

May 25, 1948.

D. BARTLETT

2,442,256

SYNCHRONIZED TIMER

Filed Feb. 5, 1947

2 Sheets-Sheet 1

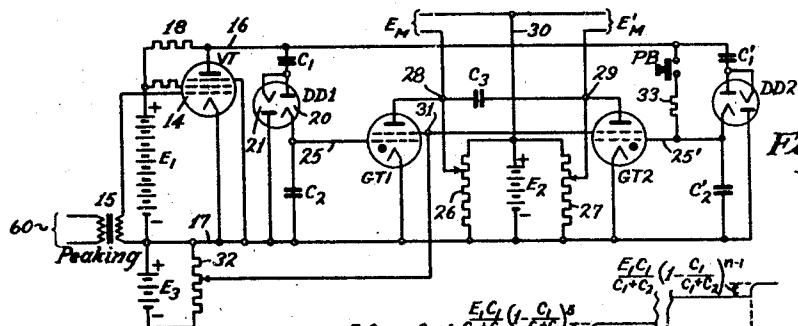


Fig. 1.

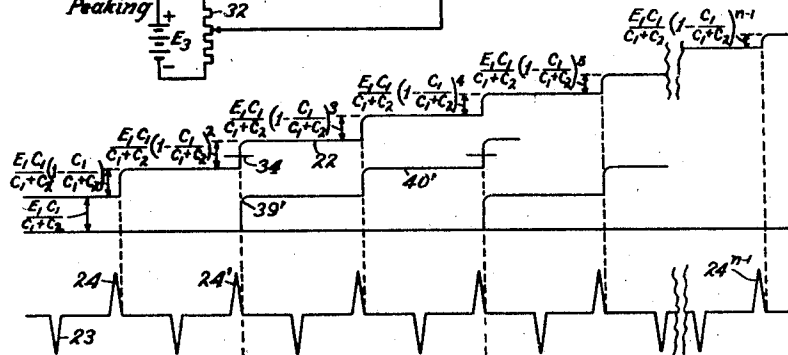


Fig. 2.

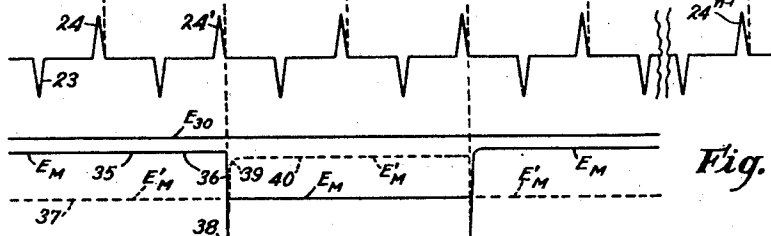


Fig. 3.

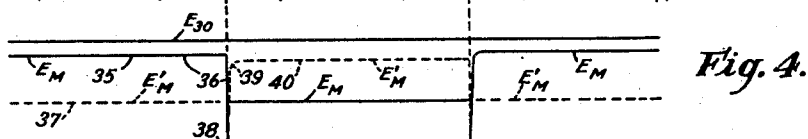


Fig. 4.

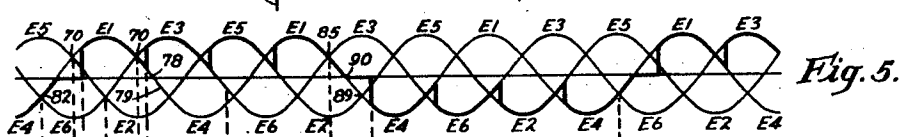


Fig. 5.



Fig. 6.

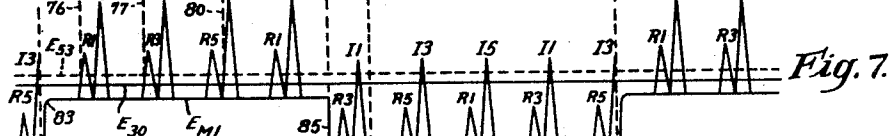


Fig. 7.

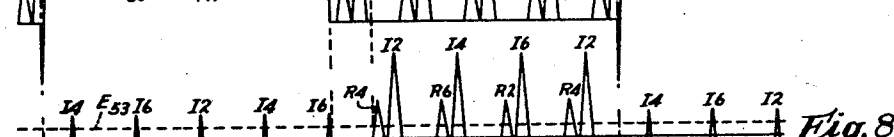


Fig. 8.

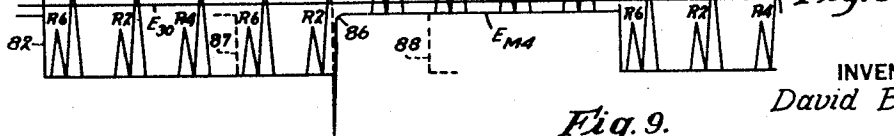


Fig. 9.

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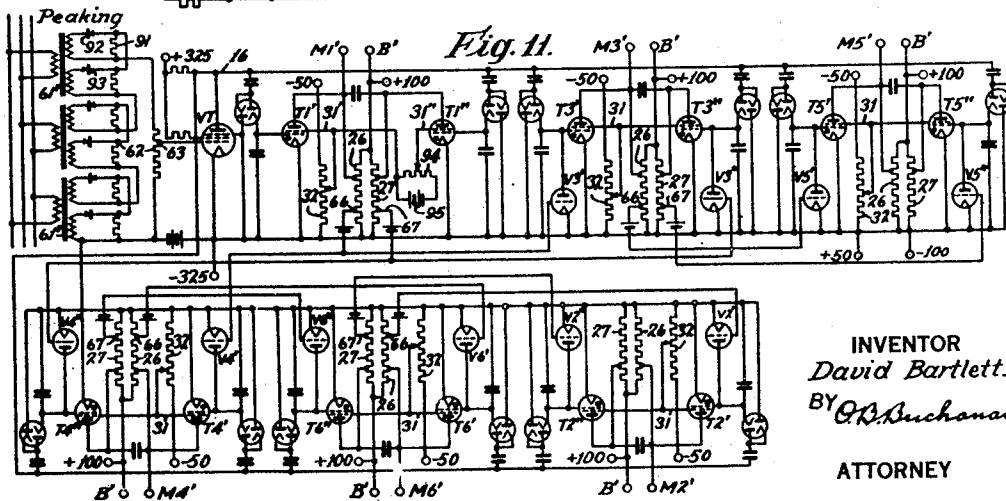
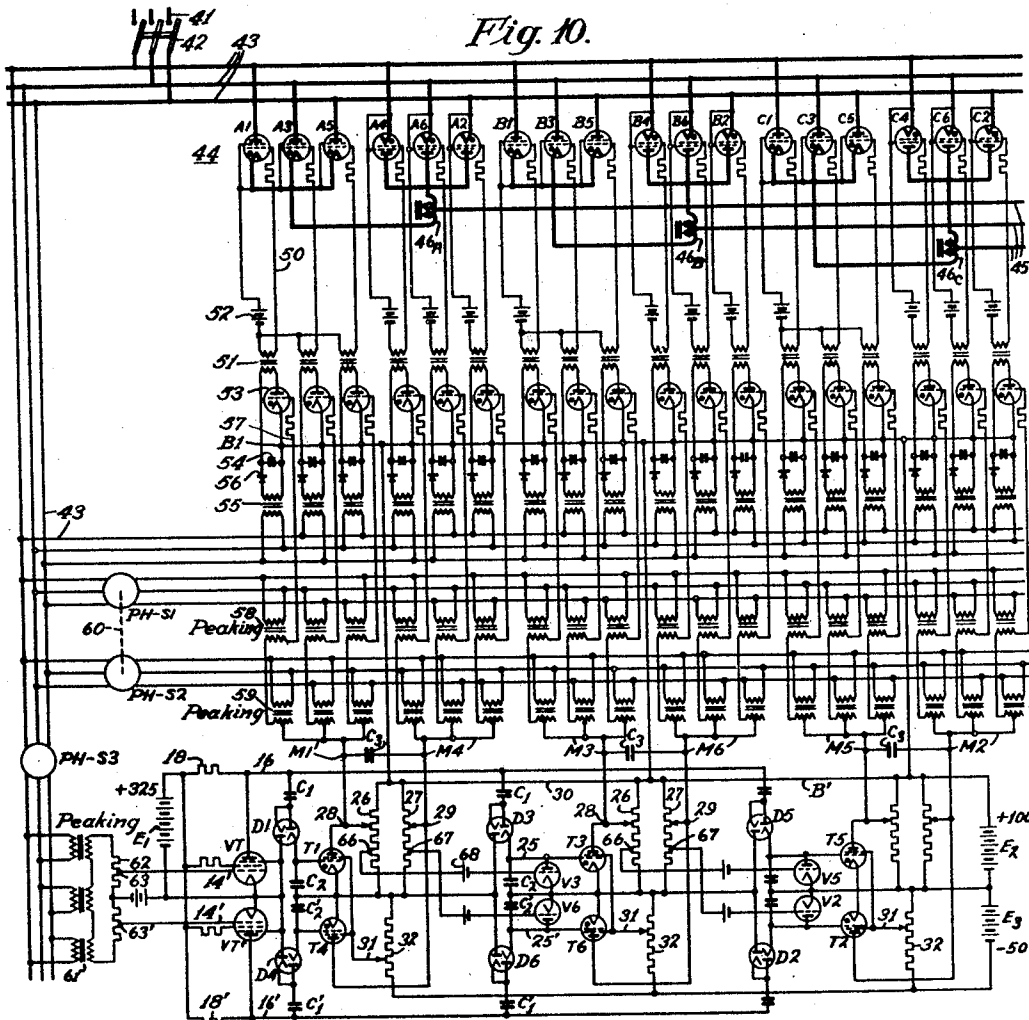
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2 Sheets-Sheet 2

Fig. 10.



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2,442,256

SYNCHRONIZED TIMER

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Application February 5, 1947, Serial No. 726,584

17 Claims. (Cl. 172-281)

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My invention relates to synchronized timers for controlling electron tubes of the sustained-discharge type, by which I mean, controlled tubes in which the grid or other control-electrode is capable of blocking the initiation of the tube-discharge until a sufficiently positive grid-potential has been reached, at a time when the main anode of the tube is sufficiently positive with respect to its cathode, the tube thereupon establishing an arc between the anode and cathode, and thereafter tending to maintain said arc, regardless of the grid-potential, until the main anode becomes negative with respect to the cathode, and remains negative for a sufficient length of time for the deionization of the tube. Such sustained-discharge tubes include ignitrons and other gas tubes.

Conventional timers, which depend upon the charging-voltage of a capacitor, suffer from the fact that the charging-curve of the capacitor has a finite and exponentially varying slope. Thus, if either a relay or an electronic tube is triggered from this rising voltage, a slight drift in the critical response-voltage of the relay or tube will have an appreciable effect upon the accuracy of the timer.

It is an object of my invention to provide a step-by-step timing-control which counts or measures a series of voltage-increments or steps which are derived from an alternating-current input-circuit. Thus, by providing a timing-voltage which increases by discrete steps, rather than according to an exponential curve, it is possible to make the tube or relay which responds to said voltage have a critical response-voltage which is in the approximate middle of one of those voltage-steps or increments, so that, even though the relay or tube does suffer slight drifts in its critical response-voltage, it will still respond to the same step or increment in the timing voltage.

It is an object of my invention to provide an accurate timing-control, which is applicable to a continuous cycle of operations, such as a series of spot-welds, a succession of photographic or X-ray exposures, or the firing of an electronic frequency-changer.

It is an object of my invention to provide a timer in which the timed interval is accurate, and in which the initiations of a succession of discrete timed intervals is synchronized with the input-frequency.

It is an object of my invention to provide an electronic frequency-converter or inverter-rectifier assembly, in which the output-frequency is controlled by such a synchronized timer, so that

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each half-wave of the output can be adjusted so as to have the same number of rectifier conducting-periods, in the same phase-relation to the input.

5 It is an object of my invention to provide a square-wave generator which is electronically timed, or counter-controlled.

10 It is a further object of my invention to provide a cycloconverter in which the output-frequency is controlled by such an electronically timed or counter-controlled square-wave generator. By a cycloconverter, I mean an assemblage of rectifier-tubes of the sustained-discharge type, in which the control-electrodes of the converter-tubes are each impressed with three voltages, namely, relatively small rectification-initiating input-frequency peaks, relatively large inverter-initiating input-frequency peaks, and a square-topped modulator-wave of the desired output-frequency, as broadly described and claimed in an application of Boyer and Hagensick, Serial No. 739,723, filed April 5, 1947, and assigned to the Westinghouse Electric Corporation; except that, according to my present invention, an electronically timed, or counter-controlled, square-wave output-frequency generator is provided.

20 When I designate a circuit as "input" or "output," I mean to refer to circuits which, either as a matter of convenience in terminology, or as a matter of normal or customary operation, may be designated as "input" or "output," with the understanding that the cycloconverter is capable of transmitting both real and wattless power, with power-transfer in either direction, between the two circuits, so that the so-called "input" circuit may sometimes receive power from the so-called "output" circuit.

30 With the foregoing and other objects in view, my invention consists in the methods, systems, combinations, apparatus and parts hereinafter described and claimed, and illustrated in the accompanying drawings, wherein:

40 Figure 1 is a diagrammatic view of circuits and apparatus illustrating a basic form of a synchronized timer in accordance with my invention,

45 Fig. 2 is a curve-diagram showing the type of stepped control-voltage which is obtained in my timer,

50 Fig. 3 is a curve-diagram showing the applied impulses or peaked-voltages which are applied to the timer of Fig. 1,

55 Fig. 4 is a voltage-diagram illustrative of the square-topped output-voltage which is produced by the timer which is shown in Fig. 1,

Fig. 5 is a view showing a three-phase supply-voltage, which is supplied to a plurality of groups of three-phase rectifier-tubes of a cycloconverter embodying an output-frequency control in accordance with a form of embodiment of my invention as shown in Fig. 10,

Fig. 6 is a voltage-diagram showing the positive and negative voltage-impulses which are applied to the timer of Fig. 10,

Figs. 7 and 8 are voltage-diagrams showing the voltages which are applied to the control-electrodes of the positive and negative groups of cycloconverter-tubes, in one of the output-phases, in the cycloconverter system which is shown in Fig. 10,

Fig. 9 is a curve-diagram showing the succession of positive impulse-voltages which are applied to the timer in Fig. 11,

Fig. 10 is a diagrammatic view of circuits and apparatus, illustrating a complete cycloconverter-system, controlled in accordance with my counter-controlled square-wave modulator, for converting from a three-phase input-circuit of sixty cycles or other frequency, to a three-phase output-circuit of a lower frequency, and

Fig. 11 is a diagrammatic view of a different form of embodiment of the timer which is utilized in Fig. 10.

In the simple form of timer which is shown in Fig. 1, a direct-current source, such as a battery E_1 , is utilized to energize the main anode-cathode circuit of a vacuum tube VT, which is illustrated as a pentode. The control-grid 14 of the pentode is controlled by means of a peaking-transformer 15 which is energized from a sixty-cycle system or other alternating-current input or control-circuit. The pentode VT is normally non-conducting, but is periodically driven to saturation by the recurrent positive peaks of the peaking-transformer 15. When the pentode VT is driven to saturation, it becomes substantially a short-circuit between the anode-circuit 16 and the cathode-circuit 17 of the tube.

The battery-voltage E_1 , which is applied to the anode-circuit 16 through a suitable resistor 18, is also utilized to charge two serially connected capacitors C_1 and C_2 , of which the capacitor C_2 is much the larger. A duodiode DD1 is utilized, or equivalent double rectifying-means, with its rectifying diode 20 connected in series with the larger capacitor C_2 , and with its inverting diode 21 connected in shunt around both the rectifying diode and said larger capacitor C_2 . The anode-circuit 16 of the pentode is also continued to a second group of two serially connected capacitors C'_1 and C'_2 , which are similar to the capacitors C_1 and C_2 , and which are similarly associated with a duodiode DD2.

The effect of the circuit thus far described is to increase the voltage on the capacitor C_2 , or C'_2 , in a succession of discrete steps or voltage-increments, as shown by the heavy-line curve 22 in Fig. 2. The peaking-transformer 15 delivers a succession of voltage-peaks, as shown in Fig. 3, these peaks being applied to the control-electrode of the pentode VT. The negative peaks 23 have no effect upon the pentode, but each positive peak 24 makes the pentode conducting, and keeps it conducting until the positive peak has subsided to a relatively small value.

Before the first positive peak 24, the pentode VT constituted substantially an open circuit on the serially connected capacitors C_1 and C_2 . Neglecting the voltage-drops in the resistor 18 and

in the rectifying diode 20, the voltage across the large capacitor C_2 , at this time, was

$$\frac{E_1 C_1}{C_1 + C_2}$$

During the time when the first positive peak 24 is being applied to the pentode VT, the smaller capacitor C_1 is substantially discharged, through a circuit including the inverting diode 21 and the main cathode-anode circuit of the pentode VT. The voltage of the smaller capacitor C_1 is thus reduced to a very small voltage, equal to the two tube-drops, this voltage being very small compared with the impressed battery-voltage E_1 . The larger capacitor C_2 is not discharged, at this time, because of the presence of the rectifying diode 20.

Near the termination of the first positive peak 24, the pentode VT again becomes non-conducting, and the smaller capacitor C_1 recharges. Neglecting voltage-drops in the tubes and in the resistor 18, the second charging of the capacitor C_1 adds a voltage

$$\frac{E_1 C_1}{C_1 + C_2} \left(1 - \frac{C_1}{C_1 + C_2} \right)$$

to the charge on the large capacitor C_2 . At the end of the second positive peak 24', the recharging of the smaller capacitor C_1 increases the voltage on the larger capacitor C_2 by the increment

$$\frac{E_1 C_1}{C_1 + C_2} \left(1 - \frac{C_1}{C_1 + C_2} \right)^2$$

The voltage of the larger capacitor C_2 thus increases by discrete steps. Furthermore, all steps except the first step, $E_1 C_1 / (C_1 + C_2)$, are timed by the positive voltage-peaks delivered by the peaking-transformer 15. Counting the first voltage-division $E_1 C_1 / (C_1 + C_2)$ as the first step or voltage-increment applied to the capacitor C_2 the n th step will occur after the subsidence of the $(n-1)$ th positive peak 24ⁿ⁻¹, and will increase the voltage on the large capacitor C_2 by an increment

$$\frac{E_1 C_1}{C_1 + C_2} \left(1 - \frac{C_1}{C_1 + C_2} \right)^{n-1}$$

The n th step or voltage-increment, on the large capacitor C_2 , is a maximum when

$$\frac{C_1 + C_2}{C_1} = n$$

Under these conditions, the n th step becomes

$$\frac{E_1}{n} \left(1 - \frac{1}{n} \right)^{n-1}$$

If n is large (5 or more), the n th step approximates

$$\left(\frac{0.368}{n} + \frac{0.2}{n^2} \right) E_1$$

The sum of the first n steps then approximates the value

$$\left(0.631 + \frac{0.20}{n} \right) E_1$$

Actually, however, each step, say the n th step, will be somewhat less than

$$\frac{E_1 C_1}{C_2} \left(1 - \frac{C_1}{C_2} \right)^{n-1}$$

because of the voltage-drops and the leakage-currents in the tubes. The exact values can be calculated, or determined experimentally, whichever is easier; but the foregoing analysis is sufficient for a first approximation for a design. It

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is usually desirable to have the ratio of capacitors C_2/C_1 of somewhere near the same order of magnitude as the maximum number of steps n which are to be counted or measured by the counter, but the design is not at all critical, and several times this value, either for the number of steps or for the capacitor-ratio, give satisfactory results. Fig. 2 is drawn for a capacitor-ratio $C_2 : C_1 = 10 : 1$. In general, however, the capacitor-ratio will be much larger.

Referring again to Fig. 1, and continuing the description of the apparatus therein shown, it is noted that the voltages appearing across the large capacitors C_2 and C'_2 are applied, respectively, to the control-grid circuits 25 and 25' of two gas tubes GT1 and GT2 (or other sustained-discharge tubes), having anode-circuits 28 and 29 which are energized from a second direct-current source E_2 , through potentiometers 26 and 27 respectively. The anode-circuits 28 and 29 of these gas tubes GT1 and GT2 are joined by a commutating capacitor C_3 . The positive terminal 30 of the second battery E_2 , and the anode-circuit 28 of the first gas tube GT1 are brought out to an output-terminal indicated by the voltage E_M , while the positive battery-terminal 30 and the anode-circuit 29 of the other gas tube GT2 are brought out to a second output-terminal marked E'_M .

The gas tubes GT1 and GT2 are shown as tetrodes, and their screen or shield-grids are utilized to control the value of the critical voltage which is necessary to be applied to the control-grid circuits 25 and 25', respectively, before the tubes will break down and become conducting. This control or adjustment is obtained by connecting the shield-grid circuit 31 to an adjustable potentiometer 32 which is excited from a negative biasing-battery E_3 .

In the operation of the synchronous timer shown in Fig. 1, it will be assumed that the second gas tube, GT2, is conducting current. This condition may be brought about, for example, by momentarily depressing a push button PB which applies the positive voltage of the anode-lead 16 to the control-grid circuit 25', through a resistance 33. While the tube GT2 is conducting, any charge on the associated large capacitor C'_2 is leaked off, as grid-current through said tube GT2.

Thus, while the tube GT2 is conducting, its increment-counting capacitor C'_2 is inoperative. However, the other increment-counting capacitor C_2 is operative, building up its voltage, in a series of discrete steps, as already described in connection with Fig. 2. The critical control-circuit voltage of the tube GT1 is chosen or adjusted to some value, such as is shown at 34 in Fig. 2, which is somewhere near the middle of the voltage-increment or step to which it is designed to respond, so that the instant of breakdown or firing of the tube GT1 is precisely and accurately timed, in synchronism with the applied peaks 24 of Fig. 3.

When the tube GT1 is fired, the voltage of its plate or anode-circuit 28, with respect to the positive battery-terminal 30, drops from its potentiometer-value 35, as shown in Fig. 4, to substantially the entire negative value of the battery-voltage E_2 (neglecting the voltage-drops in the tube GT1), as shown at 36 in Fig. 4. Meanwhile, the voltage of the anode-circuit 29 of the previously conducting tube GT2, with respect to the voltage of the positive battery-terminal 30, had already been substantially at the value of

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the negative battery-voltage E_2 , as indicated at 37 in Fig. 4. At the transition-point 38, therefore, the commutating capacitor C_3 momentarily maintains the same voltage-difference (35, 37)

between the two anode-circuits 28 and 29, thus momentarily driving the anode-circuit 29 of the previously conducting tube GT2 more negative than its cathode, as shown at 38 in Fig. 4. The time-constant of the commutating capacitor C_3 and the potentiometer 27 is made long enough for the deionization of the previously conducting tube GT2. At the expiration of the time determined by this time-constant, the potential of the anode-lead 29 of the previously conducting tube GT2 changes, as shown at 39, from the value 38 to the value 40 which is determined by the setting of the potentiometer 27 in Fig. 1.

The tube GT1 is now conducting, and the tube GT2 is not conducting. At the instant 36 when the newly fired tube GT1 became conducting, it short-circuited its increment-counting capacitor C_2 , so that it ceased counting. At the instant 39 when the previously firing tube GT2 became non-conducting, it removed a similar short-circuit from its increment-counting capacitor C'_2 , and gave the latter its first voltage-increment, as shown at 39' in Fig. 2. At successive positive voltage-peaks 24 (Fig. 3), the capacitor C'_2 builds up its voltage-steps, as shown by the light-line curve 40' in Fig. 2, until the tube GT2 again breaks down, starting the process all over. In this manner, first one tube, and then the other, is fired.

The two gas tubes GT1 and GT2 thus operate as trigger-valves, for cutting off, first one counter and then the other counter, besides cutting off each other, as each tube becomes conducting.

By adjusting the negative-bias potentiometer 32, which energizes the grid-circuit 31 of the two gas tubes GT1 and GT2 in Fig. 1, it is possible to preselect the capacitor-voltage which is required to fire each tube. It should be noted that the first voltage-peak 24, which is delivered by the counter-controlling peaking-transformer 15 after either trigger-tube GT1 or GT2 becomes non-conducting, produces the second voltage-increment or voltage-step on the associated step-counting capacitor C_2 or C'_2 , as the case may be; so that the trigger-tube GT1 or GT2, as the case may be, is fired after counting one more voltage-increment or step, than the number of timed intervals 24—24' (Fig. 3) between successive peaks of the peaking-transformer 15.

If the same bias is applied to both trigger-tubes GT1 and GT2, as shown in Fig. 1, the resulting square-topped waves E_M or E'_M will be symmetrical, with equal positive and negative half-cycles, as shown in Fig. 4. However, by using different bias-voltages on the two gas tubes GT1 and GT2, any degree of non-symmetry may be produced, as will be discussed in connection with Figs. 9 and 11.

The timer or counter, as shown, in its basic essentials, in Fig. 1, is applicable to many different types of circuits, where repetitive actions are required, under the control of the timer. However, a novel and important field of application of the timer is in connection with the control of a cycloconverter, as previously indicated.

Fig. 10 shows the application of my electronic timer in the control of a typical cycloconverter. A three-phase supply-line 41, of sixty cycles, or any other suitable frequency, is utilized to supply energy, as through a switch 42, to a three-phase input-circuit 43 of a cyclo-converter. The

cycloconverter is shown as comprising eighteen main tubes 44, arranged in six groups of three tubes each. Each of the main tubes is of the previously mentioned sustained-discharge type. They are illustrated as gas tubes 44, but they could be ignitrons or any other sustained-discharge tubes.

The cycloconverter tubes 44 are utilized to supply energy to a three-phase output-circuit 45, through paralleling reactors 46A, 46B, and 46C, as more specifically described and claimed in a Boyer application, Serial No. 739,725, filed April 5, 1947, assigned to Westinghouse Electric Corporation.

The eighteen cycloconverter tubes 44 are lettered A, B, and C, in accordance with the three output-phases; with numbers appended, to indicate the input-phases on a six-phase basis. This is done, because there are six tubes, such as A1, A4, B1, B4, C1 and C4, connected to each input-phase, and these six tubes are arranged in back-to-back pairs, such as A1—A4, B1—B4, and C1—C4. The tubes having the odd numerals, such as A1, A3 and A5, are connected to their responsive input-phases in the positive or rectifying direction, that is, with their anodes connected to the supply-circuit; while the even-numbered tubes, such as A4, A6 and A2, are connected to their respective input-phases in the negative or inverting direction, that is, with their cathodes connected to their respective supply-circuits.

The tube-group A1, A3, A5 may be conveniently referred to as the positive tube-group for supplying the output-phase A, while the tube-group A4, A6, A2, may be referred to as the negative group for supplying the output-phase A. When the output-currents are at unity power factor, the rectifying or positive tubes supply the positive current-halves, while the inverting or negative tubes supply the negative current-halves in the respective output-phases. When the output-currents have a power factor other than unity, the output-current, in each half-cycle, is shared by both groups of tubes for that output-phase.

The control-circuits 50 of the respective cycloconverter-tubes 44 are energized either directly or, as shown, through insulating transformers 51, which are known in the art. Usually, the control-circuits include also suitable biasing batteries or other sources 52. A separate insulating transformer 51 is shown, for each of the eighteen control-circuits 50 for the main cycloconverter-tubes 44. Each insulating transformer 51 is energized by means of a control-tube 53, preferably a gas or sustained-discharge tube, which is energized, in a known manner, from an individual capacitor 54, which is charged by means of charging-transformers 55, energized from the input-circuit 43, and unidirectionally charging the several capacitors 54 through rectifiers 56.

The cathodes of the eighteen control-tubes 53 are connected to a common cathode-bus B1.

The control-circuits 57 of the several control-tubes 53 are controlled by individual circuits, each serially including a relatively high-voltage input-frequency peaking-transformer 58 and a relatively low-voltage input-frequency peaking-transformer 59, plus a square-wave generator which, in accordance with my invention utilizes my electronic step-by-step counter. The broad combination of two peaking-transformers and a square-wave output-frequency source, is covered by the previously mentioned Boyer and Hagen-

sick application, Serial No. 739,723, filed April 5, 1947.

The high-voltage peaking-transformers 58 are energized, from the input-circuit 43, through a phase-shifter PH—S1, which is adjusted to phase said peaking-transformers to produce positive peaks at the proper instant for initiating the inverter-operation of the associated main tube 44; while the low-voltage peaking-transformers 59 are connected to the input-circuit 43 through a phase-shifter PH—S2 which is adjusted in phase so as to produce positive voltage-peaks at the proper instant for initiating the rectifying operation of the associated tube. The two phase-shifters PH—S1 and PH—S2 are commonly connected in opposite phase-sequence, and mounted on a common shaft 60, so as to be simultaneously adjustable, as described and claimed in said Boyer and Hagensick application.

In adapting my electronic counter to serve as the square-topped modulator-wave generator for controlling the positive and negative halves of each output-phase of the cycloconverter, in the form of embodiment shown in Fig. 10, I utilize three counters or counter-assemblies similar to that which is described in Fig. 1; the first counter-assembly being set to control the lengths of the positive and negative half-cycles of the first output-phase, while the second and third counter-assemblies are utilized to count off the proper number of steps for spacing the successive output-phases, as will be subsequently described in detail.

In the step-counting modulator-wave generator shown in Fig. 10, I also prefer to utilize an impulsing source which is energized from all three of the input-phases, so as to supply three times as many voltage-peaks or impulses as would be obtained from the single-phase peaking-transformer 15 of Fig. 1. Thus, in Fig. 10, I impulse the electronic counter by means of three peaking-transformers 61, having their secondaries connected in series with each other, and in series with tapped resistors 62. The primary windings of the three peaking-transformers 61 are energized from the different phases of the input-circuit 43, through a phase-shifter PH—S3, which makes it possible to properly adjust the timing of the voltage-impulses of the timer with respect to the input-voltage.

In Fig. 10, the counter-voltage is again supplied by means of a battery E1, which is illustrated as a 325-volt battery. Instead of utilizing a single pentode VT for controlling the energization of the two sets of serially connected capacitors C1, C2 and C'1, C'2, as in Fig. 1, my Fig. 10 circuit utilizes two pentodes VT and VT', which are energized from the same battery E1, through separate resistors 18 and 18', but which have their respective control-circuits 14 and 14' energized from separate taps 63 and 63' on the peaking-transformer resistors 62, so that the pentode VT responds to the positive peaks or voltage-impulses of the peaking-transformers 61, while the other pentode VT' responds to the negative peaks or voltage-impulses.

The anode-lead 16 of the positively responding pentode VT of Fig. 10 is utilized to energize two serially connected capacitors C1 and C2, having a duodiode D1 associated therewith in the same manner as the duodiode DD1 of Fig. 1. In the case of the negatively responding pentode VT', its anode-lead 16' energizes the serially connected capacitors C'1 and C'2, with the duodiode D4 asso-

clated therewith in the same manner as the duodiode DD2 of Fig. 1.

The two capacitors C₂ and C'₂ serve as stepped-voltage capacitors for controlling the gas tubes or valves T1 and T4 of the first counter-assembly in Fig. 10, these valves operating in the same manner as the valves GT1 and GT2 of Fig. 1, and being similarly energized from a battery E₂, which is illustrated, in Fig. 10, as being a 100-volt battery.

The same numerals are utilized, for the first counter-assembly, in Fig. 10, as in Fig. 1, with the exceptions noted, and also with the exception that the two output-circuits are numbered M1 and M4, instead of E_m and E'_m. This is because the two counted or measured square-wave circuits M1 and M4 of Fig. 10 are utilized to control the output half-cycles of the positive and negative tube-groups A1, A3, A5, and A4, A6, A2, of the first output-phase of the cycloconverter, and the numbers associated with the modulator or counter-circuits M1 and M4 are the numbers associated with two diametrically opposite vectors in a six-phase system of vectors.

In Fig. 10, the negative biasing-battery E₃ is indicated as a 50-volt battery. The negative-bias potentiometer 32 of the first counter-assembly is adjusted to cause the trigger-valves T1 and T4 to wait for the proper number of counts or voltage-steps for the correct determination of the desired length of each output half-cycle, in terms of a rectifier conducting-period of the cycloconverter, as will subsequently be explained more fully in connection with Fig. 5.

In Fig. 10, the anode-lead potentiometers 26 and 27 of the first counter-assembly are tapped, at 66 and 67 respectively, to control or release a second counter-assembly.

This second counter-assembly comprises two serially connected capacitors C₁ and C₂, and an associated duodiode D3, which I energize from the anode-lead 16, and two other serially connected capacitors C'₁, C'₂, and an associated duodiode D6, which I energize from the anode-lead 16'. The stepped-voltage capacitors C₂ and C'₂ of this second counter-assembly are utilized to energize two trigger-valves T3 and T6, having energizing and controlling circuits which are numbered the same as in the first counter-assembly, except that the output-circuits of the counter are numbered M3 and M6 respectively.

In addition to the equipment which comprises the first counter-assembly of Fig. 10, the second counter-assembly is provided with two vacuum triodes or valves V3 and V6, which are shunted across the control-circuits 25 and 25' of the trigger-valves T3 and T6 respectively. When either of these triodes V3 and V6 is cut off, its associated trigger-valve T3 and T6 responds, in the usual way, to the total voltage which is built up across its associated stepped-voltage capacitor C₂ and C'₂, as the case may be. However, when the grid of either triode V3 or V6 is positive, that triode keeps the control-circuit 25 or 25' of the associated trigger-valve T3 or T6 short-circuited, so that the step-voltage capacitor C₂ or C'₂, as the case may be, is also short-circuited, so that it does not build up its voltage.

The control-circuits of the triodes V3 and V6 of the second counter-assembly of Fig. 10 are controlled, from the square-topped output-voltage of the first counter-assembly, by means of the tapped points 66 and 67, respectively. Thus, for example, when the trigger-valve T1 of the first

counter-assembly is cut off, or non-conducting, its anode-lead potentiometer 26 supplies a small positive tapped-off voltage, at 66, to the grid of the triode V3, causing the latter to be conducting, and hence preventing the operation of the trigger-valve T3 of the second counter-assembly; but when the first valve, T1, is conducting, it short-circuits the portion of the potentiometer containing the tap 66, so that the triode V3 is no longer conducting, and the stepped-voltage capacitor C₂ of the second counter begins building up its voltage-increments which are applied to the control-circuit 25 of the trigger-valve T3.

If desired, the control-circuits of the triodes V3 and V6 may contain a negative grid-bias battery 68.

In Fig. 10, the second counter-assembly has its negative-bias potentiometer 32 adjusted to give the shield-grid circuit 31 a suitable bias so that the trigger-valves T3 and T6 each count the proper number of steps for spacing the second output-phase from the first output-phase, or a time-period which is equal to one-third of a complete output-cycle, or as close to that value as can be obtained with an integral number of counts.

In Fig. 10, there is a third counter-assembly, comprising the duodiodes D5 and D2, the trigger-valves T5 and T2, the triodes V5 and V2, and the output-circuits M5 and M2. Otherwise, the third counter-assembly is identical with the second counter-assembly, which has already been described. The third counter-assembly is controlled, or triggered off, by the tapped points 66 and 67 in the second counter-assembly, in the same manner in which the second counter-assembly is controlled or triggered off from the first counter-assembly. The setting of the negative-bias potentiometer 32 of the third counter-assembly is such as to provide the proper spacing, or output-phase-relation, between the second and third output-phases.

In Fig. 10, the six trigger-valves T1 to T6 of the three counter-assemblies are all energized from the same positive battery-bus 30 of the battery E₂, and this bus is connected to the common cathode-bus B' of the eighteen control-valves 53 which control the main valves 44 of the cycloconverter.

The six modulator-circuits M1 to M6 of the three counter-assemblies are each utilized to control the control-circuits 57 of three of the control-valves 53. Thus, the modulator-circuit M1 is connected to the secondaries of the three low-voltage peaking-transformers 59, which are associated with the positive tube-group A1, A3, A5 of the cycloconverter, namely the group which supplies the positive half-cycles of the first output-phase, A. It will be understood that the secondary of the proper high-voltage peaking-transformer 58 is serially connected with the proper secondary of a low-voltage peaking-transformer 59, and that the secondary of the high-voltage peaking-transformer is connected to the grid-circuit 57 of an individual one of the control-tubes 53.

In like manner, the modulator-circuit M4 services or controls the negative tube-group A4, A6, A2, which supplies the negative half-cycles of the output-voltage in the first output-phase, A. The modulator-circuits M3 and M6 similarly control the cycloconverter-tubes having the letter B, while the modulator-circuits M5 and M2 control the cycloconverter-tubes having the letter C.

The operation of the counter-controlled cycloconverter which is shown in Fig. 10 will be more readily understood with reference to the curve-diagrams of Figs. 5 to 8.

Fig. 5 shows the three sinusoidal voltage-waves of the three-phase input-circuit 43, the positive halves of the waves being marked E1, E3 and E5, respectively, and the negative half-waves being marked E4, E6 and E2, in accordance with the six-phase vector sequence, as previously explained. Assuming a unity-power-factor load, the rectifying periods of the cycloconverter-tubes which supply one of the output-phases, such as the tubes A1 to A6, are indicated by heavy lines in Fig. 5. It will be understood that the voltages E1, E3 and E5 are applied to the anodes of the positively connected rectifiers A1, A3, and A5, and that the voltages E4, E6 and E2 are applied to the cathodes of the negatively connected rectifiers A4, A6 and A2.

In the particular cycloconverter which has been chosen for illustration in Fig. 10, the cycloconverter-tube have three-phase rectifier-action, that is, each tube is theoretically capable of conducting for one-third of an input-frequency cycle, when operating as a rectifier. It is convenient to refer to the time-period between the crossing-points 70 of successive phases of the positive half-cycles of the input-voltages as one rectifier operating-period, as indicated in Fig. 5.

Fig. 6 shows the voltage-impulses which are supplied to the secondary circuit of the three peaking-transformers 61 which control the counters in Fig. 10. Thus, in Fig. 6, the positive voltage-peaks of the first phase of the peaking-transformers 61, may be indicated at 71, 72, etc., while the intervening negative voltage-peak is shown at 73. The first positive peak of the next phase would be 74, and the first positive peak of the third phase would be 75, as shown in Fig. 6. However, it is largely immaterial which phase of the input-voltages furnishes which one of the peaks, in Fig. 6. The really essential point is that there are a succession of positive peaks, 71, 74, 75, 72, etc., which are synchronized with the successive positive half-cycles of the voltage-waves, such as E1, E3, E5, E1, etc., of Fig. 5.

The precise phase-relations between the positive voltage-peaks 71, 74, 75, 72, etc., of Fig. 6, and the input-waves E1, E3, E5, E1, etc., of Fig. 5, may be adjusted by means of the phase-shifter PH-S3 of Fig. 10. In like manner, the negative voltage-peaks of Fig. 6 are properly phased and synchronized with respect to the negative voltage-waves of Fig. 5.

One advantage of the cycloconverter control-circuit of Fig. 10 is that it utilizes time-intervals, between the voltage-steps or increments of the counter, which are precisely and accurately synchronized with the successive input-waves, and which have an accurately fixed time-phase relation thereto, so that the pick-up points of the counters, or the square ends of the output modulator-waves of the counters, may be accurately timed with respect to the several voltage crossing-points 70, or the successive rectifier operating-periods, whatever they may be. These points are accurately determined, because the pentodes VT and VT' of the counter are controlled by the voltage-impulses of Fig. 6, with sufficiently large voltage-impulses to drive the pentodes all the way to saturation, very suddenly, so that the pentode-response is sharp and accurate; while the trigger-valves T1 to T6 of the counter are also

fired on very steep voltage-increments, as explained in connection with Fig. 2.

Figs. 7 and 8 respectively show the square-topped modulator-circuit voltages EM1 and EM4 of the output-circuits M1 and M4 of the first counter-assembly in Fig. 10, plotting these voltages with respect to the voltage E30 of the bus 30, which is also the common cathode-bus B' of the eighteen control-tubes 53.

Imposed upon these square-topped modulator-waves EM1 and EM4 of Figs. 7 and 8, are the rectification-initiating peak-voltages R1, R3, R5, and R4, R6, R2, of the first six low-voltage input-frequency peak-transformers 59, and the inverter-initiating peak-voltages I1, I3, I5, and I4, I6, I2, of the first six high-voltage input-frequency peaking-transformers 58 of Fig. 10. It must be understood that each rectifier or cycloconverter-tube receives only the voltage-peaks having the same number as the rectifier.

In Figs. 7 and 8, an exemplary critical response-voltage of the control-tubes 53 of Fig. 10 is indicated at E53. The intersections of this critical response-voltage with the various rectification-initiating peaks R1, etc., control the various firing-points 76, etc., for the rectifying actions of the several cycloconverter-tubes.

It will be noted, from the heavy-line output-voltage curve of Fig. 5, that the positive and negative output-voltage half-waves are exactly identical in wave-shape, both as to the number of rectifier operating-times which are contained in each output half-wave, and as to the input-frequency phase-angle at which each output half-wave commences, this being accurately synchronized with the input-frequency, by reason of the operation of the counter. The starting-point of each output half-phase may be controlled by the phase-adjustment of the phase-shifter PH-S3 of Fig. 10, and this starting-point may be made any point between two successive voltage crossing-points 70 in Fig. 5. This is true, of course, only for particular output-frequencies which correspond to an integral number of rectifier operating-times in each output half-cycle of each output-phase, as will be subsequently explained. In this way, my invention is unique, in accomplishing something which was impossible of accurate timing heretofore.

My invention is also utilizable, of course, to determine output-cycles which are not characterized by the same numbers and phase-relations of the input rectifier operating-times in each output half-cycle, in which case, as in previous cycloconverter systems, there will be some dissymmetry between successive output half-cycles.

The operation so far described has referred to the assumption of a unity-power-factor load, in which the load-current is in phase with the output-voltage. In case of an output power-factor other than unity, some of the cycloconverter-tubes will fail to have their anodes at a positive potential with respect to their cathodes, at their rectifier-firing moment, such as 77 in Fig. 7. In such a case, the previously firing cycloconverter-tube will continue to fire as a rectifier, if necessary to the end of the positive voltage half-wave, as at 78 in Fig. 5; and if further necessary, the tube will continue to fire on into the inverter operation of that tube, on the negative half-wave, as indicated at 79 in Fig. 5, until the out-of-phase load-current becomes zero, thus extinguishing the tube, or until the next tube receives an inverter-firing impulse,

as at 80 in Fig. 7, if the output-current is that much out of phase.

The counter-controlled cycloconverter which is shown in Fig. 10 can be utilized with any adjustments of the three count-controlling potentiometers 32, so as to determine the number of counter-steps in each output half-cycle, as determined by the first counter-assembly in Fig. 10, and also the number of counter-steps between successive output-phases, as determined by the last two counter-assemblies of Fig. 10. It is not essential that the total number of counter-steps in a complete output-cycle shall be exactly divisible by three, but if this total number of steps is not exactly divisible by three, then the successive output-phases will be neither uniform in magnitude nor uniform in the number of output-frequency cycles between successive output-phases.

If the count-adjustment of the first counter-assembly, in Fig. 10, is such as to count five impulse-timed steps, or six steps in all (including the first step which is not responsive to a control-impulse of Fig. 6), and if the count-adjustments of both the second and third counter-assemblies are for three impulse-timed steps, or four steps in all, a perfectly balanced three-phase output will be obtained. Thus, if the trigger-valve T4 of Fig. 10 fires at, or nearly at, the subsidence of the negative voltage-peak 81 of Fig. 6, as shown at 82 in Fig. 8, the firing of the trigger-valve T4, in Fig. 10, will extinguish the trigger-valve T1 and initiate a positive half-cycle of the modulator-wave E_{M1} in Fig. 7, as shown at 83. The trigger-valve T1 will thereupon count the next five positive voltage-peaks of Fig. 6, namely, the peaks 71, 74, 75, 72, and 84. At, or near, the subsidence of the fifth positive peak, 84, the trigger-valve T1 will fire, as indicated at 85 in Fig. 7, thereby extinguishing the trigger-valve T4 and initiating a positive half-cycle of the modulator-wave E_{M4} , as indicated at 86 in Fig. 8.

The positive half-cycle of the modulator-wave E_{M1} , from 83 to 85 in Fig. 7, determines the time during which the rectifier-initiating peaks R1, R3 and R5 may initiate the rectifier-operation of their respective cycloconverter-tubes. The inverter-operation of the tubes, under the control of the inverter-initiating peaks I1, I3 and I5, is independent of the magnitude of the modulator-voltage E_{M1} , because of the magnitude of the inverter-initiating peaks, as explained and claimed in the previously mentioned Boyer and Hagensick application.

It will be noted that the positive, or rectification-initiating, half-cycle of the modulator-wave E_{M1} in Fig. 7 is initiated at the termination of a negative counter-controlling voltage-peak 81, in Fig. 6, but that the time duration of this positive half-wave of modulator-voltage E_{M1} in Fig. 7 is determined by the counting of five positive voltage-peaks in Fig. 6. As shown in Fig. 6, the time-displacement between a negative counter-controlling peak 81 and the next positive counter-controlling peak 71 is sixty input-frequency degrees, or just one-half of the time-interval between two successive positive counter-controlling peaks, such as 71 and 74.

The alternation between a negative-peak control, and a positive-peak control, therefore results in the counting of a time-interval equal to a half-step less than the total number of positive-peak counts. Thus results, in the assumed case, in a rectification-initiating modulator-control of exactly four and a half impulse-controlled

counter-intervals. Since the counter-intervals are equal to the rectifier operating times, there are thus exactly four and a half rectifier operating-times in each half-cycle of the output-frequency, in Fig. 10. On this basis, a total output-cycle equals exactly nine counter-intervals, and the displacement between successive output-phases is therefore exactly three counter-intervals. In Fig. 8, if the point 82 is the firing-point for initiating the first output-phase, which may be designated A, the firing-points for initiating the other two output-phases would be as indicated, in dotted lines, at 87 and 88 in Fig. 8.

It will be noted, from Figs. 5 to 8, that the successive output-frequency rectification-permitting times, for both the positive and negative tube-groups of the cycloconverter, are always terminated at exactly the beginning of a rectifier operating-period of its own polarity. Thus, the positive-tube rectification-permitting output-frequency period is initiated at the point 83 in Fig. 7, which very quickly follows the point 82, in Fig. 8, which corresponds to the negative voltage-crossing point 82 in Fig. 5. This rectification-permitting output-frequency period terminates at the point 85 in Fig. 7, which corresponds exactly to the positive voltage-crossing point 85 in Fig. 5. This phase-coincidence is adjusted by means of the phase-shifter PH—S3 of Fig. 10. Any other phase-relationship could have been utilized, with obvious changes in the phase-positions of the four voltage-humps in each half-cycle of each output-phase.

Between the positive voltage-crossing point 85, after which no more cycloconverter-tubes of the positive group will be fired, in that output half-cycle, and the next negative voltage-crossing point 89, before which no cycloconverter-tube of the negative group could be fired, there is a time-interval of one-half of a rectifier operating-period, as shown in Fig. 5. This provides a time-interval in which the voltage E_1 can drop to zero, at 90 in Fig. 5, on the last positive-group rectifier which was fired in the output half-cycle in question. In this manner, a certain time-interval is provided, whereby the simultaneous rectifier-operations of positive and negative-group tubes may be avoided, as more particularly described and claimed in a Boyer and Hagensick application, Serial No. 739,724, filed April 5, 1947, and assigned to the Westinghouse Electric Corporation.

As previously intimated, it is possible, with my counter, to produce square-topped modulator-waves having shorter positive periods than negative periods, and in this manner, an interval longer than one-half of a rectifier operating-time may be provided, between the rectification-initiating firing of tubes in the positive and negative tube-groups, as described and claimed in the last-mentioned Boyer and Hagensick application.

Such a variation is shown in the counter-control modulator-wave generator which I have shown in Fig. 11.

Fig. 11 also shows a further variation in the counter-mechanism of Fig. 10, in regard to the impulsing of the counter. In Fig. 10, the counter was impulsed by a three-phase impulsing-system, and it was necessary to distinguish between the positive and negative impulses, in order to obtain the necessary half-step time-period. In Fig. 11, my counter is impulsed by a six-phase impulsing-system, which is obtained with three peaking-transformers 61', each having two secondary windings, which are connected to load-

ing resistors 91 through oppositely directed rectifiers 92 and 93 respectively. The two secondaries of each peaking-transformer 61' are connected in opposite polarity, and all six secondaries are connected in series with each other, and in series with the resistor 62, which is tapped, at 63, to control the pentode VT, only one pentode being utilized in the particular counter-system which is shown in Fig. 11.

In Fig. 11, there are six counter-assemblies, all energized from the anode-lead 16 of the same pentode VT. The first counter-assembly has two trigger-valves marked T1' and T1'', the second counter-assembly has two trigger-valves T3' and T3'', the third has T5' and T5'', the fourth has T4' and T4'', the fifth has T6' and T6'', and the sixth has T2' and T2''.

The first counter-assembly, having the trigger-tubes T1' and T1'' in Fig. 11, is similar to that which has been described in connection with Fig. 1, except that the screen-grid control-circuits for the two trigger-tubes are separated. The trigger-tube T1' has a screen-grid circuit 31' which is energized from the negative-bias potentiometer 32, as in Fig. 1; but the trigger-tube T1'' has a separate screen-grid circuit 31'', which is connected to the screen-grid circuit 31' through a potentiometer 94, which is energized from a separate negative biasing-battery 95, so that a predetermined, but adjustable, negative potential-difference may be maintained between the screen-grids of the two trigger-tubes. The result of this connection is that the trigger-tube T1' counts a smaller number of steps than the trigger-tube T1''. The steps counted by T1' are determined by the negative-bias potentiometer 32, and the number of additional steps counted by the trigger-tube T1'' is determined by the potentiometer 94. The anode-circuit of the trigger-tube T1' is utilized as the modulator-frequency output-circuit M1', corresponding to the output-circuit M1 of Fig. 10. The anode-circuit potentiometers 26 and 27 of the two trigger-tubes T1' and T1'' are tapped, at 66 and 67, to control the starting and stopping of the second and fourth counter-assemblies, as will be subsequently described.

The second counter-assembly, having the trigger-tubes T3' and T3'' in Fig. 11, is similar to the counter-assembly which is shown in Fig. 1, except for the addition of the tapped points 66 and 67, and the addition of the operation-controlling triodes V3' and V3'', which are associated with the respective trigger-tubes T3' and T3''. The grid-circuits of the counter-controlling triodes V3' and V3'' are energized from the tapped circuits 66 and 67 of the first counter, as shown. The two trigger-tubes T3' and T3'' of the second counter-assembly have a common screen-grid circuit 31, which is controlled by a negative-bias potentiometer 32 which is adjusted to count the proper number of cycles for the spacings between the output-phases. The anode-circuit of the trigger-tube T3' is utilized as the modulator-frequency output-circuit M3', corresponding to the output-circuit M3 of Fig. 10.

The third counter-assembly, having the trigger-tubes T5' and T5'' in Fig. 11, is similar to the counter-assembly of Fig. 1, except for the addition of the counter-controlling triodes V5' and V5'', which are controlled from the tapped circuits 66 and 67 of the second counter-assembly of Fig. 11. The anode-circuit of the trigger-valve T5' is utilized as the modulator-circuit out-

put lead M5', corresponding to the output-lead M5 of Fig. 10.

The fourth counter-assembly, having the trigger-tubes T4' and T4'' in Fig. 11, is similar to the second counter-assembly of Fig. 11. Its counter-controlling triode V4', which controls the trigger-valve T4', is energized from the tapped circuit 66 of the first counter-assembly of Fig. 11, so as to respond to the functioning of the first trigger-tube T1'. The counter-controlling triode V4'', which controls the other trigger-tube T4'' of the fourth counter-assembly, is controlled from the tapped point 67 of the first counter-assembly, so as to be responsive to the operation of the second trigger-tube T1'' of said first counter-assembly. The step-counting adjustment of the fourth counter-assembly is so adjusted, by means of the negative-bias potentiometer 32, that the trigger-tubes T4' and T4'' count the number of steps necessary for the spacing between the positive and negative half-cycles of the first output-phase, which I have designated as the A-phase. In other words, this timing is equal to one-half the total number of steps which make up a complete output-cycle. The anode-circuit of the trigger-tube T4' is utilized as the modulator-frequency output-lead M4', corresponding to the output-lead M4 of Fig. 10.

The fifth and sixth counter-assemblies of Fig. 11 are dependent upon the fourth counter-assembly, to provide the negative-tube modulator-waves of the output-phases B and C, in the same manner that the second and third counter-assemblies are dependent upon the first counter-assembly, to produce the positive-tube modulator-waves of the output-phases B and C. The anode-leads of the tubes T6' and T2' are utilized as the modulator-circuit output-leads M6' and M2', corresponding to the output-circuits M6 and M2 of Fig. 10.

The operation of the step-counting modulator-control of Fig. 11 will be understood from the foregoing explanations, and also by reference to Fig. 9, which shows the counter-controlling voltage-impulses which are applied to the pentode VT of Fig. 11. Although the assembly of Fig. 11 can be operated with any adjustment of the various count-controlling negative-bias potentiometers 32 or 94, it will be illustrated as if the counter-settings are so adjusted that the first trigger-valve T1' responds to 9 counts, thus measuring 8 time-intervals of the counter, while the second trigger-valve T1'' responds to 11 counts, or 10 time-intervals of the counter. This gives a total of 18 counter-intervals for a complete output-cycle. The trigger-valves T4' and T4'' respond, therefore, to 10 counter-steps, or 9 counter-intervals, so as to provide the correct timing for 180 output-frequency degrees. The other four trigger-valves of Fig. 11 each respond to 7 counter-steps, or 6 counter-intervals, to provide the correct spacings for 120 output-frequency degrees.

In Fig. 9, the first twenty counter-controlling voltage-peaks or impulses are shown, marked from 100 to 119. If the rectification-permitting modulator-frequency period, for the positive cycloconverter-tubes A1, A2, A3, serving the first output-phase, A, began near the end of the first impulse, 100, in Fig. 9, as shown by the point 120, then this rectification-permitting period would terminate near the end of the eighth impulse thereafter, namely the impulse 108, as indicated at 121. A rectification-blocking period will

then follow, for this same positive group of tubes, extending through the next ten impulses, or to a point 122, near the end of the impulse 118. The second and third counter-assemblies of Fig. 11 will then count off six steps from the point 120, yielding the point 123, and six more steps from the point 123, yielding the point 124, marking the beginnings of the modulator-frequency rectification-permitting periods for the positive tubes B1, B3, B5 and C1, C3, C5, which serve the second and third output-phases respectively. The fourth counter-assembly in Fig. 11 will measure off nine steps from the point 120, determining the point 125 at which there commences the rectification-permitting modulator-frequency period for the negative tube-group A4, A6, A2 which serves the first output-phase, A. The fifth counter-assembly of Fig. 11 will count six steps from the point 125 yielding the point 126, marking the beginning of the modulator-frequency rectification-permitting period of the negative tube-group B4, B6, B2. The last counter in Fig. 11 will measure off six more steps, not shown in Fig. 9.

The following additional general discussion is applicable to my invention. If we have a three-phase input-circuit, and if we obtain three positive counter-impulses and three negative counter-impulses during each input-cycle, as in Figs. 6 and 10, the time-intervals or steps between the positive impulses will be $\frac{1}{2}$ of an interval out of phase with the time-intervals or steps between the negative impulses. If we distinguish between the positive and negative impulses, as in Fig. 10, we have a counter-system which is capable of measuring or counting an integral number of steps or time-periods, if the measured period is terminated by an impulse of the same polarity as the initiating impulse; but if the measured period is terminated by counting impulses of a polarity opposite to the polarity of the impulse which initiated the measured period, then the number of steps or time-periods will be decreased by a half-step, or one-sixth of an input-cycle, or 60 input-frequency degrees.

If we derive a six-phase counter-controlling circuit from a three-phase input-circuit, and if we eliminate the negative impulses, as in Figs. 9 and 11, we still have a counter-system which is capable of determining a time-period or step which is one-sixth of an input-cycle, or 60 input-frequency degrees.

If we had derived a twelve-phase counter-controlling circuit from a three-phase input-circuit, still eliminating the negative impulses, we would have had a counter-system capable of determining a time-period or step which is one-twelfth of an input-cycle, or 30 input-frequency degrees. With an impinging-means or system in which each impulse is about 30 degrees in width, at its base, 30 cycles is about the smallest time-period which can be counted.

By using less than three phases for impinging the counter, as in Fig. 1, or by omitting the negative-impulse response, the counter could be made to respond to a smaller number of time-periods or counts, during each input-cycle.

In regard to the rectifier-operation, given a three-phase supply-circuit, it is possible, by suitable rectifier-connections, to obtain rectifier-operation having 2, 3, 4, 6, or even more, operating-times per input-cycle, defining an operating-time as the period between successive crossing-points of the positive voltage half-waves of the input-phases which are effectively applied to the several rectifiers.

These considerations are useful in determining the conditions under which a perfectly balanced three-phase output may be obtained, with exactly 120 output-frequency degrees between phases, and with exactly 180 output-frequency degrees between the beginnings of the positive and negative portions or half-cycles of each phase. One of the advantages of my invention is that both the positive and negative portions (or half-cycles) of each output-phase may be precisely timed so as to begin at the same phase-point of an input-frequency operating-period of a rectifier-tube, thereby obtaining exactly uniform output half-cycles, in all of the output-phases. It should be understood, of course, that, for many, or even most, applications, it may not be necessary to operate my invention with such refinement, because the output half-cycles are necessarily somewhat non-sinusoidal, so that there are harmonics present anyway, and frequently no great harm is caused by more or less departure from exact 120-degree output-phase relations, or by more or less inequality in magnitude, in the output-phases or in the output half-cycles, the harmful effects of which are only a slight increase in the heating of the output-circuit motor, and double-frequency torque-pulsations due to the single-phase power-component. Many motors are quite capable of operating satisfactorily with a rather considerable degree of unbalance, and with considerable harmonics in the voltage wave-form. This is particularly true of motors (not shown) having squirrel-cage windings or damper-windings.

However, it is useful, for some applications or load-circuits, to know the conditions for obtaining a perfectly balanced three-phase output, which is possible with my invention. There are two cases to be considered.

Case 1.—When there are an odd number (as 3) of rectifier operating-times per input-cycle, the rectifier operating-times of the positive group of tubes (or tubes operating on the positive half-cycles of the successive phases of input-voltage) are displaced from the operating-times of the negative tube-group, in each output-phase, by one-half of an operating-time, (paying no attention to which rectifier-phase is which, but simply noting the crossing-points of successive voltage-waves which are applied to the positive and negative tube-groups, respectively). Hence a complete output-cycle includes an odd number, say $(2n+1)$, of operating periods, so that 180 output-frequency degrees equals $(n+\frac{1}{2})$ operating-periods, where n is an integer, subsequently to be defined more definitely. The counters will count or measure m timed intervals, which we will call steps, for each output-frequency rectifying-permitting period, and $(m+d)$ steps for each output-frequency rectifying-blocking period, and p steps for the time-lags between the output-phases, where d and p are integers, and m is either an integer or an integer plus $\frac{1}{2}$, as has previously been explained. These integers will subsequently be defined more definitely.

The number of operating-periods in one output-cycle is

$$2n+1 = \frac{2m+d}{c} = \frac{3p}{c} \quad (1)$$

where c is the ratio of the length of a rectifier operating-time to the length of the step or time-period between impulses of one polarity, which is measured or counted by the counter.

An important example is where three-phase impulses are applied to the counter, and where three-phase rectifier-operation is obtained, as in Fig. 10. Under these conditions, Equation 1 is satisfied by the following constants:

$c=1$ =the number of counter-periods per rectifier operating-time

k =any integer greater than zero

$p=2k-1=1, 3, 5, 7, 9, 11$, etc.

$n=3k-2=1, 4, 7, 10, 13, 16$, etc.

$$m=3k-\frac{3+d}{2}=(3, 6, 9, 12, 15, 18, \text{etc.})-\frac{3+d}{2}$$

d =any positive integer (including zero), which will make the measured count, m , greater than zero.

Thus, in Fig. 10, if we choose k to equal 2, and ($d=0$) difference between the rectification-permitting and rectification-blocking output-frequency periods, we will have ($p=3$) counter-intervals between successive output-phases, and ($2n+1=9$) rectifier operating-times for a complete output-cycle, and ($m=4$ and $\frac{1}{2}$) counter-periods per output half-cycle.

Another important example is where a six-phase counter-controlling circuit is used, as in Fig. 11, and where the counter is used with a three-phase rectifier of the type shown in Fig. 10. Under these conditions, Equation 1 is satisfied by the following constants:

$c'=2$ =the number of counter-periods per rectifier operating-time

k' =any integer greater than zero

$p'=4k'-2=2, 6, 10, 14, 18, 22$, etc.

$n'=3k'-2=1, 4, 7, 10, 13, 16$, etc.

$$m'=(6k'-3)-\frac{d'}{2}=(3, 9, 15, 21, 27, 33, \text{etc.})-\frac{d'}{2}$$

d' =any even number (including 0), which will make the measured count, m' , greater than zero.

Thus, in Fig. 11, if we choose k' to equal 2, and ($d'=2$) counter-intervals for the difference between the rectification-blocking and rectification-permitting output-frequency periods, we will have ($p'=6$) counter-intervals, or 3 rectifier operating-times, between successive output-phases; and ($3n'=18$) counter-intervals or ($2n'+1=9$) rectifier operating-times for a complete output-cycle; and ($m'=8$) counter-intervals for each rectification-permitting output-frequency period; and

$$(m'+d'=10)$$

counter-intervals for each rectification-blocking output-frequency period; and ($18/2=9$) counter-intervals between the beginnings of the rectification-permitting square-wave half-cycles of the positive and negative tube-groups of any output-phase.

Case 2.—When there were an even number (as 2, 4 or 6) of rectifier operating-times per input-cycle, the operating-times of the positive and negative tube-groups would be in phase with each other (paying no attention to which rectifier-phase is which, but simply noting the crossing-points of successive voltage-waves which are applied to the positive and negative tube-groups, respectively). Hence a complete output-cycle would include an even number, say $2N$, of operating-periods, so that 180 output-frequency degrees equals N operating-periods, where N is an integer, subsequently to be defined more definitely. The counters would count or measure M steps or counter-intervals for each output-frequency rectifying-permitting period, ($M+D$) steps for each output-frequency rectifying-blocking period, and P steps for the time-lags be-

tween the output-phases, where D and P are integers, and M is either an integer or an integer plus $\frac{1}{2}$, as has previously been explained. These integers will be defined more definitely.

5 The number of operating-periods in one output cycle is

$$2N=\frac{2M+D}{C}=\frac{3P}{C} \quad (2)$$

10 where C is the ratio of the length of a rectifier operating-time to the length of the step or time-period between impulses of one polarity, which is measured or counted by the counter.

15 An example would be where three-phase impulses are applied to the counter, and where the rectifiers have six-phase operation. Under these conditions, Equation 2 would be satisfied by the following constants:

$C=\frac{1}{2}$ =the number of counter-periods per rectifier operating-time

20 P =any integer greater than zero=1, 2, 3, 4, 5, 6, etc.
 $N=3P=3, 6, 9, 12, 15, 18$, etc.

$$M=\frac{3P}{2}-\frac{D}{2}=\left(\frac{3}{2}, 3, \frac{9}{2}, 6, \frac{15}{2}, 9, \text{etc.}\right)-\frac{D}{2}$$

25 D =any positive integer (including zero), which will make the measured count, M , greater than zero.

Thus, if we should choose ($P=5$) counter-intervals, or ($5 \times 2=10$) rectifier operating-times, between successive output-phases, and ($D=2$) counter-intervals, or ($2 \times 2=4$) rectifier operating-times, for the difference between the rectification-blocking and rectification-permitting output-frequency periods, we would have ($3P=15$) counter-intervals, or ($2N=6P=30$) rectifier operating-times, for a complete output-cycle; and ($M=6$ and $\frac{1}{2}$) counter-intervals, or 13 rectifier operating-times, for each rectification-permitting output-frequency period; and ($M+D=8$ and $\frac{1}{2}$) counter-intervals, or 17 rectifier operating-times, for each rectification-blocking output-frequency period; and ($15/2=7$ and $\frac{1}{2}$) counter-intervals between the beginnings of the rectification-permitting square-wave half-cycles of the positive and negative tube-groups of any output-phase.

Another example would be where six-phase impulses are applied to the counter, and where the rectifiers have six-phase operation. Under these conditions, Equation 2 is satisfied by the following constants:

50 $C'=1$ =the number of counter-periods per rectifier operating-time

K' =any integer greater than zero

$P'=2K'=2, 4, 6, 8, 10, 12$, etc.

55 $N'=3K'=3, 6, 9, 12, 15, 18$, etc.

$$M'=3K'-\frac{D'}{2}=(3, 6, 9, 12, 15, 18, \text{etc.})-\frac{D'}{2}$$

D' =any even number (including 0), which will make the measured count, M' , greater than zero.

60 Thus, if we should choose K' to equal 4; and ($D'=2$) counter-intervals (or rectifier operating-times) for the difference between the rectification-blocking and rectification-permitting output-frequency periods, we would have ($P'=8$) counter-intervals (or rectifier operating-times) between successive output-phases; and ($3P'=24$) counter-intervals, or ($2N'=24$) rectifier operating-times, for a complete output-cycle; and ($M'=11$) counter-intervals (or rectifier operating-times) for each rectification-permitting output-frequency period; and ($M'+D'=13$) counter-intervals (or rectifier operating-times) for each rectification-blocking output-frequency period; and ($24/2=12$) counter-intervals between the beginnings of the rectification-permitting

square-wave half-cycles of the positive and negative tube-groups of any output-phase.

While I have shown certain specific forms of embodiment of my invention, and have described its mode of operation in accordance with my present understanding, I wish it to be understood that my invention is not limited to the specific forms of illustration, or to the specific examples, or to my present understanding thereof; as many changes of omission, addition, and substitution of equivalents, may be made, by those skilled in the art, without departing from the essential spirit of my invention, particularly in its broader aspects. I desire, therefore, that the appended claims shall be accorded the broadest construction consistent with their language.

I claim as my invention:

1. An impulse-counting timer-assembly, comprising a pair of serially connected capacitors, one capacitor being considerably larger than the other; a unidirectional voltage-source for charging said capacitors; a charging rectifier in series with the larger one of said serially connected capacitors; a discharging rectifier in shunt around both said charging rectifier and said large capacitor; electro-responsive control-means for, in effect, periodically alternately establishing, and substantially opening, a discharging-circuit for said smaller capacitor, said discharging-circuit including said discharging rectifier; a source of counter-controlling voltage-peaks for controlling said electro-responsive control-means; and an electro-responsive controlled device which is responsive to the total accumulated voltage of said larger capacitor.

2. An electronically timed square-wave generator, comprising a pair of trigger-tubes of the sustained-discharge type; means for unidirectionally energizing the anode-cathode circuits of said trigger-tubes; the anode-cathode circuit of at least one of said trigger-tubes including a means containing resistance, and output-leads associated with said resistance-means, for supplying an output-voltage having a magnitude which is responsive to the firing or non-firing of said trigger-tube; a commutating capacitor so interconnected between the anode-cathode circuits of the two trigger-tubes as to extinguish one trigger-tube when the other trigger-tube fires; a separate pair of serially connected capacitors associated with each one of said trigger-tubes, one capacitor of each pair being very much the larger; means for connecting the larger capacitor across the control-circuit of the associated trigger-tube; a unidirectional voltage-source for charging both pairs of serially connected capacitors; a charging rectifier in series with each of the larger capacitors of said pairs; a discharging rectifier in shunt around both the charging rectifier and the larger capacitor of each pair; electro-responsive means for, in effect, periodically alternately establishing, and substantially opening, a discharging-circuit for each of the smaller capacitors of said pairs, each discharging-circuit including the associated discharging rectifier; and a source of counter-controlling voltage-peaks for controlling said electro-responsive control-means.

3. A step-counting timer-assembly, comprising a step-measuring capacitor; means for applying, to said step-measuring capacitor, a succession of timed, discrete voltage-increments of the same polarity; and an electro-responsive controlled device which is responsive to the total accumulated voltage of said step-measuring capacitor, the critical response-voltage of said

controlled device being such as to fall in some intermediate portion of the final step to which the controlled device responds.

4. A synchronized timer, comprising the combination, with an alternating-current input-circuit, of a step-measuring capacitor; electro-responsive control-means, responsive to the alternations of said input-circuit, for applying, to said step-measuring capacitor, a succession of timed, discrete voltage-increments of the same polarity; and an electro-responsive controlled device which is responsive to the total accumulated voltage of said step-measuring capacitor, the critical response-voltage of said controlled device being such as to fall in some intermediate portion of the final step to which the controlled device responds.

5. A counter-controlled inverter-rectifier assembly comprising a plurality of rectifier-tubes of the sustained-discharge type; an input-circuit associated therewith; an alternating-current output-circuit associated therewith; and a plurality of step-counting timer-assemblies for determining the times of operation and non-operation of the rectifier-tubes, and thus determining the frequency and the phase-positions of the output-circuit; each step-measuring timer-assembly comprising a step-measuring capacitor; means for applying, to all of the step-measuring capacitors, a succession of timed, discrete voltage-increments of the same polarity; and a separate electro-responsive controlled device which is responsive to the total accumulated voltage of each step-measuring capacitor, the critical response-voltage of each controlled device being such as to fall in some intermediate portion of the final step to which the controlled device responds.

6. A counter-controlled electronic frequency-changer assembly, comprising an alternating-current input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to the alternations of said input-circuit, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, responsive to said counter-controlling impulses, for also controlling said rectifier-tubes.

7. A counter-controlled electronic frequency-changer assembly, comprising an alternating-current input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to the alternations of said input-circuit, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of output-frequency square-wave generators, each square-wave generator comprising step-counting means, responsive to said counter-controlling impulses, for alternately raising and lowering a control-voltage of said rectifier-tubes.

8. A counter-controlled electronic frequency-changer assembly, comprising an alternating-

current input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to the alternations of said input-circuit, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, responsive to said counter-controlling impulses, for so controlling said rectifier-tubes that each half-wave of the output can be adjusted so as to have the same number of rectifier conducting-periods, in the same phase-relation to the input, defining a rectifier conducting-period as the time-interval between successive crossing-points of the voltage half-waves of the input-phases which are effectively applied to the several rectifier-tubes.

9. A synchronized timer comprising the combination, with a three-phase input-circuit, of means for obtaining a positive counter-controlling impulse and a negative counter-controlling impulse for each cycle of each phase of the input-circuit, in timed, predetermined phase-relation thereto; circuit-means for combining said counter-controlling impulses in a single circuit; counter-means for selectively responding to a predetermined integral number of counts of said positive counter-controlling impulses; and counter-means for selectively responding to a predetermined integral number of counts of said negative counter-controlling impulses.

10. A synchronized timer comprising the combination, with a three-phase input-circuit, of means for obtaining two timed, discrete, positive counter-controlling impulses from each cycle of each phase of the input-circuit; circuit-means for combining said counter-controlling impulses in a single circuit; and counter-means for responding to a predetermined integral number of counts of said counter-controlling impulses.

11. A counter-controlled electronic frequency-changer assembly, comprising a polyphase input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to all of the input-phases, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, responsive to said counter-controlling impulses, for also controlling said rectifier-tubes.

12. A counter-controlled electronic frequency-changer assembly, comprising a polyphase input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to all of the input-phases, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of output-frequency square-wave generators,

each square-wave generator comprising step-counting means, responsive to said counter-controlling impulses, for alternately raising and lowering a control-voltage of said rectifier-tubes.

13. A counter-controlled electronic frequency-changer assembly, comprising a polyphase input-circuit; an alternating-current output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to all of the input-phases, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, responsive to said counter-controlling impulses, for so controlling said rectifier-tubes that each half-wave of the output can be adjusted so as to have the same number of rectifier conducting-periods, in the same phase-relation to the input, defining a rectifier conducting-period as the time-interval between successive crossing-points of the voltage half-waves of the input-phases which are effectively applied to the several rectifier-tubes.

14. The combination, with a three-phase input-circuit, of an electronically timed square-wave generator, comprising a pair of trigger-tubes of the sustained-discharge type; means for unidirectionally energizing the anode-cathode circuits of said trigger-tubes; the anode-cathode circuit of at least one of said trigger-tubes including a means containing resistance, and output-leads associated with said resistance-means, for supplying an output-voltage having a magnitude which is responsive to the firing or non-firing of said trigger-tube; a commutating capacitor so interconnected between the anode-cathode circuits of the two trigger-tubes as to extinguish one trigger-tube when the other trigger-tube fires; a separate pair of serially connected capacitors associated with each one of said trigger-tubes, one capacitor of each pair being very much the larger; means for connecting the larger capacitor across the control-circuit of the associated trigger-tube; a unidirectional voltage-source for charging both pairs of serially connected capacitors; a charging rectifier in series with each of the larger capacitors of said pairs; a discharging rectifier in shunt around both the charging rectifier and the larger capacitor of each pair; means for obtaining a positive counter-controlling impulse and a negative counter-controlling impulse from each cycle of each phase of the input-circuit, in timed, predetermined phase-relation thereto; circuit-means for combining said counter-controlling impulses in a single circuit; electro-responsive means, selectively responsive to said positive counter-controlling impulses, for, in effect, periodically alternately establishing, and substantially opening, a discharging-circuit for the smaller capacitor of one of said pairs; and electro-responsive means, selectively responsive to said negative counter-controlling impulses, for, in effect, periodically alternately establishing, and substantially opening, a discharging-circuit for the smaller capacitor of the other one of said pairs; each discharging-circuit including the associated discharging rectifier.

15. A counter-controlled, polyphase, electronic frequency-changer assembly, comprising a polyphase input-circuit; a polyphase output-circuit;

a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to all of the input-phases, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, each responsive to said counter-controlling impulses, one of said timer-assemblies counting the same number of impulse-counts for controlling the durations of the rectification-permitting periods of both the positively and negatively connected groups of the rectifier-tubes associated with one of the output-phases; and the other timer-assemblies counting the number of impulse-counts for spacing the successive output-phases.

16. A counter-controlled, polyphase, electronic frequency-changer assembly, comprising a polyphase input-circuit; a polyphase output-circuit; a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to all of the input-phases, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising a plurality of input-frequency tube-controlling means, and a plurality of step-counting timer-assemblies, each responsive to said counter-controlling impulses, one of said timer-assemblies counting a predetermined number of impulse-counts for controlling the duration of the output-frequency rectification-permitting period of one of the tube-groups of the pair of positively and negatively connected tube-groups which are associated with a first one of the output-phases; another timer-assembly counting a larger number of impulse-counts for controlling the duration of the output-frequency rectification-blocking period of the same tube-group; two other timer-assemblies counting the proper number of impulse-counts for spacing the rectification-permitting and rectification-blocking periods of the other one of the tube-groups of said pair of positively and negatively connected tube-groups which are associated with said first output-phase; and the remaining counter-assemblies counting the proper number of impulse-counts for spacing the successive output-phases.

17. A cycloconverter for converting from an

input-circuit of one frequency to an output-circuit of a lower frequency, comprising a plurality of positively and negatively connected groups of rectifier-tubes of the sustained-discharge type, for interchanging power between said input and output circuits; electro-responsive control-means, responsive to the alternations of said input-circuit, for producing a succession of timed, discrete counter-controlling impulses; and tube-controlling means, associated with said rectifier-tubes, and comprising means for supplying relatively low-voltage input-frequency rectifier-firing peaks to the control-circuits of the several rectifier-tubes, means for supplying relatively higher-voltage input-frequency inverter-firing peaks to the control-circuits of the several rectifier-tubes, and a plurality of square-wave generators for supplying substantially square-topped output-frequency waves to the control-circuits of the several groups of rectifier-tubes, for alternately permitting and blocking the rectifier-firings, while always permitting the inverter-firings, at least one of said square-wave generators comprising: a pair of trigger-tubes of the sustained-discharge type; means for unidirectionally energizing the anode-cathode circuits of said trigger-tubes; the anode-cathode circuit of at least one of said trigger-tubes including a means containing resistance, and output-leads associated with said resistance-means, for supplying an output-voltage having a magnitude which is responsive to the firing or non-firing of said trigger-tube; a commutating capacitor so interconnected between the anode-cathode circuits of the two trigger-tubes as to extinguish one trigger-tube when the other trigger-tube fires; a separate pair of serially connected capacitors associated with each one of said trigger-tubes, one capacitor of each pair being very much the larger; means for connecting the larger capacitor across the control-circuit of the associated trigger-tube; a unidirectional voltage-source for charging both pairs of serially connected capacitors; a charging rectifier in series with each of the larger capacitors of said pairs; a discharging rectifier in shunt around both the charging rectifier and the larger capacitor of each pair; and electro-responsive means, responsive to the discrete counter-controlling impulses, for, in effect, periodically alternately establishing, and substantially opening, a discharging-circuit for each of the smaller capacitors of said pairs, each discharging-circuit including the associated discharging rectifier.

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