THESIS

The Effect of Circulating Currents in Y-Delta Transformer Banks on Harmonic and Unbalanced Voltages in Transmission Systems.

by

Verne D. Elliott

Class of Nineteen Hundred and Fifteen
Department of Electrical Engineering.

THROOP COLLEGE OF TECHNOLOGY
Pasadena, California.

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INTRODUCTION

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The following investigation was undertaken after a consultation with Mr. H. A. Barre, Electrical and Mechanical Engineer for the Pacific Light and Power Company. Mr. Barre outlined some of the experiences of his company and questions that arose regarding them. The work of this thesis was to make a laboratory study of some of these questions.

CONDITIONS ON P. L. AND P. SYSTEM.

In order to give a clear idea of the application of the experimental work to the actual case a brief description will be given of the essential features of the P. L. and P. system and the phenomena that have here been given attention.

At present, the main portion of energy comes from two water-power stations in the mountains east of Fresno. The generators are Y connected, 3 phase, 6600 volts. Voltage is stepped up to 150 kv. in delta-Y transformer banks. Generator and transformer neutrals are both grounded. Transmission is at 150 kv. over 241 miles of line to Eagle Rock Substation which is near Los Angeles. At the receiving station, voltage is stepped down to 60 kv. and 18 kv. in delta-delta transformer banks. 18 kv. is the "local" distribution voltage and 60 kv. the one used for longer lines.

At Redondo steam-station is a bank of auto-transformers Y connected between the 9 kv. generators and 18 kv. line. This auto-transformer bank is grounded at the neutral.

The 18 kv. lines form an extended network covering a large area and feeding most of their power into the systems of the Pacific Electric and Los Angeles Railway companies. At one time there was considerable trouble from arc-overs on the 18 kv. lines. With grounded neutral at Redondo and one line arcing to ground, high frequency and high maximum voltages were apparently produced from the other two lines to ground. The Company's engineers were led to this conclusion by evidence left on the wall of a bus-room in one of the substations where a flash-over occurred, caused presumably by a "short" on the line. The laboratory tests have borne out this conclusion.

One feature of especial interest is the fact that some of the worst "spill-overs", in point of damage to apparatus, occurred when the Redondo auto-transformers were disconnected and there was no grounded neutral in the circuit. The exact reason for the flash-overs is unknown but there is a possibility that they started from static charges on the line. Such phenomena involve electrostatic conditions of lines which it was not practical to duplicate in the laboratory.

The important part however from the standpoint of the P. L. & P. CO. is that serious trouble occurred both with and without the grounded auto-transformers at Redondo.

The scheme adopted by the Company to stop it was to connect at Vernon substation a Y-delta bank of transformers. The neutral point of the Y was grounded and the terminals were connected to the 18 kv. line. The secondary windings were connected delta and free from any line. Arc-overs occurred on the 18 kv. lines after the installation of this bank of transformers but apparatus was not damaged and the trouble was entirely localized.

5000 kv-a. transformers had been used because they were at hand and because no data was available which would indicate the proper capacity of transformers to use.

The problem was for practical purposes solved, but it was thought that perhaps smaller transformers would do just as well, leaving the larger ones for other use. The question was, what rating should these transformers have?

Another question that came up was what size transformers to use for a similar purpose at Eagle Rock on the Y connected bank of auto-transformers. These auto-transformers raise the 50 kv. of the Borel line to 60 kv. which is the standard high voltage of the system.

Plate I is a diagrammatic representation of the connections of the P. L. & P. system. Only such connections as bear a relation to the following tests are shown. For the sake of clearness no ? switches or selecters are shown. There are many small generating stations and substations and branch feeders not shown. The 60 kv. lines are tied to the 18 kv. lines through transformers at convenient points. (not shown.)

HARMONIC AND UNBALANCED VOLTAGES AND CURRENTS.

It is known that there are conditions arising in transmission work which will set up voltages having a frequency higher than the fundamental. Harmonic voltages may occur between lines of a three phase transmission line or from lines to neutral. High frequency voltages are by far the most likely to occur from lines to neutral and it is here that they do the most harm.

The most common and prominent harmonic voltages met with in power transmission are the third and fifth. Harmonic voltages are induced in any alternating current circuit which is linked with a magnetic circuit containing iron. This is due to the varying permeability of the iron throughout the magnetic cycle. While it is true that many harmonics are generated, the third is with ordinary conditions the one that is most prominent and demands consideration in power work. A study of the diagrams of Plate II will show how the third or powers of the third harmonic will build up in a three-phase system. Any others will combine in such a way as to partly neutralize each other. Since the reactance of a circuit goes up directly with the frequency, it is evident that harmonic currents which would tend to flow due to harmonic voltages will receive the damping effect of any inductance in the circuit directly proportional to their frequencies. For this reason also the triple frequency, being the lowest, stands the best chance of surviving. A shunted capacity or its equivalent in the circuit will greatly amplify and exaggerate high frequency currents.

The shape of voltage wave resulting from a combination of the fundamental and a triple frequency will depend of course upon the relative amplitude of the two parts and their phase angle. Take as an example the primary of a bank of transformers connected Y on one side and with the other winding open. With a sine wave impressed at the terminals of the Y the voltage from lines to neutral will show on an oscillograph the effect of the third harmonic. The amplitude of this triple frequency voltage varies with the maximum magnetic density in the iron. The oscillograms Plate V show what occurs at ordinary transformer densities, i.e. 80 to 90 thousand lines per square inch. Curve A is the voltage from lines to neutral with sine waves at the terminals. Across each open secondary, a voltage wave of the same shape is also induced.

If the secondaries are connected to form a delta with one corner open, the three windings are then in series as regards the triple frequency voltages. Since these are in phase they will add up and show as a triple frequency voltage across the open corner of the delta. If the delta be closed a triple frequency current will circulate and generate a flux which will act to neutralize the original triple frequency flux and therefore eliminate the third harmonic in the voltages from line to neutral. Curve B (Plate V) shows the voltage at the same place and to the same scale as curve A but with the secondary windings forming a closed delta. A voltmeter reading shows the effective value of curve B as about 7% less than A and it is seen that the maximum of B is considerably less than A.

UNBALANCED FUNDAMENTALS AND HIGH FREQUENCY VOLTAGES CAUSED BY AN ARC FROM LINE TO GROUND.

Another condition which occurs in power transmission and causes high harmonic voltages is an arc. Take the case of a three-phase transmission line which has a grounded neutral point at one or both ends. If one line gets down so as to make an arcing contact with the ground or arcs over an insulator, an abnormal load is thrown on one phase. Oscillogram curve C (plate VI) shows that high frequency voltages are set up between the two free lines and ground on account of the arc; the voltmeter readings show that the effective voltages are greatly increased due to the drop in voltage from the "shorted" line to neutral. In the case of a "dead ground" only high fundamentals are set up. The diagrams (Plate III) drawn from the data of test represent graphically the voltage relations for a typical case. Some investigators hold that under certain conditions the neutral point may move clear outside of the voltage triangle, but with the conditions under which I worked I found no readings that would point to such a case.

In the above described conditions there was assumed to be no Y-delta transformer bank in the circuit which would act to neutralize unbalanced voltages. Such a bank of transformers with the terminals of the Y connected to a transmission line and neutral grounded would act in the following way. A "short" on one phase tends to reduce the voltage across one leg of the Y; this reduces the induced voltage across one side of the secondary delta thereby making a potential unbalancing that causes a current to circulate around the delta. This current generates flux which opposes the unbalancing effect of the "short" on the line.

APPARATUS AND TEST PROCEDURE
RESULTS AND CONCLUSIONS FROM TESTS.

It must be borne in mind in the interpretation of the results of these tests that there are no capacity or inductance effects such as would be found on a long transmission line.

The transformers used were all exactly alike and rated at 3 kv-a. Taps were brought out from both windings so that different voltage combinations could be obtained. As a source of power a 7.5 kv-a. 3 phase, Y connected alternator was used for some tests, and for others the 110 three phase supply circuit of the College.

The first tests were made with the 7.5 kv-a. alternator and connections as shown in Plate IV. This arrangement represents in a small way the connections of the P. L. & P. system. The generator is the high voltage side of the Big Creek transformers; the delta-delta transformer bank is Eagle Rock Substation and the Y-delta bank is the grounding transformer bank at Vernon Substation.

Line C was grounded through a low resistance which could be varied. By changing the field excitation of the alternator, different no-load voltages were obtained and readings taken for each case. The alternator had a high reactance and poor regulation and for this reason the voltages fell off considerably when the grounding switch was closed. By holding the generator voltage constant as it would be in practice, another set of readings was taken with varying resistance and varying current from line to ground.

For the next set of tests the source of power was the bank of delta-delta 7.5 kv-a. transformers which step down from 2200 volt mains to 110 volts for use in the College. These transformers, on account of their higher rating and better regulation, held the voltage up quite satisfactorily.

Since there had been no current flow between the two neutral points in the previous test I decided that for the laboratory work the connections used at the source of power did not affect the results. I therefore used the transformer bank because it required no manipulation as did the generator and its driving motor.

TESTS WITH ARCING GROUND

In order to find the effects of an arcing ground, the low tension coil of a high voltage transformer was connected in series with the adjustable resistance from line to ground. Across the high tension winding was a spark gap which was also adjustable. This gap was horn shaped and imitated somewhat a flash over on a transmission line. The effective voltages as shown by the voltmeter are not much different from those with a solid ground, but the curve C (Plate V) shows the sharp peaks and high harmonics in so far as an oscillograph is able. Some of the worst irregularities were undoubtedly "ironed out" by the core of the high tension transformer, but the tendency during an arcing ground is illustrated. On closing the delta of the Y-delta bank all voltages become perfectly smooth and regular. (See curve D, Plate VI). Curve E (Plate VII) shows the circulating current in the delta during an arc-over. The amount of unbalancing is shown by the voltmeter readings.

RESULTS OF TESTS

From the experience of the P. L. and P. Company, and the results of the foregoing tests, it is seen that any disturbance or unbalancing on a transmission line causes voltages which may become dangerous to apparatus, especially when they are accentuated by the capacity of a long line or net work of lines. Further, a bank of transformers connected Y-delta in the manner described is seen to be entirely effective in eliminating high frequency and abnormal voltages from lines to ground.

As an aid in determining the kv-a. rating of transformers for this purpose ratios of $\frac{\text{kv-a. delta}}{\text{kv-a. ground}}$ have been calculated. "Kv-a. delta" is the delta circulating current multiplied by the kilo volts across one side. The "kv-a. ground" is the current to ground multiplied by the corresponding voltage.

In the tests with the small generator as a source of power this ratio varies from 0.49 to 0.38. In the other tests where conditions were better it varies between 0.37 to 0.38. With the arcing ground it is 0.33 to 0.35.

In view of this close agreement I think 0.4 is a reliable ratio to use for practical application. It must be understood however that this load is only carried for a very few minutes at most and that the nominal rating of transformers may be reduced accordingly. In fact, such a bank of transformers might well be a part of the system and in use like any other transformers. If a number of such banks were distributed throughout a network they would take care of trouble and involve no additional investment.

EFFECT OF RESISTANCE IN THE DELTA OF GROUNDING TRANSFORMER BANK

As another test, resistance was placed in the delta of the grounding transformer bank. The purpose of this was to see whether or not the ratio $\frac{\text{kv-a. delta}}{\text{kv-a. ground}}$ could be reduced by limiting the circulating current in the delta. It was surmised that this would have to be done at the expense of letting the voltages from neutral to lines A and B rise, but the data from this test show the effect of resistance is to greatly increase the ratio even when a great rise of voltage AN and BN is permitted. We may conclude then that the less resistance in the delta the better. I think the reason for this is that the emf is consumed across the resistance instead of building up a counter emf in the transformers.

AUTO-TRANSFORMER TEST

In order to get data on the effects of auto-transformers, the delta-delta bank used in the previous tests was replaced by a bank of auto-transformers Y connected as is the case at Eagle Rock Substation. Tests were run as before by grounding one line. The results show the ratio of $\frac{\text{kv-a. delta}}{\text{kv-a. ground}}$ to be practically the same as before.

In case it is desired to eliminate only small harmonic voltages due to transformer iron, much smaller transformers may be used. A test of this feature indicates that the ratio $\frac{\text{kv-a. delta rating}}{\text{kv-a. auto-transformer rating}}$ is about 0.01. Such a bank of small transformers should have fuses to protect them in case a line became grounded and produced a large circulating current in the delta. Such an arrangement would not be very desirable because just at the time of a "short" when a balancing effect is most needed the small transformers would become inoperative. In case of inductive interference where harmonic currents in a transmission line rendered a parallel telephone line noisy, the above arrangement would be just as useful in eliminating noise from the telephone line as a bank of large transformers.

SUMMARY

A Y-delta bank of transformers connected to a transmission line in the manner that has been discussed, is effective for holding normal voltages on the line during "shorts" or arc-overs. The circulating current in the delta is directly proportional to the current from line to neutral and on an equivalent voltage basis is about 0.4 of the current from line to ground.

With constant delta circulating current and therefore constant current from line to ground, insertion of resistance in the delta allows unbalanced voltages to build up from lines to ground.

Harmonic voltages caused by Y connected auto-transformers may be eliminated with a Y-delta bank of transformers of about 0.01 the rating of the auto-transformers.

INSTRUMENT READINGS FROM TEST.

Letters refer to connections shown on Plate III.

Volts						Amperes							
AB	BC	AC	AN	BN	CN	I_1	I_2	I_3	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
198	198	198	114	114	114	0	0	0	0	0			
162	162	162	93	93	93	0	0	0	0	0			
140	133	74	60	86	51	16.1	15.8	15.8	47	13.9	2.40	0.92	0.38
146	146	146	84	84	84	0	0	0	0	0			
121	105	64	54	76	46	13.7	13.3	13.3	40	11.9	1.84	0.89	0.48
137	140	99	65	84	64	10.6	10.0	10.0	30	9.1	1.92	0.80	0.42
140	140	140	80	80	80	0	0	0	0	0			
112	106	57	50	70	42	12.7	12.4	12.4	37.5	11.0	1.57	0.72	0.46
140	Voltage AB held constant												
140	140	140	80	80	80	0	0	0	0	0			
140	146	116	73	87	74	7.6	7.0	7.0	21.0	6.3	1.55	0.59	0.38
140	140	94	66	88	63	12.6	12.1	12.1	37.0	10.8	2.33	0.95	0.41
140	137	84	64	88	58	14.4	14.0	14.0	42.0	12.4	2.44	1.00	0.41
140	140	140	85	85	85	0	0	0	0	open			
140	139	138	138	137	10	0	0	0	"Short"	open			

INSTRUMENT READINGS FROM TEST
(Continued)

Source of Power, 110 3-phase supply circuit.

Volts						Amperes							
AB	BC	AC	AN	BN	CN	I_1	I_2	I_3	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
274	250	260	160	156	140	14.0	13.5	13.5	40.0	12.0	4.90	1.76	0.37
275	275	275	158	158	158	0	0	0	0	0			
274	250	260	159	155	141	12.0	11.4	11.4	35.0	10.4	5.40	2.04	0.38
274	246	258	159	154	137	15.4	14.8	14.8	45.0	13.1	6.20	2.22	0.36
274	242	256	159	153	134	17.2	16.7	16.7	50.0	14.5	6.70	2.46	0.37
Water rheostat in delta side of grounding transformer bank between A and B.													
276	243	260	186	192	80	17.5	17.0	17.0	50.0	14.6	4.00	2.46	0.62
Delta resistance taken out.													
274	242	256	159	153	134	17.2	16.7	16.7	50.0	14.5	6.70	2.5	0.37
Delta resistance inserted; resistance from line to ground same as for preceding line.													
276	251	263	178	181	100	12.7	12.2	12.2	37.0	10.8	3.70	1.84	0.50
Delta resistance taken out													
274	273	272	170	168	168	0	0	0	open	open			
274	273	270	274	266	0	2.0	2.0	2.0	"short"	open			

INSTRUMENT READINGS FROM TEST.
(Continued)

In this test the low tension coil of a high voltage transformer is placed in series with the resistance from line to ground. An arc is maintained across the high tension side of the transformer.

Volts						Amperes							
AB	BC	AC	AN	BN	CN	I_1	I_2	I_3	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
272	262	269	160	157	145	10.4	10.6	10.2	31.0	9.3	4.50	1.58	0.35
272	262	269	160	157	145	8.3	8.3	8.0	25.0	7.2	3.72	1.22	0.33
274	264	269	160	158	148	7.0	7.0	6.4	20.0	6.0	2.96	1.02	0.35
High tension condenser placed in parallel with spark gap.													
273	260	264	160	158	143	10.0	10.0	9.6	30.0	8.6	4.33	1.46	0134
273	261	265	160	158	144	8.6	8.5	8.0	25.0	7.3	3.61	1.24	0 .34
273	263	265	160	156	146	6.9	6.8	6.4	20.0	5.9	2.89	1.00	0.35

INSTRUMENT READINGS FROM TEST.
(Continued)

Constant resistance to ground. Variable resistance in the delta of grounding transformer bank.

Volts							Amperes					
AB	BC	AC	AN	BN	CN	I_1	I_1	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
270	273	274	158	157	159		0	0	0			
272	266	262	256	254	0		7.5	20	11.6			
271	264	258	247	252	0		9.4	25	14.8			
271			244	250	5		10.6	30	17.4			
271			234	242	10		14.0	40	23.3	0.4	1.75	4.40
274	264	251	173	173	120		13.7	40	23.3	4.8	1.75	0.36
274	267	258	197	200	80		10.3	30	17.4	2.4	1.13	1.55

Constant current to ground. Variable resistance to ground. Variable resistance in delta.

AB	BC	AC	AN	BN	CN	I_1	I_1	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
274	267	262	167	166	129		7.0	20	11.8	2.58	0.78	0.30
274	267	262	209	210	65		7.0	20	11.8	1.30	0.78	0.60
				164	132		7.0	20	11.8	2.64	0.78	0.30
				158	148		7.0	20	11.8	2.97	0.78	0.27

INSTRUMENT READINGS FROM TEST.
(Continued)

AUTO TRANSFORMER TEST.

Connections as shown on Plate IV.

AN	BN	CN	I_1	I_2	I_n	I_g	I_d	Kva_g	Kva_d	$\frac{Kva_d}{Kva_g}$
85	85	85	0	0	0	0	open			
79	79	79	0	0	0.325	0	0.240			
79	79	76	7.5	6.6	20.8	20.0	6.0	1.52	0.54	0.36
79	79	75	9.2	8.3	25+	25	7.3	1.87	0.66	0.35
79	79	74	10.7	9.9	30+	30	8.8	2.22	0.80	0.36
80	80	74	12.4	11.5	35+	35	10.2	2.60	0.92	0.35
80	80	73	14.2	13.2	40+	40	11.6	2.90	1.05	0.36
80	80	72		14.8	45+	45	13.0	3.30	1.17	0.35
80	80	73			50+	50	14.4	3.70	1.30	0.35
80	80	72			55+	55	14.9	4.00	1.34	0.34
136	131	0				"short"	open			

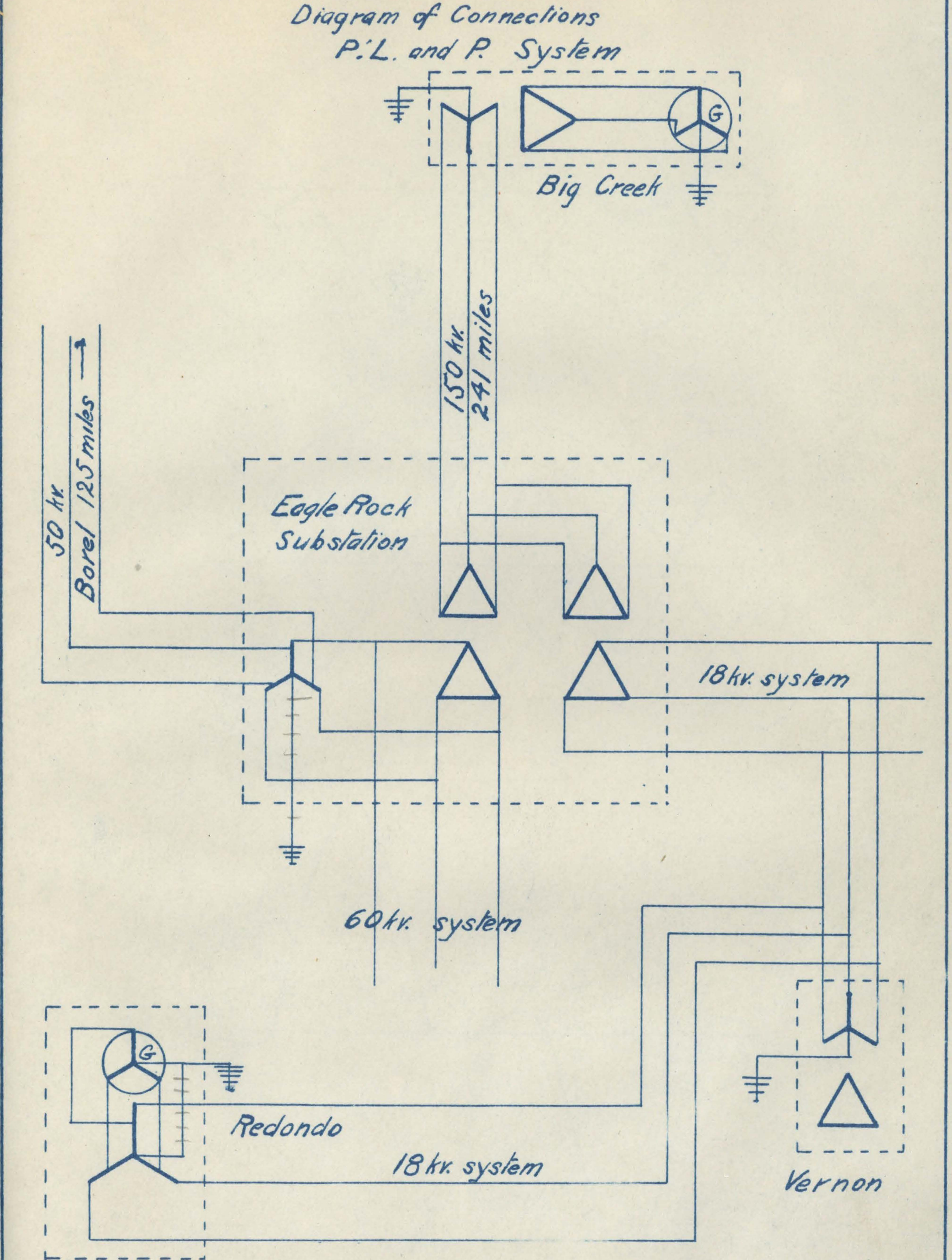
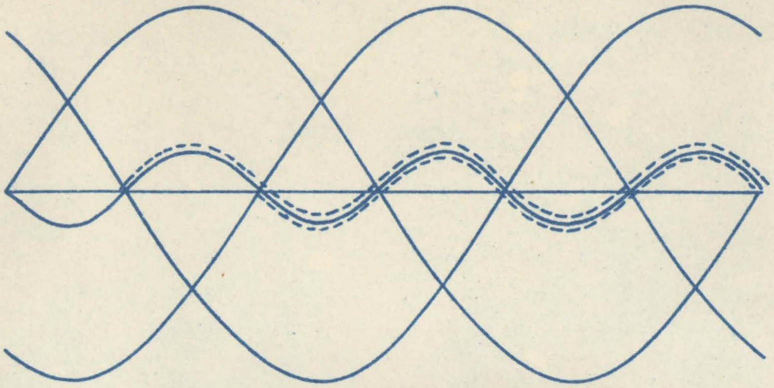
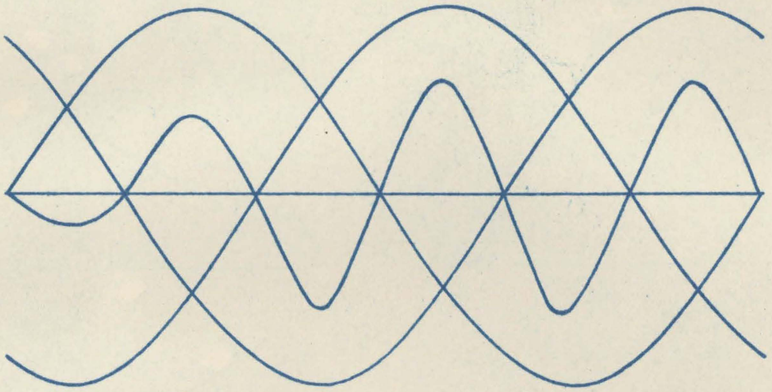


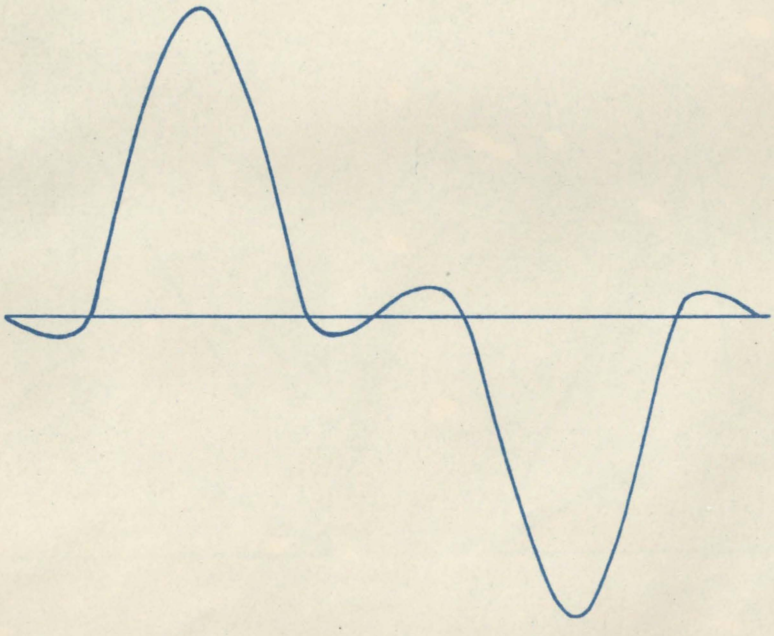
Diagram of Connections
P.L. and P. System
G
Big Creek
150 kv.
241 miles
50 kv.
Borel 125 miles →
Eagle Rock
Substation
18 kv. system
60 kv. system
G
Redondo
18 kv. system
Vernon

Plate II

Diagram of triple frequency waves building up in a threephase circuit







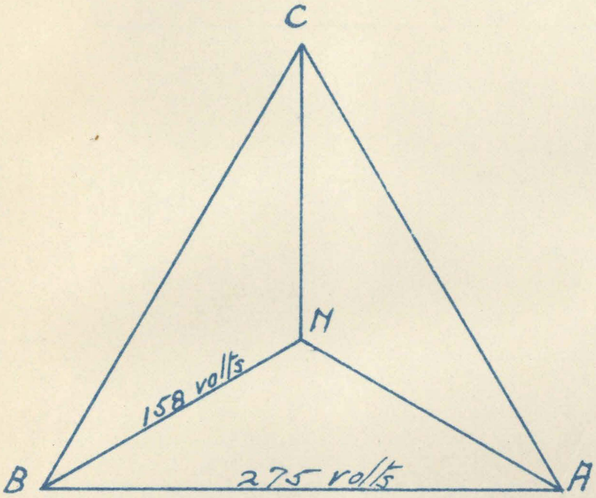
Combination of fundamental and triple frequency waves

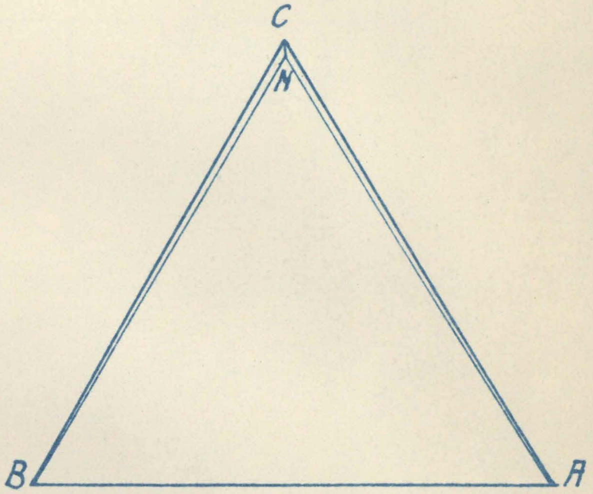
Plate III

Voltage Diagrams

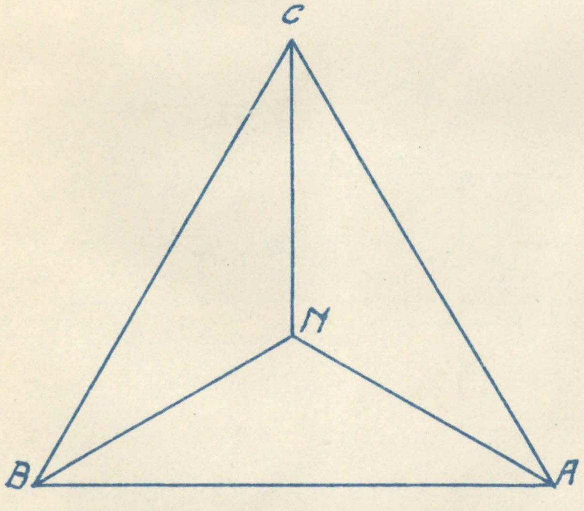
Normal condition — Condition during short-circuit

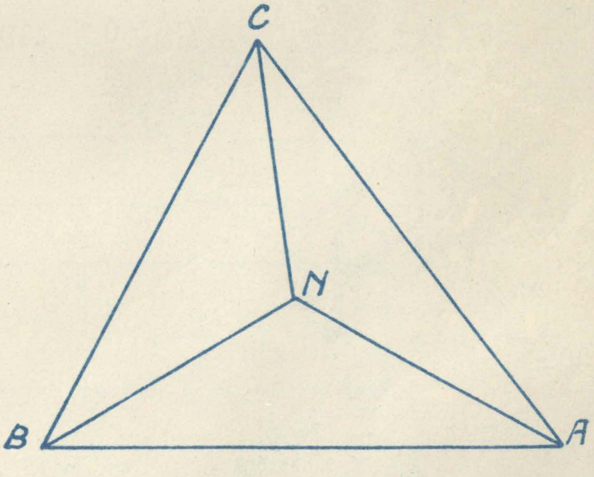
Delta open



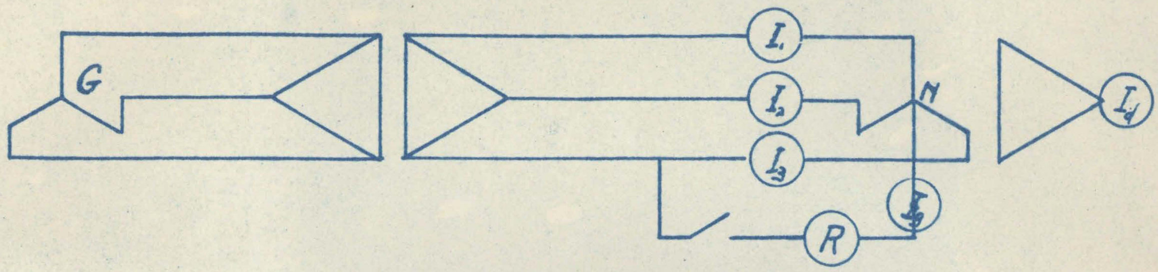


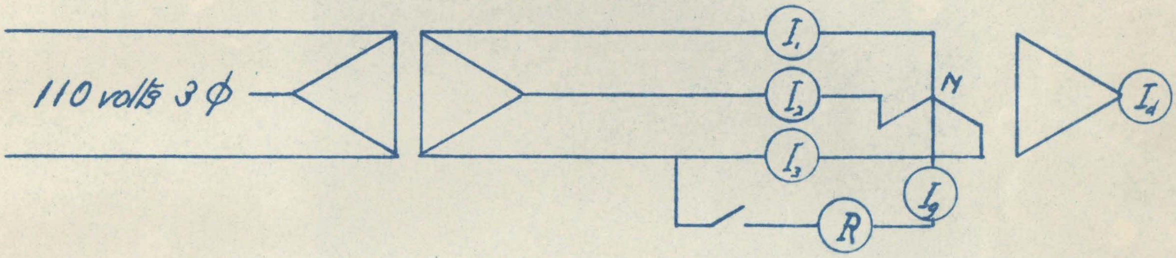
Delta closed





Diagrams of connections used in Tests





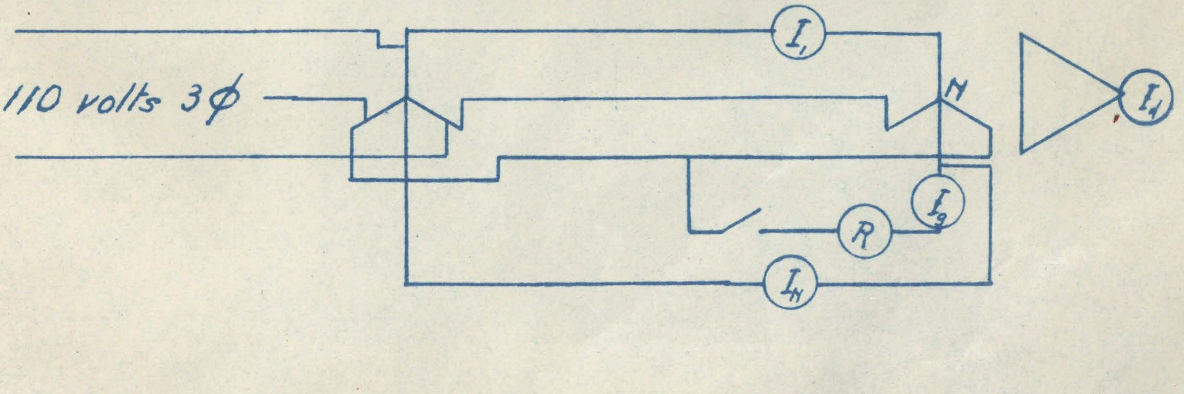
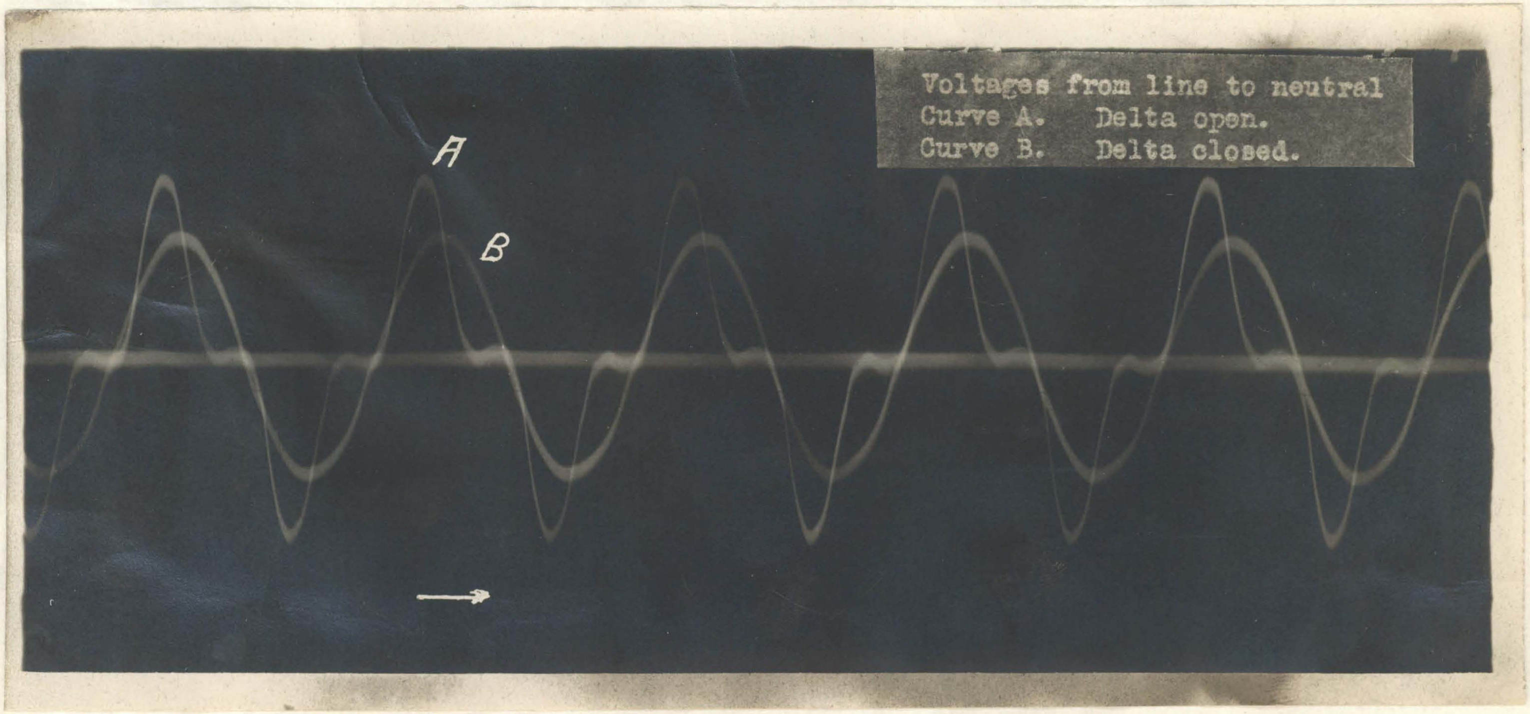


PLATE V.



Voltages from line to neutral
Curve A. Delta open.
Curve B. Delta closed.

PLATE VI.

Voltages from line to neutral
with one line arcing to ground.

Curve C Delta open
Curve D Delta closed.

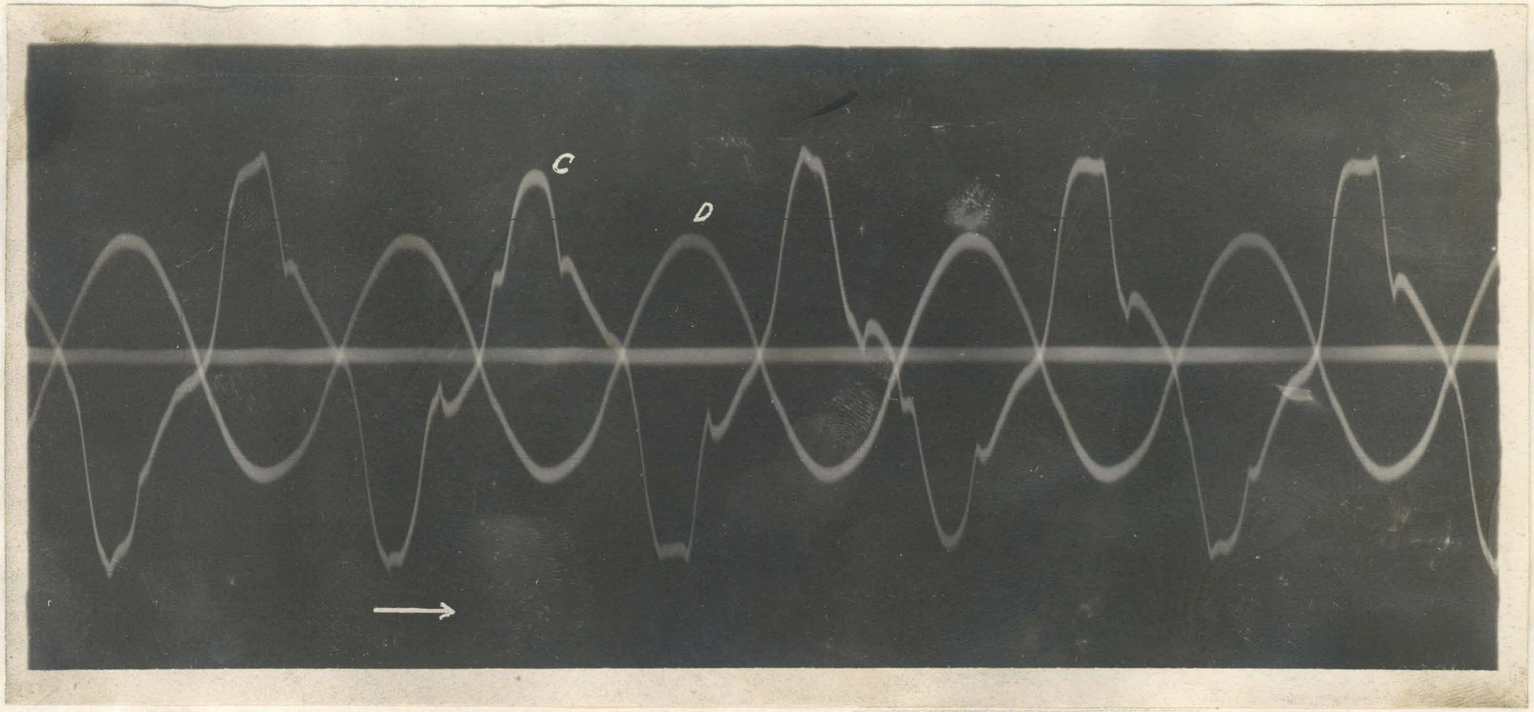


PLATE VII.

Circulating Current in Delta
with one line arcing to ground.