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INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

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ABSTRACT OF PAPER

In this paper the relative advantages and disadvantages in operation of the more important three-phase transformer connections are discussed. Three conditions of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation.

The paper is not complete, particularly in that high-frequency or switching phenomena are not discussed. Its major purpose is to give a fairly adequate presentation of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system.

The behavior of three-phase auto-transformers under the various conditions of operation given above is also analyzed.

Transformers for use on three-phase systems are in the majority of cases connected either delta-delta or delta-Y, these two being almost universally considered superior to the few other connections which may be used for three-phase transmission. Opinions differ, however, as to their relative merits, and the purpose of this discussion is to analyze some of the factors involved.

Operation in Case of the Disabling of One Phase. In the delta-delta connection, operation can be continued by running open delta after removing the disabled phase, under which condition the bank can handle 58 per cent of its original capacity. When, however, there are two or more delta-delta banks operating in parallel, the advantage of open delta operation of one bank becomes less on account of the fact that a mutual relation exists between the loads in the two banks. For example, if one phase of one bank is removed, instead of being able to operate the good bank at 100 per cent capacity and the open delta bank at 58 per cent capacity, making a total of 158 per cent (assuming all transformers alike and that 200 per cent was the original total capacity of the two banks) it will only be possible to derive from the five transformers 133 per cent capacity.[1] When two delta-delta banks are operated in parallel with one open delta bank, a total capacity of 233 per cent instead of 258 per cent is obtainable. Thus it is evident that with increasing numbers of delta-delta banks connected in parallel, the advantage of being able to operate any one of them in open delta decreases. This, however, is not a serious objection, because, by placing the proper amount of reactance in series with the weakened phase, the capacity can be considerably increased.

Open delta operation of a three-phase core type transformer is, in the majority of practical cases, not possible, on account of the interlinked magnetic structure.

In delta-Y connections, the disabling of one phase renders the whole bank inoperative, except in the case when it is possible to change the voltage of the line connected to the Y side of the transformers. For example, if a line transmits power from one bank of delta-Y transformers at one end to another bank of Y-delta transformers at the other end, operation can be continued in case of the disability of one phase by changing the Y connection to open delta in both step-up and step-down transformers, thus reducing the transmission line voltage to 58 per cent of its original value. Under this condition the capacity of the transmission line and transformers is reduced to 58 per cent of the original value, which is equal to the capacity obtained in the case of operating one delta-delta transformer bank in open delta. When, however, two or more Y-delta banks are operated in parallel, the disability of one phase renders the whole of one bank inoperative.

The Effect of Differences in Characteristics of the Transformers Making up a Transformer Bank. When transformers of slightly different ratios are connected in delta-delta, large circulating currents will result in the delta circuits, depending upon the amount of off ratio and the impedance of the transformers; and when transformers having different impedances are connected for delta-delta operation, the division of load between them will be very unequal. In general, a delta-delta connection is very sensitive to variations in impedances and ratios. A Y-delta bank of transformers is far less sensitive to such variations, and in fact transformers having considerable differ-

1. See article entitled " Delta-Delta Transformer Banks in Multiple," by W. W. Lewis, *General Electric Review*, January, 1912, page 47.

ences in ratio and impedances can be used to make up a Y-delta bank without appreciably affecting the current or voltage division of the phases. From this it is evident that, in cases where a three-phase bank is to be made up of dissimilar units of equal kilovolt-ampere capacity, more satisfactory operation can be obtained by connecting delta-Y than delta-delta. On the other hand, if the kilovolt-ampere capacities of the units are different, the delta-delta connection will probably result in a greater combined capacity than Y-delta, because in the delta-delta banks the currents will divide to a certain extent, at least in proportion to the kilovolt-ampere capacity of the units, whereas in the Y-delta connection the currents in all three phases are equal.

Insulation Stresses

The potential stresses on the insulation at fundamental frequency are worthy of consideration and become particularly important in high-voltage transformers. Under normal conditions of operation, that is, when the connected line is free from grounds, the maximum value of these stresses is equal to 58 per cent of line potential. In the delta connection the minimum value of the insulation stress is equal to 29 per cent and occurs at the middle point of the winding, whereas in the Y connection the stress is zero at the neutral end of the winding, and increases uniformly to its maximum value of 58 per cent at the line end. These stresses are tabulated below for convenience in comparison, together with corresponding insulation safety factors, the latter being based on the assumption that the windings are insulated to withstand a test equal to twice normal voltage.

TABLE I

Insulation Stresses from High-Voltage Winding to Ground, in Three-Phase Connections, at Fundamental Frequency, under Normal Operating Conditions.

	Stresses in per cent of line voltage			Safety Factor		
	maximum	minimum	average	maximum	minimum	average
delta	57.7	28.8	43.2	7	3.46	4.64
Y	57.7	0	28.8	infinity	3.46	7

When one terminal of the transformer is grounded, these stresses are all materially increased. Their values at various portions of the winding are shown in Fig. 1. Here high-potential stresses in the insulation from winding to core in per cent of the normal line voltage for every portion of the high-voltage winding are plotted as ordinates. The curve shows that the stress in the insulation of delta winding is practically equal to line voltage at all points of the winding, the voltage at the middle point, however, being reduced to 87 per cent of this value. On the other hand, in the Y connection the stress in the winding is graded, being a minimum at the neutral and a maximum at the line end. Three cases are given: Curve *a* shows the condition when the neutral is not grounded; curve *b* shows the condition when the neutral is grounded, and when the line is capable of maintaining normal voltage notwithstanding the short circuit produced by a ground on the line; and curve *c* shows the stresses in delta-Y transformers excited on the delta side and operating with a grounded neutral. A particularly large reduction of stress is obtained in the latter case, the maximum never exceeding 58 per cent of line potential. These stresses, together with their corresponding safety factors, are given in Table II.

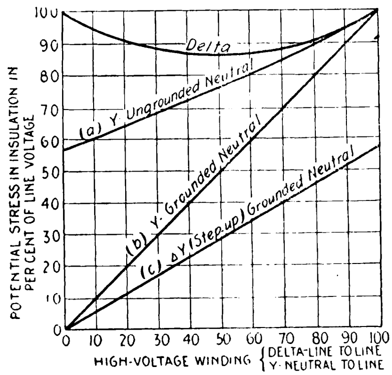


FIG. 1—EFFECT OF GROUNDS ON POTENTIAL STRESSES AT FUNDAMENTAL FREQUENCY ON THREE-PHASE CONNECTIONS

TABLE II

INSULATION STRESSES FROM HIGH-VOLTAGE WINDING TO GROUND, IN THREE-PHASE CONNECTIONS, AT FUNDAMENTAL FREQUENCY, WITH ONE TERMINAL GROUNDED.

	Stresses in per cent of normal voltage			Safety factor		
	minimum	maximum	average	maximum	minimum	average
delta	86.6	100.	93.3	2.3	2	2.1
Y (a)	57.7	100.	78.8	3.46	2	2.54
Y (b)	0	100	50	infinity	2	4
Y (c)	0	57.7	28.8	"	3.46	7

Although the above stresses are relatively small and on that account probably never immediate causes of breakdown, nevertheless it should be borne in mind that stresses of higher frequency are superimposed upon these. It therefore follows that with the transformer connection possessing the smallest average insulation stress at fundamental frequency, or conversely, that connection which possesses the maximum insulation safety factor (when fundamental stresses only are considered), a greater margin is available for withstanding stresses at higher frequencies. These margins, which are obtained by subtracting the insulation stresses given in Tables I and II from the transformer test voltage (200 per cent of normal voltage), are given in Tables III and IV.

TABLE III

INSULATION MARGINS FOR NORMAL OPERATIONS, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	171 per cent	142.3 per cent
Y	200	142.3

TABLE IV

INSULATION MARGINS WITH ONE TERMINAL GROUNDED, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	113 per cent	100 per cent
Y (a)	142	100
Y (b)	200	100
Y (c)	200	142

These tables, however, only roughly indicate that the Y connections, particularly in the case represented by curve *c* of Fig. 1, are capable of withstanding greater stresses at higher frequencies than the delta connection; it would be a true indication provided the insulation is only capable of withstanding twice the line voltage. The table should therefore have been worked out in terms of the actual strength of the insulation instead of the test voltage for which it was designed.

Line Grounds on Isolated Systems. In an isolated system, when a solid ground occurs on the line, the grounded wire is reduced to zero potential and the potentials of the other lines are raised to line potential above ground. If a ground occurs on the line, a considerable distance from the transformers, the charging current flowing through the reactance of the line will cause the potential of the grounded line at the transformer to be somewhat above zero, and since the induced voltage of the transformer will also be somewhat greater than its normal value on account of the reactance drop caused by the charging current (particularly when the transformer possesses high inherent reactance), the free line is raised to a fair percentage above its normal potential above ground. This effect is also somewhat larger than one would ordinarily assume, on account of the fact that the electrostatic capacity of a transmission line having one of its lines solidly grounded is in the majority of cases considerably greater than when the lines are thoroughly insulated. However, none of these effects are very large, and in general the result of a dead

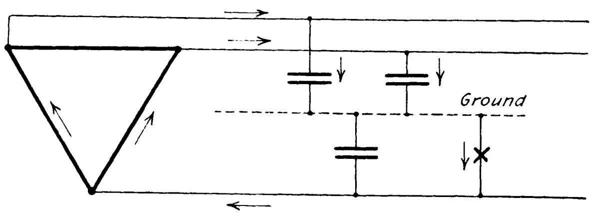


FIG. 2

ground on an isolated system is to bring the other two wires to a potential somewhat greater than normal above ground. The insulation safety factor has thereby been reduced to a value slightly less than two. It is evident that the values of insulation stresses and safety factors given in Tables I and II and the curves in Fig. 1, are not quite correct when transformers are connected

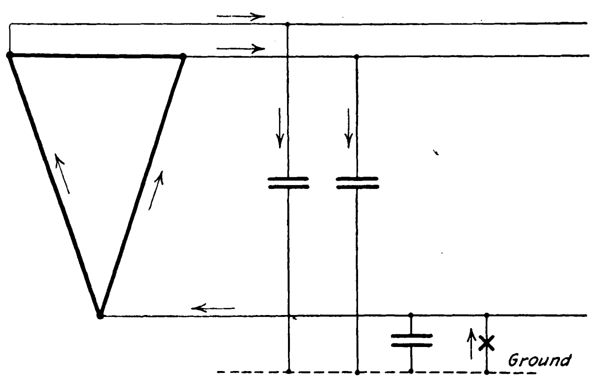


FIG. 3

to transmission lines of considerable electrostatic capacity. It is possible to operate an isolated system with one of its lines solidly grounded without serious risk, and there have been cases of high-voltage, long-distance transmission lines operating in this manner for several hours with a solidly grounded or even a broken line.

But when the ground occurring on the line is not a dead ground, an arc results between line and ground which, on account of the fact that it is in series with the electrostatic capacity of the transmission line (see Fig. 2), generally results in an unstable arc or an arcing ground.

If the arc, however, is stable, the potential of the arc and line is reduced to ground and may have its potential reversed if higher harmonics introduced by the arc happen to be in resonance with the natural period of the grounded system. This is shown diagrammatically in Fig. 3.

Such conclusions are corroborated by the results obtained in the experiments made by Dr. E. J. Berg, and reported in an Institute paper[2] in June, 1908, entitled *Tests with Arcing Grounds and Connections*.

Grounds on a System Having Neutral Grounded. A ground on a system having a neutral grounded results in a short

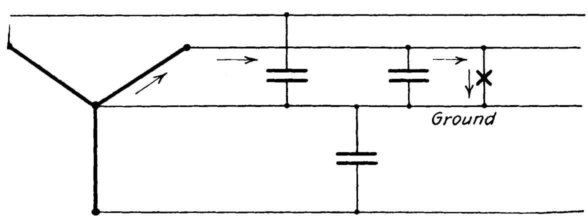


FIG. 4

circuit, and a dynamic current flows, the value of which depends upon the combined impedance of the circuit through ground and impedance of the transmission line and connected apparatus through which the short circuit flows. (See Fig. 4). This results in an impedance drop throughout the circuit and a consequent lowering of the voltage. The resultant arc is in series with the reactance of the transmission line, and since reactance tends to stabilize an arc, the likelihood of an arcing ground resulting is therefore much more remote than in the case of the isolated system.

In general, with the grounded Y system, resonance on account of the electrostatic capacity of the line is not likely, since the line capacity is not in series with line grounds. There is one particular case, however, when resonance may be produced. For example, in a delta-Y system with grounded neutral, suppose

2. TRANSACTIONS A. I. E. E.. 1908, XXVII, Part I, page 741.

one phase on the delta side is burned open, resulting in open delta excitation. The high-voltage side of the burned-out phase then constitutes a reactance in series with electrostatic capacity of the transmission line and excited by the voltages from the other two phases. If the charging current of the transmission line is equal to the magnetizing current of the transformer, resonance is established at fundamental frequency. However, the increase in voltage is limited by the saturation of the transformer; for example, assuming that the normal flux density of the transformer is 80,000 lines per sq. in. (6.452 sq. cm.), it follows that more than a 50 per cent increase in voltage can hardly be expected. The resulting stresses on the insulation are therefore less than those reached in isolated systems when grounds occur on the line.

If the voltage impressed on the low-voltage side contains a

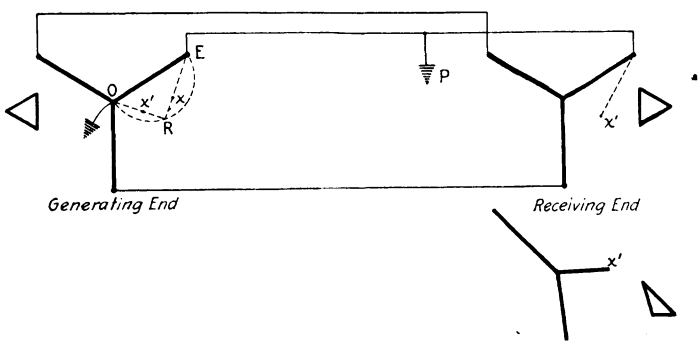


Fig. 5

prominent fifth harmonic, there is a probability of establishing resonance at five times normal frequency, and dangerous voltages built up thereby. However, the likelihood of obtaining resonant conditions at five times normal frequency is not very great, and moreover the fifth harmonic in impressed voltage is generally small. Also the importance of this consideration is small on account of the fact that it can only take place when one delta bank is connected to the transmission line and when one phase of the low-voltage delta becomes open-circuited.

The effect upon the distribution of the voltage, of a line ground on a grounded Y system, is shown diagrammatically in Fig. 5. The portion consumed by line resistance and reactance brings the potential of P to some point X' and the potential OX' is consumed in overcoming the resistance of the current path from the line ground P to neutral O.

The worst short circuit occurs when a dead ground happens on the line near transformer A, which causes a collapse of the short-circuited phase throughout the system, and a short-circuit current only limited by transformer reactance.

Resistance in Neutral. To reduce the value of this short-circuit current, resistances are often inserted between the neutral point and ground.

A resistance inserted in the neutral causes the neutral o to shift with respect to ground when a ground occurs on the line, or relatively speaking, the ground will shift along the line OX_1. If resistances of ground is small compared to resistance at neutral the ground potential in Fig. 5 is X'. A dead ground on the line near the transformers causes the neutral to shift a value equal to $\frac{rE}{r + jx}$, where r equals resistance of neutral and x equals reactance of transformer. It is evident that an increase in potential stress on the remaining phases results.

Assume a transformer with six per cent reactance, and resistance of neutral which will limit the current resulting from a dead ground to three times normal (that is, the resistances and reactances together are equivalent to an impedance of 33 per cent). The reactance of neutral must, therefore, be $\sqrt{(33)^2 - (6)^2} = 32.5$ per cent, and the neutral shift will be equal to $3 \times 32.5 = 97$ per cent. *Evidently any resistance inserted in the neutral, if it is to limit currents to values appreciably less than those obtained when the neutral is dead grounded, must be capable of withstanding practically normal phase potential.* More-over, the purpose of grounding the neutral is destroyed, for a neutral shift of 75 per cent or more of the phase voltage means that the free lines have been raised to practically full line potential above ground.

A neutral will therefore remain stable only when the IR drop produced across the neutral resistance by the short-circuit current is small compared with the line voltage. Practically all the voltage must be consumed by the resistance of the ground and resistance of neutral in series. From this we can conclude that *a neutral with resistance will hold the neutral fairly steady and prevent undue rises in potential, provided the line grounds do not occur with resistance* (including line resistance to point of ground) *less than ten times the resistance in the neutral.*

The ratings of the resistance inserted in the neutral for various limiting values of short-circuit current are given in Table V. These are worked out on the basis of transformer reactance equal to six per cent, resistance one per cent, and on the assumption that the short-circuit current is limited only by the resistance in the neutral and the impedance of the transformers.

TABLE V

Short-circuit current	Volts across neutral in per cent of transformer normal voltage	Rating of kv-a. resistance in per cent of normal kv-a. of one phase
16.4 times normal	0	0
12 " "	57	644
10 " "	70	700
5 " "	90	450
3 " "	94	280
2 " "	98	196
1 " "	100	100
0.5 " "	100	50

The size of the resistance will also depend upon the length of time short circuit is maintained. For example, if the system is protected by relays which disconnect the apparatus in two minutes, the resistance must be designed to dissipate the power given in the table for this period of time.

Grounding the Neutral at Receiving End. In the preceding discussion the neutral at the generating station was in every case considered grounded. However, when the neutral of the step-down transformers at the far end of the transmission line is grounded, and the neutral at the generating station isolated, a different condition exists. In this case, when one line near the step-down transformers becomes grounded, one phase is short-circuited thereby, and current flows as indicated by the arrows in Fig. 6. If the step-down transformers are small compared with the kilovolt-ampere capacity of the system to which they are connected, the line voltage is not appreciably affected by this short circuit, although the grounded line assumes ground potential. Line potential is therefore impressed across two phases, as indicated in *a* of Fig. 6, and the ungrounded lines assume a potential of practically line voltage above ground. The currents flowing are single-phase and produce in each phase a reactance drop equal to *ab*, that is, phase voltage.

If, on the other hand, the step-down transformers have a kilovolt-ampere rating comparable with the rating of the transformers at the generating station, the resulting short-circuit currents are severe enough to reduce the line potential at the step-down transformers very materially. On that account they are not as liable to an increase in induced potentials and potential stresses from winding to ground.

Complete protection, however, is not given in this case to the step-up transformers, for if a ground occurs near the generating station, the short-circuit currents must flow through the ground between the generating station and receiving end, in which case the voltage drop on the ground and in lines may be sufficient to limit the short-circuit currents, and therefore decrease the reactance drop within the transformers. Under this condition, the terminals of the step-up transformers will assume a potential above ground equal to line voltage.

Auto-Transformers. Wherever it is desired to interconnect two high-voltage systems of not very great voltage difference,

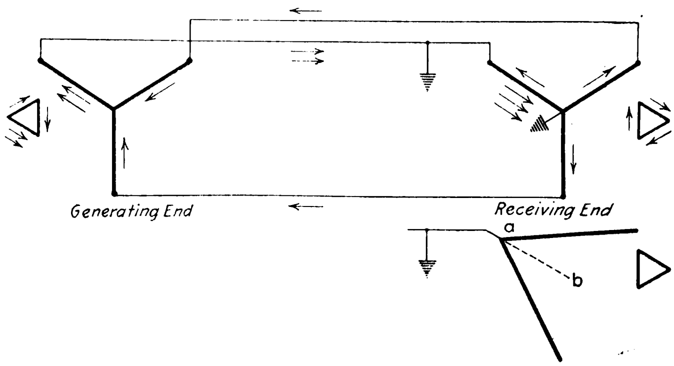


FIG. 6

as, for example, 100,000 volts and 60,000 volts, the use of Y-connected auto-transformers is cheaper than transformers, because a large saving is effected due to the fact that the rating is only a fraction of the power which the auto-transformer can transmit from one system to the other. Since reduction in rating is only material when the connection is Y, a delta-connected auto-transformer is seldom used. But when the transformation ratio is three or more, the saving in the use of auto-transformers instead of transformers is too small to outweigh the disadvantages which their use entails.

As auto-transformers are cheaper from the standpoint of first cost, it is of interest to investigate potential stresses at normal or fundamental frequency resulting from abnormal conditions, as line grounds, etc., in order to determine their reliability and therefore their eventual cost. These insulation stresses depend upon whether the system is isolated or grounded Y, and whether the neutral of the auto-transformer is grounded. There are four cases:

CASE I. SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL UNGROUNDED (SEE FIG. 7)

(a) A triple-frequency e.m.f. exists from line to neutral, increasing the induced potential stress from 20 to 50 per cent, depending upon the flux density in the iron. The insulation stress from winding to core is increased at the neutral, but not at the line ends of the winding. The presence of the triple-frequency voltage, therefore, is not serious, for although the average potential stress on the insulation is increased, the maximum stress is not affected.

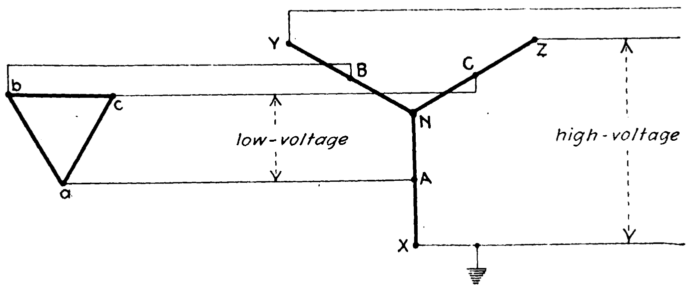


FIG. 7—SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL UNGROUNDED

(b) A ground at X (Fig. 7) places the low-voltage lines B and C at a potential above ground approximately equal to 0.58 high-voltage + 0.42 low-voltage.

Thus, if the auto-transformer steps up from 60,000 volts to 100,000 volts, a solid ground existing on the high-voltage line raises the potential of the low-voltage line to 81,000 volts above ground.

CASE II. SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL GROUNDED (FIG. 8)

(a) The triple-frequency e.m.f. which is present as in Case I, is now exerted across the line insulation to ground. This is particularly dangerous if the auto-transformer is connected to systems having considerable electrostatic capacity. Electrostatic capacity between lines and ground causes a charging current in which the third harmonic is prominent, which reacts on the triple-frequency e.m.f., intensifying it. Potential peaks equal to three times normal can easily be obtained in this way at ordinary densities, although at very low densities and at saturation densities, the danger is less. The charging current necessary to produce these voltages is not large.

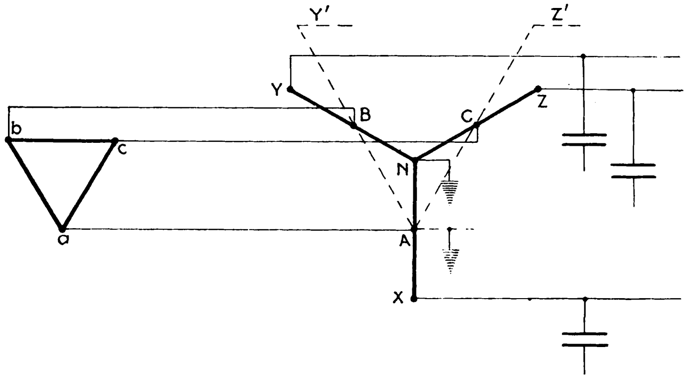


FIG. 8—SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

(b) A ground at A causes NA to collapse, NA and X are reduced to ground potential and the remaining phases receive open delta excitation at 1.73 normal flux density. This is shown by the dotted lines in Fig. 3. B and C are placed at low-voltage potential above ground.

(c) A ground at X produces the same result as a ground at A.

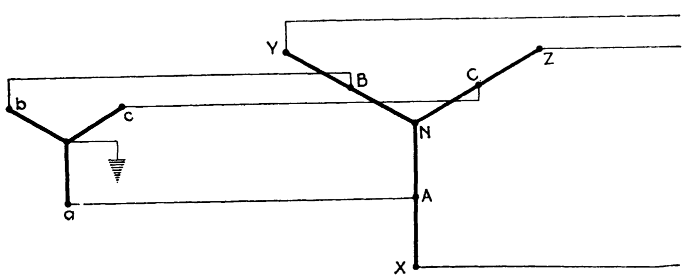


FIG. 9—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL UNGROUNDED

CASE III. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL ISOLATED (SEE FIGS. 9 AND 10)

(a) Triple-frequency voltage present as in Case I. Since the neutral is isolated, there is no danger of the triple-frequency voltage being intensified.

(b) A ground at *A* short-circuits one phase of the low-voltage system.

(c) A ground at *X* results in distortion of and increase in induced voltage in the auto-transformers, as shown in Fig. 5. The low-voltage system does not receive an abnormal voltage or abnormal insulation stress.

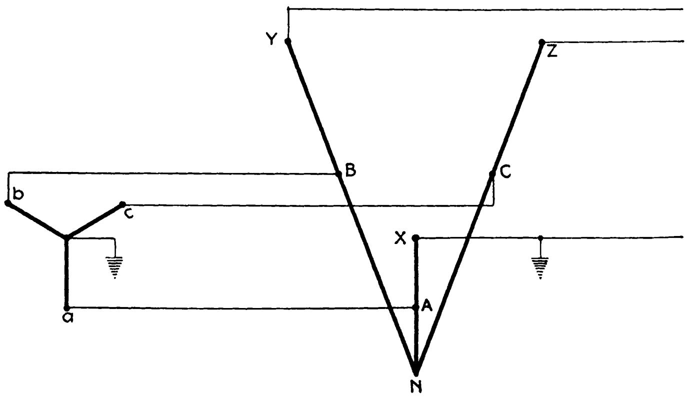


FIG. 10—SYSTEM GROUNDED, AUTO-TRANSFORMER UNGROUNDED, SHOWING EFFECT OF DEAD GROUND OCCURRING ON LINE

CASE IV. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED (SEE FIG. 11)

(a) Triple-frequency e.m.f. is much reduced because triple-frequency currents can flow through ground connections. The

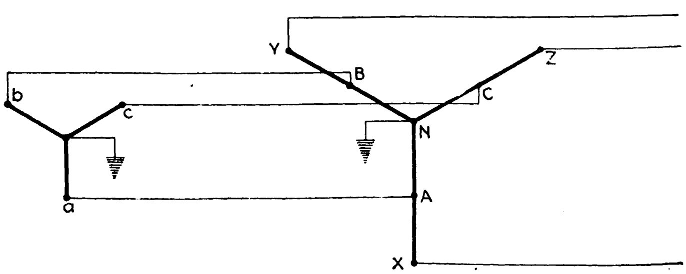


FIG. 11—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

reduction in triple-frequency e.m.f. depends somewhat upon the resistance of the ground circuit.

(b) A ground at *A* short-circuits one phase of the low-voltage circuit.

(c) A ground at X short-circuits one phase of the auto-transformer and one phase of the low-voltage circuit through the auto-transformer reactance. The potential of B and C cannot rise above normal values.

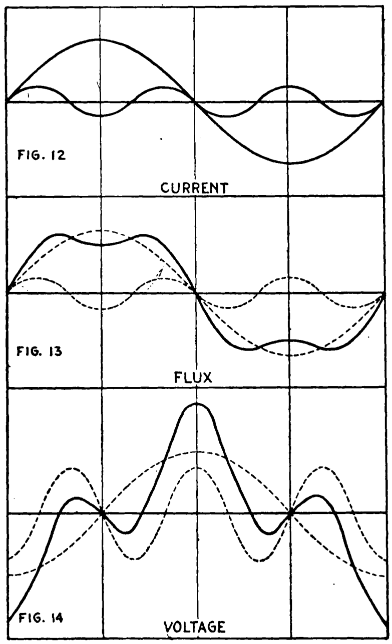
In the above cases, single-phase auto-transformers were assumed, although the same results are obtained in three-phase shell type units. In the three-phase core type transformers, the triple-frequency e.m.f. is reduced to negligible proportions on account of the interlinked magnetic circuit. Moreover, in the case of a grounded neutral, when a ground occurs on the line, the interlinked magnetic circuit resists the collapse of one phase, by causing heavy currents to flow in all three phases. The value of this current depends upon the resistance of the ground, a dead ground in the majority of cases causing currents comparable to short-circuit currents.

If the neutral of the system is grounded through a resistance to limit short-circuit currents, excessive currents are prevented when a ground occurs on the line. However, in that case the neutral will remain stable only for high-resistance line grounds. If a dead ground occurs on the line, full phase voltage is impressed across the neutral resistance and potential stresses will exist similar to those occurring in isolated delta systems. In general, it may be said that the grounded neutral, with a resistance to limit the current flow, acts like a solidly grounded system as long as grounds of high resistance only occur on the line. When a dead ground occurs, the resulting potential stresses will be practically the same as if the system were operating ungrounded.

It should be borne in mind that the conditions in the majority of practical cases considerably depart from those cited here. For example, in the case shown by Fig. 7, the normal flux density may be so high that the magnetizing current required for 73 per cent increase in voltage will be so great as to cause a line reactance drop sufficient to reduce considerably the voltages applied to the transformers. However, the diagram applies rigidly to all cases where the normal flux density is made low enough so that, when a ground occurs, the cores will not be supersaturated. Similarly, the conditions shown by Fig. 5 will not occur in practise on account of the excessive magnetizing currents resulting.

It is evident from the analysis of the four cases given above, that high-voltage auto-transformers should not be used without solidly grounding the neutrals. Grounding the neutral necessitates the elimination of the triple-frequency e.m.f., which may be done either by using the three-phase core type structure or by having a Y-delta transformer with ground neutral connected to the same system. The latter method, is, however, questionable because the safety of the auto-transformer then depends upon proper operation of another piece of apparatus.

If such precautions are taken, auto-transformers should operate successfully, although they still possess the objection that the high-voltage and low-voltage systems are rigidly connected together by means of an electrical conductor, whereas a transformer connects the systems in a more flexible manner, *i.e.*, magnetically. Due to this, a disturbance occurring on one line is likely to be felt on the other, when auto-transformers are used. With tie-in transformers, operating on isolated systems, it is possible for grounds to occur on line without disturbing the operation or increasing the stresses on the other lines.



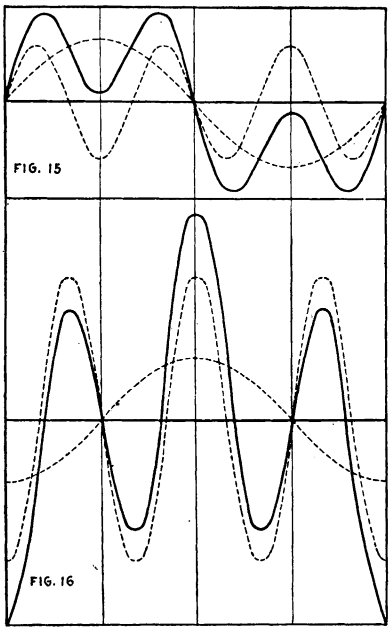
FIGS. 12, 13, 14—CURRENT, FLUX AND VOLTAGE RELATIONS IN Y-CONNECTED AUTO-TRANSFORMERS

THE THIRD HARMONIC IN THE Y CONNECTION

Due to the fact that the permeability of iron decreases as the flux density increases, the wave shape of magnetizing current in a transformer is different from the wave shape of the electromotive force. When the impressed electromotive force is a sine wave, the magnetizing current shows a peak, which, when analyzed, resolves itself into a prominent third harmonic and higher harmonics of lesser values.

In the Y connection, third harmonic currents and currents having frequencies multiples of the third cannot flow on account of the fact that these currents in the three phases would be in phase with each other, and to permit them to flow, a circuit must be provided at the neutral.

Owing to the fact that the triple harmonic current necessary for sinusoidal excitation cannot flow in Y-connected transformers the resulting flux wave takes a flattened form, which, when analyzed, resolves itself into the fundamental and a triple harmonic. The flux wave under this condition is shown in Fig. 13, and the corresponding voltages induced from line to neutral are given in Fig. 14. For average operating densities in transformers, the triple harmonic voltage is approximately 60 per cent of fundamental voltage.



FIGS. 15, 16—ANALYSIS OF THIRD HARMONIC INTENSIFICATION IN Y AUTO-TRANSFORMERS

When the neutral of the auto-transformer is grounded, the triple harmonic together with the fundamental is impressed between line and ground across the capacity of the connected transmission line. A triple-frequency charging current flows into the line and through the auto-transformer windings. The phase angle of this current with reference to the fundamental magnetizing current is shown in Fig. 12. This triple-frequency current constitutes an additional magnetizing current in the auto-transformer, and a comparison with Fig. 13 shows that it is in phase with the triple-frequency flux which was produced by the original sine wave magnetizing current. Therefore the triple-frequency current acts to increase the triple-frequency flux and a corresponding intensification of triple voltage ensues. The increased triple harmonic voltage results in a greater triple current, which causes a further increase in flux. This intensification is only limited by the saturation of the transformer. Figs. 15 and 16 show flux and voltage waves in which the third harmonic has reached its maximum value. It is evident that under such conditions of operation the core loss of the transformers will be about three times normal and the insulation stress about four times normal.

Conclusions

The following are the more important conclusions which may be drawn from this paper:

First: Isolated systems are subject to greater insulation stresses than grounded systems.

Second: In grounded systems, the average insulation factor of safety is greater than in isolated systems under similar conditions of operation.

Third: In isolated systems, the stresses at lower frequencies under certain conditions, may reach values sufficiently high to injure or destroy the transformer and other apparatus connected to the system.

Fourth: In an isolated system, a ground on the line is more likely to result in an arcing ground or intermittent arcs than in a grounded system.

Fifth: A ground on the line in a solidly grounded system, reduces the potential of the system with respect to ground, whereas in the isolated system, a ground on the line increases the potential of the system with respect to ground.

Sixth: A resistance inserted between neutral and ground to limit the value of short-circuit current increases thereby the insulation stresses resulting from line grounds.

Seventh: If it is desired to limit the value of potential at fundamental frequency above ground of any part of the system to 57 per cent of line potential, it is necessary to solidly ground the neutrals at both receiving and generating ends of transmission line.

Eighth: If receiving transformers of relatively small kilovolt-ampere capacity are connected with grounded neutral to an otherwise isolated system, they are liable to severe short circuits, and the grounded neutral only partially protects the system from potential rises.

Ninth: In Y-connected auto-transformers, it is dangerous to operate with isolated neutral except when the ratio of transformation is very small.

Tenth: In Y-connected auto-transformers, it is dangerous to operate with isolated neutral except when the entire system is isolated.

Eleventh: In Y-connected auto-transformers, it is dangerous to operate with grounded neutral unless the triple harmonic voltage between line and neutral is eliminated or kept negligibly small.