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CONTENTS

TAYLOR'S FREQUENCY TRIPLER.

BY

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Taylor's frequency tripler was introduced in 1914 (*J.I.E.E.*, 1914, **54**, 701), and although it has proved to be useful as a frequency changer the principle of its action does not appear to be fully understood. The explanation of its action in Taylor's original paper (*loc. cit.*) is inadequate, but no further work on the subject has been recorded and recent books (Morecraft, *Principles of Radio Communication*, 1927, 708) explain it in practically the same terms as in Taylor's paper. The present communication aims at explaining its action more fully, removing some misconceptions and describing some experiments which serve to throw light on its action.

THEORY.

The tripler consists of three saturated choke coils, each connected in series with one of the three windings of an unsaturated transformer of which they jointly form the primary. When the arrangement is

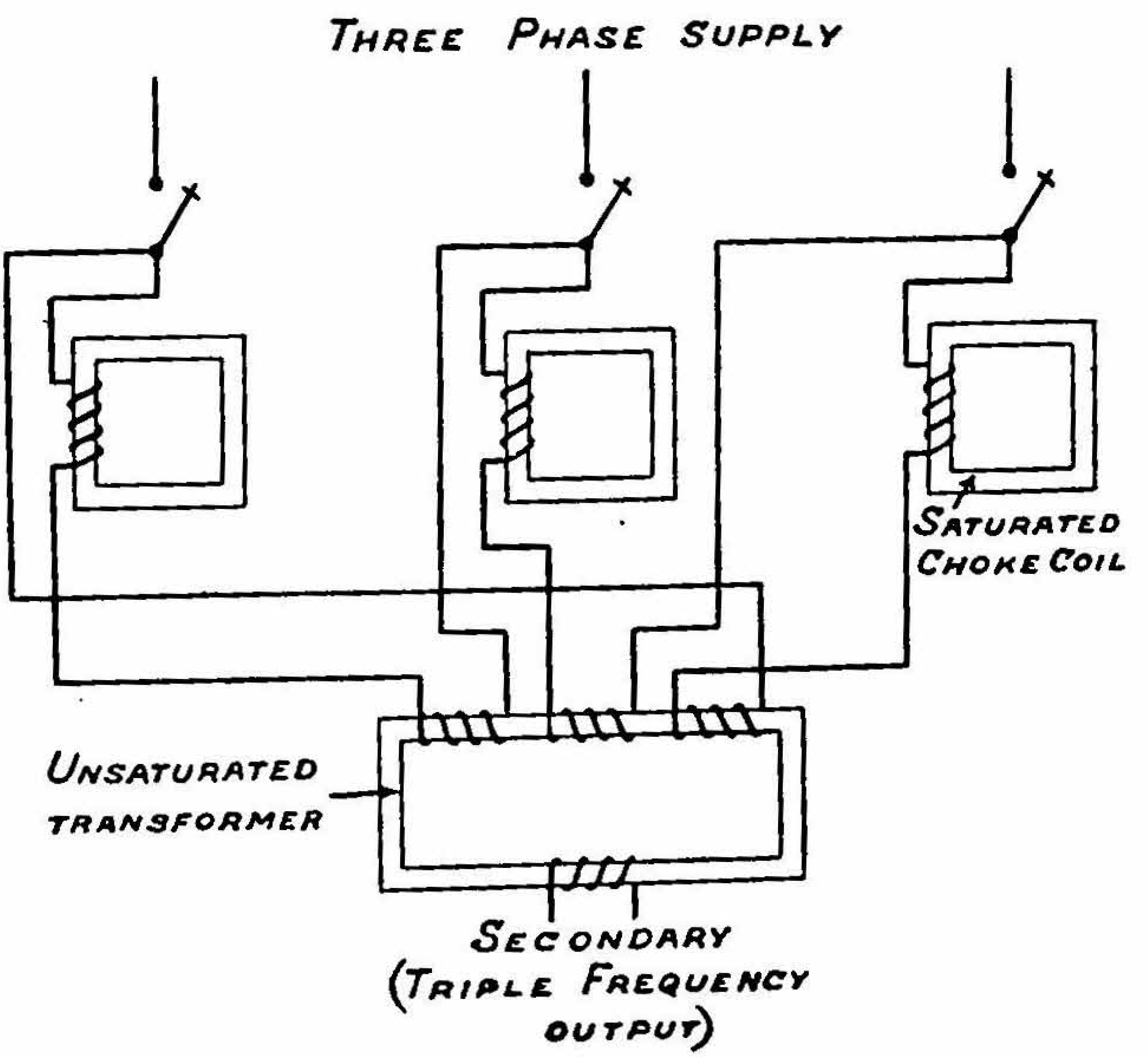


FIG. 1

DIAGRAM OF CONNECTIONS FOR TAYLOR'S FREQUENCY TRIPLER connected in delta and supplied with three-phase currents as shown in fig. 1, single-phase current of triple frequency can be obtained from the secondary of the transformer.

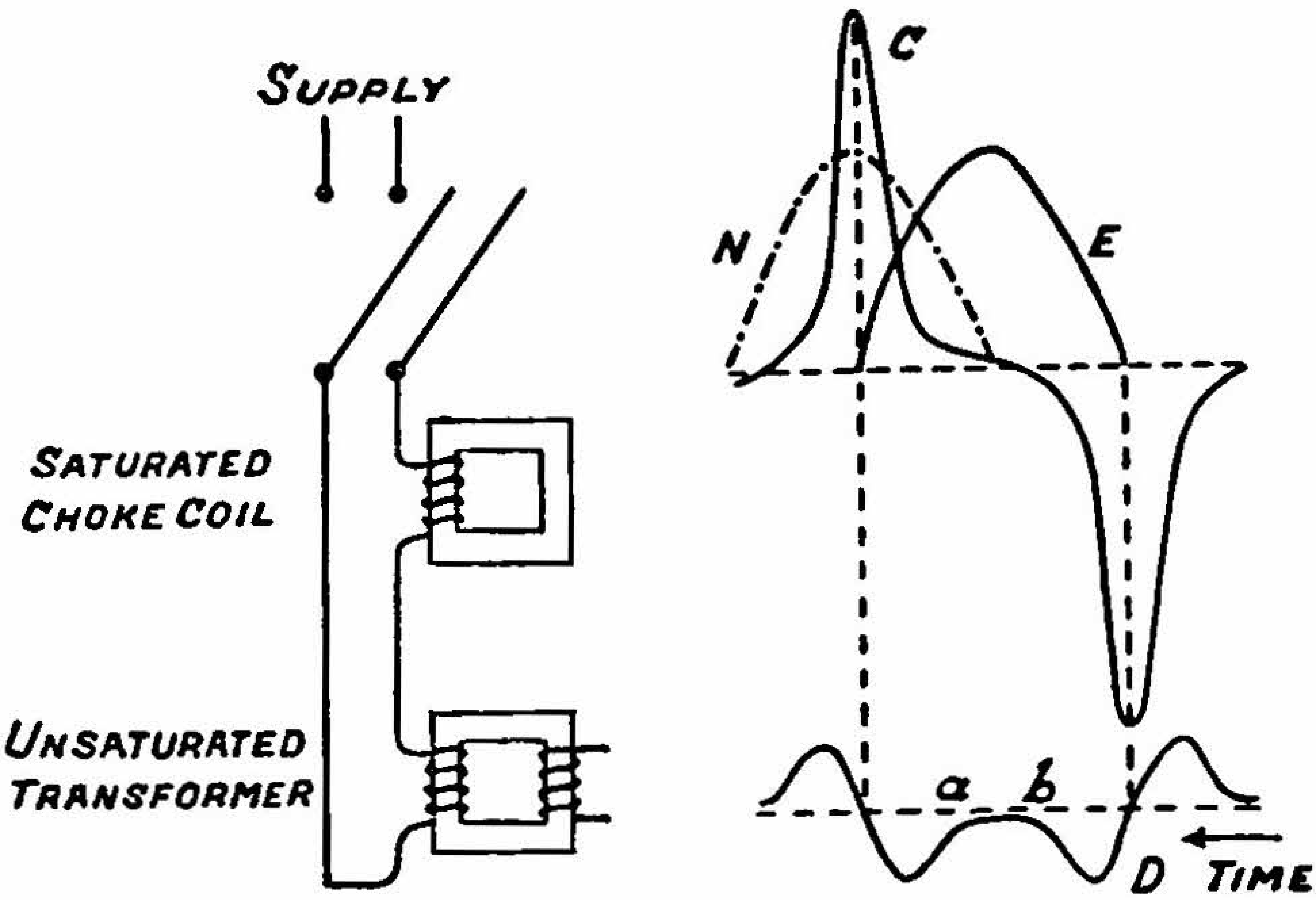


FIG. 2
PRINCIPLE OF TAYLOR'S ARRANGEMENT

Taylor's theory.—Taylor has explained the principle of the frequency changer as follows. A single-phase E.M.F., E is impressed on the saturated choke coil (fig. 2), and N represents the flux in the choke coil and C the current required to produce the flux. The current C, flowing through the unsaturated transformer produces a flux similar to itself in shape. The rate of change of this flux produces the E.M.F. represented by D, in the primary and secondary windings of the transformer. This E.M.F. wave is a symmetrical mutilated triple harmonic wave in which every third half-wave is suppressed. If three of these triple harmonic waves produced by three-phase currents are combined, the resultant is a complete triple harmonic wave as shown in fig. 3. Taylor does not give any experimental curves in support of his theory and it is not borne out by the experiments carried out by the authors.

Proposed theory.—Curve D (fig. 4) was obtained experimentally and represents the E.M.F. induced in the secondary of the unsaturated transformer when a sinusoidal P.D., V was impressed on the circuit shown in fig. 2. E is the P.D. across the terminals of the choke coil and is equal to the difference between V and D.

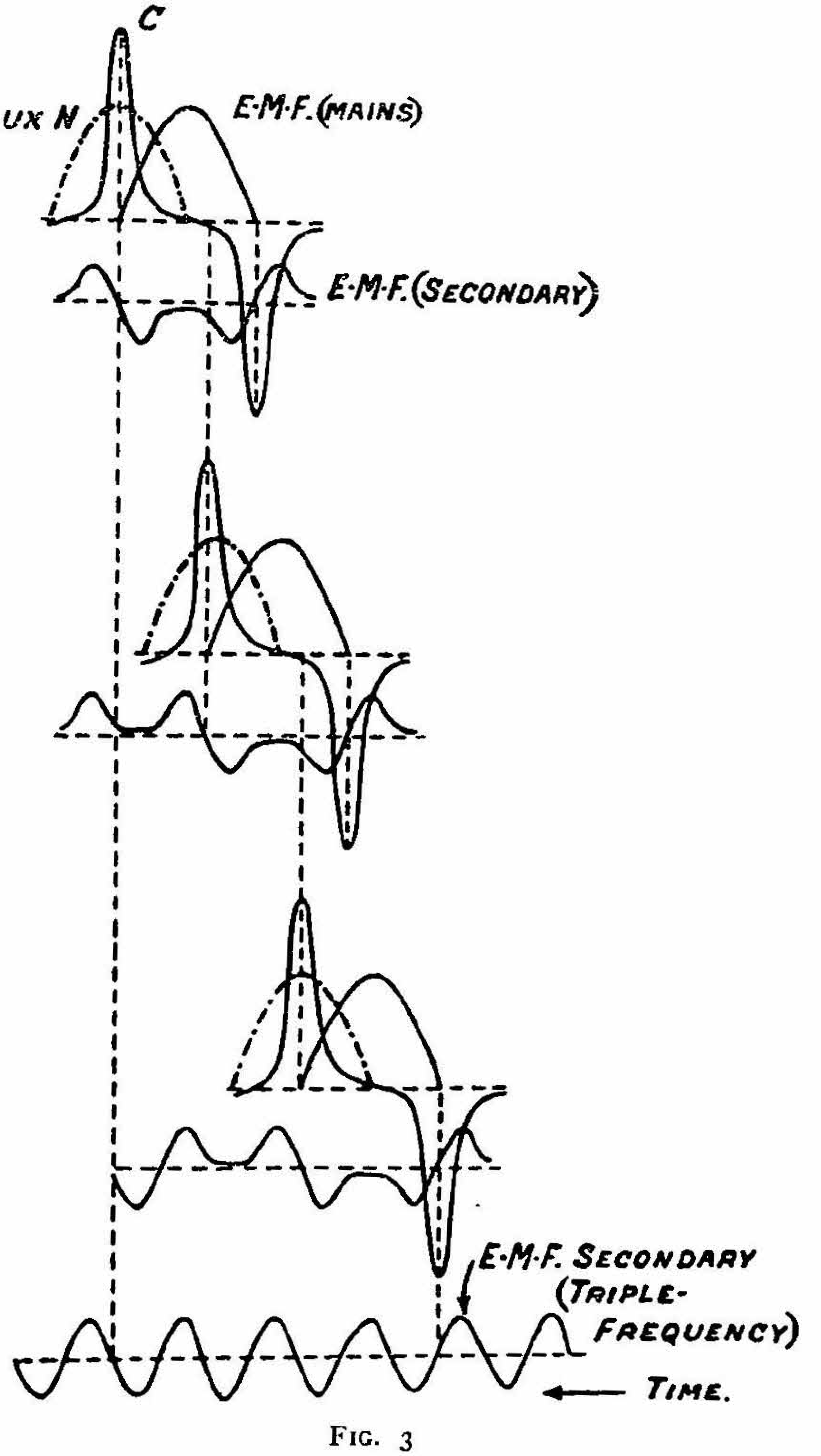
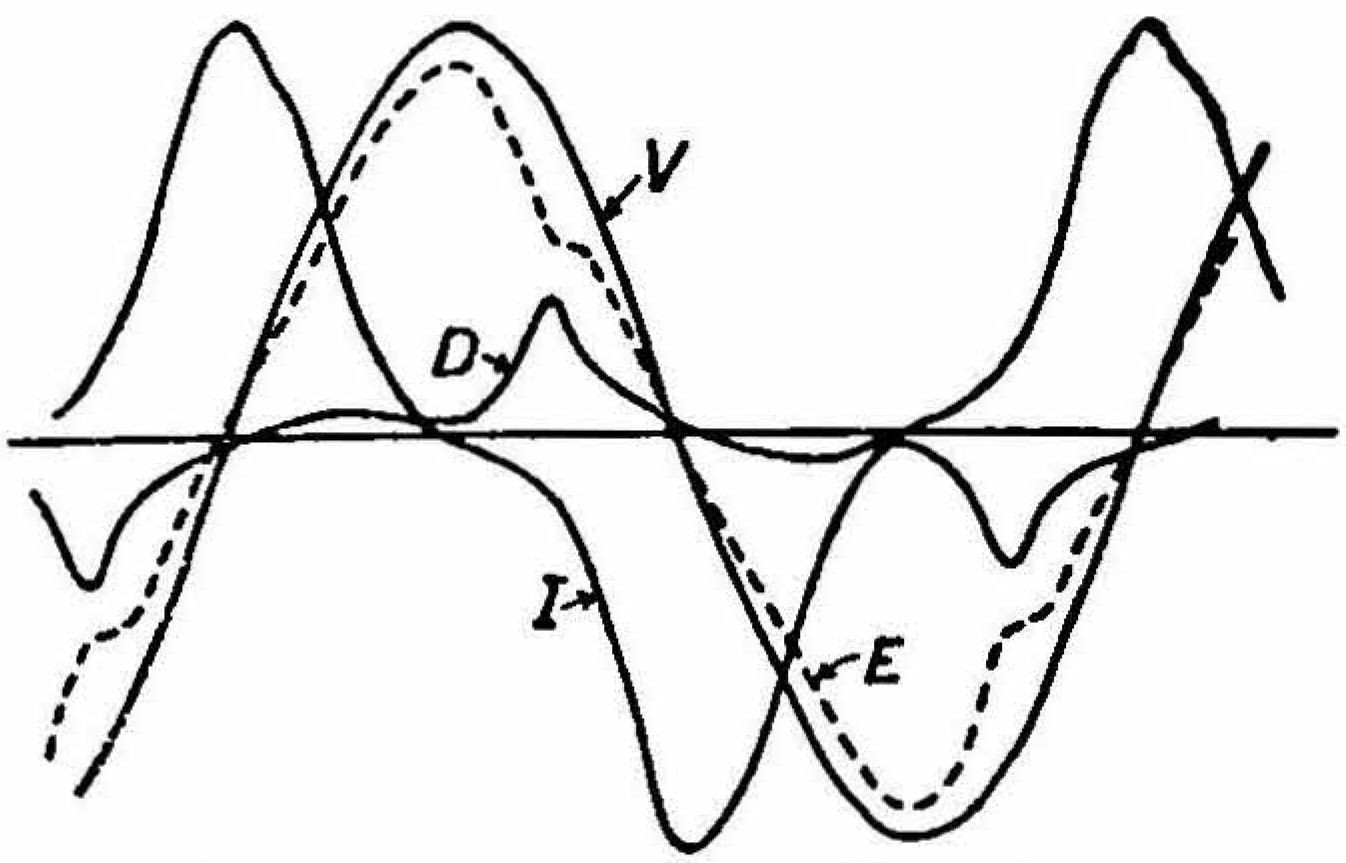


FIG. 3

PRINCIPLE OF COMBINING THREE PHASES TO FORM SINGLE PHASE TRIPLE FREQUENCY OUTPUT (TAYLOR'S ARRANGEMENT)

Fig. 4 shows that the E.M.F. wave D (fig. 2) cannot be regarded as a mutilated triple-harmonic wave as Taylor has assumed. It is a distorted wave composed of the fundamental and higher harmonics and



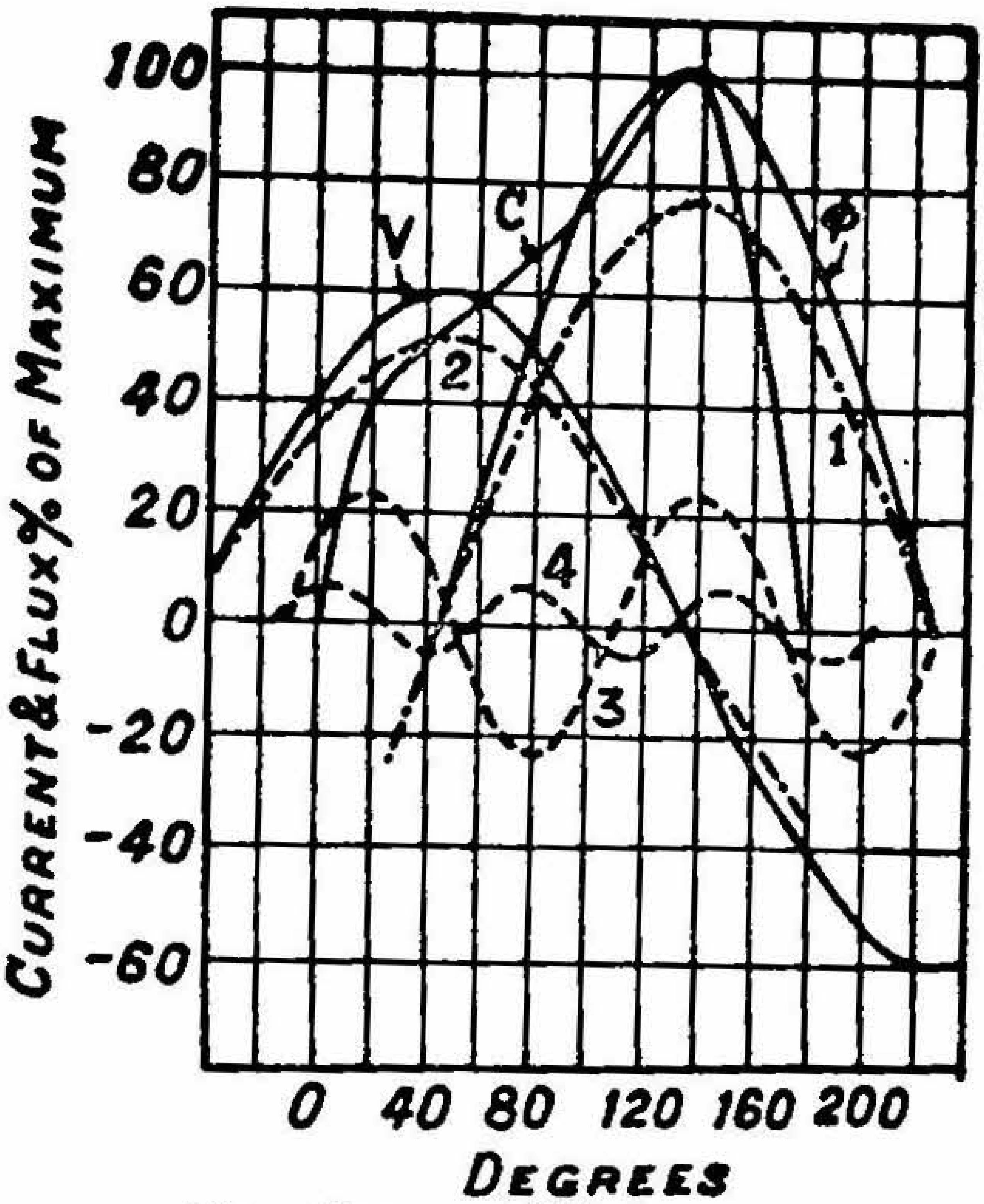
V = 126 VOLTS E = 108 VOLTS
D = 24 VOLTS I = 10 AMPS

FIG. 4

has two unequal peaks in each half-wave. The difference in the magnitude of the peaks varies with saturation on account of the change in the relative magnitudes and phases of the component harmonics.

Assuming that a sine wave of P.D. is impressed on the choke coil, the true wave shape of its exciting current at comparatively low values of induction is represented by C in fig. 5, which also shows its phase relation with the impressed P.D., V and the flux, ϕ (as in fig. 5). It can be analysed into four components : (1) the magnetising component in phase with flux, (2) the energy component in phase with P.D., (3) the triple harmonic component and (4) the fifth harmonic component (Frank, *Trans. A.I.E.E.*, 1910, **29**, 845; Faccioli, *J.A.I.E.E.*, 1922, **41**, 351). When the value of the induction is increased the curve assumes the shape shown in fig. 6. These figures indicate that, as the induction varies, the magnitudes R_1, R_3, and R_5 and phase angles ϕ_1, ϕ_3 and ϕ_5 of the fundamental, third and fifth harmonics change and also that the relative magnitudes of the magnetising and energy components of the fundamental vary considerably. In addition to the above components, higher odd harmonics are also present in the exciting current wave, but these are not shown in figs. 5 and 6, as their magnitudes are considerably lower than those of the third and the fifth harmonics.

As the choke coil P.D. differs but little from a sine wave, the E.M.F., D in fig. 4 represents the resultant of E.M.F.'s induced in the transformer by the various components of the complex exciting current C. It must therefore contain the third and the fifth harmonic in addition to the two fundamental components. Taylor has, however, assumed only the magnetising and the third harmonic components in his analysis.



MAX. COMPLEX WAVE = 100

$R_1 = 90{\cdot}7$ $\phi_1 = -11°52'$

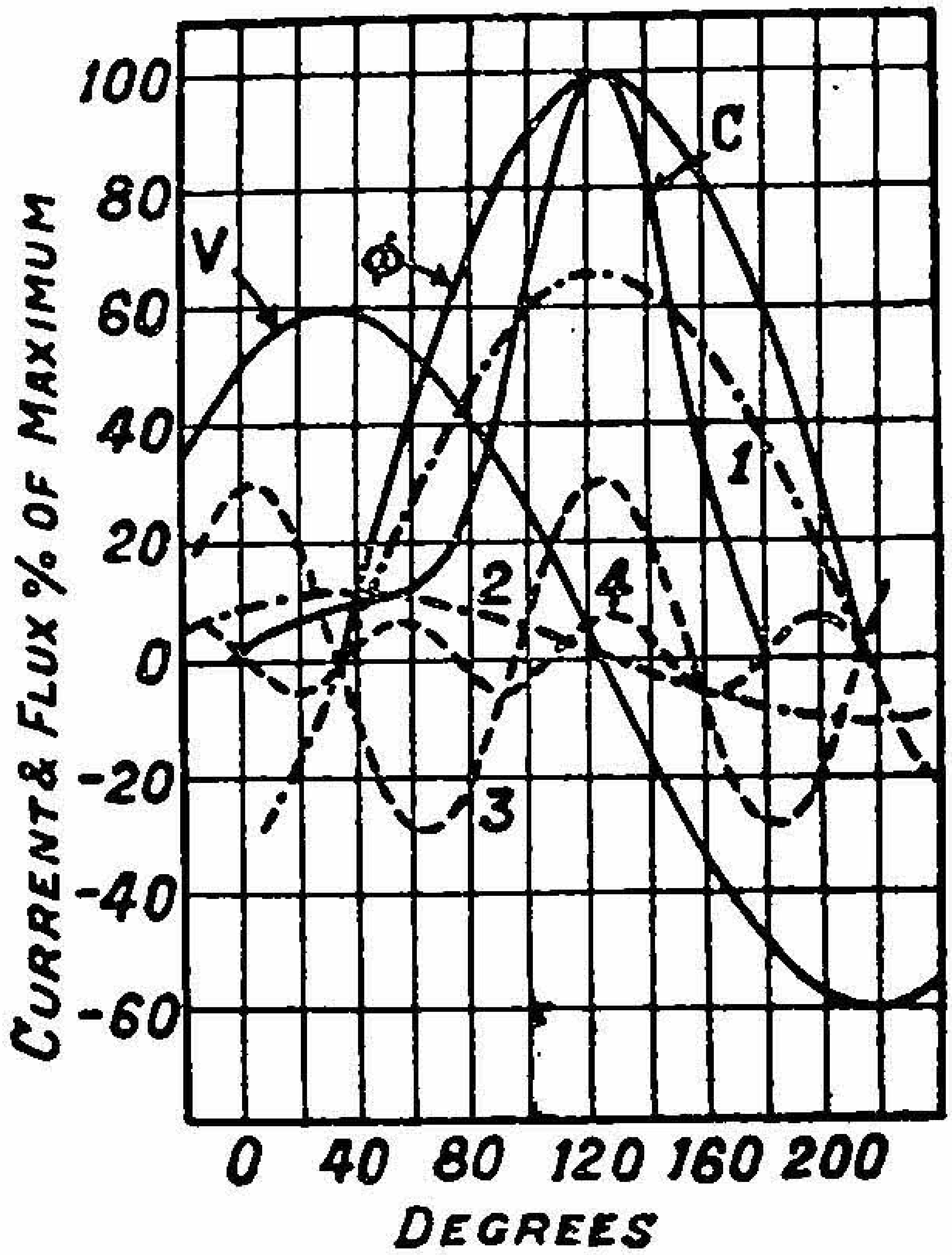
$R_3 = 23{\cdot}3$ $\phi_3 = 30°43'$

$R_5 = 6{\cdot}6$ $\phi_5 = 66°52'$

FIG. 5

Considering the frequency tripler (fig. 1), the E.M.F. induced in the secondary of the transformer is caused by the resultant flux due to the currents flowing through its primary windings. The waves of these three currents are similar in shape, but displaced from each other by 120° in terms of their fundamental. Consequently, the resultants of their fundamental, fifth, seventh, eleventh, etc., components vanish at all instants. Thus the only flux present in the transformer is that due to the third harmonic and its multiples. The E.M.F. induced in the secondary is therefore a triple frequency wave together with its multiples which are, however, too small to be noticeable. The action of the frequency changer therefore depends upon the production of higher harmonics in the exciting current wave due to the saturation of the choke coils and the elimination of the fundamental, fifth, seventh, etc., harmonics from the flux wave of the transformer by the interaction of the three phases on one another.

Effect of distortion of choke coil P.D.—The essential part of the action of the tripler has been dealt with above. It is, however, further



MAX. COMPLEX WAVE = 100

$R_1 = 65{\cdot}0$ $\phi_1 = 27°1'$
$R_3 = 29{\cdot}9$ $\phi_3 = 73°55'$
$R_5 = 6{\cdot}2$ $\phi_5 = 170°24'$

FIG. 6

complicated by the fact that, if the supply P.D. is sinusoidal the choke coil P. D. becomes distorted and contains a triple harmonic component equal and in phase-opposition to the triple harmonic P.D. across the transformer. The exciting current wave therefore differs from those shown in figs. 5 and 6, as explained below.

With a sinusoidal P.D. wave the magnetising current of the choke coil contains a third harmonic component of definite magnitude. If, however, a suitable third harmonic component is present in its P.D. wave, the third harmonic component of the magnetising current is correspondingly reduced. If this third harmonic component in the P.D. wave is gradually increased, the third harmonic component of the current will steadily fall until, when the former has attained a certain value, the third harmonic component of the current will vanish and the current wave will become sinusoidal.

Effect of number of turns of transformer.—Assuming that the magnetic circuit of the transformer remains constant and the number of turns of its primary is varied, the choke coil P.D. and the exciting current will vary in the following manner when the supply P.D. is maintained constant. With a very small number of turns in the transformer its induced E.M.F. is small and the shape of the choke coil P.D. will be very nearly similar to that of the supply voltage. If this latter is sinusoidal the current will contain a large third harmonic component. If the number of turns of the transformer is now increased its induced E.M.F. will increase, the choke coil P.D. will become more distorted and the third harmonic component of the current will decrease. This decrease will, however, be smaller than the increase in the number of turns. Consequently, as the number of turns of the transformer is increased, its E.M.F. will rise, the choke coil P.D. will become more distorted and the current wave will contain a decreasing triple-harmonic component until with a very large number of turns it will have a very small amplitude. However, since the product of the triple harmonic component of the current and the number of turns of the transformer will increase, the transformer will become more and more saturated. It will thus be seen that under suitable conditions it is possible for the tripler to function satisfactorily as a frequency changer even with extremely small triple-frequency component in its current.

Effect of saturation of the transformer.—The effect of saturation of the transformer is as follows. Since the fundamental and fifth harmonic components of the M.M.F. in the transformer vanish, its magnetism is determined solely by the third harmonic component of the current and its multiples which are very small. The M.M.F. wave can therefore be regarded as a more or less sinusoidal triple harmonic wave. At low values of induction the flux and the induced E.M.F. waves will be nearly sinusoidal, but as the core becomes more and more saturated, the flux and the E.M.F. waves will become more and more distorted.

Tripler on load.—When a load is connected across the secondary of the transformer it gives rise to third harmonic ampere-turns in the secondary. In order to neutralise these, equal and opposite ampere-turns are called into play in the primaries and the third harmonic component of the tripler current increases. As this current is the magnetising current of the choke coil, the choke coil P.D. becomes more sinusoidal. Since the transformer P.D. is the difference between the choke coil P.D. and the sinusoidal impressed P.D., its magnitude decreases as the choke coil P.D. becomes more sinusoidal. Consequently, as the load increases, the current contains an increasing triple-harmonic component, the choke coil P.D. becomes more sinusoidal and the transformer P.D. decreases until, on short-circuit, the current contains a large triple-harmonic component, the choke coil P.D. becomes practically sinusoidal and the transformer P. D. vanishes except for the small internal drop due to its impedance. The tripler then behaves as if the transformer were not present and the choke coils connected directly across the supply mains.

EXPERIMENTAL.

The following experiments serve to illustrate the action of the frequency tripler more fully.

DELTA CONNECTION

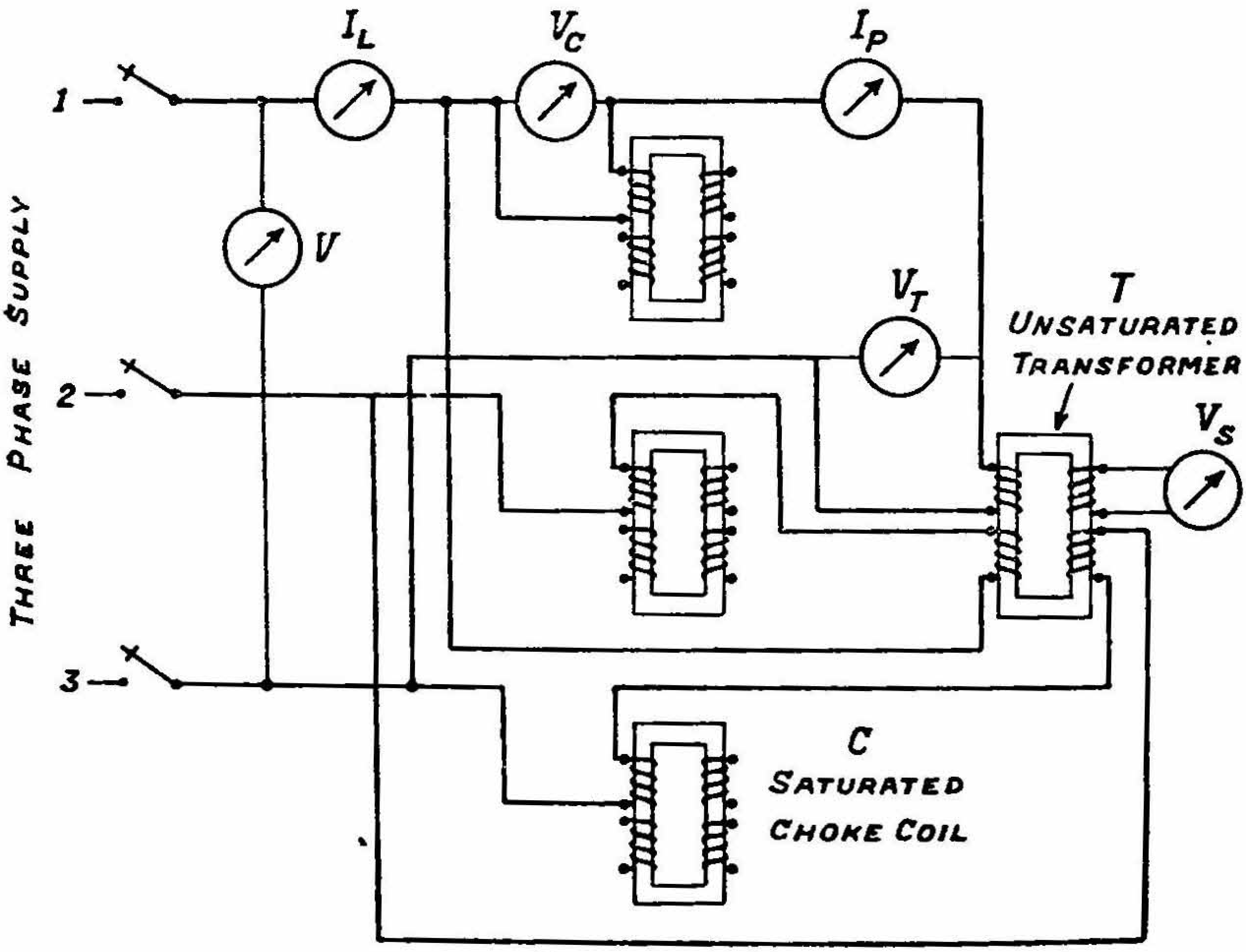
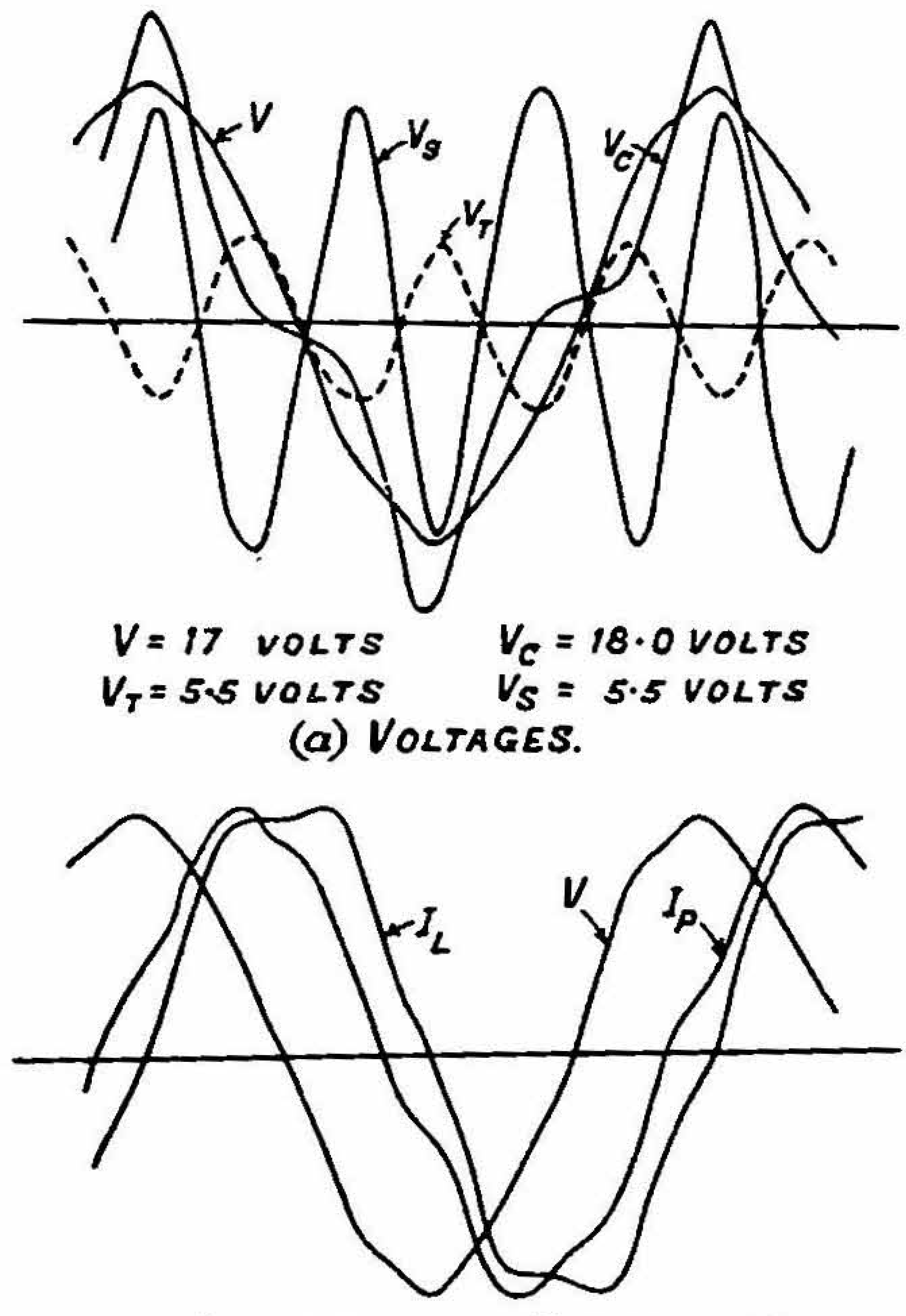


FIG. 7
DIAGRAM OF DELTA CONNECTION

Fig. 7 shows the diagram of connections of the tripler which was supplied at 25 cycles from a 25/60 cycle, three-phase, 92/220 volt, 12.5/30 kW., sine-wave generator. Four similar 100/200 volt, 25 cycle, 10 kVA., core type, single-phase transformers each having four separate windings on the primary side were used as choke coils C and also as transformer T. In the case of the choke coils only one of the four primary windings was used, while in the case of the transformer T, one coil was connected to each phase and the fourth coil was used as the secondary.

The results of the experiments are shown in figs. 8 and 9 which correspond to no load condition with impressed P.D.'s of 17 and 37



$V = 17$ VOLTS $V_C = 18{\cdot}0$ VOLTS
$V_T = 5{\cdot}5$ VOLTS $V_S = 5{\cdot}5$ VOLTS
(*a*) VOLTAGES.

$I_L = 10$ AMPS. $I_P = 6$ AMPS.
(*b*) CURRENTS

FIG. 8

DELTA CONNECTION

volts, respectively. As stated above the E.M.F., V_S induced in the secondary of the transformer is a triple-frequency wave due to the resultant triple-frequency flux in the transformer. Similarly the voltage, V_T across each of the other three windings of the transformer is a triple-frequency wave since it is also caused by the same flux. The slight impurity of this wave is due to leakage in the transformer, particularly at the higher voltage. It must be noted that V_S and V_T are equal in magnitude but drawn to different scales. The voltage V_C across the choke coil is the difference between V and V_T and thus contains a considerable third harmonic component.

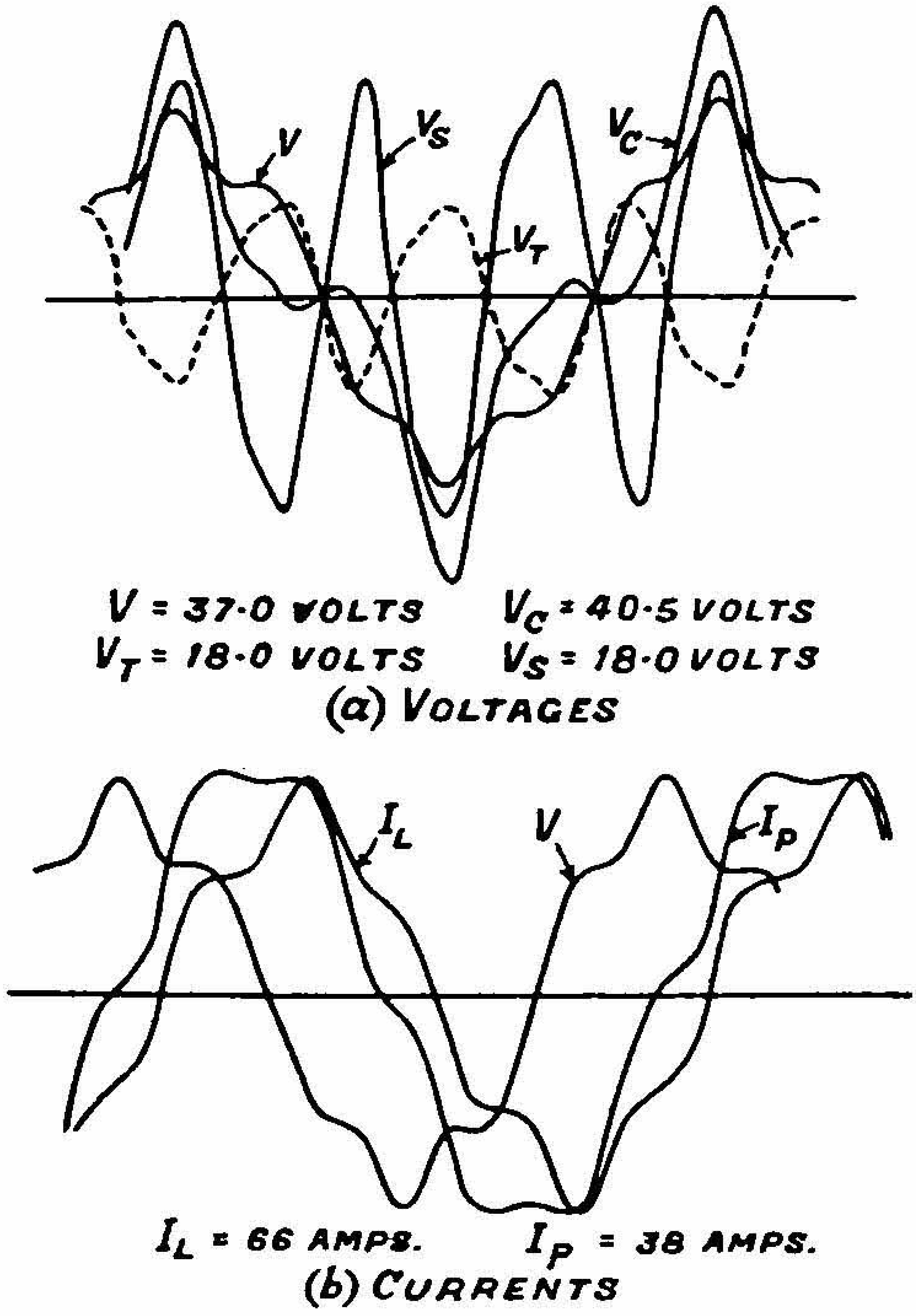


FIG. 9
DELTA CONNECTION

The phase current I_P is a complex wave containing the fundamental, the third and the fifth harmonic components. The line current I_L is the vector difference of currents in phases 1 and 2, which have a phase difference of 120°. It therefore contains only the fundamental and the fifth harmonic, the third harmonics of the two phases being neutralised by each other.

It will be seen that the impressed P.D. wave, V in fig. 9 (*a*) is distorted and contains a prominent fifth harmonic. This is no doubt due to the armature reaction of the fifth harmonic component of I_L on the generator.

Star Connection—Neutral Isolated

When the frequency tripler was star-connected as shown in fig. 10 and the neutral not connected to the neutral of the generator, the results shown in fig. 11 were obtained.

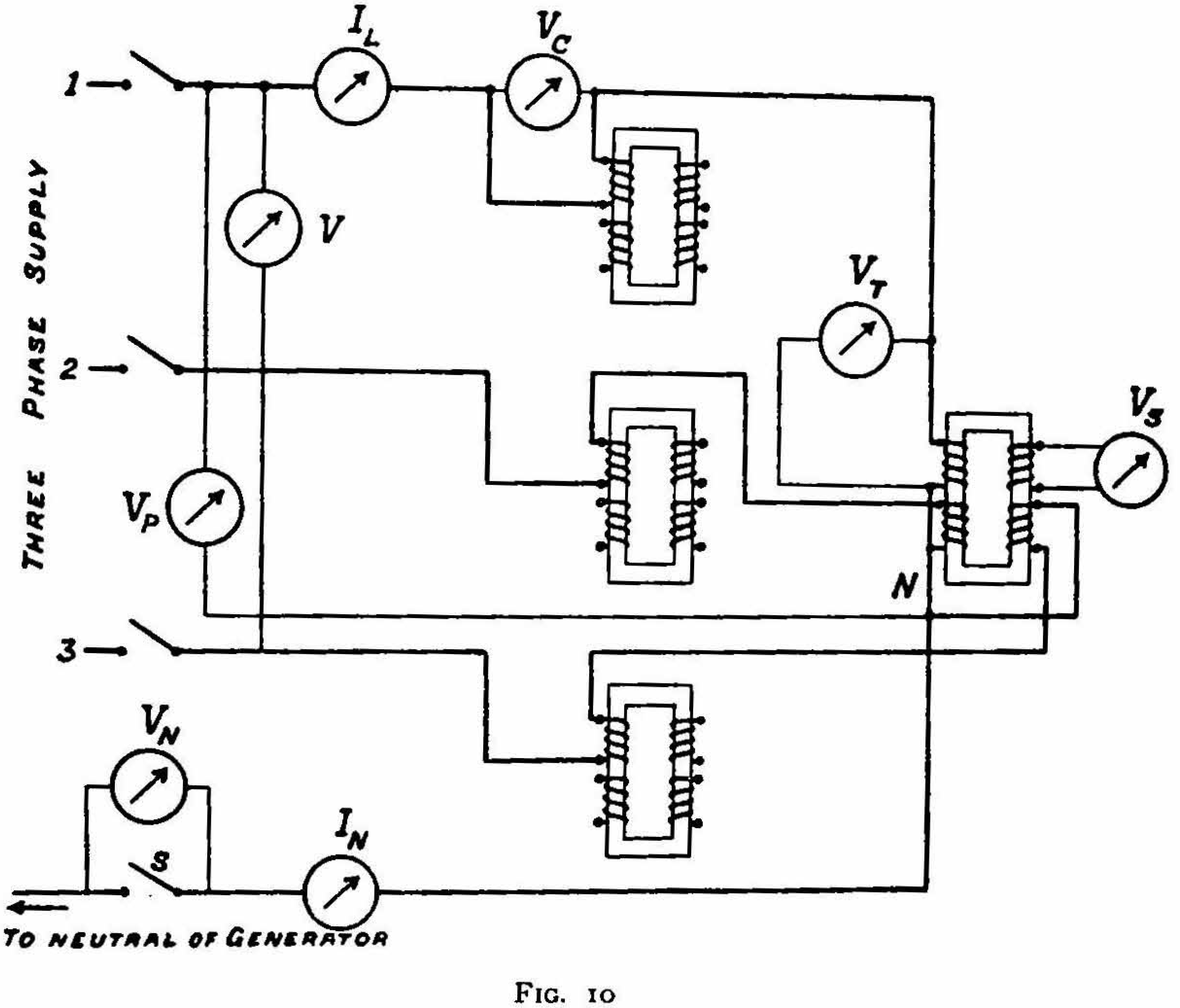
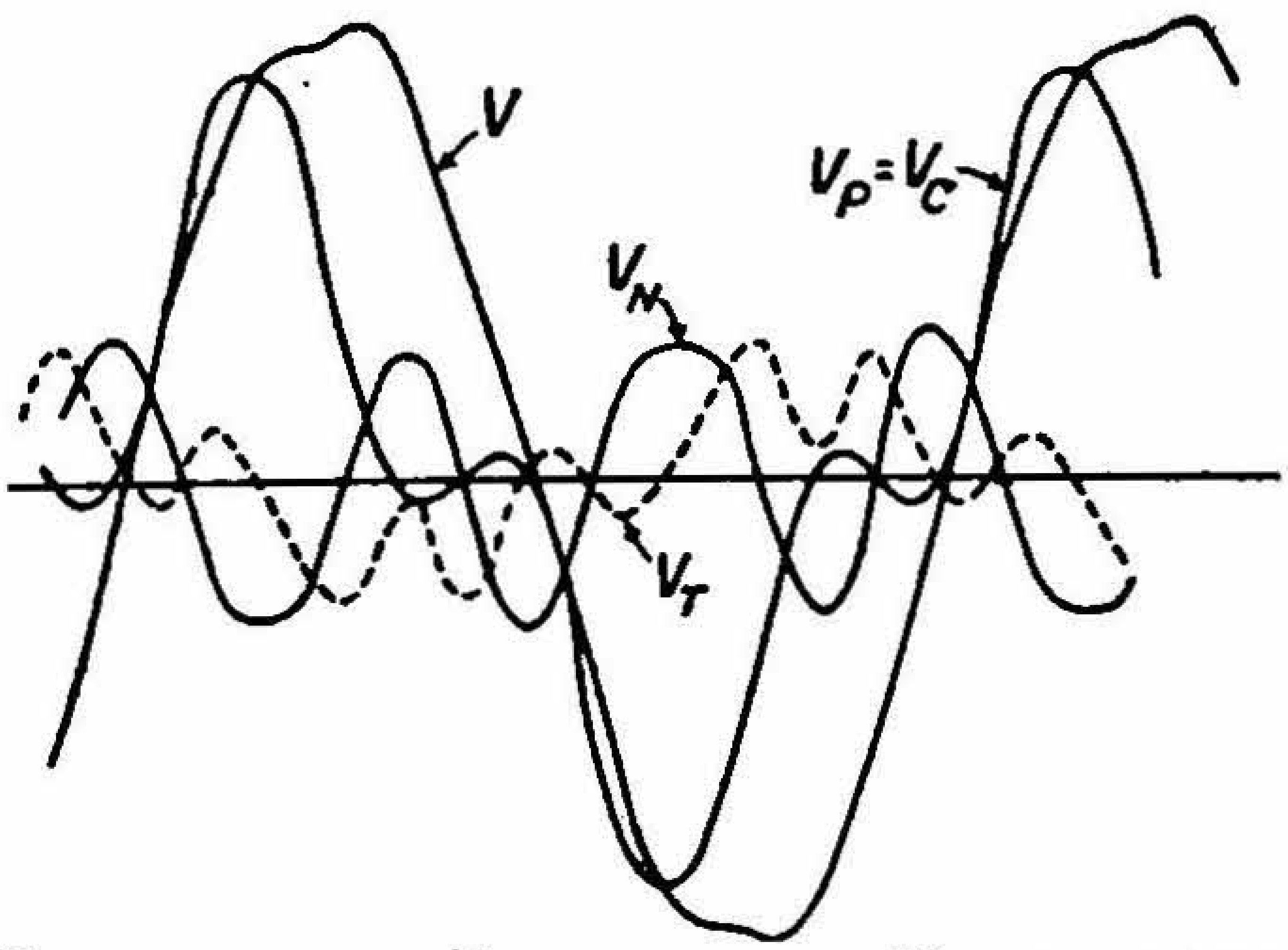


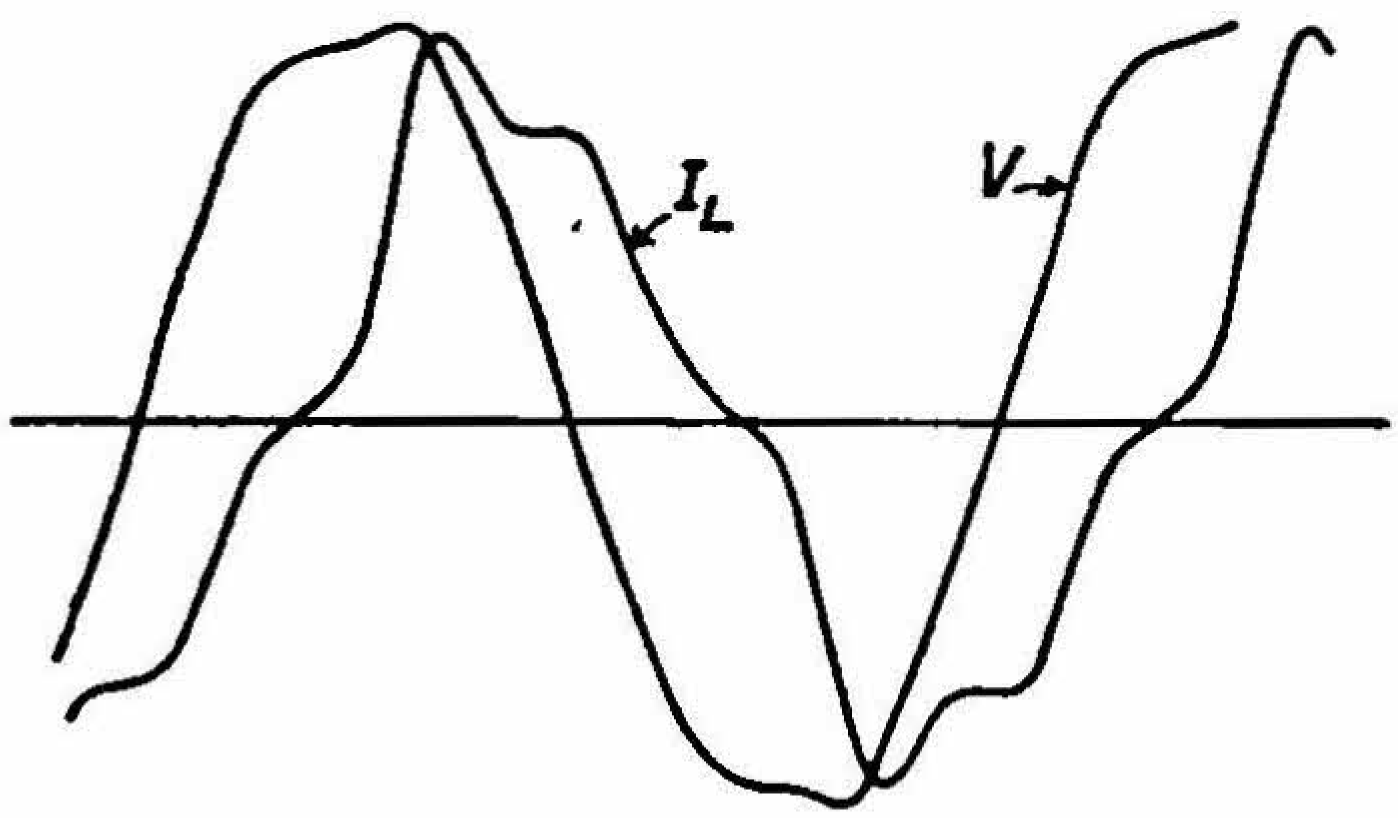
Fig. 10
Diagram of Star Connection

As the neutral is isolated from the neutral of the generator, there is no path for the flow of the triple-frequency component of the exciting current. Consequently the phase voltage becomes distorted and contains a strong third harmonic. The current wave contains the fundamental and the fifth harmonic together with feebler higher harmonics. As it does not contain a third harmonic and as the fundamental and the fifth harmonic of M.M.F. in the transformer are neutralised by the joint action of the three phases, there is no resultant flux in the transformer and consequently no E.M.F. is induced in its windings.

The small P.D., V_T across it is due to the resistance drop and asymmetry of the transformer. The whole arrangement behaves as if the transformer were not present and the choke coils star-connected across the supply mains. As the phase voltage contains the third harmonic,



$V = 61{\cdot}75$ VOLTS. $V_C = 40{\cdot}25$ VOLTS. $V_P = 40{\cdot}25$ VOLTS
$V_N = 17{\cdot}50$ VOLTS $V_T < 1{\cdot}00$ VOLTS
(a) VOLTAGES



$I_L = 39$ AMPS.
(b) CURRENT

FIG. 11

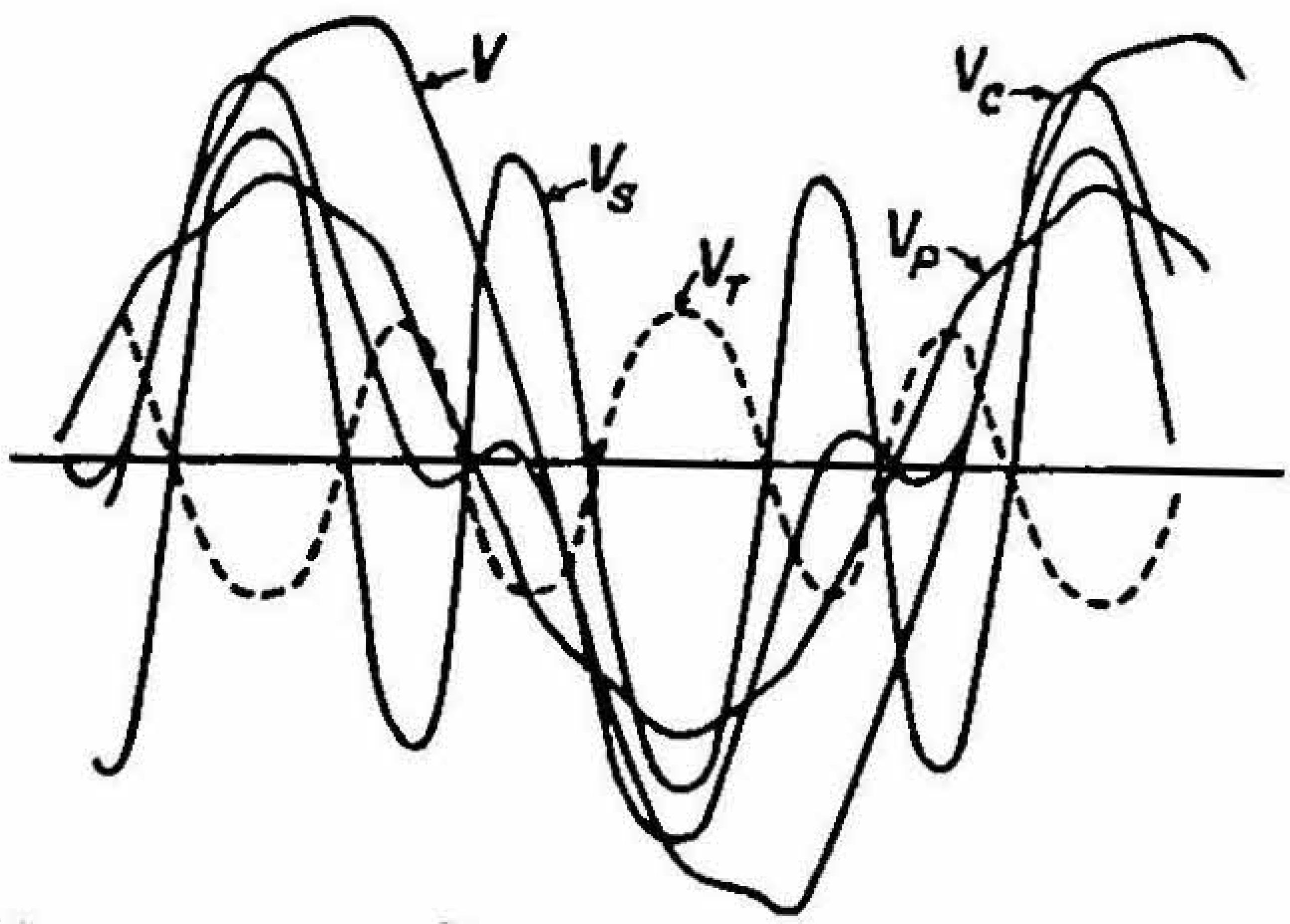
STAR CONNECTION—NEUTRAL ISOLATED

the neutral is unstable and there is a triple-frequency P.D. between it and the neutral of the generator as indicated by V_N. This connection is therefore incapable of functioning as a frequency changer.

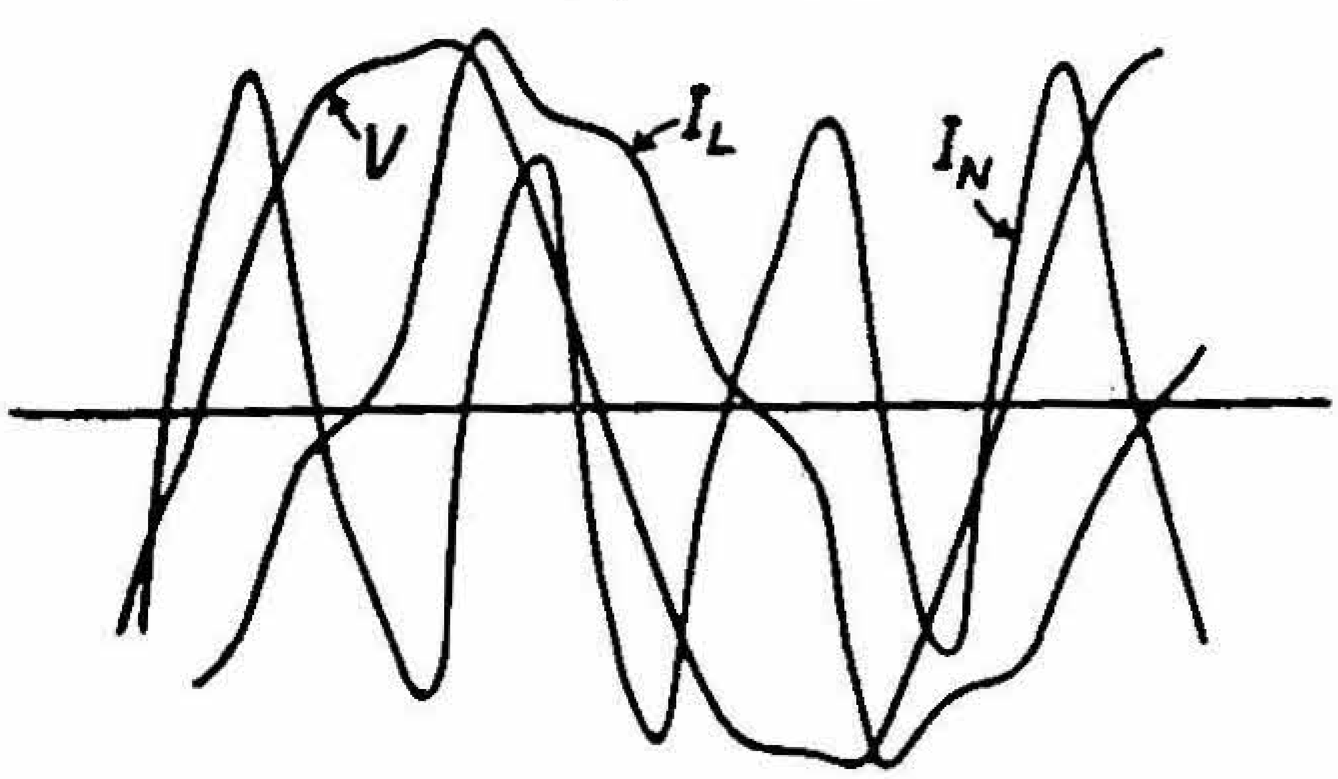
In this experiment the supply was obtained from a 25 cycle, 3 phase, 100 volt, 20 kVA. generator with accessible neutral.

STAR CONNECTION—NEUTRAL CONNECTED

If the neutral is now connected to the neutral of the generator by closing the switch S, the whole action is transformed, the arrangement behaves like the delta connection and functions again as a frequency tripler, as shown in fig. 12.



V = 61·75 VOLTS. V_C = 40·25 VOLTS. V_P = 36·50 VOLTS
V_T = 17·50 VOLTS. V_S = 17·50 VOLTS.
(a) VOLTAGES



I_L = 39 AMPS. I_N = 2·0 AMPS.
(b) CURRENTS

FIG. 12
STAR CONNECTION—NEUTRAL CONNECTED
(22 TURNS IN TRANSFORMER)

A path is now provided for the third harmonic component of the exciting current and this flows through each phase, down the neutral, to the neutral of the generator, as shown by I_N in fig. 10. This third harmonic component gives rise to a third harmonic flux in the transformer as in the case of delta connection, and thus induces a triple frequency E.M.F. in each of its windings. The neutral, being directly connected to the neutral of the generator, is stabilised and the phase P.D., V_P is reduced to a sine wave except for a slight distortion due to armature reaction in the supply generator. As the transformer P.D. is a triple-frequency wave, the choke coil P.D. becomes distorted and contains a third harmonic.

The line current contains the third and the fifth harmonic in addition to the fundamental. The presence of the fifth harmonic is apparent from the current wave I_L, while the amplitude of the third harmonic component is obviously one third of that of the neutral current I_N.

Effect of number of turns of the transformer.—Since the neutral current is proportional to the third harmonic component, this connection affords a very easy means of investigating the relation between this component and the number of turns of the transformer. Fig. 13 shows

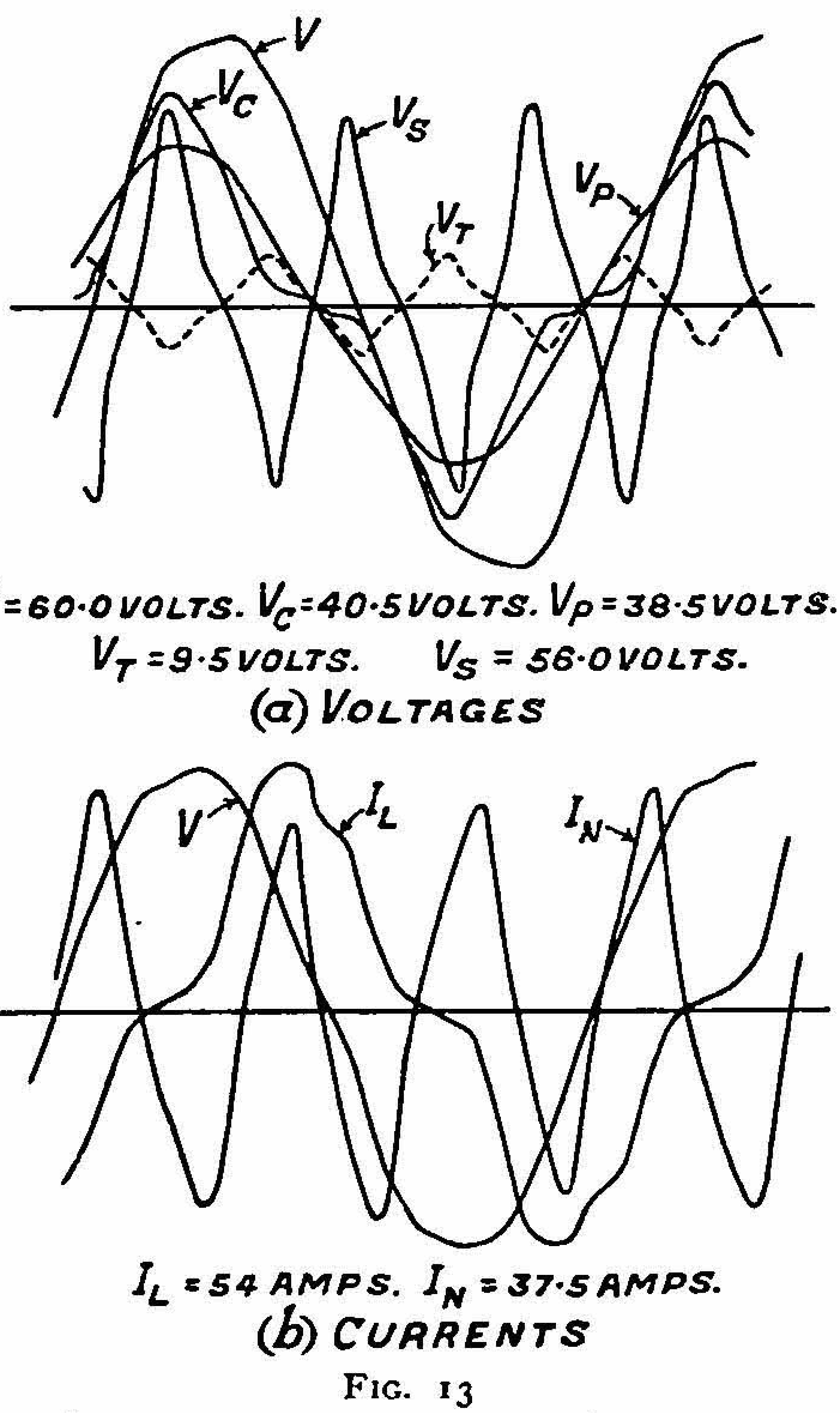


FIG. 13

STAR CONNECTION—NEUTRAL CONNECTED

(4 TURNS IN TRANSFORMER)

the curves obtained when each of the transformer primaries was provided with four turns. These can be compared with those shown in fig. 12 which were obtained with 22 turns in the primaries of the transformer. The neutral current has increased from 2 amps to 37.5 amps; the wave shape of current I_L has been considerably modified by the presence of the strong third harmonic; the secondary voltage of the transformer contains the ninth harmonic due to saturation of the transformer; and the choke coil P.D. contains a visible ninth harmonic due to the presence of a strong ninth harmonic in the transformer P.D. It may be mentioned that intermediate values were obtained with 8 and 12 turns in the primaries of the transformer. These experiments clearly show that under suitable conditions the third harmonic component of the current may be very small without affecting the operation of the tripler.

Effect of leakage.—If the three primary windings of the transformer are arranged on the three limbs and the secondary on the fourth

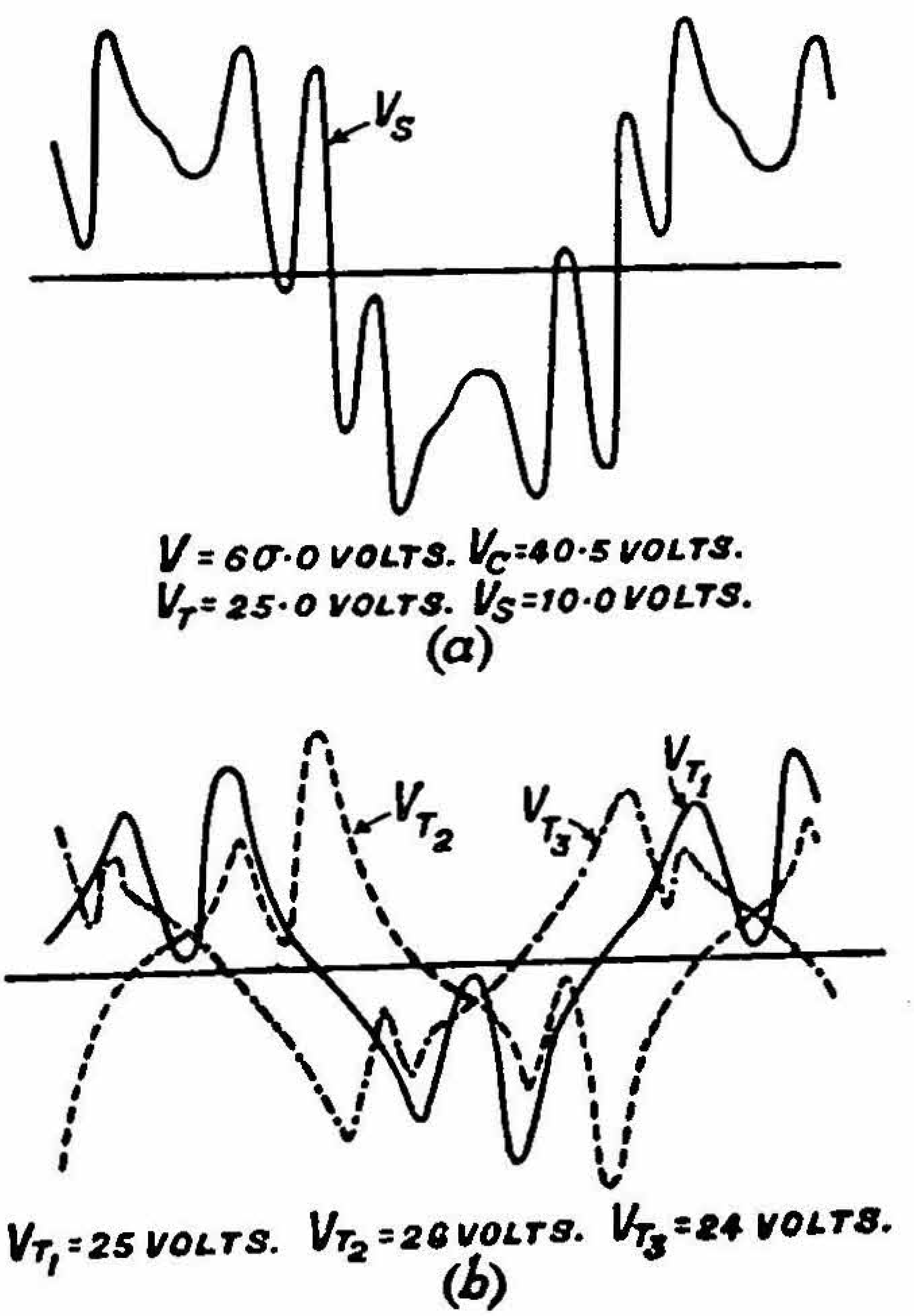


FIG. 14
DELTA CONNECTION—EFFECT OF LEAKAGE

limb of an Epstein Tester and if the cross section of its core is small so as to become easily saturated, there would be considerable leakage of flux between the ends of each limb. Consequently, the fundamental and fifth harmonic components of the fluxes due to the three-phase primary currents would not be completely neutralised and the resultant flux through the secondary would contain these components in addition to the third harmonic. The wave of E.M.F. induced in the secondary would therefore not be a pure triple harmonic wave, but be highly distorted due to the presence of the fundamental and the fifth harmonic. Fig. 14 (a) shows such a wave obtained when the transformer in fig. 7 was replaced by an Epstein Tester and a large P.D. (60 volts) impressed on the tripler. Fig. 14 (b) represents the

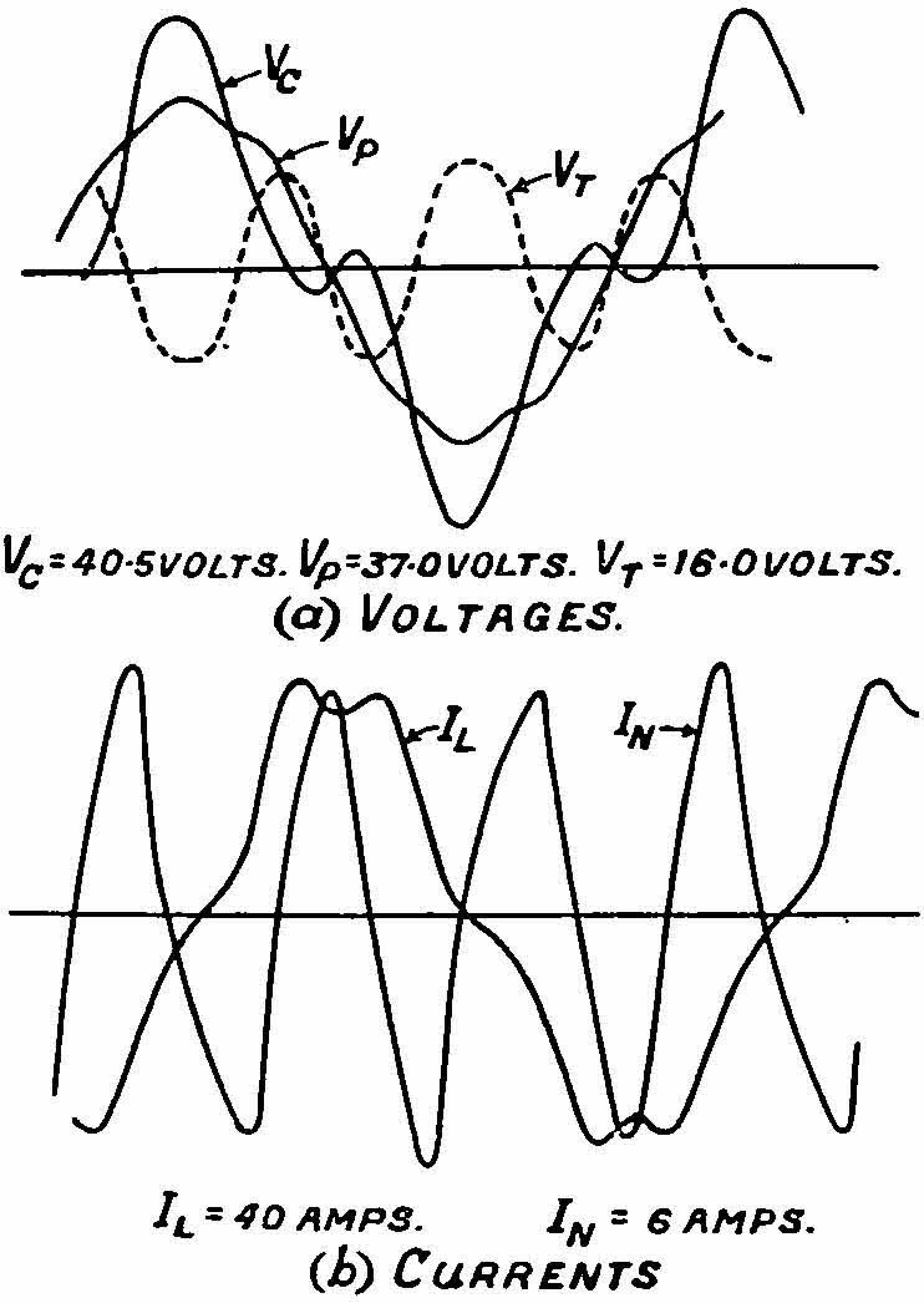


FIG. 15
STAR CONNECTION—NEUTRAL CONNECTED
(12 TURNS; OPEN-CIRCUIT CONDITIONS)

E.M.F.'s induced in the primary windings and indicates that the fluxes in the cores surrounded by these windings contain the fundamental, third and fifth harmonics. Consequently, the secondary E.M.F. shown in fig. 14 (a) can be regarded as resulting from a combination of these. Experiment at a much lower impressed voltage gave a more or less pure triple harmonic secondary E.M.F., because in that case the leakage was small due to the low value of induction in the Epstein Tester.

Effect of load.—Figs. 15 and 16 shows respectively the open and short circuit conditions in the tripler with 12 turns in each winding of

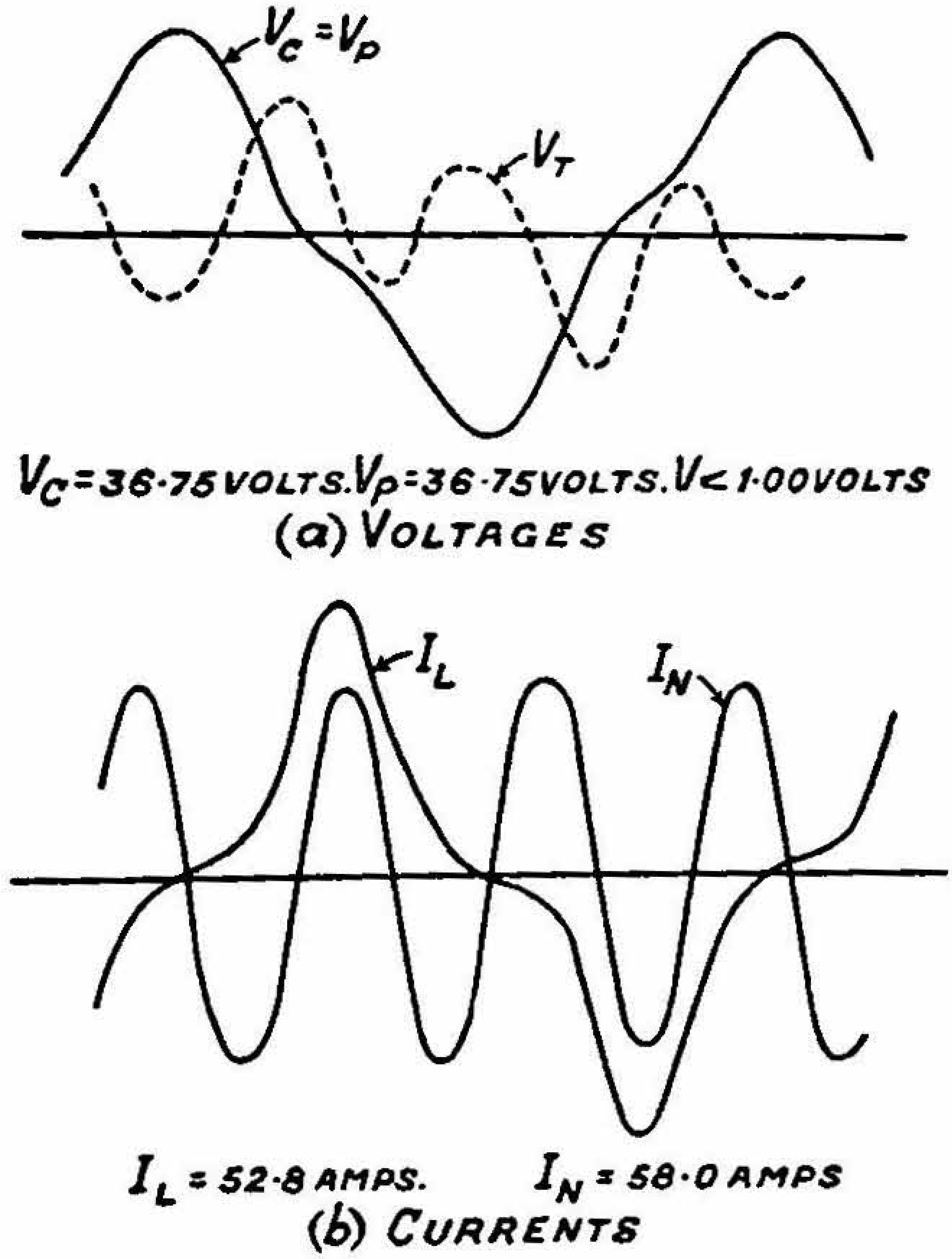


FIG. 16

STAR CONNECTION—NEUTRAL CONNECTED

(12 TURNS; SHORT-CIRCUIT CONDITIONS)

the transformer. It will be seen that the choke coil P.D., V_C is considerably purer on short-circuit than on open-circuit, its slight distortion in the former case being due to the impurity of the supply P.D. The transformer P.D. has dropped from 16 volts to a very small value and the triple harmonic component of the main current represented by I_N, has increased from 6.0 amps. to 58.0 amperes.

The following table shows the change in the magnitudes of the various quantities with a constant impressed P.D. as the load current is increased :—

Transformer secondary current (amps)	Transformer secondary P.D. (volts)	Third harmonic component of current (amps)	Total current (amps)
0.0	31.0	2.0	45.0
5.0	26.5	5.5	45.25
10.0	23.5	7.75	45.5
15.0	20.0	10.25	46.5
20.0	15.5	13.0	48.0
25.0	11.0	15.50	50.0
30.0	5.0	18.25	52.0
32.5	0.0	19.3	52.8

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