is revolved at the rate of 600 rev. per min. In recording the oscillations, however, this speed was reduced to 200 rev. per min. That is, the $12\frac{7}{8}$ -in. film passed the light aperture in three-tenths of a second. At this rate of speed 18 cycles of a 60-cycle wave could be recorded. This, in most cases of switching, would be ample to record the complete oscillation, providing the ex-

FIG. 15

posure of the film could be so timed that the oscillation commenced sufficiently near the beginning of the film.

The first method of operating the shutter, that is, by the worm contact requires that the shutter lever be operated a trifle more than three-tenths of a second before the oscillation commences; the second method requires that the shutter lever be operated only in time to make sure that it is open before the

oscillation takes place, probably one one-hundredth of a second before the oscillation begins, and it has the disadvantage that the exposure may begin at any point on the film.

The second method was found to be the most suitable and some excellent results were obtained. For example see Fig. 14, which shows the complete record. Here the exposure commenced about one-fourth the film length from the end, ran off the end, commenced again at the beginning of the film and ran along to the starting point. The oscillation took place about one-third of the length from the beginning of the film or about one-sixth of a second after the shutter opened. Fig. 15 shows a record that is not satisfactory. The exposure began about the middle of the film. The oscillation commenced nearly at the end of the film and had not been completed when the starting point was again reached. Other records were obtained in which

FIG. 16

the exposure commenced at the beginning of the film and the oscillation was wholly completed within the length of the film, Fig. 16 shows one of these.

It will be readily appreciated that this required very accurate timing. Automatic timing devices were tried, but were found to be unduly complicated, in view of the nature of the power plant wiring and switching; and especially so when the switching was done in one station and the oscillograph located in another.

To overcome the shortcomings of the regular film and insure more certain results, the arrangement for long films was devised. This arrangement immediately extended the usefulness and accuracy of the apparatus. The films used were $3\frac{1}{2}$ in. wide by 48 in. long, so that instead of three-tenths of a second in which to make the exposure, about 1.1 seconds were now available, and approximately 66 cycles could be recorded; the exposure always commencing at the beginning of the film.

The procedure in loading these films is as follows: They are loaded in daylight as with an ordinary roll film camera, the film being placed in the box and the end of the black paper covering drawn through the aperture in the holder and inserted in the slot in the drum (see Fig. 17). About one-half turn is made around the drum with the black paper and the box drawn up and fastened to the holder.

The routine in exposing the standard or short films was to first start the motor that revolved the film, next open the aperture in the film holders and lastly to operate the electromagnetic shutter at the proper instant. With the long films the routine was in the reverse order, that is, to first open the light shutter and keep it open, next open the aperture in the film holder, the black paper protecting the film from exposure, and finally at the

FIG. 17.—Showing method of loading a long film

proper instant to start the motor and wind the film from the spool onto the drum.

The motor was operated at high speed and the reduced speed required by the film secured by means of counter-shafting, which is clearly shown in Fig. 18. The belts, which consisted of heavy twine, were made very tight. By this means acceleration was secured in probably one-fiftieth of a second, or practically instantaneously. The film was preceded by 20 in. of black paper of which about one-third had already been wrapped around the drum, leaving two-thirds, or one turn, to be wound around the drum before the film could be exposed. This allowed about three-tenths of a second to elapse between the starting of the motor and the exposure of the film, giving a wide factor of safety for acceleration.

As familiarity was gained with this device, the efficiency of operation was increased from probably 50 per cent with the short films to approximately 95 per cent with the long ones. At one particular station where fifteen exposures were made, all were successful—an efficiency of 100 per cent.

The significance of this can be appreciated when it is stated that all the signals were manual and vocal. When the switching was done in the station where the oscillograph was located, the signal passed from the oscillograph operator to the switchboard attendant either direct or through an intermediate person.

FIG. 18.—Oscillograph and testing equipment at Big Bend

When the switching took place at one station with the oscillograph located at another, a telephone and two or three additional men were needed in the signalling chain. As described in the paper, Records 18 and 20 were taken at Big Bend Power Plant, while the switching was done at Oakland, 154 miles distant (see map, Fig. 1). The oscillograph set-up and the station layouts necessitated a singaling chain consisting of five men; the oscillograph operator, an intermediary and a telephone attendant at Big Bend; a telephone attendant and a switchboard attendant at Oakland. In addition to allowing time for

the transmission of the signals, it was necessary to make an allowance for the lag in the switch mechanism, which was sometimes appreciable.

Several exposures were made in which a line was switched on and off the generating system and both operations recorded on the same film.

To assist in judging the proper time to be allowed for the transmission of the signals, etc., one trial switching operation was usually performed, the movement of the beam of light being noted on a ground glass inserted in place of the film.

None of the records given in the foregoing paper show more than 10 in. of the 48 in. of the film exposed, with the exception of Record 15, which shows 20 in.

In most of the exposures the zero line was not recorded, as it was not necessary and only complicated the records. To record the zero line the procedure with the short films is to make a second exposure with the vibrator switches open. With the long films a second exposure is not possible, but the zero line is recorded at the time of the original exposure by using the beam from the third or idle vibrator.

When two vibrators were in use it was found most satisfactory to cause their zero positions to coincide, in some cases reversing one of the waves, to better distinguish them when the two waves were nearly in phase. A few records were taken in which the zero positions of two waves were widely separated, thus separating the waves and preventing confusion. This, however, necessitated waves of small amplitude, and owing to the uncertainty as to the probable amplitude during an oscillation the method of using coinciding zeros in the center of the film was found most suitable.

The unloading is done in a dark room. To unload the standard film, the cover is removed, the drum taken out and the film unfastened—the reverse of the loading operation. With the long films it is only necessary to loosen the hooks and remove the wooden box. The film is then pulled out through the aperture in the holder. The cover and the driving pin need never be removed.

During all the switching operations one terminal of the vibrator was connected to one of the poles of the electromagnet between which it vibrated, in order to eliminate the effects due to electrostatic differences of potential, which were sometimes present.