

Oct. 31, 1939.

W. PETERSEN

2,178,432

METHOD OF AND APPARATUS FOR PRODUCING A VARIABLE ALTERNATING CURRENT

Filed Aug. 12, 1938

8 Sheets-Sheet 1

Fig. 1.

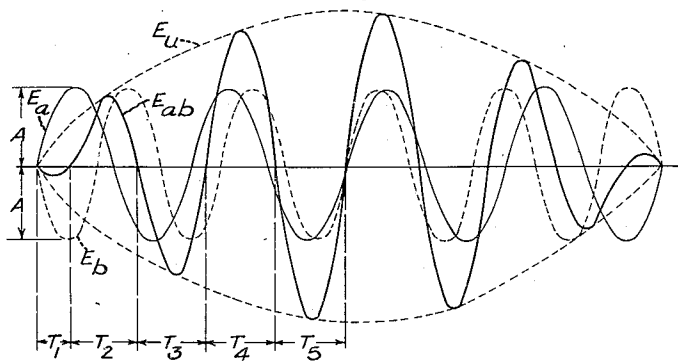
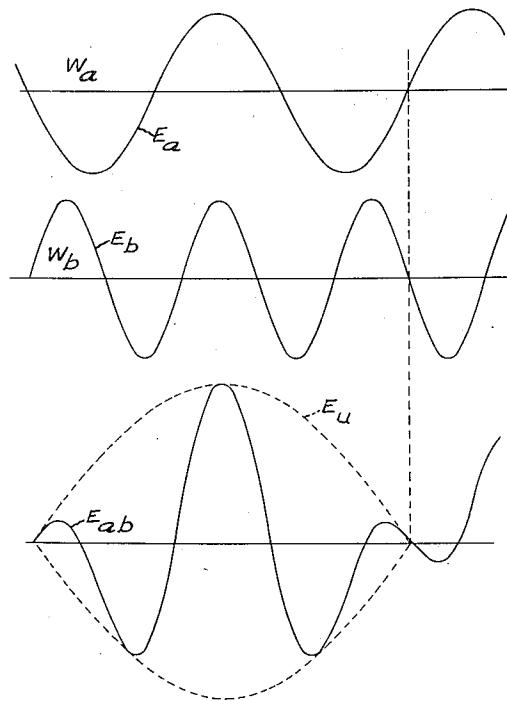


Fig. 2a



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Fig 2b

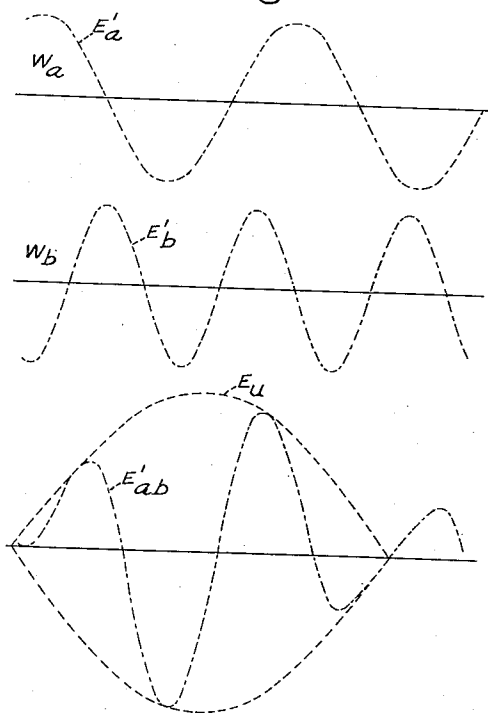
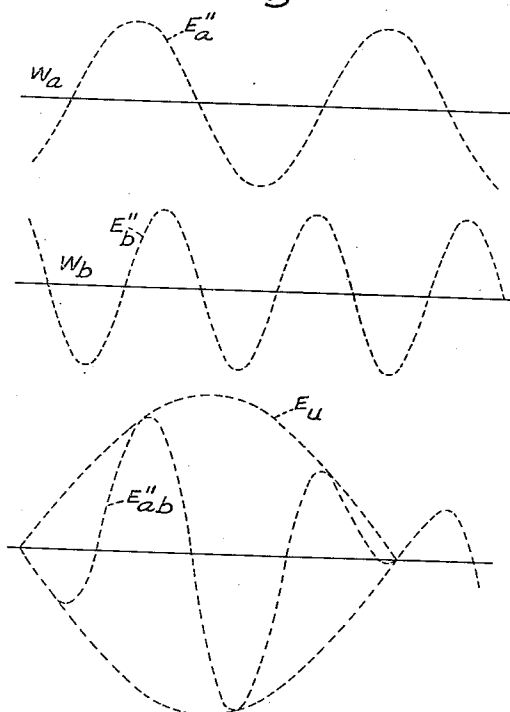


Fig 2c



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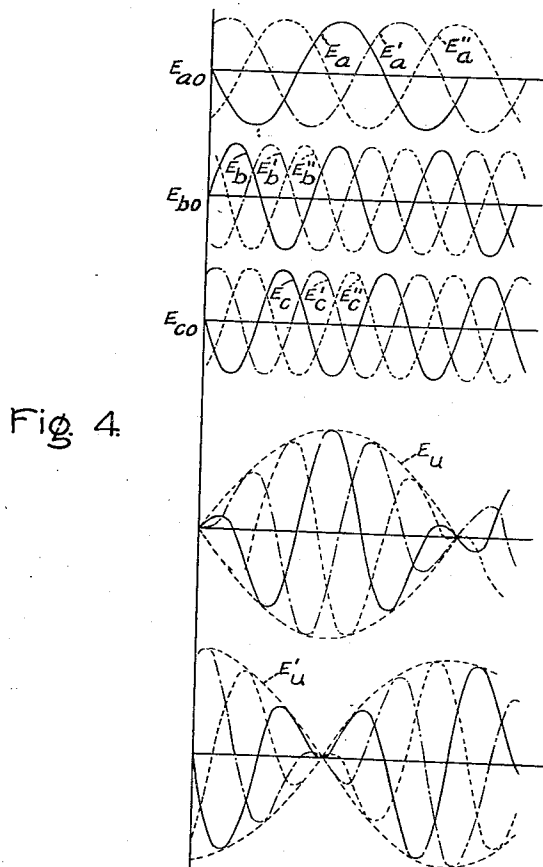
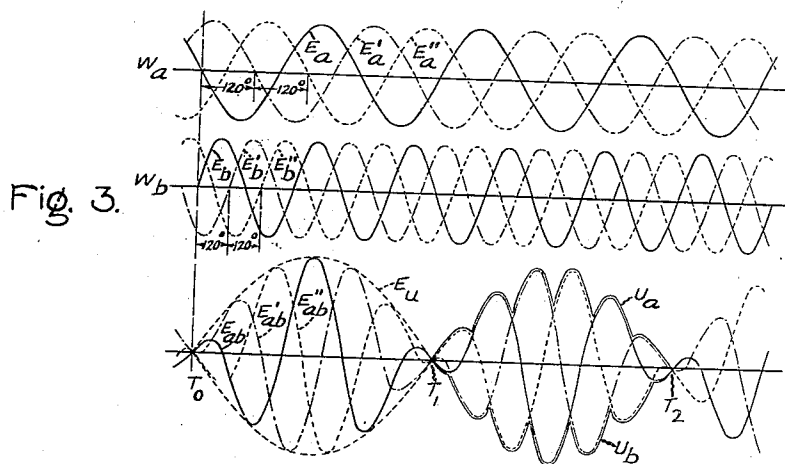
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Fig. 5.

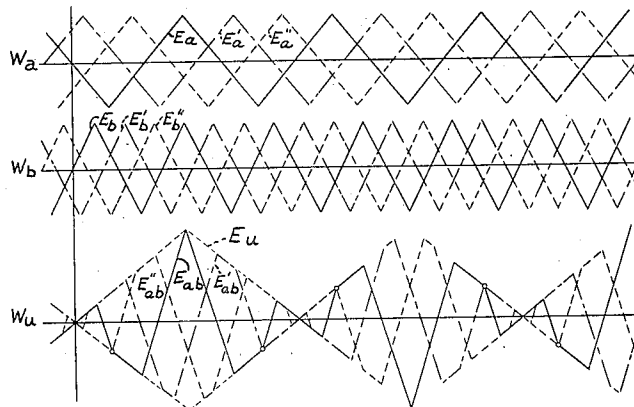
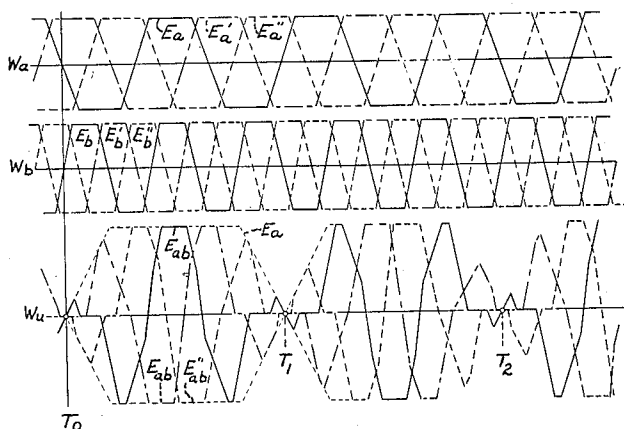


Fig. 6.



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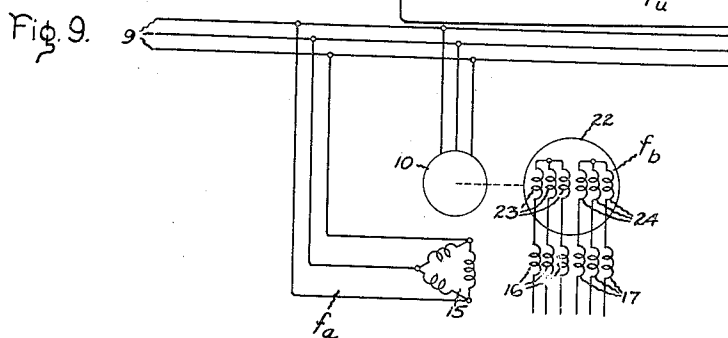
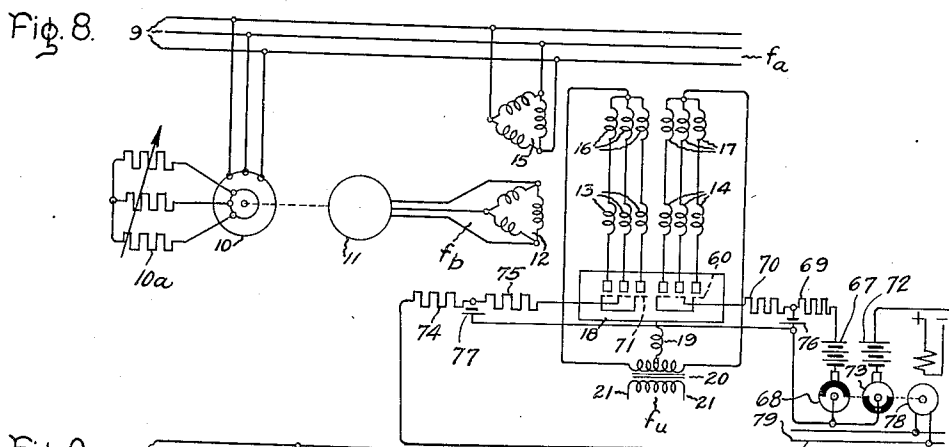
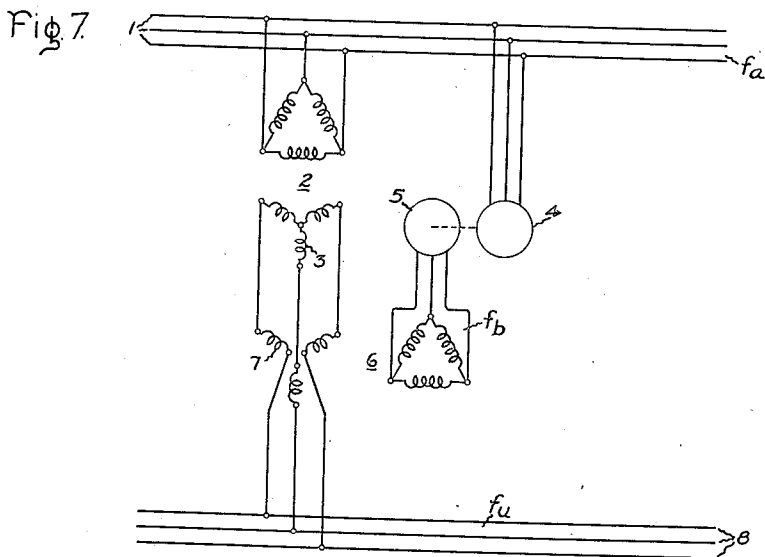
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Fig 10.

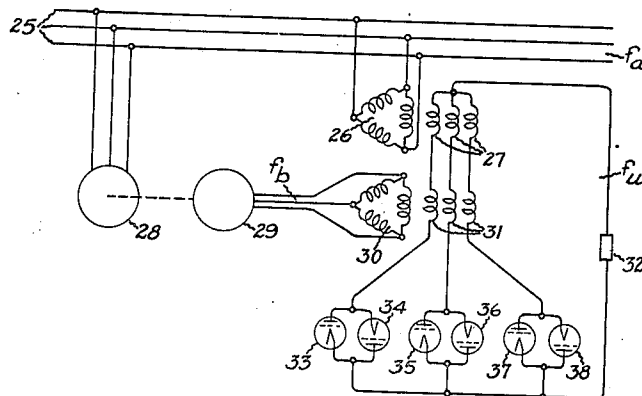
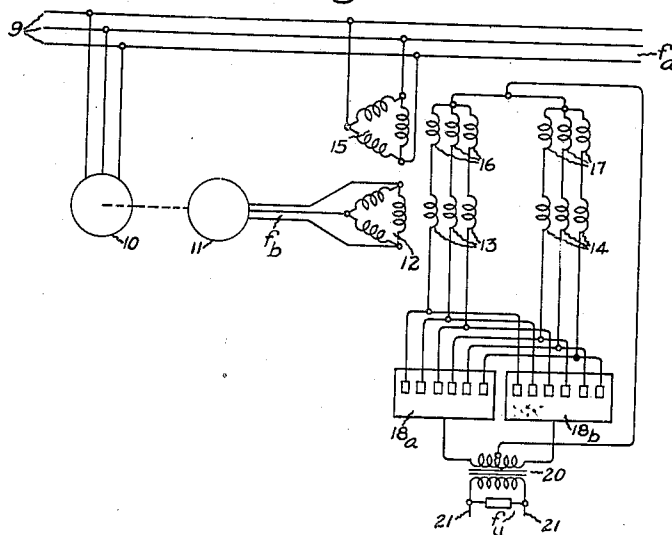


Fig 11.



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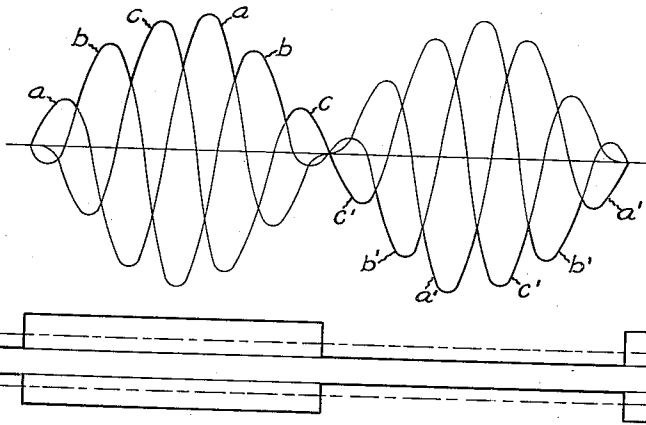


Fig 12.

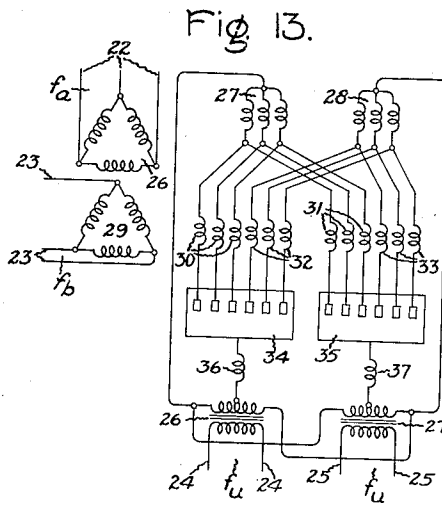


Fig 13.

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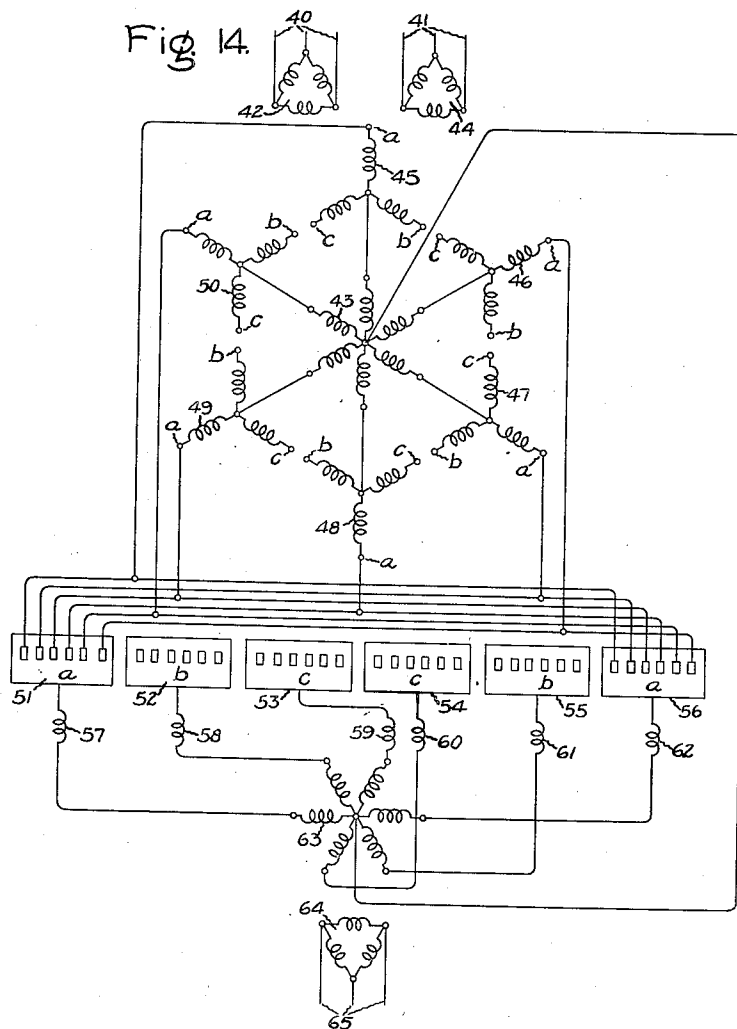
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METHOD OF AND APPARATUS FOR PRODUCING A VARIABLE ALTERNATING CURRENT

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8 Sheets-Sheet 8

Fig 14.



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UNITED STATES PATENT OFFICE

2,178,432

METHOD OF AND APPARATUS FOR PRODUCING A VARIABLE ALTERNATING CURRENT

Waldemar Petersen, Berlin, Germany, assignor to General Electric Company, a corporation of New York

Application August 12, 1938, Serial No. 224,439½
In Germany June 1, 1937

10 Claims. (Cl. 172-281)

My invention relates to the method of and the apparatus for producing a variable alternating current and more particularly to frequency changing systems operated from a variable amplitude or frequency alternating current or from two alternating currents both of which are higher in frequency than the output current.

In certain instances such as motor drives for Pilger mills it is desirable to obtain a variable speed or variable torque drive and for this purpose there may be produced a variable frequency or variable amplitude alternating current which is supplied to the motor in order to obtain the desired speed torque characteristic. Particularly where it is desired to transmit energy from a higher frequency alternating current circuit to a lower frequency alternating current circuit by means of frequency changers it will be found that frequency changers of the type utilizing electric valve converting system will have improved operation characteristics if these valve arrangements are energized from a source of variable frequency alternating current. In accordance with my invention such variable frequency alternating currents are obtained by adding together the voltages obtained from two alternating currents of different frequency. When these voltages are utilized to supply an electric valve frequency changing arrangement the output frequency will be an alternating current having a frequency equal to half the difference between the two alternating current supply frequencies.

It is an object of my invention to provide a method of and an apparatus for producing a variable frequency alternating current which will be reliable and simple in operation.

Another object of my invention is to provide an improved frequency changer apparatus operating to transmit energy between two or more alternating current circuits.

The novel features which I believe to be characteristic of my invention are set forth with particularity in the appended claims. My invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood by reference to the following description taken in connection with the accompanying drawings in which Figs. 1 to 6 illustrate graphically the method of producing variable frequency alternating currents; Fig. 7 shows a circuit arrangement by means of which my method may be carried out; Fig. 8 shows an electric valve frequency changing apparatus operating in accordance with my invention; Fig. 9 shows a

further modification of the arrangement shown in Fig. 8; Figs. 10 and 11 are further examples of frequency changing apparatus embodying the principles of my invention; Fig. 12 graphically illustrates the application of my invention to frequency changing apparatus utilizing zero or neutral point anodes; and Figs. 13 and 14 show further frequency changing apparatus to which my invention has been applied.

Referring to Fig. 1 of the drawings I have shown therein a graphical representation of how the superimposition of two sine waves of approximately like frequency will produce a resultant wave whose frequency is the arithmetical mean of the sum of the frequencies of the two alternating waves. This resultant wave indicated as E_{ab} in Fig. 1 has periodic variations in amplitude which are commonly called "beats". As is well known, two resultant "beat frequencies" are obtained by such superimposition of two sine waves having the same amplitudes and slightly different frequencies, namely, one having a frequency equal to the difference between the original frequencies and the other having a frequency equal to the sum of the original frequencies. Since a "beat cycle" is defined as one complete rise and fall in amplitude, Fig. 1 discloses one "beat cycle" of a frequency equal to the difference between the two frequencies of the superimposed waves which is quite obvious from a study of Fig. 2a. The locus of the amplitudes of the resultant curve E_{ab} describes an envelope E_a Figs. 1 and 4, which varies in sinusoidal form if one considers alternate positive and negative loci of the amplitudes of successive beat cycles and the frequency of this sinusoidal envelope is equal to half the difference between the frequencies of the two alternating current waves which produce the resultant wave E_{ab} . Where the envelope is of sinusoidal form it is to be understood that this resultant envelope is obtained from the superimposition of two sinusoidal curves having equal amplitude. Mathematically the values of such curves or voltages are added in accordance with the following formula:

$$\begin{aligned} (1) \quad E_a &= \sin w_a t, \quad E_b = A \sin w_b t \\ E_{ab} &= E_a + E_b = A (\sin w_a t + \sin w_b t) \\ &= 2A \sin \frac{(w_a + w_b)t}{2} \cdot \cos \frac{(w_a - w_b)t}{2} \\ E_{ab} &= 2A \sin \pi t(f_a + f_b) \cdot \cos \pi t(f_a - f_b) \end{aligned}$$

Wherein E_a and E_b represent the instantaneous values of the two alternating voltages of equal amplitude, similar wave shape, and slightly different frequency, E_{ab} is the resulting wave

obtained by superimposing E_b on E_a , w is the circuit frequency in radians per second, f is the frequency in cycles per second and A is the amplitude of the voltages E_a and E_b . It is observed that the resulting wave E_{ab} contains a product of two trigonometric functions. Considering the coefficient of the cosine term in the above derived equations, it is observed that the value of this term becomes zero at successive values of t differing by values of

$$\frac{1}{f_a - f_b}$$

It is evident therefore, that the beat frequency, as far as the coefficient of the cosine term of the above mentioned equation is concerned, is equal to $f_a - f_b$ or the difference between the frequencies of the two superimposed waves. This expression indicates that the envelope E_u when considered to include the alternate loci of the positive and negative amplitudes of successive beat cycles varies with a frequency of

$$\frac{f_a - f_b}{2}$$

or one-half of the beat frequency and the amplitude varies between the value $2A$ and 0 . Therefore the alternating wave E_u thus obtained contains two beat cycles for each cycle of E_u as is quite obvious from Fig. 3 since a beat cycle extends from T_0 to T_1 while a complete cycle of the alternating wave E_u extends from T_0 to T_2 . It will be seen that the frequency of the envelope E_u is considerably less than either of the frequencies of the alternating waves E_a and E_b . This method of lowering the frequency has the disadvantage that a number of gaps exist in the energy flow. This is apparent from Fig. 1 by observing the envelope E_u of the resultant voltage E_{ab} . Thus there are energy gaps during the time T_1 , T_3 , T_5 , etc., relative to the upper limit of the curve E_u . Where it is necessary to deliver a large energy output, such wave shapes would therefore be undesirable. It therefore, would be necessary to supply additional energy during these periods and such energy supply would also operate at a frequency equal to one-half of the sum of the frequencies of the supply circuit and at the same time a "beat" would result having a frequency equal to the difference of the two supply frequencies.

In accordance with my invention it is possible to reduce the frequency by combining two alternating current waves and yet at the same time maintain a substantially continuous energy flow. This is accomplished by superimposing the alternating voltage or current waves of a plurality of polyphase angularly symmetrical systems having a like direction of rotation and which waves have approximately like amplitude and similar wave shape. The degree of continuity in the energy flow with reference to the envelope E_u may be increased by increasing the number of phases used. In the instance of three phases of sine wave form the values are added in accordance with the following mathematical formulae:

$$(2) E_a = A \sin (w_a t + a); E'_a = A \sin (w_a t + 'a);$$

$$E''_a = A \sin (w_a t + ''a)$$

$$E_b = A \sin (w_b t + b); E'_b = A \sin (w_b t + 'b);$$

$$E''_b = A \sin (w_b t + ''b)$$

where E_a , E'_a and E''_a are the instantaneous voltages of each phase of a three-phase alternating current voltage of one frequency and E_b , E'_b and

E''_b are instantaneous phase voltages of another three-phase alternating current voltage of a slightly different frequency and a , a' and a'' , b , b' and b'' indicate the phase displacement in radians of the individual phase voltages compared with a starting point which is assumed to be zero. By superimposing E_a and E_b , E'_a and E'_b , and E''_a and E''_b the following equations are obtained:

$$E_{ab} = 2A \sin \left[\frac{(w_a + w_b)}{2} t + \frac{(a + b)}{2} \right] \cos \left[\frac{(w_a - w_b)}{2} t + \frac{(a - b)}{2} \right] \quad 10$$

$$E'_{ab} = 2A \sin \left[\frac{(w_a + w_b)}{2} t + \frac{('a + 'b)}{2} \right] \cos \left[\frac{(w_a - w_b)}{2} t + \frac{('a - 'b)}{2} \right] \quad 15$$

$$E''_{ab} = 2A \sin \left[\frac{(w_a + w_b)}{2} t + \frac{(''a + ''b)}{2} \right] \cos \left[\frac{(w_a - w_b)}{2} t + \frac{(''a - ''b)}{2} \right] \quad 20$$

Let

$$w_m = \frac{w_a + w_b}{2}; w_d = \frac{w_a - w_b}{2}; m = \frac{a + b}{2}; d = \frac{a - b}{2} \quad 25$$

Then

$$E_{ab} = 2A \sin (w_m t + m) \cos (w_d t + d)$$

$$E'_{ab} = 2A \sin (w_m t + 'm) \cos (w_d t + 'd)$$

$$E''_{ab} = 3A \sin (w_m t + ''m) \cos (w_d t + ''d) \quad 30$$

When these equations are compared with Equation (1) it will be apparent that the expressions containing the prime and those containing the double prime represent different phases of the voltages which are to be added. Half of the sum of the original frequencies has been assumed as the mean frequency w_m and half of the difference of the original frequency as w_d . The graphical representation of these equations is shown in Figs. 2A to 2C. Figs. 2A to 2C differ from each other in that the voltages E_a , E'_a , E''_a and the voltages E_b , E'_b , E''_b are displaced 120° with respect to each other. The addition of these two voltages produces a resultant voltage E_{ab} , E'_{ab} , and E''_{ab} , each of which has a similar envelope E_u as is apparent from Figs. 2A to 2C. In Fig. 3 there is shown the manner in which the three phase voltages are combined. From this figure it will be apparent that at the time T_0 , T_1 , T_2 , etc., the voltages E_a and E_b have an instantaneous value which is zero with the result that the resultant voltage E_{ab} is zero. At the same time the remaining voltages E'_a and E'_b and E''_a and E''_b have instantaneous values which are of equal value in opposite phase so that the resultant values E'_{ab} or E''_{ab} at the time T_0 , T_1 , T_2 , etc., are likewise equal to zero. These conditions can also be verified by reference to the mathematical Equation (2), which give the standards for the reduction of frequency in the cosine function. This function is identical for all three phases E_{ab} , E'_{ab} and E''_{ab} when the differences of the phase angles a and b is zero or of equal value for all phases. From this it follows that the displacement of the individual voltages which are added together in multiphase must be the same in each system with reference to the actual frequency scale.

The mathematical Formula (2) also gives an indication as to the manner in which the resultant envelopes E_u are displaced in phase relation with respect to each other in multiphase systems. The factor d which occurs in Equation (2) indicates the difference in phase in radians

between the individual voltages participating in the voltage formation as compared with the initial value. If measures are taken so that the values a and b differ from each other by certain predetermined angular amount, that is, in contradistinction to the previous requirements of equality, then envelopes will be obtained which have a different phase position. Thus, for example, if it were desired to obtain a system having envelopes corresponding to a three-phase system one would displace one of the two producing voltages by 180° and then the phase displacement of the envelope would be 90° . Fig. 4 illustrates graphically how this occurs. If the voltages represented by the curves E_{a0} which comprise the individual voltages E_a , E'_a , E''_a , are combined with the voltages of the curves E_{b0} which comprise the individual voltages E_b , E'_b , E''_b , an envelope E_u corresponding to the fourth curve in this figure would be obtained. If now the voltages similar to the curves E_{a0} are combined with voltages shown by the curves E_{c0} which are 180° out of phase with respect to the curves E_{b0} then the envelope E_u forming the last portion of Fig. 4 would be obtained which envelope has a phase displacement of 90° with respect to the envelope E_u . The same results would follow if instead of displacing the voltages E_{b0} by 180° as shown by E_{c0} , the voltage E_{a0} were displaced by the same amount. It will be apparent to those skilled in the art that this illustration is not limited to the three-phase example just described but can be applied equally well to other multiphase arrangements.

While for the purposes of illustration up to this point it has been shown that sinusoidal voltages may be added by these methods, it is also possible to combine multiphase voltages having non-sinusoidal wave shapes. These non-sinusoidal wave shapes when added, however, will produce similar shaped non-sinusoidal envelopes. The only limitation to be observed is that the higher harmonics should not exhibit any phase displacement relative to the fundamental wave with respect to the passage through zero of the latter wave and that both forces of energy should have mutually equal mean symmetrical wave shapes. This is adequately illustrated by the graphical representation of Figs. 5 and 6 which show the possibilities of adding non-sinusoidal wave shapes such as triangular waves and trapezoidal wave shapes.

The mathematical representation of such curves may be obtained from the following analysis: Each individual phase of the two fundamental supply components is based on a time function which corresponds to the following formula:

$$(3) \quad E_a = Af(w_a t); E_b = Af(w_b t)$$

wherein the function $f(wt)$ fluctuates with the circuit frequency w between the values $+1$ and -1 ; A is the amplitude which is the same for both alternating current voltages. In comparison to the sinusoidal form this formula is developed into a Fourier series the coefficients of which (a for a system with a frequency of w_a , b for a system with a frequency of w_b) assume such values that E_a and E_b for different time instants are given values corresponding to those of the triangular or trapezoidal shape. Such a phase is represented by the following equation:

$$(4) \quad f(wt) = a_1 \sin wt + a_2 \sin 2wt + a_3 \sin 3wt + a_4 \sin 4wt$$

This simple equation is obtained by assuming

that the higher harmonics do not exhibit any phase displacement relative to the fundamental wave. If a series is set up for each of the two producing functions or alternating current sources, then these will differ only in the circuit frequencies w_a and w_b and in the phase angles a and b but not in the values of the Fourier coefficients a_1 to a_n and b_1 to b_n . From this it is apparent that it is necessary to have two wave shapes which are similar with the exception of their phase displacement. If now two such waves are added, which waves are produced by the individual currents or voltages E_a and E_b , then the following formula is obtained:

$$(5) \quad E_a = a_1 \sin(w_a t + a) + a_2 \sin(2w_a t + 2a) + a_3 \sin(3w_a t + 3a) +$$

$$E'_a = a_1 \sin(w_a t + a') + a_2 \sin(2w_a t + 2a') + a_3 \sin(3w_a t + 3a') +$$

$$E''_a = a_1 \sin(w_a t + a'') + a_2 \sin(2w_a t + 2a'') + a_3 \sin(3w_a t + 3a'') +$$

$$E_b = b_1 \sin(w_b t + b) + b_2 \sin(2w_b t + 2b) + b_3 \sin(3w_b t + 3b) +$$

$$E'_b = b_1 \sin(w_b t + b') + b_2 \sin(2w_b t + 2b') + b_3 \sin(3w_b t + 3b') +$$

$$E''_b = b_1 \sin(w_b t + b'') + b_2 \sin(2w_b t + 2b'') + b_3 \sin(3w_b t + 3b'') +$$

Let

$$a_1 = b_1; a_2 = b_2; a_3 = b_3; a_4 = b_4$$

$$\frac{w_a + w_b}{2} = w_m; \frac{w_a - w_b}{2} = w_d; \frac{a + b}{2} = m; \frac{a - b}{2} = d$$

Then

$$E_{ab} = 2a_1 \sin(w_m t + m) \cos(w_d t + d)$$

$$+ 2a_2 \sin(2w_m t + 2m) \cos(2w_d t + 2d)$$

$$+ 2a_3 \sin(3w_m t + 3m) \cos(3w_d t + 3d) +$$

$$E'_{ab} = 2a_1 \sin(w_m t + m') \cos(w_d t + d')$$

$$+ 2a_2 \sin(2w_m t + 2m') \cos(2w_d t + 2d')$$

$$+ 2a_3 \sin(3w_m t + 3m') \cos(3w_d t + 3d') +$$

$$E''_{ab} = 2a_1 \sin(w_m t + m'') \cos(w_d t + d'')$$

$$+ 2a_2 \sin(2w_m t + 2m'') \cos(2w_d t + 2d'')$$

$$+ 2a_3 \sin(3w_m t + 3m'') \cos(3w_d t + 3d'') +$$

If the first and last members of the resulting voltages E_{ab} to E''_{ab} are combined, then there will be obtained voltages which have cosine functions with the frequency w_a and its multiples as a limit and which exhibits an associated phase angle of a and its multiples. The combination of the individual limits then take place in the same manner as in the case of the fundamental functions E_a and E_b . The intermediate quantities, the sine functions, indicate the course of the voltages between the envelopes. As has been stated, curve forms similar to the fundamental wave shapes are only obtained when both fundamental components or voltages have similar forms, since otherwise the Fourier coefficients a_1 to a_n and b_1 to b_n would differ from each other and it would not be possible to add in the individual harmonic components, or a zero value would not be obtained at the same time that the fundamental wave passes through zero.

From these equations it will become apparent that in order to obtain a predetermined shaped output wave the same harmonics relative to the fundamental frequency must be provided in each of the fundamental frequency waves or voltage sources. From this it will be apparent that a

frequency change may be obtained which will have a wave shape satisfactory for all purposes, without the use of additional or auxiliary energy supply forces or energy storage devices, by adding together two polyphase voltages of different frequencies of any one of a large number of symmetrical wave shapes.

The resultant voltages obtained by the addition of a plurality of voltages of different frequencies to produce an envelope which varies periodically in accordance with this invention may be utilized for power purposes. A number of examples showing the manner in which such resultant voltages having an envelope of a relatively low frequency may be used will now be explained. The arrangement shown in Fig. 7 shows a simple form of frequency changer operated from an alternating current source or line 1 which has a frequency equal to f_a which supplies energy to a transformer 2 having a star connected secondary winding 3. A suitable motor 4 is utilized to drive an alternating current generator 5 which has a frequency f_b which is supplied to the primary winding of a transformer 6, the secondary winding 7 of which is connected in series with the secondary winding 3 of the transformer 2 and the resultant voltages are supplied to the alternating current circuit 8, which has a frequency which varies so as to have an envelope of a frequency f_n . The voltages combined in the transformer secondaries 3 and 7 are similar to the graphical representations of voltages disclosed in Figures 2A to 2C and Fig. 3. If a three phase motor is now connected to the alternating current circuit 8 the torque thereof will be varied in accordance with the frequency difference between the two voltages f_a and f_b . The difference between the frequencies, however, is not apparent in the operation of the motor since the torque is proportional to the square of the voltage or to the square of the current. As will be apparent from formula 1 the motor will operate at a frequency which is equal to the arithmetical mean of the sum of the frequencies of the two supply voltages. If the moment of inertia of the motor is not too great or if the motor is not connected to an extremely heavy load, then a change in speed will occur which has a rhythm corresponding to the frequency difference between the two supply voltages. Such motors may be used with advantage to drive Pilger mills and any other drives which require similar movement as for instance drives for riddles and certain feed movements in seam welding operation.

A further important field of use to which the idea of this invention may be applied is found in those instances where it is advantageous to supply single or multiphase low frequency systems from a multiphase system of higher frequency or where it is desired to transfer energy between two such systems. Since rotating machines have certain disadvantages static electric valve converting devices have been utilized. By means of my invention it is now possible in a simple manner to satisfy all the requirements of converter operation and asynchronous connection between alternating current systems. Heretofore the wave shape produced by electric valve converting frequency changing systems have had the disadvantage of producing wave shapes which were non-sinusoidal in form. Numerous methods have been suggested, such as tap transformers, for improving the wave shape of such systems. The disadvantages of such additional complications and apparatus may be obviated by the application of my

invention to electric valve converting apparatus. In Fig. 3 reference is made to the possibility of reducing the frequency by producing a resultant wave having an envelope E_n . From this it is apparent that there is only the problem of converting such resultant waves into a pure alternating current wave. The resultant polyphase voltages will therefore be supplied to an electric valve converting apparatus in which one group of discharge devices will operate to produce a positive half wave and another group will operate to produce a negative half wave. Such an arrangement is disclosed in Fig. 8 wherein the polyphase alternating current supply line 9 is used to supply energy to a motor 10 which is coupled to an alternating current generator 11. It will be assumed that the supply line has a frequency equal to f_a and the output of the generator 11 has a frequency equal to f_b . The generator 11 is connected to a transformer having a primary winding 12 and a plurality of groups of secondary windings 13 and 14. The alternating current supply line 9 is also connected to a transformer having a primary winding 15 and a plurality of groups of secondary windings 16 and 17. The secondary winding 16 of the one transformer and the secondary winding 13 of the other transformer are connected in series and similarly the secondary winding 17 of the one transformer and the secondary winding 14 of the other transformer are likewise connected in series. These two sets of series connected secondary windings of the transformers operate as two polyphase networks supplying voltages to two groups of arc discharge paths which may comprise a single cathode, multi-anode electric discharge device 18. Any of the types of electric valves well known in the art may be utilized although it is preferable to use those having an anode and a cathode contained within an envelope filled with an ionizable medium. The cathode of the electric discharge path 18 is connected through a suitable reactor 19 to the midpoint of the primary winding of a transformer 20 the secondary winding of which is connected to the alternating current load circuit 21. One extremity of the primary winding of the transformer 20 is connected to the neutral point of the transformer secondary winding 16 and the other extremity of the primary winding of the transformer 20 is connected to the neutral point of the transformer secondary winding 17. Thus when the voltages which result from the voltage component introduced by the transformer primary windings 12 and 15 are such as to produce positive resulting potentials in the network comprising the secondary windings 13 and 16 the various arc discharge paths associated therewith will become conductive to supply to the transformer 20 energy serving to produce one-half wave of the alternating current appearing in the output circuit 21. If, for example, it is shown that the alternating current circuit 9 has a commercial frequency of 60 cycles and it is desired to supply 25 cycles to the alternating current output circuit 21, the frequency of the generator 11 will be equal to 110 cycles. Obviously of course it is immaterial as to whether the alternating current supply line or the generator 11 is of a lower frequency since it is only necessary to supply to the two transformer secondary networks comprising the polyphase networks of the electric valve converting apparatus two frequencies which differ by a sum equal to twice the frequency to be transmitted to the alternating current load circuit 21. If desired, the alternating current supplied by the generator 11 may be variable in frequency and hence

the alternating current in the output circuit 21 will be variable in frequency. For this purpose I have schematically illustrated motor 10 as of the wound rotor induction motor type having a variable resistor 10_a connected to the rotor terminals whereby variation of the speed of motor 10 may be obtained and hence also variation of the output frequency of generator 11. The various arc discharge paths of the electric valves may be controlled by control grids. Any suitable control circuit well known in the art may be utilized in conjunction with the control electrodes or grids. For example, in Fig. 8 I have shown the well known control circuit described and illustrated in United States Letters Patent No. 1,408,118, granted February 28, 1922, to F. W. Meyer. The control electrodes or grids 66 for the discharge paths associated with the secondary windings 14 and 17 are energized with a positive potential from battery 67 through distributor 68 and resistances 69 and 70 every 180 electrical degrees with reference to a voltage cycle of the output frequency f_a ; that is,

$$\frac{f_a - f_b}{2}$$

During the other half cycle control electrodes or grids 71 for the discharge paths associated with secondary windings 13 and 16 are energized with positive potentials from battery 72 through distributor 73 and resistances 74 and 75. A negative bias potential from batteries 76 and 77 is impressed upon control electrodes 66 and 71, respectively, during the alternate half cycles for which the associated discharge paths are to be maintained nonconductive. Distributors 68 and 73 may be driven by a synchronous motor 78 energized from a suitable source of supply 79 having a frequency equal to half the difference between frequencies f_a and f_b . If the frequency changer illustrated in Fig. 8 is operating, synchronous motor 78 may be energized directly from the output circuit 21. It will be understood by those skilled in the art that any other control circuit well known in the art may be used where only a single frequency is utilized for controlling the arc discharge paths and this frequency corresponds to the alternating current output frequency. During one half cycle of the output frequency f_a control electrodes 66 are energized with positive potential and the three associated discharge paths become successively conductive twice during each half cycle as illustrated by Fig. 12. The current commutates from one discharge path to the other whenever the voltage impressed on the succeeding anode to become conductive is equal to or higher than the voltage impressed upon the anode of the discharge path which is conducting current. At the end of the half cycle the negative bias impressed upon control electrodes 66 by virtue of bias battery 76 maintains the associated discharge paths nonconductive and during the next half cycle the discharge paths associated with control electrodes 71 conduct current so as to produce a resultant output voltage of a frequency equal to half the difference between the two supply frequencies.

If desired the arrangement shown in Fig. 8 may be modified in accordance with that shown in Fig. 9 wherein similar parts have been given similar reference characters. In this instance, however, the motor 10 is of the synchronous type and the generator 11 has been replaced by a generator 22 which is of the double winding type. A set of windings of the generator is in series with a different set of secondary windings such as 16 and 17, respectively, of the transformer the primary

winding 15 of which is connected to the alternating current circuit 9. As shown here it would be preferable to connect the extremities of the output transformer 20 to the neutral points of the two groups of windings 23 and 24 of the machine or generator 22 in order to simplify the number of connections to the generator.

Still another system to which my invention may be applied is shown in Fig. 10. An alternating current supply circuit 25 supplies energy to a transformer having a primary winding 26 and a secondary winding 27. The circuit also supplies energy to a motor 28 which drives a generator 29 the output of which is connected to a transformer having a primary winding 30 and a secondary winding 31. The alternating current supply circuit will be assumed to have a frequency equal to f_a and the generator 29 will be assumed to have a frequency equal to f_b . The two secondary windings 27 and 31 of the transformers are connected in series, the one being connected in star relation so that the neutral point thereof is connected to one side of the alternating current load 32. The remaining connections to the secondary windings 27 and 31 are each connected by a pair of oppositely connected valves such as 33, 34; 35, 36; 37, 38; to the other side of the alternating current load 32. For the purposes of illustration each of the valves 33 to 38 have been shown as comprising an anode, a cathode and a control grid contained within an envelope filled with an ionizable medium, but it will be understood that any other valves commonly known in the art may be utilized. Any suitable control circuit which is well known in the art may be used to render conductive these valves in proper sequence so as to transmit to the alternating current load 32 alternating current energy having a frequency equal to one-half of the difference between the frequencies f_a and f_b .

Fig. 11 shows another embodiment similar to that shown in Fig. 8 and hence similar parts have been given similar reference characters. In this arrangement, however, the electric arc discharge paths have been arranged in two groups 18_a and 18_b. Both the neutral points of the transformer secondary groups 16 and 17 have been connected together to the midpoint of the primary winding of the transformer 20. The outer extremities of the transformer primary winding have each been connected to a different one of the cathodes of the discharge groups 18_a and 18_b. This arrangement has the advantage over Fig. 8 of supplying a still more constant flow of energy to the alternating current circuit 21.

Heretofore in electric valve frequency converting systems it has been common to control the activities of the various arc discharge paths by a control circuit having two control components one corresponding to the input frequency and the other corresponding to the output frequency. Such an arrangement operated to prevent certain arc discharge paths from becoming conductive so that only those anodes having the proper phase voltages for production of the alternating current output would be rendered conductive. In accordance with the present invention, however, only a single frequency is utilized for controlling the arc discharge paths and this frequency corresponds to the alternating current output frequency. The conduction of the various anodes of such an arrangement as shown in Figs. 8 and 9 is illustrated in Fig. 12 wherein the first curve shows the manner in which the successive arc discharge paths are rendered conductive and the remaining curves show the current flow through the primary wind-

ing of the output transformer. Therefore, in the arrangement shown in Figs. 8, 9 and 11 it is only necessary to provide three arc discharge paths for each polyphase network group since each of the arc discharge paths is rendered conductive twice during each half cycle of alternating current in the output circuit. Thus it will be seen that each discharge occurs over a considerable period thereby providing a good utilization of the transformer and yet the entire electric valve apparatus operates only intermittently thus providing good operation with reference to the necessity for dissipating the heat with the result that the danger of arc back is materially reduced. The harmonic content of the electric valve converting apparatus by a three phase converter utilizing my invention is about equal to that of a six phase converter of the usual type.

If it is desired further to improve the shape of the low frequency wave, then this can be accomplished by utilizing a greater number of phases for example six phases. The output voltage will therefore be composed of several partial voltages which have equal or different phase positions. It will be apparent from Fig. 3 that the addition of additional phases are similarly dependent upon whether one considers either the upper or the lower limits of the envelope E_u . Thus in a six phase rectifier one group of three phases will supply an envelope corresponding to U_a and the other group will supply an envelope corresponding to U_b .

The systems disclosed in Figs. 7, 8, 9, 10 and 11 are capable of producing a constant frequency alternating current output since it is relatively easy to maintain the speed of these generators constant in view of the fact that the frequency of the output current f_u is equal to

$$\frac{f_a - f_b}{2}$$

from which it is apparent that any variation of the generator only produces half as great a variation in the output frequency. If it is desired to produce a variable frequency alternating current output it furthermore will be apparent that the arrangements disclosed in these figures provide a simple arrangement for accomplishing this. Such arrangements have numerous advantages over the arrangements in the prior art since at all output frequencies the power factor of the converter is relatively high. Such arrangements furthermore have the advantage of producing symmetrical alternating current outputs in contrast to the asymmetrical wave shape produced by ordinary electric valve translating means which have rectangular or trapezoidal alternating current wave shapes. While the frequency relation between the input frequency and the output frequency is not an integral factor it is apparent that in the more simple systems the output waves are not symmetrical in shape. Symmetry in the conventional arrangements can only be approximated by utilizing a large number of phases in a large number of arc discharge paths so that each wave in the output circuit is produced by a plurality of partial wave components supplied by the different electric discharge paths. From this it will be apparent that the arrangements disclosed in accordance with my invention have a relatively high power factor, relatively low harmonic components, and produce symmetrical alternating current wave outputs for both rigid frequency relation and variable frequency relation between the input and output circuits.

While my invention has been shown as applied to a frequency changing system operating between a polyphase alternating current source and a single phase load circuit, it is equally applicable to transmission of energy between two polyphase alternating current circuits. An example of such an arrangement is disclosed in Fig. 13 wherein an alternating current source 22 having a frequency f_a and a second alternating current source 23 having a frequency f_b supplies energy to an electric valve converting system connected to the two phase alternating current circuits 24 and 25. One of the alternating current supply circuits may be energized from a source of energy comprising a generator such as shown in Figs. 7 to 11. The alternating current source 22 is connected to energize a transformer having a primary winding 26 and two secondary windings 27 and 28. The alternating current source 23 is connected to energize a transformer having a primary winding 29 and a plurality of secondary windings 30 to 33. Two groups of electric discharge valves 34 and 35 are provided to supply energy to the primary winding of the transformers 36 and 37 which are connected, respectively, to the output circuits 24 and 25. The secondary winding 27 of the one transformer and the secondary windings 30 and 31 are connected together so that the winding 27 is in series with the winding 30 and supplies energy through the valve group 34 and the primary winding of the transformer 26 through a suitable smoothing reactor 36. Winding 27 connected in series with the winding 31 supplies energy through the group of valves 35 through a suitable smoothing reactor 37 to the primary winding of the transformer 27. The winding 28 in series with the winding 32 supplies energy through the group of valves 34 and the smoothing reactor 36 to the primary winding of the transformer 26 and the winding 28 in series with the winding 33 supplies energy through the group of valves 35 through the smoothing reactor 37 to the primary winding of the transformer 27. The alternating currents appearing across the circuits 24 and 25 are 90° out of phase and obviously if desired these may be connected to a T-connected transformer to supply three phase current. It will be apparent to those skilled in the art that any of the arrangements disclosed herein may be utilized for supplying an alternating current load with an alternating current variable in frequency. For example, if in Fig. 13 the frequency of the alternating current circuit 22 is constant and the frequency of the other alternating current circuits such as 23 is variable the resultant frequency appearing in either of the output circuits 24 or 25 will also be variable. Still another manner of obtaining a variable frequency output would be to vary the frequency of both the input circuits since the frequency of the alternating current load circuit corresponds to a frequency which is half of the difference between the frequency of the input circuit. Thus in order to produce a variable frequency output current it is only necessary to vary the frequency relation between the two alternating current supply circuits.

In Fig. 14 there is shown an arrangement for transmitting energy between two three phase systems. Two alternating current supply lines 40 and 41 are provided, one of which may be energized from a generator. The alternating current circuit 40 is connected to a transformer having a primary winding 42 and a six phase secondary winding 43. The alternating current circuit 41

is connected to a transformer having a primary winding 44 and a plurality of three phase secondary windings 45 to 50. Each of the outer extremities of the phase windings of the star-connected secondary transformer winding 43 is connected to the neutral point of a different one of the secondary transformer windings 45 to 50. Each of the outer extremities of the secondary windings 45 to 50 is connected to two different electric valve groups. Six groups of electric valves 51 to 56 each having six arc discharge paths are provided and each group is connected through a suitable smoothing reactor 57 to 62, respectively, to the outer extremities of a six phase star-connected primary winding 63 of a transformer the secondary winding 64 of which is connected to the alternating current output circuit 65. For the purposes of simplicity only one of each of the outer extremities of the six secondary transformer windings 45 to 50 has been shown connected to the two valve groups 51 to 56 since it will be apparent to those skilled in the art that the remaining transformer terminals are similarly connected to the valve groups 52, 55; 53, 54.

While my invention has been shown and described in connection with certain specific embodiments it will, of course, be understood that it is not to be limited thereto, since it is apparent that the principles herein disclosed are susceptible of numerous other applications, and modifications may be made in the circuit arrangements and in the instrumentalities employed without departing from the spirit and scope of my invention as set forth in the appended claims.

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

1. The method of producing a lower frequency alternating current quantity from two alternating current quantities of higher frequency which comprises vectorially adding together said higher frequency alternating current quantities to produce a resultant alternating current quantity having a variable frequency and a variable amplitude, and converting said resultant quantity to produce an alternating current quantity corresponding to the envelope of said resultant quantity.

2. The method of transmitting energy from a higher frequency alternating current circuit to a lower frequency alternating current circuit which comprises generating an alternating current having an amplitude and a wave shape similar to the amplitude and wave shape of said source of alternating current, the frequency of said generated alternating current being greater than that of said lower frequency alternating current circuit, adding together vectorially said generated alternating current with energy from said higher frequency alternating current circuit, and converting said resultant alternating current to produce an alternating current having a frequency equal to that of said lower frequency alternating current circuit.

3. The method of producing a lower frequency alternating current quantity from two alternating current quantities having higher frequencies, similar wave shapes and similar amplitudes which comprises adding vectorially said alternating current quantities of higher frequency to produce a resultant alternating current quantity of variable frequency and variable amplitude, and converting said resultant value to produce an alternating current value having a wave shape corre-

sponding to the envelope of said resultant quantity.

4. A method which comprises adding vectorially two alternating current quantities of different frequency but of similar amplitude and similar wave shape to produce a resultant alternating current quantity of variable frequency and variable amplitude, varying the frequency relation between said higher frequency alternating current quantities, and rectifying and converting said resultant alternating current quantity to produce a variable frequency alternating current quantity having a wave shape corresponding to the envelope of said resultant alternating current quantity.

5. An electric frequency changing system comprising a source of alternating current having a certain frequency, amplitude and wave shape, means energized from said source for producing an alternating current of different frequency and similar amplitude and wave shape, and means energized from said latter means and from said source for combining said alternating currents to produce a resultant alternating current of variable frequency and variable amplitude.

6. An electric valve frequency converting system comprising two sources of alternating current of different frequencies and of similar wave shape and similar amplitude, means for adding together said alternating currents, electric valve converting means energized from said latter means for producing an alternating current having a frequency equal to half of the difference between the frequencies of said first mentioned alternating currents.

7. In combination, an electric valve frequency changing apparatus including a plurality of arc discharge paths and two groups of serially connected polyphase inductive networks, an alternating current output circuit for said apparatus, said output circuit having a predetermined frequency, and means for supplying energy to said groups of polyphase connected networks, said energy comprising two alternating currents having similar wave shapes and like amplitudes and differing in frequency by an amount equal to twice the frequency of said alternating current output circuit.

8. The combination comprising an electric valve converting apparatus including a plurality of arc discharge valves and two groups of serially connected polyphase inductive networks, means for energizing one of said inductive networks from a source of polyphase alternating current having a certain frequency amplitude and wave shape, means for energizing the other of said inductive networks with alternating current of similar wave shape and amplitude and means for varying the frequency relation of the alternating currents supplied to said networks.

9. The combination comprising an electric valve frequency converting system including a plurality of arc discharge devices, two groups of polyphase inductive networks, said networks being connected in series relation, an output circuit having a predetermined frequency, and means for energizing each of said inductive networks with alternating current having similar wave shapes and amplitudes, said alternating currents differing in frequency by an amount equal to twice the frequency of said alternating current output circuit.

10. An electric frequency changing system comprising a source of alternating current hav-

ing a predetermined frequency, amplitude and wave shape, means energized from said source for producing a second alternating current of different frequency and similar amplitude and
5 wave shape, means energized from said latter means and from said source for vectorially combining said alternating currents of different frequencies to produce a resultant alternating cur-

rent of variable frequency and variable amplitude, and electric valve frequency covering means energized by said resultant alternating currents for producing an alternating current having a frequency corresponding to the frequency of the envelope of said resultant alternating current. 5

WALDEMAR PETERSEN.

Certificate of Correction

Patent No. 2,178,432.

October 31, 1939.

WALDEMAR PETERSEN

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows: Page 1, first column, line 20, for the word "system" read *systems*; and second column, line 46, in the formula, for " $E_a = \sin w_a^t$," read $E_a = A \sin w_a^t$; page 2, second column, line 31, for "3A" read $2A$; page 3, first column, line 18, for " E'_b, E''_b " read E'_b and E''_b ; and second column, line 44, for " $(3a^t + 3a') +$ " read $(3w_a^t + 3a') +$; page 5, first column, line 5, for "resistor" read *resistance*; page 6, second column, line 47, for "cennected" read *connected*; page 7, first column, line 5, for "seconudary" read *secondary*; and second column, line 59, claim 8, after "amplitude" insert a comma; page 8, second column, line 2, claim 10, for "covering" read *converting*; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 12th day of December, A. D. 1939.

[SEAL]

HENRY VAN ARSDALE,
Acting Commissioner of Patents.

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