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INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS

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ABSTRACT OF PAPER

The paper gives the results of experiments made with a miniature simple transmission system to demonstrate the inherent voltage relations with different combinations of Y and delta connections.

The experimental system consisted of a 7.5-kv-a. revolving field generator, with coil terminals which could be connected either Y or delta, and two banks of transformers each composed of three shell-type 3-kv-a. units. All inductive and capacity effects in the transmission line were eliminated. The tests were made under constant conditions, with non-inductive load.

The authors give the results of four groups of tests, on four different systems of connections, pointing out the advantages and disadvantages of the several systems. In each case tests were made without load, with balanced load, and with load on one phase only, for various conditions of grounding. Typical voltage diagrams are given, to show what happens under various conditions of load.

The authors discuss certain cases where the use of auto-transformers is advantageous, and the effects of different ways of connecting them.

THE HIGH survival value which the subject of Y and delta systems has as a matter of discussion almost warrants the assumption that inherently neither system can be said to be generally inferior to the other for the transmission and distribution of electric energy. On the other hand, if there is to be any choice of either system even for special work such as long-distance transmission at high voltage, it would seem as though the choice must be based upon certain features inherent in the method of connections even though these features may not in themselves be bad, but rather become conducive to trouble only when combined with other features incident to that particular condition.

It is the purpose of this paper, therefore, merely to bring to the attention of those interested, experiments made with simple Y-connected and delta-connected systems and to show, if possible, wherein the advantages of one with respect to the other may lie.

The simplest system which could be constructed would be that of a single three-phase line supplied at one end through step-up transformers by the generator and at the other end giving out its energy to the connected load through a bank of step-down transformers.

As there can be made with each three-phase bank of transformers four combinations of connections, and as the generator and the receiving motor may be connected either Y or delta, it is readily evident that even in a very simple system there may be made a large number of combinations.

The generators as a rule are connected Y because of the better wave form obtained, as seen in Figs. 1 and 2, and because of the convenient ground point which is then provided. Experience has practically made standard the delta connection for the low-tension windings of both the step-up and step-down transformers, thus leaving for consideration only the arrangements of the high-tension windings of step-up or step-down transformer banks. These may both be connected Y, as has been very generally done, and the neutral points may be grounded or not grounded, the grounded condition being, however, the one in general use. They may both be connected delta or one may be connected delta and the other connected Y, a condition not usual, but one which in some cases has been thought desirable.

Having made a selection as to the arrangement to be adopted in any particular system, it is of course obvious that this system must be carried throughout for any points of multiple connection of transformer banks or transmission lines, because of the impossibility of delta-Y banks being run in parallel with delta-delta banks.

Description of Tests

To determine the inherent relations, a miniature system consisting of a 7.5-kv-a., revolving field generator, with coil terminals brought out so that it could be readily connected Y or delta, and two banks of transformers each consisting of three shell-type 3-kv-a. units, was constructed. All inductive and capacity effects in the transmission line, which was in this case only the necessary leads for connecting together the high-tension windings of the step-up and step-down transformer banks, were entirely eliminated. This must be kept in mind when considering the conclusions drawn from the tests.

All tests were made for constant conditions and the load used was non-inductive. Potentials were measured with a multicellular electrostatic voltmeter, which on closed circuits was carefully checked with a standard portable dynamometer instrument.

All connections were carefully insulated from each other and from ground, as was also the frame of the generator, except

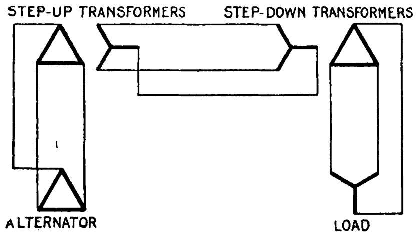


FIG. 3

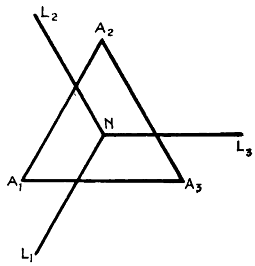


FIG. 4

in such cases as it was well grounded with a copper ground. In all tests the transformer cores and cases were well grounded.

The first group of tests was made on the system connected as in Fig. 3, without load, with balanced load, and with load

TABLE I*

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
0	None	None	57.7	57.7	82.0	163.0	0
0	Neutral	"	"	"	"	"	"
Balanced	None	"	"	"	"	"	"
"	Neutral	"	"	"	"	"	"
1 phase	None	One H.T. line	51.0	69.5	90.0	180.0	18.2
"	Neutral	"	73.0	167.0	138.0	276.0	0
"	None	One load lead	74.5	70.0	100.0	200.0	4
"	Neutral	"	62.4	71.5	104.0	209.0	0
Balanced	One H.T. line	None	100.0	65.0	—	—	—
	N & 1 " "	"	91.2	57.7	—	—	0

*In these tables readings with ungrounded generator frame are omitted (exceptions noted in Tables II and IV), as this condition so rarely exists in practise.

on one phase only, for various conditions of grounding. Some typical results of these tests are shown in Table I. When one phase only is loaded such condition is obtained in one of two ways: by opening a high-tension line, or by opening a low-tension line on the load end.

Fig. 4 shows the no-load voltage diagrams of high- and low-tension lines superimposed upon one another. The step-up and step-down transformers being identical, the delta represents voltages of generator, primaries of step-up transformers and secondaries of step-down transformers. Line voltages, secondaries of the step-up, and primaries of the step-down transformers are shown by the Y. If, as was assumed, the diagram is drawn to scale, it would be supposed that a measurement from any point on the delta to any other point on the Y would give the voltage between corresponding points on primary and secondary of transformers. This, however, was found not to be true in many instances. With no ground point on the system except the transformer cases, the electrostatic strains would be anywhere from 50 to 100 per cent greater than the values obtained by measurements from the diagram. The neutral point of the Y, which should normally be at ground potential, was found to be at some distance above. It was in fact found

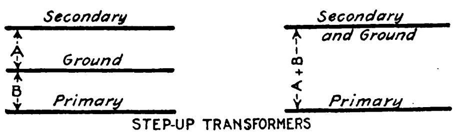
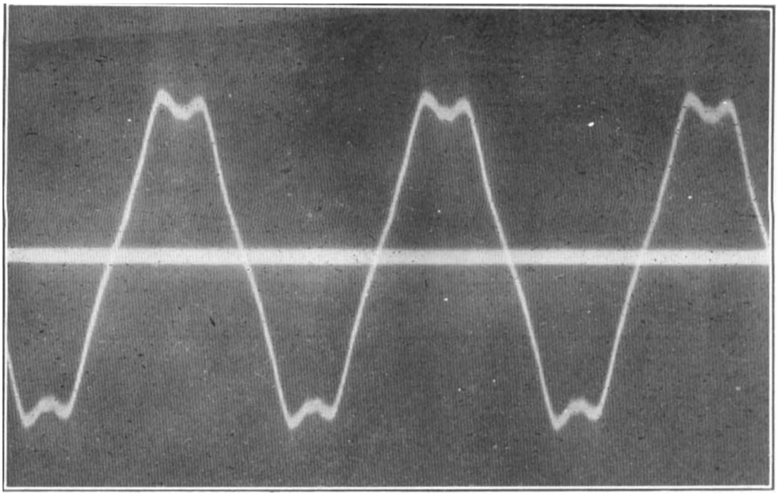


FIG. 5 FIG. 6

that no point on the entire system was exactly at ground potential, except of course the transformer cases, and even the frame of the alternator was found to be at a potential above ground greater than normal line voltage. These facts can lead to but one conclusion, namely, that the conditions on all systems cannot be truly represented on one plane.

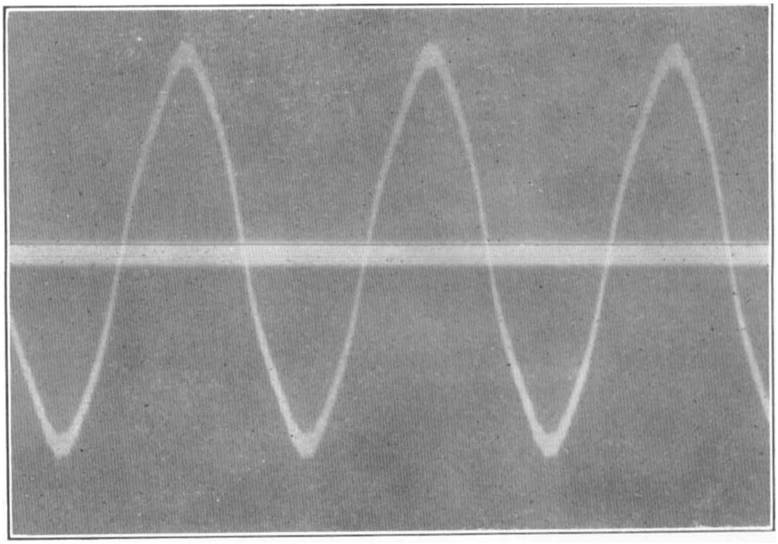
On this assumption, a great number of readings were taken and it was found that each section of the system might lie in a totally different plane, but that these planes are always approximately parallel.

An end view, then, of Fig. 4 would appear as in Fig. 5, in which each line represents the plane on which the respective diagrams would have to be drawn to represent correctly the readings obtained. No definite law seems to govern the relative position of these planes. On one day the distance between them may be twice that obtained on another. However, the primary and secondary planes are always on opposite sides of ground, as shown.



[SORENSEN AND NEWTON]

FIG. 1—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. DELTA-CONNECTED.



[SORENSEN AND NEWTON]

FIG. 2—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. Y-CONNECTED.

The grounding of the Y neutral brings the transmission line plane to ground potential, but maintains a nearly constant potential between this plane and the generator plane, so that the potential between generator plane and ground is doubled, as in Fig. 6. When the generator frame, which heretofore had been well insulated, was thoroughly grounded, all potentials were brought to the same plane and the voltages read corresponded to those measured from the diagram, in Fig. 4.

As load is added to the ungrounded system, the distance between the respective planes decreases, and appears to be some function of the load. When loaded, the difference between them is inappreciable. This is true of unbalanced as well as balanced loads. Conditions, then, are better at load than at no load, or very light load. (See Table I.)

The second group of tests was made with the same trans-

TABLE II

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
† 0 Balanced	None "	None "	57.7 "	61.0 "	85 "	167.0 "	0 "

†Generator frame not grounded.

former arrangement but with the generator connected Y. The tests made under these conditions gave results as in Table II, which are very similar to those of the first group, in that there still remains the tendency for the voltage planes to separate on the ungrounded system, at light load. This condition is probably better, however, than the first, due to the better wave shape obtained with the generator in Y, as can be seen by a comparison of Figs. 1 and 2.

From these data the following conclusions for a Y-connected transmission line may be drawn: The generator should be connected Y. The neutral point should be well grounded at both ends to relieve electrostatic strains. There is, of course, the objection to a grounded neutral, that if a line becomes grounded also, one phase is short-circuited. The second point, which fortunately does not often arise in practise, is that all alternator frames, motor frames, and transformer cases should be thoroughly grounded, not only for the foregoing considerations, but also to protect the lives of operators and linemen.

The disadvantages of Y-connected transmission lines may be summed up: Difficulty of obtaining a satisfactory ground on the neutral and overload or short circuit of one phase by partial or complete grounding of a line.

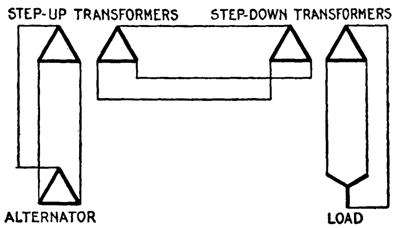


FIG. 7

The third group of tests was made with the system connected as in Fig. 7, with the same load conditions as in the previous set of tests. With this arrangement the normal stresses are about the same as with the Y connections (see Table III), and the unbalancing of load causes no serious variation in voltage relations, but there remains the tendency for the circuits to

TABLE III

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
0	None	None	58.3	57.7	91.2	105.0	—
Balanced	"	"	"	59.0	"	"	—
1 Phase	"	OneH.T. line	60.1	69.1	104.0	120.0	—
"	"	One load lead	65.0	67.2	109.0	126.0	—
0	OneH.T. line	None	100.0	64.5	135.0	156.0	—

lie in different planes, which separate decidedly with a removal of the ground connections to the generator frame. In this case, again, the bad wave form of the alternator connected delta is objectionable. On the whole this system is not to be recommended, as conditions seem to be particularly unstable, and there is no possibility of obtaining a ground point if occasion demands.

The fourth group of tests was made with the same transformer connections as in group three, but with the generator connected Y, giving the better wave form. This is apparently the ideal condition, as with such an arrangement it is unnecessary to ground this neutral in order to relieve abnormal elec-

TABLE IV

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
† 0	Gen. N. (Ng)	None	58.7	57.7	94.4	109.0	0
"	None	"	58.2	"	"	"	3
Balanced	Gen. N.	"	57.7	60.0	"	"	0
1 Phase	"	OneH.T. line	71.7	90.0	167.0	192.0	4
"	"	One load lead	81.2	84.0	142.0	164.0	"
0	1 H. T. line & Ng	None	100.0	58.0	145.0	167.0	"
"	OneH.T. line	"	"	63.7	148.0	168.0	"
Balanced	1 H. T. line & Ng	"	"	58.0	145.0	167.0	"

†Generator frame not grounded.

trostatic strains between windings. (See Table IV.) All neutral points remain close to ground potential, even under unbalanced load. There being no grounded neutral on the system, the danger of a short-circuited phase by grounding is entirely obviated, unless two lines should become grounded simultaneously.

VOLTAGE DIAGRAMS

A few voltage diagrams might help to make clear just what happens under various conditions of load. To avoid needless repetition of similar figures, diagrams of the results obtained in the fourth group of tests are taken as typical.

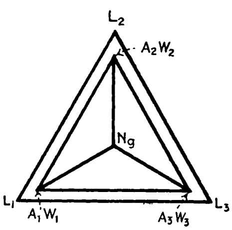


FIG. 8

Fig. 8 represents conditions under balanced load, in which the Y is the generator diagram, with the neutral at *Ng*. The delta A_1, A_2, A_3 represents the primaries of the step-up bank of transformers, and L_1, L_2, L_3 the secondaries of this bank and the primaries of the step-down transformers. The diagram of the secondaries of step-down transformers connected in Y, corresponds to A_1, A_2, A_3 and is indicated by W_1, W_2, W_3.

If, now, one line is opened between step-up and step-down transformers, conditions result as in Fig. 9, which is lettered to correspond with Fig. 8. The heretofore symmetrical figures become considerably distorted. W_1, W_2, W_3 becomes a straight

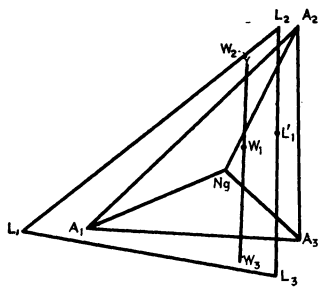


FIG. 9

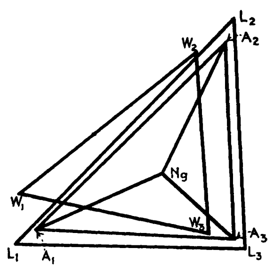


FIG. 10

line, and is therefore in series from W_2 to W_3. The diagrams of the secondaries of the step-up bank and of the primaries of the step-down bank of transformers are no longer coincident. The former is shown by the triangle L_1, L_2, L_3 and the latter by the straight line L_2, L_1', L_3. The distance L_1-L_1' represents the voltage across the open switch.

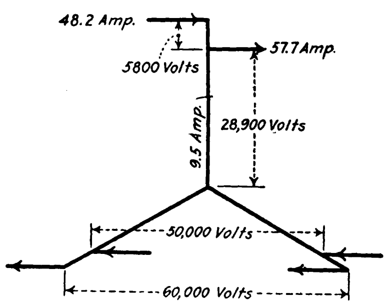


FIG. 11

An open line between step-down transformers and the load gives Fig. 10. The distortion is not so noticeable as in the previous case.

AUTO-TRANSFORMERS

The economic advantage of using auto-transformers for changing from one phase to another and for making slight voltage changes when it has not been necessary to keep the two systems insulated from each other has caused them to be quite extensively used.

Example: A certain large power company had as one source of supply a plant which delivered power to the main distribution center, over a 125-mile (201-km.) line at a potential of 50,000 volts. In the new development 60,000 volts was selected

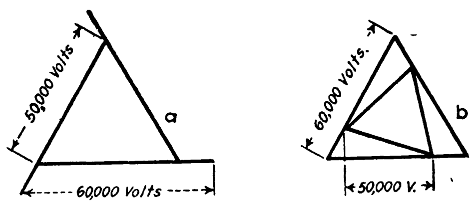


FIG. 12

as a standard for long distribution feeders, and as the line insulation would not permit the old system to be raised to this voltage, the two projects were tied together by means of three auto-transformers, which were Y-connected and would carry, on the 50,000-volt taps, 5000 kv-a. The connections and currents for this bank of auto-transformers are shown in Fig. 11.

This is the most common arrangement of auto-transformers because it is both convenient and economic, and the only one

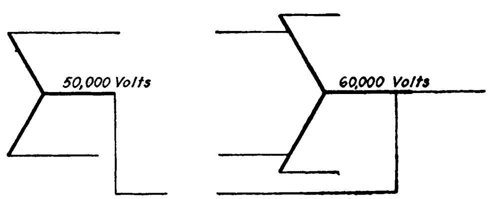


FIG. 13

which will be considered, although either the extended delta or the delta connection as shown in Fig. 12, *a* and *b*, might have been used to good advantage.

When such an auto-transformer is used, it is connected as in Fig. 13. For such an arrangement there may be two conditions; grounded neutral and ungrounded neutral. With grounded neutral the triple-frequency e.m.f. which exists from line to ground may become very dangerous, particularly if the line has considerable electrostatic capacity, as would be the case in the assumed problem, because of the intensifying effect of the third harmonic in the charging current. In some tests made, the maximum stress was found to approach three times normal potential for the neutral of the auto-transformer bank grounded.

With the neutral of the auto-transformer bank ungrounded, stresses running up to 50 per cent of line voltage may be measured from ground to neutral, which is of course not a serious matter, as the maximum stress will remain from line to ground and will not be changed from normal value.

Laboratory tests for this connection indicated that the maximum voltage strain from the lower potential lines to ground would be about half the sum of the high-voltage and the low-voltage, which in this case would be one-half of 60,000 volts plus 50,000 volts, or 55,000 volts.

Transformer Design

When transformers were made in small sizes only, particularly if they were shell type, there was some advantage in having the windings connected Y for the high-tension side of the bank, as this allowed a smaller number of coils and less insulation, because the normal strain was 57.7 per cent of that of delta-connected transformers. The increase in size of units and the provision for maximum strain where one line becomes grounded have made these economic advantages obsolescent, except in some very special cases of small, high-voltage units. Hence, from the point of design and manufacture, there is no advantage for either Y or delta construction.

Appendix

It may be of interest to consider an actual network diagram of the system of a large western power company, as shown in Fig. 14. The following nomenclature is used:

A, engine-driven alternator.
TA, turbine-driven alternator.
T, transformers.
AT, auto-transformers.

The numerals indicate the voltage at various points on the system. For simplicity, the location of switches has not been shown. Several small generating stations on the system are not shown.

Power house No. 1 contains three (shown as one in diagram) engine-driven alternators delivering power at 15,000 volts directly to the busbars. The two turbo-generator sets generate at 9000 volts and step up to the busbar voltage through auto-transformers. In substation No. 1 this is stepped up through transformers to connect with a 50,000-volt line, and in substation No. 2 it connects with a 60,000-volt line through transformers.

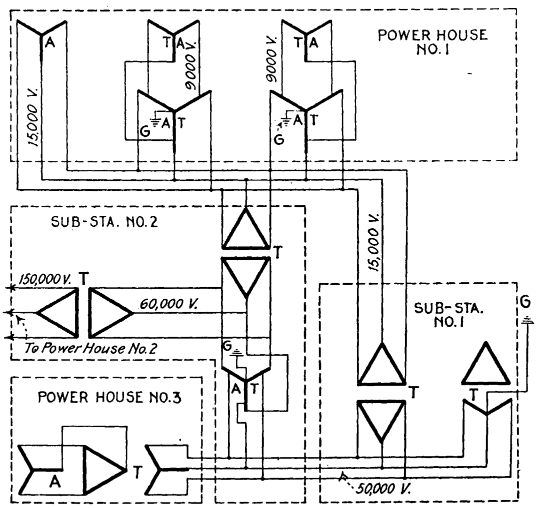


FIG. 14

Power house No. 2 (not shown) is a hydroelectric plant. The generator voltage is stepped up with delta-Y (grounded neutral) transformers to 150,000 volts, at which voltage it is delivered to substation No. 2, where it is transformed to 60,000 volts as shown. The 50,000-volt line from power house No. 3 is connected to the 60,000-volt line through auto-transformers. Substation No. 1 contains a bank of transformers connected Y-delta, with the neutral grounded and the secondary on open circuit.