Sept. 21, 1943. Z. O. ST. PALLEY 2,330,088

TRANSFORMER SYSTEM

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Fig. 1.

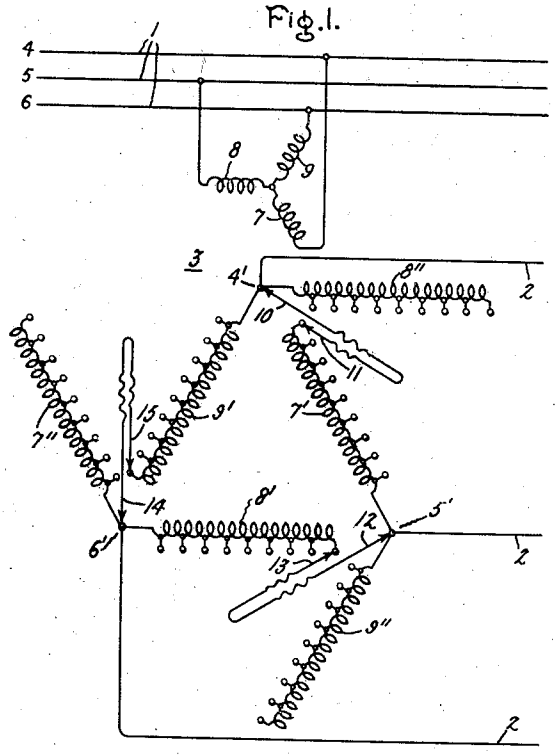


Fig. 2.

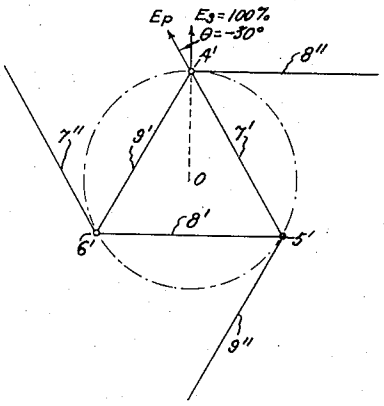


Fig. 3.

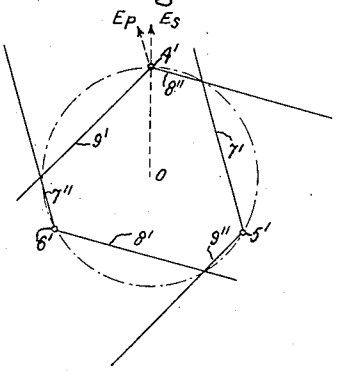


Fig. 4.

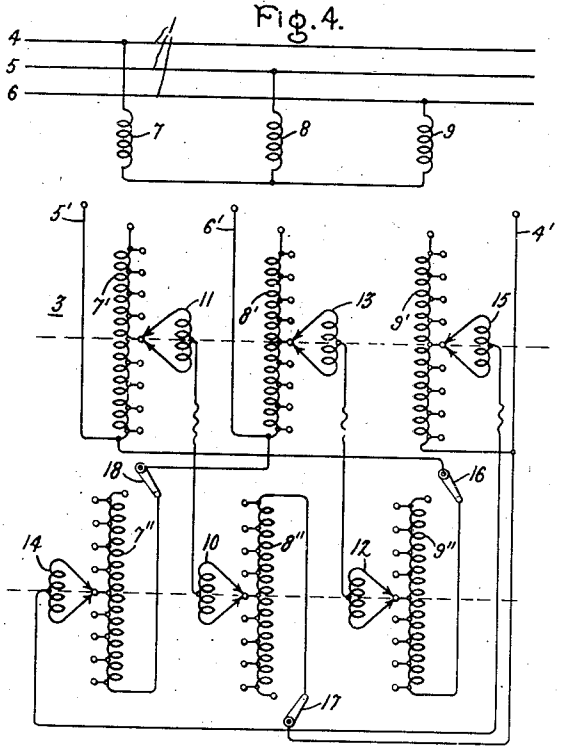
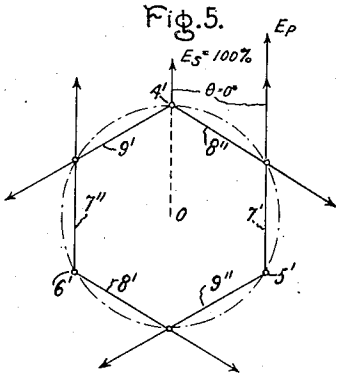


Fig. 5.



Inventor:
Zoltan O. St. Palley,
by Harry E. Dunham
His Attorney.

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Fig.6.

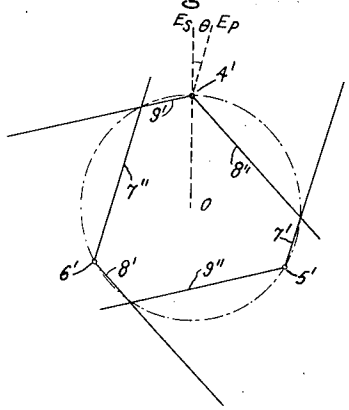


Fig.7.

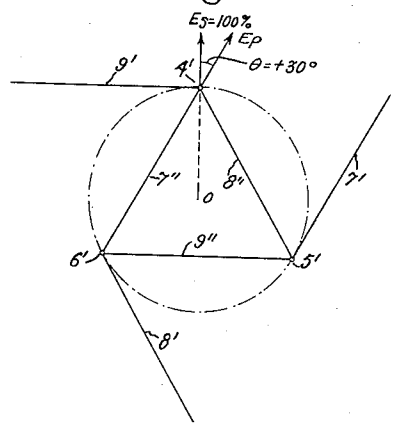


Fig.8.

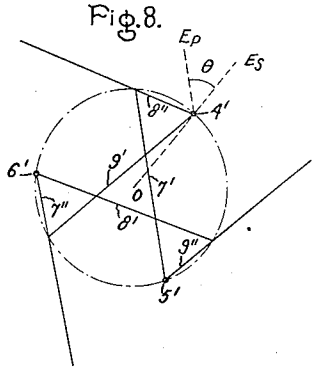


Fig.9.

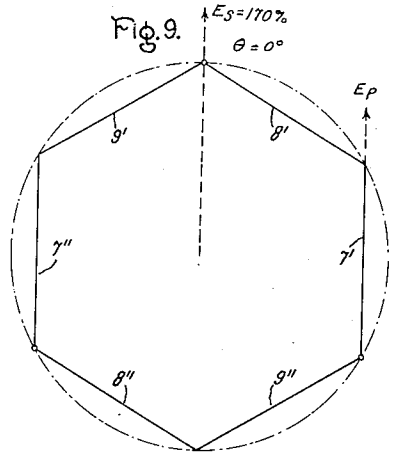


Fig.11.

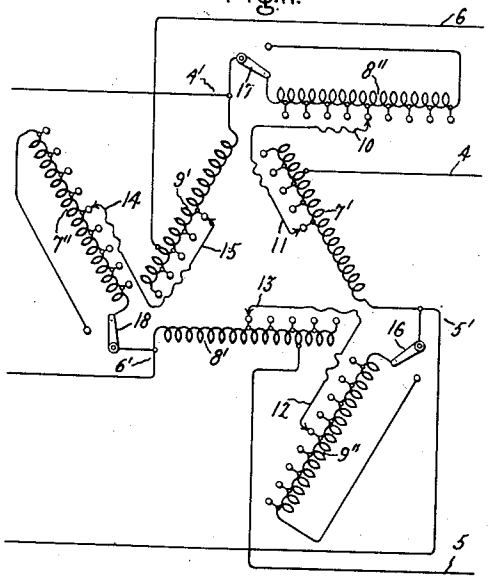
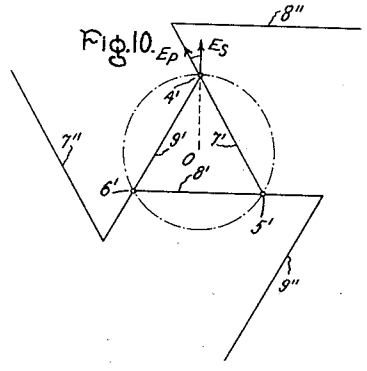


Fig.10.



Inventor:
Zoltan O. St. Palley.
by Harry E. Dunham
His Attorney.

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UNITED STATES PATENT OFFICE

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TRANSFORMER SYSTEM

Zoltan O. St. Palley, Pittsfield, Mass., assignor to General Electric Company, a corporation of New York

Application March 20, 1942, Serial No. 435,473

11 Claims. (Cl. 172—238)

This invention relates to transformer systems and more particularly to a new and improved method and apparatus for changing taps on a transformer so as to adjust the phase angle between and the relative magnitudes of two polyphase voltages.

The invention is characterized by a mesh connection of multi-tapped transformer windings combined with tap-changing means for varying the effective number of turns of the windings constituting the mesh so as to shift the phase angle of the vector voltages of one polyphase system, such as the voltages to neutral of certain terminals of the mesh, with respect to the vector voltages of another polyphase system, such as the voltages of certain of the windings of the mesh, without changing the relative magnitudes of these voltages, as well as changing the relative magnitudes of these voltages without shifting the phase angle between them.

An object of the invention is to provide a new and improved transformer system.

Another object of the invention is to provide a new and improved method and apparatus for shifting the phase angle between two polyphase voltages.

A further object of the invention is to provide a new and improved method and apparatus for adjusting the relative magnitudes of two polyphase voltages.

Still another object of the invention is to provide a polyphase autotransformer for independently shifting the phase angle between, and varying the relative magnitudes of, its input and output voltages.

The invention will be better understood from the following description taken in connection with the accompanying drawings and its scope will be pointed out in the appended claims.

In the drawings Fig. 1 illustrates diagrammatically an embodiment of the invention in which the axes of the various windings lie along the directions of their voltage vectors and in which the tap changers are in the positions which cause a certain voltage phase shift in one direction, Fig. 2 is a vector diagram which illustrates the voltage relationships existing when the tap changers are in the positions shown in Fig. 1, Fig. 3 is a vector diagram corresponding to a different tap changer position which reduces the phase shift angle without changing the voltage ratio, Fig. 4 is a circuit diagram in which the windings for each phase are grouped axially and the various groups are spaced transversely as would be the actual physical arrangement in polyphase transformer constructions and in which the tap changers are in still different relative positions from those shown in Fig. 1, Fig. 5 is a vector diagram showing the voltage relationships existing in Fig. 3, Fig. 6 is a vector diagram corresponding to a reversed phase shift at constant voltage ratio, Fig. 7 is a vector diagram showing the voltage relationships when the tap changers are moved to produce another voltage phase shift in the direction opposite to that shown in Fig. 2, Fig. 8 shows how the phase shift range may be extended by reversing one set of windings, Fig. 9 is a vector diagram having the same phase shift as in Fig. 5 but having a different ratio between the voltages, Fig. 10 is a vector diagram showing the same phase shift as in Fig. 2 but a different ratio of voltages, and Fig. 11 is an autotransformer connection.

Referring now to the drawings and more particularly to Fig. 1, there is shown therein a pair of polyphase circuits 1 and 2 which are interconnected by a transformer 3. The system is shown three-phase because that is the most common form of polyphase system which is used but it should be understood that my invention is not limited to any particular number of phases. Circuit 1 is provided with conductors 4, 5 and 6 and circuit 2 is provided with corresponding conductors 4', 5', and 6'. Connected to the respective conductors 4, 5 and 6 are the phase windings 7, 8 and 9 of a three-phase winding which is shown, for example, as being star connected. Connected at certain of its symmetrically located corners to the conductors 4', 5' and 6' is a mesh-connected winding comprising phase windings 7', 7'', 8', 8'', 9' and 9''. The similarly numbered windings correspond to the same phases so that their vector voltages are all in line with each other, as shown by the parallelism of the axes of the similarly numbered windings and in actual practice each set of three similarly numbered windings will be wound on the same core (as when single phase transformers are used) or core leg (as when a single polyphase transformer is used) so as to be threaded by the same flux.

Each of the primed and double-primed windings of the mesh connection is provided with a plurality of taps and selective connections are made and broken with respect to these taps by means of tap changers 10, 11, 12, 13, 14 and 15. These tap changers have been illustrated in one of their extreme positions for voltage phase shifting purposes and, as shown, they exclude the double-primed windings from the mesh and

include all of the primed windings so that in this particular case the mesh becomes a delta connection instead of a hexagon as would be the case if all six of the primed and double-primed windings formed the mesh connection.

For simplicity in describing the operation of the invention it will be assumed that circuit 1 is the supply circuit and circuit 2 is the load circuit so that the star-connected winding is the primary winding and the mesh-connected winding is the secondary winding. It should be understood, however, that the invention is not limited to such use and that power could flow in the opposite direction. Furthermore, the invention is not limited to exciting the mesh winding in the manner shown and other well-known ways of exciting a mesh-connected winding from a polyphase voltage could be utilized. It will be observed that the direction of the vector voltages of the windings 7', 8' and 9' are the same as the vector voltages to neutral of the conductors 4, 5 and 6 of the circuit 1 and that the vector voltages of the conductors 4', 5' and 6' of the circuit 2 are the voltages to neutral of the corners of the delta. Thus, in Fig. 2 the vector E_P indicates the direction of the phase voltage of conductor 4 and the vector Es represents the direction of the vector voltage of the conductor 4'. The phase angle between them is 30 degrees and assuming the conventional counterclockwise direction of phase rotation the voltage Es lags the voltage E_P so that the angle may be designated as —30 degrees. It will also be assumed that the voltage to neutral of the conductors 4', 5' and 6', when the mesh consists of a delta connection, each of whose sides contains the full length or full number of turns of the primed windings, is 100 per cent. The vectors in Fig. 2 are designated by the same reference numerals as designate the windings in Fig. 1 which have these voltages and whose axes are parallel to these vectors. By reason of symmetry the same —30-degree phase relation exists between the primary and secondary voltages of the other two phases.

Fig. 3 illustrates the vector voltage relationships when the six tap changers 10—15, inclusive, of Fig. 1 are adjusted so as to remove some of the effective turns of the primed windings and insert some of the effective turns of the double-primed windings. These changes are such that the corners of the resulting hexagon all lie on the same circle as do the corners of the delta in Fig. 2. Consequently the line to neutral voltage of the conductors 4', 5' and 6' remains unchanged but, as shown, the angle of phase shift between Es and E_P has been reduced from that shown in Fig. 2.

It will be observed in Fig. 4 that the conductor 4' is permanently connected to one terminal of winding 9' and selectively to either terminal of winding 8'' by means of a switch 16 and that conductor 5' is permanently connected to one terminal of winding 7' and selectively to either terminal of winding 9'' by means of a switch 17 and that conductor 6' is permanently connected to one terminal of winding 8' and selectively to either terminal of winding 7'' by means of a switch 18. The tap changers 11, 13 and 15 cooperate respectively with the taps of windings 7', 8' and 9' and they may be a three-phase tap changer so as to operate in unison while the tap changers 10, 12 and 14 cooperate respectively with the taps of windings 8'', 9'' and 7''. The latter tap changers also are preferably operated by a common operating means.

In Fig. 4 all of the windings are shown parallel to each other with correspondingly-numbered windings having common axes which are horizontally displaced from each other, so that if the transformer system is a three-phase transformer having a common core, each set of correspondingly-numbered windings may be mounted on its respective core leg. In this figure all of the tap changers have been moved from the positions shown in Fig. 1 to positions where they are spaced slightly more than half the effective length of their respective windings away from the permanently-connected terminals of these windings. As shown in Fig. 5, the exact displacement is such that the vector voltages between the permanent connections and the tap changers form an equilateral hexagon. Furthermore, this hexagon is characterized by having all of its corners lie on the same circle as do the corners of the delta in Fig. 2. Therefore, Es being the voltage to neutral of the terminal 4' is the same in Fig. 4 as in Fig. 2. However, by reason of the change from a delta connection to an equilateral hexagon the voltage E_P which is parallel to the voltage of winding 7' is now parallel to the voltage Es so that the phase shift angle between the primary and secondary voltages is zero. There has thus been a 30-degree phase shift between Figs. 2 and 4 corresponding respectively to Figs. 1 and 3 without any change in the relative magnitudes of the voltages.

Fig. 6 represents the voltage hexagon when the tap changers are adjusted so that the voltages or effective turns of the double-primed windings exceed the voltages or effective turns of the primed windings. This reverses the phase shift angle so that Es now leads E_P. The corners of the hexagon still are in the same circle so that the voltage ratio remains unchanged. Further increases in the effective voltage of the double-primed windings and further decreases in the effective voltage of the primed windings while maintaining the voltage ratios of the primary and secondary circuits unchanged can be continued until the limiting condition in which the effective voltage of the primed windings is reduced to zero. This condition is illustrated in Fig. 7 wherein the diagram has returned to a delta connection which, however, differs from that of Fig. 2 in that the double-primed windings now form the delta whereas in Fig. 2 it was the primed windings. The result is that Es now leads E_P by 30 degrees so that the phase shift is now +30 degrees instead of —30 degrees as in Figs. 1 and 2. If the primed and double-primed windings have the same number of turns the magnitude of Es will be the same in Fig. 5 as in Fig. 2 so that the ratio of the primary and secondary voltages is the same as in Figs. 2 and 4. This shows that the circuit has a range of phase shift of at least 60 degrees with the same ratio of voltages.

Figs. 2 and 7 illustrate the two extremes or limits of phase shift operation at constant voltage ratio obtainable with the circuit of Fig. 1 but it will be seen from a consideration of Figs. 3, 5 and 6 that there are many possible phase shift angles between zero and ±30 degrees. Thus, so long as the tap changers are operated so as to keep the corners of the hexagon on the same circle the ratio will be unchanged and the phase shift angle can be made to vary in any desired number of steps between —30 degrees as one limit and +30 degrees as the other limit depending upon how finely divided are the tap spacings on the windings. However, the phase shift

range may be further extended in both the plus and minus directions by operation of the reversing switches 16, 17 and 18 shown in Fig. 4. Thus, if the ratios of the effective voltages of the primed and double-primed windings are as shown in Fig. 3 but the reversing switches 16, 17 and 18 are operated, then the resulting vector diagram produces the so-called crossed mesh or crossed hexagon shown in Fig. 8. As will be seen from this figure, the phase angle between the voltage 0–4' and the voltage of winding 7' is considerably greater than the 30-degree relation shown in Figs. 2 and 7.

Fig. 9 is similar to Fig. 5 in that it represents zero phase shift but differs therefrom in that the ratio of the voltages has been varied by making voltage Es the maximum possible. This is done by leaving tap changers 11, 13 and 15 in the position shown in Fig. 1 and moving the tap changers 10, 12 and 14 to the opposite ends of their respective windings so that the full turns of all of the secondary phase windings are used to form the equilateral hexagon. With this position of the tap changers the voltage Es is approximately 170 per cent of voltage Es shown in Fig. 4.

Fig. 10 illustrates the vector relations of the voltages of the secondary phase windings when it is desired to reduce the secondary voltage below 100 per cent instead of increasing it above 100 per cent as in Fig. 6. This figure shows, for example, the condition where the phase shift is —30 degrees so that it corresponds in this respect with Fig. 2. This result is obtained by leaving the tap changers 10, 12 and 14 in the position shown in Fig. 1 and moving the tap changers 11, 13 and 15 equal amounts toward the other ends of respective windings so as to produce the effective number of turns of the windings 7', 8' and 9' forming the delta connection. In this manner the symmetry of the figure remains unchanged but the radius of the circle on which the corners of the delta lie is progressively decreased thereby progressively decreasing the phase voltages of the secondary circuit.

By this means the ratio of the voltages of the circuits 1 and 2 may be varied over wide limits at constant phase angle or at varying phase angle and the phase angle or phase relation of the voltages of these circuits may be varied over wide limits at constant magnitude ratio or at variable magnitude ratio.

The hexagonal mesh connection although formed by two sets of three-phase windings is really a six-phase winding because the instantaneous directions of the voltages of the correspondingly-numbered primed and double-primed windings are opposite to each other in order that the vector sum of all six voltages in the mesh will be zero which, of course, is necessary for successful operation with a closed mesh connection.

The tap changers may either be operated by hand or by suitable power driven automatic mechanism and they may either be of the type which only operates on dead circuits or they may be of the load ratio control type which permits operation while the transformer is carrying load. The latter type is shown diagrammatically in Fig. 3 in which each tap changer consists of a double finger contact arrangement, the fingers being connected to opposite ends of a mid-tapped reactor or so-called preventive autotransformer, the center point of which is connected to the circuit conductor for the winding. By moving the separate contact fingers alternately the winding circuit is never interrupted.

An arrangement in which the mesh-connected winding, consisting of the windings 7', 8', 9', 7'', 8'' and 9'', is connected as an autotransformer is shown in Fig. 11. This is done by connecting the circuit 4, 5, 6 to symmetrically located intermediate points on the windings 7', 8' and 9'. In this manner changing the tap changers 11, 13 and 15 from one side of the above-mentioned point to the other will change the transformer ratio from that of a step-up transformer to that of a step-down transformer. In the case of the conductors 4 and 4' the phase shift between the voltages to neutral of these conductors will be produced by the vector sum of the voltage of the effective turns of the winding 8'' and the voltage of the portion of the winding 7' between the tap changer 11 and the conductor 4. In a like manner the voltage phase shift between the corresponding conductors of the other phases will be the vector sum of the voltages of two windings. By suitably operating the tap changers the voltage ratio may be changed independently of the voltage phase shift or the voltage phase shift may be changed independently of the voltage magnitude ratio as in Figs. 1 and 2. Similarly, the operation of the reversing switches 16, 17 and 18 will produce the crossed hexagon as shown in Fig. 8.

As can be seen from all of the vector diagrams, they are characterized by what may be called triangular symmetry. This is obvious in the delta diagrams as shown in Figs. 2, 7 and 10. However, it is also true that in all of the other diagrams the partial diagram existing between any pair of the terminals 4', 5' and 6' is the same as all of the others except that it is shifted through an angle of 60 or 120 degrees, as the case may be. In other words, considering Fig. 3, for example, the partial diagram between the terminals 4' and 5' consisting of the vectors 7' and 8'' is exactly the same as the partial diagram between the terminals 5' and 6' and which consists of the vectors 8' and 9'' except that they are out of phase with each other by 60 degrees. With respect to polyphase systems in general the vector diagram of an n-phase system embodying my invention would in all cases have what might be termed n-angled symmetry.

While there has been shown and described particular embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications can be made therein without departing from the invention and, therefore, it is aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. In an n phase transformer system, a pair of windings per phase, all of said windings being serially connected in a closed mesh whose vector voltages form a figure having n-angled symmetry, and means for varying the effective number of turns of all of said windings while maintaining such symmetry.

2. In an n phase transformer system, a pair of windings per phase, all of said windings being serially connected in a closed mesh whose vector voltages form a figure having n-angled symmetry, means for reversing the connection of one winding per phase in said mesh, and means

for varying the effective turns of the other windings.

3. In a three-phase transformer system, at least two windings per phase, all interconnected in a closed mesh whose vector voltages have triangular symmetry, means for varying the effective turns of one of said windings per phase so as to maintain such symmetry, and independent means for varying the effective turns of the other windings so as to maintain such symmetry.

4. The method of shifting the phase angle between two polyphase voltages which exist respectively in certain windings of a mesh connection of windings and in the voltages to neutral of certain terminals of said mesh connection which comprises varying the relative effective turns of adjacent windings of said mesh while maintaining such ratio of effective turns that the corners of said mesh all lie on the same circle.

5. The method of shifting the phase angle at constant magnitude ratio between two polyphase voltages which exist respectively in certain windings of a mesh connection of windings and in the voltages to neutral of certain terminals of said mesh connection which comprise varying the relative effective turns of adjacent windings of said mesh between a first limit of zero effective turns of one set of non-adjacent windings and a second limit of zero effective turns of the other set of non-adjacent windings while maintaining such ratio of effective turns that the corners of said mesh all lie on the same circle.

6. In combination, two similar sets of windings, means for establishing a voltage in each of said windings such that the voltages of each set of windings constitute a polyphase system of voltages, each of said windings having a plurality of taps, and means for interconnecting the taps of said windings so as to produce various mesh connections which are characterized by having their corners all lie on the same circle.

7. In combination, two equal-numbered sets of equal windings, means for establishing a voltage in each of said windings such that the voltages of each set of windings constitute a similar polyphase system of voltages, each of said windings having a plurality of taps, means for interconnecting certain of the taps of said windings so as to produce various mesh connections which are characterized by having their corners all lie in the same circle, additional taps on said windings, and means for interconnecting said additional taps so as to vary the diameter of said circle without varying the configuration of said mesh.

8. In combination, two equal-numbered sets of equal windings, means for establishing a voltage in each of said windings such that the voltages of each set of windings constitute a symmetrical polyphase system of voltages, each of said windings having a plurality of taps, means for permanently connecting a point on each of the windings of one set respectively to a point on a winding of the other set, the voltages of each pair of permanently interconnected windings being out of phase, means for interconnecting certain of the taps of said winding so as to produce various mesh connections which are characterized by having their corners all lie on the same circuit, said mesh connections including each set of windings to the exclusion of the other as well as various amounts of all of the windings, and means for interconnecting certain others of said taps so as to vary the diameter of said circuits without varying the configuration of said mesh.

9. In combination, two equally-numbered sets of windings whose voltages form similar polyphase systems interconnected to form a polyphase mesh of twice the number of phases of said systems, and tap-changing means for varying the effective length of the windings of one set relative to the effective length of the windings of the other set while keeping the corners of the mesh formed by the vector voltages of said windings on the same circle, said means having a first limiting position in which the effective length of one set of windings is zero and a second limiting position in which the effective length of the other set of windings is zero.

10. In combination, an n phase autotransformer having a mesh connection of twice n phase windings whose vector voltages form a figure of n-angled symmetry, said mesh having two sets of n electrically symmetrically located terminals for connection respectively to the conductors of n phase input and output circuits, means for simultaneously changing the effective number of turns of n electrically non-adjacent of said phase windings, and means for simultaneously varying the effective number of turns of the n remaining phase windings.

11. The method of independently shifting the phase angle between and varying the relative magnitudes of the voltages of two n-phase circuits which comprises, interconnecting said circuits through a mesh-connected autotransformer winding having twice n phase windings connected respectively between different pairs of conductors of said circuits, varying the effective number of turns of certain of said phase windings so as simultaneously to shift the phase angle between said voltages and vary their relative magnitudes, and compensating for said phase shaft by varying the number of effective turns of the remaining phase windings so as to shift the phase angle between said voltages without varying their relative magnitudes.

ZOLTAN O. ST. PALLEY.