

March 21, 1961

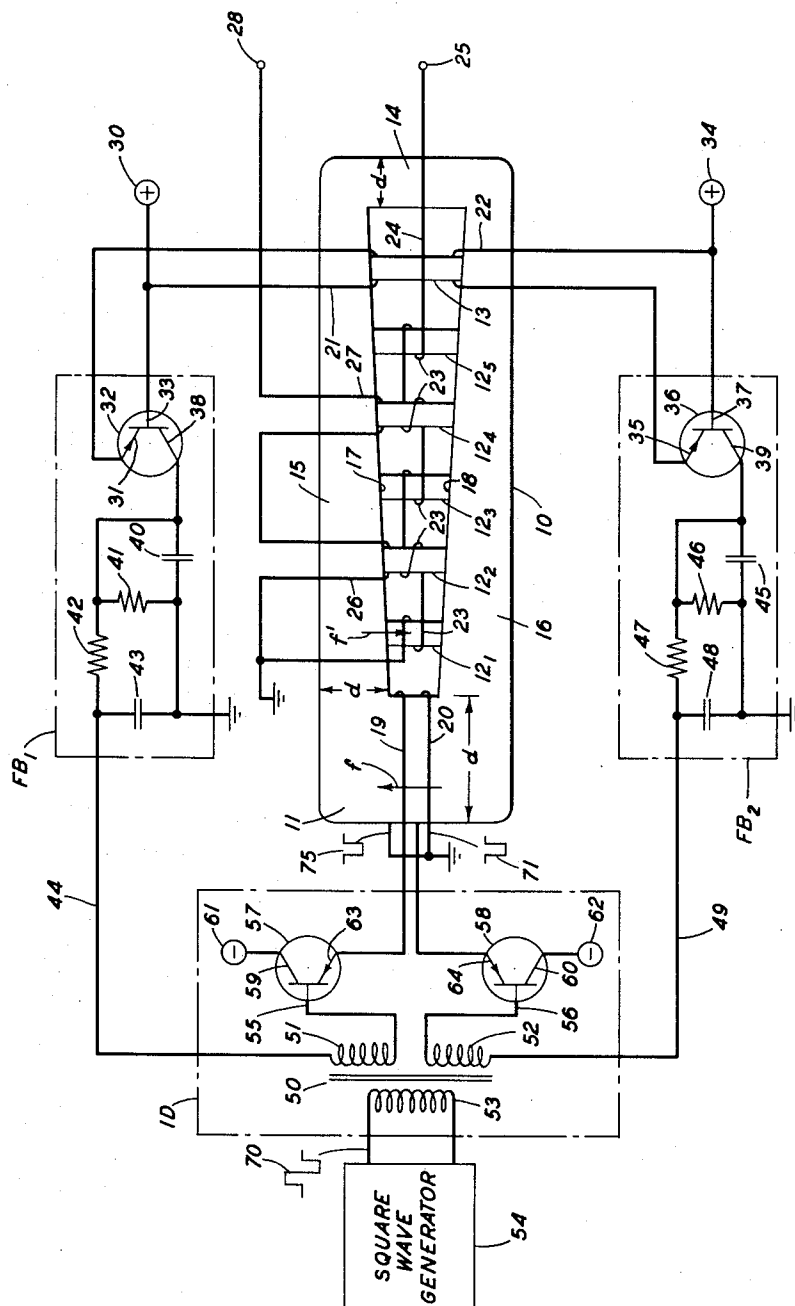
E. E. NEWHALL ET AL
MAGNETIC CONTROL CIRCUITS

2,976,472

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3 Sheets-Sheet 1

FIG. 1



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3 Sheets-Sheet 2

FIG. 2A

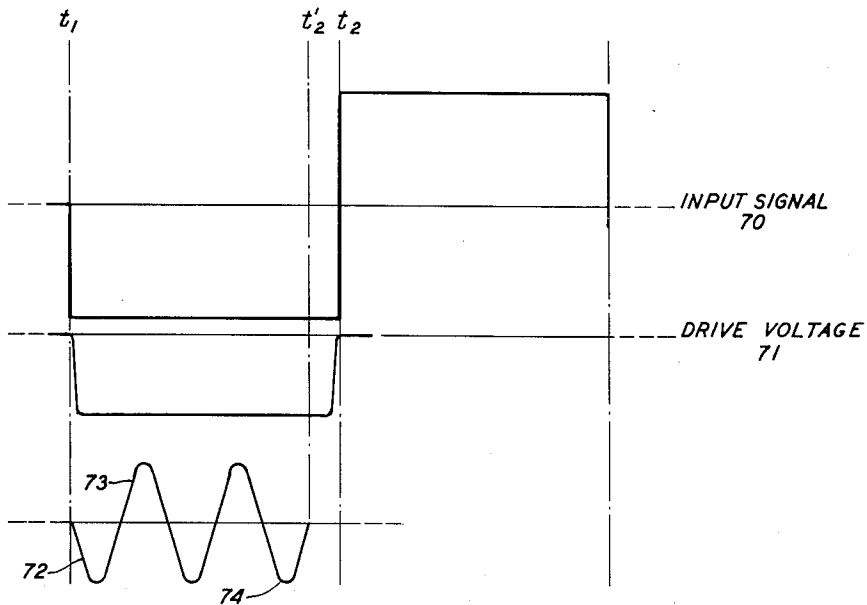
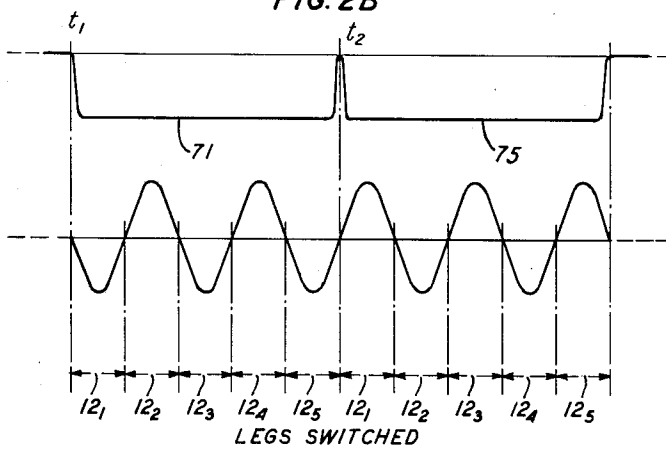


FIG. 2B



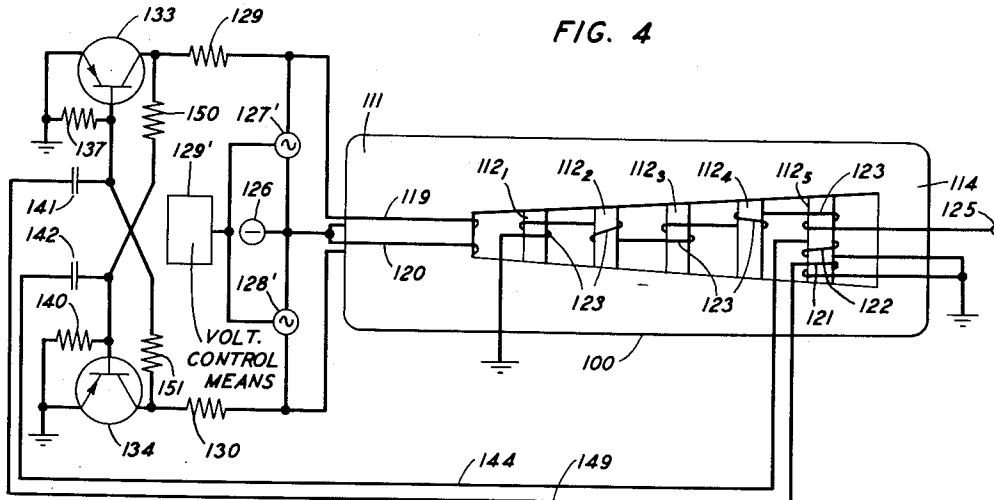
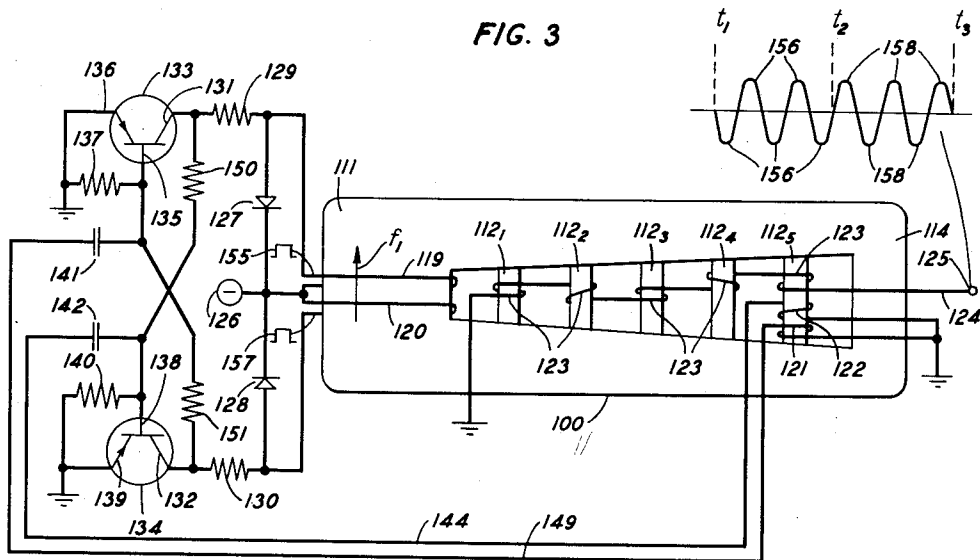
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3 Sheets-Sheet 3



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2,976,472

MAGNETIC CONTROL CIRCUITS

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17 Claims. (Cl. 332—12)

This invention relates to electrical frequency generating circuits and more particularly to such circuits in which the flux switching properties of multi-apertured magnetic structures are utilized to provide the basic frequency control means.

Electrical frequency generating circuits capable of providing a periodic output signal or signals of a predetermined frequency are well known in the electrical arts. Oscillators, pulse generators, frequency multipliers, and the like, have been represented in the art in various and numerous forms and examples of each type capable of performing specific frequency control functions are readily envisioned by one skilled in the art. With the introduction of ferrite magnetic cores of the conventional toroidal type which display substantially rectangular hysteresis characteristics, advances in the frequency control art have been made possible. Thus, in terms of power requirements, reliability, and general circuit simplicity magnetic cores have made possible advantages in this art not hitherto available in analogous circuits employing vacuum tubes for current switching purposes. More recently the principles of magnetic flux switching based on the substantially rectangular hysteresis loop manifested by certain ferrite materials have been extended to more complex structures presenting a plurality of flux switching paths. A wide range of signal control functions are possible by the use of such magnetic structures and all of the switching and signal control operations are performed within the confines of a single integrated magnetic element.

One such element is described, for example, by E. E. Newhall in the copending application Serial No. 818,130, filed June 4, 1959, and comprises a magnetic structure in which flux is propagated in discrete steps through successive flux paths presented by the structure.

By suitably controlling the application of a drive voltage applied to a common drive leg of the structure, magnetic flux may be induced in the latter leg which flux is successively closed through a succession of isolated flux legs as the drive voltage is periodically interrupted. The succession of flux legs of the structure is arranged to present flux paths of progressively increasing lengths and the successive flux closures through the flux legs are based on the well known magnetic principle that an induced flux will be closed through the shortest available closure path without regard to the magnitude of the applied drive. By coupling an output winding to each of the flux legs, successive signals generated by the flux closures through the legs may be used to control the interruption of the applied drive. This principle of operation is advantageously utilized to achieve sequentially operating switches specifically embodied in counting circuits, pulse code conversion circuits, and the like, described in the aforementioned copending application.

It will be appreciated that, in a magnetic element such as generally described in the foregoing, the successive flux switching will also occur if the drive is applied to the common leg of the element without interruption

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until the last and longest flux path of the element is saturated. By employing a feedback from the individually flux saturating legs periodically to interrupt the drive, specific and advantageous control operations are made possible. In accordance with the principles of the present invention, the successive propagation of flux in a multi-apertured magnetic element presenting a succession of flux legs as the result of an uninterrupted drive is contemplated.

It is an object of the present invention to achieve a new and novel frequency generator circuit by applying the principles of flux propagation in discrete steps in magnetic structures.

Another object of this invention is to provide a new and improved frequency multiplier circuit.

A further object of this invention is to provide new and novel frequency control circuits employing multi-apertured magnetic elements as switching elements.

Yet another object of this invention is to generate a continuous series of output pulses by the successive and continuous propagation of flux in discrete steps in a multi-apertured magnetic switching element.

Still another object of this invention is to simplify and improve the reliability of frequency control circuits.

The foregoing and other objects of this invention are realized in one specific frequency multiplier circuit comprising a multi-apertured magnetic element which presents a plurality of isolated flux switching legs and a single common drive leg. Flux paths through the flux switching legs thus share a common drive leg as a closure path. A periodic square wave input signal of a constant predetermined frequency is applied to a first drive winding inductively coupled to the common drive leg in one sense. Assuming that, as a result of a previous cycle of operation, the drive leg is flux saturated in one direction and each of the flux switching legs is consequently saturated in the opposite direction, then the flux switching legs will begin to switch successively as the input drive signal is applied to the drive winding. The switching legs will switch in the order as determined by their respective distances from the drive leg. To each of the switching legs is coupled an output winding, the output windings being connected in a series output circuit in alternating senses. As a result of the successive flux switching in the same direction in the switching legs, output signals of alternating polarity will be induced in the output circuit. The magnetic structure and its number of switching legs is so arranged that the input drive signal is transferred to a second drive winding coupled to the drive leg in the opposite sense just as a last switching leg of the structure completes its flux switching. The latter control is advantageously achieved by generating an error control signal as a result of flux switching in an added control leg of the switching structure. This error control signal is then employed to control the associated drive circuitry such that the amplitude of the input drive signal is just sufficient to switch completely a last switching leg of the switching structure. This operation is thus completely in accord with the principles stated previously herein with respect to the relation of the magnitude of the applied drive signal and the preferential flux switching of the shortest available path.

By establishing an odd number n of switching legs to which output windings are coupled, a continuous alternating output may be generated in output circuit, which output will be a multiple n of the frequency of the input drive signal. The continuity of output is advantageously obtained since, as the last of the n switching legs has its flux switched therein, the drive signal is transferred to the second drive winding to repeat the successive flux switching process but in the opposite direction. The out-

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put alternations induced in the output circuit, as a result continue without interruption with the first of the alternations in the new cycle of flux switching being opposite in polarity to that of the last alternation of the previous flux switching cycle. In this specific circuit, in addition to the output signals generated for external use, an additional signal is generated to control the volt-second area of the input drive signal; the frequency of the latter signal being held constant as its amplitude is varied in accordance with any variations in the total drive required to complete flux switching of the n th switching leg of the element substantially at the time that the input signal is transferred to the second drive winding. In accordance with this specific embodiment of the present invention the frequency multiplying factor is advantageously determinable by the number of switching legs in the switching structure.

In another specific circuit embodying the principles of this invention, the volt-second area of a periodic input drive signal is also varied. However, in this case the amplitude of the input drive signal is held constant while the frequency is modified in accordance with the timing of flux switching in the n th leg of the switching element. In this mode of practicing this invention an illustrative pulse generator circuit may be advantageously realized. In this circuit a multi-apertured magnetic element again presents a succession of flux switching legs which share a common flux closure path through a common drive leg. A periodic input drive signal of constant amplitude is applied to a first drive winding coupled to the drive leg. As a result, a switching flux in one direction is successively induced in the flux switching legs. However, in this case, the magnitude of the input drive signal is adjusted so as to switch completely the last or n th switching leg of the element.

To each of the switching legs of the element is again coupled an output winding, the output windings again being connected in a series output circuit in alternating senses. As a result of the successive flux switching in the same direction in the switching legs, output signals of alternating polarity are again induced in the output circuit of this embodiment. In this case, the amplitude of the input signal which is held constant, determines the number of flux switching legs through which successive flux closures are to be had and hence the frequency of the generated pulses.

A control signal is also generated by the flux closure in a last leg of the element, which control signal is employed to effect the transfer of the input drive current from the first drive winding to a second drive winding coupled to the drive leg of the element in the opposite sense. The flux closure cycle of the switching element is then repeated to continue the generation of output pulses in an unbroken sequence. Since the amplitude of each input drive signal determines the output frequency of the generator, the latter frequency may be advantageously modulated by amplitude modulating the input drive signal. The circuit may thus be used to generate a number of frequency modulated output signals of different carrier frequency. The amplitude modulation may be accomplished by voice currents, for example, to generate the frequency modulated output signals. Highly useful and reliable frequency control circuits may thus be realized in accordance with the principles of this invention, which circuits are economical to construct and, due to their low power requirements, are also economical to operate.

It is a feature of this invention that a multi-apertured magnetic element presents a sequence of flux switching legs within which legs a switching flux is successively closed in one direction in discrete steps responsive to an input drive voltage. The frequency of the drive voltage is held constant with the result that the amplitude of the drive voltage determines the number of switching legs through which the switching flux is closed. By generating an error control signal in an output winding on

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a final control leg of the element, input drive circuitry is controlled thereby to exercise a constant variable control over the amplitude of the drive voltage. The amplitude of the drive voltage is thus automatically adjusted so that a last switching leg of the element is completely flux saturated as the input drive voltage is applied to a second drive winding to cause successive flux closures in the switching legs in the opposite direction.

It is another feature of this invention that serially connected output windings are coupled to an odd number of switching legs of a multi-apertured magnetic element such that a continuous sequence of alternating output signals are a predetermined multiple of the frequency of an input drive current. The frequency of the output signals is generated, which output signals are a predetermined multiple of the frequency of an input drive current. The frequency of the output signals generated is maintained at a constant multiple of the frequency of the input drive voltage by adjusting the volt-second area of the latter signal, the frequency of which is held constant. According to a further feature of this invention the latter adjustment is accomplished responsive to an error control signal generated when other than the required odd number of flux switching legs are successively flux saturated by the input drive voltage.

According to another aspect of this invention it is a feature thereof that a sequence of flux switching legs in a multi-apertured magnetic element has a switching flux induced therein in successive steps responsive to a drive voltage the amplitude of which is maintained constant. In accordance with known principles of flux propagation in magnetic structures, a predetermined number of the switching legs may be flux saturated by the fixed amplitude of a drive signal. A control signal generated by flux closure through a control leg following the switching legs of the element is then used to adjust the volt-second area of the input drive current such that the latter current is transferred to a second drive winding as the last of the switching legs has a switching flux closed therethrough. Thus, in accordance with this feature, the amplitude of the input drive is maintained constant while the frequency is continuously variable as determined by the rate at which the sequence of switching legs is successively saturated.

It is still another feature of this invention that serially connected output windings are coupled in alternating senses to the switching legs of a multi-apertured magnetic element as described in the foregoing paragraph. As the switching legs are successively flux saturated in one direction by a fixed amplitude input drive voltage, output signals of alternating polarity are generated which bear a fixed relationship to the frequency of the input drive voltage. When the last of the switching legs is flux saturated, transfer to a second drive winding of the input drive voltage is controlled to successively flux saturate the switching legs in the opposite direction. An unbroken sequence of alternating output signals is thus achieved.

According to yet another feature of this invention, the output frequency of a frequency generating arrangement is frequency modulated by also adjusting the amplitude of the variable frequency input drive current in accordance with voice currents, for example.

A further feature of this invention is a progressive increase in the lengths of the flux switching legs to achieve a greater differential in flux path lengths in magnetic elements adapted to have a magnetic flux induced therein in successive discrete steps.

A still further feature of this invention is a flux guard leg provided in a multi-apertured magnetic element which guard leg advantageously provides a by-pass leg for surplus switching flux induced in other legs of the magnetic element.

The foregoing and other objects and features of the present invention will be better understood from a consideration of the detailed description of specific illustra-

tive embodiments thereof when taken in conjunction with the accompanying drawing in which:

Fig. 1 is a schematic diagram of an illustrative frequency multiplier circuit according to the principles of this invention;

Figs. 2A and 2B are comparison diagrams showing input and output signals at different operative stages of the multiplier circuit of Fig. 1;

Fig. 3 is a schematic diagram of an illustrative frequency generator circuit according to the principles of this invention;

Fig. 4 is a schematic diagram of a specific illustrative modification of the circuit shown in Fig. 3 to achieve frequency modulation.

An illustrative frequency multiplier circuit embodying the principles of this invention is shown in Fig. 1 and comprises as its control means a magnetic element 10. The element 10 is fabricated of a magnetic material exhibiting substantially rectangular hysteresis characteristics such as is well known in the magnetic switching art. A plurality of apertures divide the element 10 into a plurality of individual and isolated flux paths which paths share a common path through a common drive leg 11 of the element 10. The individual paths are completed through a plurality of transverse flux switching legs 12₁ through 12₅, an error control leg 13, and a guard leg 14. Each of the legs thus far described is magnetically connected at either end to each of the other legs by a pair of side rails 15 and 16 of the element 10 through which side rails each of flux paths presented in the element 10 are also completed. The physical dimensions of the element 10 are determined such that the minimum cross-sectional areas and hence the saturation flux capacities of the flux switching legs and control legs 12 and 13 are substantially equal. The cross-sectional area of the guard leg 14 is substantially larger than the cross-sectional area of any of the legs 12 and 13 in a degree as will be described more particularly hereinafter. The minimum cross-sectional areas, and hence the saturation flux capacities of the common drive leg 11 and the portions of each of the side rails 15 and 16 connecting the common drive leg 11 and the switching leg 12₁ are each equal at least to the sum of the minimum cross-sectional areas, and hence the sum of the saturation flux capacities, of the flux switching legs 12, the control leg 13, and the guard leg 14. In order to maintain the foregoing relationships between the various portions of the element 10 and at the same time achieve an economical and manageable structure, the portion of the element 10 bounding the switching legs 12 and control leg 13 may be undercut as indicated in Fig. 1 by the shoulders 17 and 18. The dimensions *d* of the element 10 may in this manner be reduced while the required relationship between the minimum cross-sectional areas is maintained. Additionally, the side rails 15 and 16 are tapered to decreasing cross-sectional areas away from the common drive leg 11. The taper of the side rails 15 and 16 is possible since clearly a diminishing magnitude of flux is carried thereby as the flux legs through which flux closure is to be had become more remote from the common drive leg 11. Additionally, the taper provides a greater differential between the lengths of the flux paths closed through the various flux legs 12, 13, and 14. The advantages to be gained by the latter increased differentials will become apparent from a description of illustrative operation of this invention to be considered in detail hereinafter.

Inductively coupled to various portions of the element 10 are a plurality of energizing and output windings. A pair of input drive windings 19 and 20 are coupled to the common drive leg 11 and a pair of control output windings 21 and 22 are coupled to the control leg 13. Each of the flux switching legs 12 has coupled thereto a signal output winding 23. The latter windings are serially connected in alternating senses in a signal output circuit 24, which output circuit terminates at one end in an output

terminal 25 and at the other end in ground. Additional signal output windings 26 and 27 are also connected to the flux switching legs 12₂ and 12₄, the windings 26 and 27 being connected in series between ground and an output terminal 28.

The control output windings 21 and 22 are each connected to feed back circuits FB₁ and FB₂ which ultimately control the amplitude of the input drive current applied to the common drive leg 11. The control output winding 21 is connected at one end to a source of positive potential 30 and at its other end to the emitter 31 of a transistor 32. The base 33 of the transistor 32 is also connected to the potential source 30. The control output winding 22 is connected at one end to a source of positive potential 34 and at its other end to the emitter 35 of a transistor 36. The base 37 of the transistor 36 is also connected to the potential source 34. The collector 38 of the transistor 32 is connected via a coupling circuit to an input drive circuit ID as is the collector 39 of the transistor 36. The coupling circuit connected to the collector 38 comprises a capacitor 40 which is connected in parallel with a resistor 41 between ground and the collector 38. Also connected to the collector 38 is a resistor 42 the other end of which is connected through a second capacitor 43 to ground. The other end of the resistor 42 is also connected via a conductor 44 to the input drive circuit ID.

The coupling circuit connected to the collector 39 comprises a capacitor 45 which is connected in parallel with a resistor 46 between ground and the collector 39. Also connected to the collector 39 is a resistor 47 the other end of which is connected through a second capacitor 48 to ground. The other end of the resistor 47 is also connected via a conductor 49 to the input drive circuit ID. The conductors 44 and 49 are each connected to one end of oppositely poled secondary windings 51 and 52, respectively, of a transformer 50, the primary winding 53 of which is connected to a source of alternating square wave signals 54. The other ends of the secondary windings 51 and 52 are connected respectively to the bases 55 and 56 of transistors 57 and 58. Collectors 59 and 60 of the transistors 57 and 58 are connected to sources of negative potential 61 and 62, respectively. The input drive windings 19 and 20 are each connected at one end to ground and at the other ends to the emitters 63 and 64 of the transistors 57 and 58, respectively. The windings 19 and 20 are thus coupled to the common drive leg 11 of the element 10 in opposing sense with respect to the direction of the drive current to be applied from the input drive circuit ID. The organization and structural elements of one specific frequency multiplier circuit according to this invention has thus been described. A representative operation of the aforescribed circuit may now be considered.

In describing a particular cycle of operation of the circuit of Fig. 1, it will be assumed that as a result of a previous operative cycle, a saturation flux is remanent in the common drive leg 11 in the downward direction as viewed in the drawing. This flux is closed in the opposite direction, that is, upward through each of the legs 12₁ through 12₅, 13 and 14. In this magnetic flux state of the element 10, the circuit is prepared for the application of a first drive current. The latter current is applied from the input drive circuit ID which latter circuit is in turn driven by a square wave alternating signal 70 supplied by the generator 54. The latter generator 54 may comprise any suitable generator well known in the art capable of generating a square drive alternating signal of a predetermined fixed amplitude and frequency. During the first half of a cycle of operation a negative going alternation of the signal 70 is applied via the primary winding 53 to the oppositely wound secondary winding 51 and 52 of the transformer 50. The negative alternation of the signal 70 is reversed with respect to the winding 51 and is thus applied as a positive signal to

the base 55 of the transistor 57. The negative alternation of the signal 70 is applied in that polarity to the base 56 of the transistor 58. As a result, the transistor 58 conducts and the transistor 57 is cut off. A negative drive voltage is therefore applied to the winding 20 connected to the emitter 64 of the conducting transistor 58. This negative drive voltage is shown in Fig. 2 of the drawing as beginning at the time t_1 and is there designated as the idealized wave form 71.

As the negative going drive voltage 71 is applied to the common drive leg 11 a magnetic switching flux is induced therein as the drive voltage 71 is continued, the switching flux being in a direction as indicated by the arrow f in Fig. 1. In accordance with known magnetic principles, the switching flux will close first through the shortest available path which path is presented by the flux switching leg 12₁. The direction of the latter closure is indicated in the drawing by the arrow f' in the leg 12₁. As the switching flux closes through the leg 12₁ to reverse the flux initially in the latter leg an output signal voltage is induced in the output winding 23 coupled thereto. The sense of the winding 23 of the leg 12₁ is such that the output signal generated is negative and is so shown as the idealized wave form 72 in Fig. 2. As the duration of the negative portion of the drive current continues, further flux induced in the common drive leg 11 will be closed through the next switching leg 12₂ as the leg 12₁ becomes saturated. The switching flux reverses the flux initially in leg 12₂ to induce an output voltage signal in its coupled output winding 23. However, the latter winding is wound on the leg 12₂ in a sense opposite to that of the output winding 23 wound on the leg 12₁. Accordingly, in this case the output signal generated is positive and this signal is shown as the idealized wave form 73 in Fig. 2.

The foregoing reversal of flux in the switching legs continues during the duration of the input drive voltage 71 to successively develop output signals in the remaining output windings 23. The direction of the latter reversals will be in the same direction as the reversals in the previously considered legs 12₁ and 12₂. Since the output windings 23 of the legs 12₃, 12₄, and 12₅ also alternate in their coupling sense a continuous series of alternating signals will be generated in the latter windings until the last of the switching legs 12₅ is saturated by the switching flux. These output signals will appear successively on the output terminal 25 connected to the circuit 24 which serially connects the windings 23. The output signal generated as a result of the flux reversal in the leg 12₅ is represented as the last signal 74 generated during the first half of the cycle of operation being described.

Normally at this time the input drive circuit 10 is so arranged and timed that at the moment that the last switching legs 12₅ completes its flux reversal, the input signal 70 reverses polarity to apply a negative drive voltage 75 to the drive winding 19 to be in the last half of a cycle of operation. As a result, the common drive leg 11 will have a switching flux in the opposite direction induced therein. The latter flux will be successively closed through the legs 12₁ through 12₅ thereby again switching these legs. The alternating signals induced as a result of the latter switching will again appear on the terminal 25 and advantageously as an unbroken sequence of alternating signals. This condition will obtain when the operation of the frequency multiplier of Fig. 1 has stabilized and the latter operation in which possible errors are corrected will now be considered.

It will be recalled that the frequency and amplitude of the input signal 70 was fixed. As a result, the time duration of the negative drive voltage 71 is also fixed and the interruption of the latter voltage when the input signal 70 changes polarity is indicated in Fig. 2 as the time t_2 . Clearly, in this unstabilized operative state the drive voltage 71 continues beyond the time t_2 at which

the last switching leg 12₅ completes its flux reversal. Since the frequency of the input signal and hence the time duration of the drive current on the drive winding 20 is fixed, the circuit advantageously must provide a way to synchronize the frequency of the input signal with the timing of the completion of the flux reversals in each of the legs 12₁ through 12₅. This is accomplished in the embodiment of this invention being described by means of an added control leg 13 in the magnetic element 10. As the drive current 71 continues beyond the time t_2 the additional flux induced in the common drive leg 11 closes through the control leg 13. As a result of the initiation of a flux reversal in the latter leg an output signal is induced in each of the control windings 21 and 22 coupled thereto. The output control signals so induced are applied in the base-emitter circuits of the transistors 32 and 36, respectively. However, the windings 21 and 22 are oppositely poled with respect to the direction of flux reversals in the control leg 13. As a result only one of the transistors 32 and 36 will be caused to conduct by a particular reversal of flux in the control leg 13. In the present case during which a negative signal is generated in the winding 22, the latter signal is applied across the base-emitter circuit of the transistor 36. The latter transistor conducts and as a result capacitor 45 charges and the voltage developed thereacross is filtered by capacitor 48 and resistor 47. When control leg 13 is fully saturated or when the drive current 71 terminates, capacitor 45 discharges slowly through resistor 46 but will retain most of its charge until the next half of a drive cycle begins. The time constant of the R-C circuit comprising the resistor 46 and capacitor 45 is thus longer than the input current duration measured from the time t_1 to the time t_2 . During the following half cycle of operation, which corresponds to the second half of a complete cycle of the input signal 70, the voltage across the capacitor 45 is algebraically added to the voltage induced across the secondary windings 51 and 52 of the transformer 50 by means of the conductor 49. The voltages so added will be of opposite polarity so that the amplitude of the drive voltage applied to the drive winding 19 during the cycle following the one described previously herein will be reduced.

In accordance with known magnetic principles, when the amplitude of the drive voltage is reduced as its time duration is held fixed, that is as the volt-second area of the input drive is reduced, the extent of the flux propagation in a magnetic structure such as the element 10 is correspondingly reduced. Thus, in the second half of the cycle of operation being described, fewer legs of the element 10 will have flux reversed therein. If the circuit has attained its normal operating state, the amplitude of the drive voltage 71 will have been so adjusted that the last switching leg 12₅ will just complete its reversal, and hence the output signal 74 developed responsive thereto will be fully formed, at the time t_2 . The multiplying factor of the frequency of the output signals 72, 73, etc. with respect to the input signal 70 will thus have been precisely determined. This normal state is shown in Fig. 2B where the drive voltages applied to each of the drive windings 19 and 20 are shown in their relationship to the alternations of the input signal 70 and the sequence of output signals generated during a complete cycle of operation of the circuit of Fig. 1.

Should the circuit of Fig. 1 not have obtained its normal operating state after the completion of the second half of a complete cycle of operation, the voltage across the capacitor 45 will continue to build up until the normal state as above described is reached. The foregoing adjustment operation as described in connection with the first half cycle of operation in which the switching legs 12 are switched down as viewed in the drawing, is augmented by an identical adjustment operation accomplished when the legs 12 are flux reversed in the opposite direction in the second half of the cycle of operation.

The feedback circuit FB_1 is a duplicate, in principle, of the feedback circuit FB_2 , the operation of which was described above. Thus, a voltage building up across the capacitor 40 performs the same regulating function on the input drive across the transformer secondary winding 51 as the voltage across the capacitor 45 performs on the drive across the winding 52. The multiplier circuit of Fig. 1 is thus symmetrical, each half of the associated circuitry being operative during a particular half of a cycle of operation. In the illustrative embodiment of Fig. 1, it is clear that the multiplying factor of the output frequency with respect to the input frequency is 5. Accordingly, 5 flux switching legs were provided in the element 10, each of which has its flux switched twice during a complete cycle of operation. It will be appreciated, however, that any desired multiplying factor may be achieved simply by adding or subtracting the number of flux switching legs 12 in the element 10. In order to maintain continuity in the sequence of alternating signals generated at the time t_2 at which the input signal reverses polarity and the drive switches from one of the drive windings 19 and 20 to the other, it is only required that there be an odd number of switching legs 12.

In accordance with another mode of operation of the circuit of Fig. 1, a secondary pair of serially connected output windings 26 and 27 coupled to the switching legs 12₂ and 12₄, respectively, are energized. During each half of a cycle of operation as described in the foregoing, a pair of equally spaced current pulses as a result will appear on the terminal 28. The pulse pairs of each half cycle will be of opposite polarity, but of equal amplitude and bear a predetermined relationship to the input signal 70 and hence may advantageously be employed as clock pulses suitable for timing purposes.

In describing the step-by-step propagation of flux in the element 10 in connection with a representative operation of the circuit of Fig. 1, a discrete, separable flux closure was assumed with respect to each of the switching legs 12₁ through 12₅. However, in practice this normal flux closure may not always be fully achieved. As a result, at the same time that one switching leg 12 has its flux completely reversed the next succeeding leg or legs may undergo a partial flux excursion. In the early legs 12 of the sequence of switching legs this presents little difficulty in view of the number of legs of the sequence through which such surplus of flux may find closure paths. However, as the successive flux closures progress through the sequence of switching legs, fewer legs remain to absorb the surplus of flux. Consequently, to guard against the possibility of a later switching leg of the sequence alone remaining to absorb the flux surplus and, as a result, undergoing a complete flux reversal before its scheduled time, the guard leg 14 is provided in the element 10. Thus, whatever flux is induced in the common drive leg 11 over and above that required to saturate the switching legs 12 and the control leg, is absorbed by the guard leg 14 without affecting the operation of the circuit as described in the foregoing.

The amplitude of the input signal 70 may be initially established to be sufficient to saturate the switching legs 12 before the time t_2 as was assumed in the representative operation described. This operation was in accordance with the specific illustrative circuit organization shown in Fig. 1. A similar circuit may also be envisioned in which the amplitude of the drive voltage 71 or 75 is established as insufficient to cause a complete saturation of each of the legs 12₁ through 12₅. In such a case a control winding not shown in Fig. 1, could be coupled to the last switching leg 12₅ with the signals or absence of signals induced thereon being employed to control feedback circuitry such as the circuits FB_1 and FB_2 , to increase the amplitude of the drive voltages. Both a lower and an upper control of the drive current amplitude would thus fall within the scope of the present invention. It is further to be understood that the feedback circuits FB_1

and FB_2 and the input drive circuit ID are merely illustrative of means for achieving the error control and adjustment functions described. Other and different circuits for achieving these functions may readily be envisioned by one skilled in the art without departing from the scope of this invention so far described.

The separation of the flux closures through the switching legs 12 may manifestly be enhanced by simply making the spacings between the legs, and hence the differential in flux path lengths large enough so that no surplus of flux will cause any flux reversal in a subsequent leg before the preceding adjacent leg is completely saturated in the switching direction. However, aside from whatever additional power may be required, the element 10 may itself become unwieldy as a result. This same result may advantageously be achieved in accordance with the principles of the present invention by forming the legs 12, 13, and 14 in progressively increasing lengths. A greater disparity in flux path lengths is thus achieved without a commensurate increase in overall physical dimensions or change in the outside configuration of the magnetic element.

In the embodiment of this invention described in the foregoing and shown in Fig. 1, the frequency of the input signal and hence the multiplied output frequency is held fixed. The amplitude of the input drive is then adjusted to insure the proper timing of the output signals. In the embodiment of this invention depicted in Fig. 3, a pulse generator is realized in which the amplitude of the drive input current is maintained fixed to determine the frequency of the generated pulses. The frequency of the input drive is adjusted as determined by the timing of the last signal generated during each half of a cycle of operation. An illustrative pulse generator so operated and depicted in Fig. 3 comprises a magnetic element 100 which is also fabricated of a magnetic material exhibiting substantially rectangular hysteresis characteristics. The element 100 is similar in operation and function to the element 10 of the embodiment of Fig. 1 except in the number of apertures and hence the number of flux legs presented. Accordingly, the various portions of the element 100 need be described only in sufficient detail to gain an understanding of the organization and structure of this frequency generator embodiment. A pair of drive windings 119 and 120 are inductively coupled to a common drive leg 111 of the element 100 and an output winding 123 is coupled to each of a sequence of flux switching legs 112₁ through 112₅. The last of the sequence of flux switching legs 112₅ also serves as a control leg and has coupled thereto a pair of control output windings 121 and 122 and the element 100 terminates in a guard leg 114. The output windings 123 are coupled to the legs 112 in alternating senses and are serially connected in an output circuit 124 which latter circuit is connected between ground and an output terminal 125.

The drive windings 119 and 120 are connected at one end to each other and to a source of negative potential 126. A pair of diodes 127 and 128 are connected across the drive windings 119 and 120 and the other ends of the latter windings are connected respectively to one end of each of a pair of resistors 129 and 130. The other ends of the latter resistors are connected to the collectors 131 and 132 of transistors 133 and 134, respectively. The base 135 of the transistor 133 is connected to ground and to the emitter 136 of the latter transistor through a biasing resistor 137. In a similar manner, the base 138 of the transistor 134 is connected to ground and to the emitter 139 of the latter transistor through a biasing resistor 140. The bases 135 and 138 are also connected respectively through capacitors 141 and 142 to one end of each of the control windings 121 and 122 via a pair of conductors 144 and 149. In addition, the base 138 of the transistor 134 is connected to the collector 131 of the transistor 133 through a resistor 150. Similarly, the base 135 of the transistor 133 is connected to the collector 132

of the transistor 134 through a resistor 151. The circuit elements thus described as connected to the input drive windings 119 and 120 comprises a well known bistable alternately conducting flip-flop circuit.

Assuming in the foregoing flip-flop circuit that the transistor 133 is just beginning to conduct, then the current from the collector 131 generates a potential across the resistor 129. The potential so developed applied across the resistor 150 cuts off the transistor 134 in the conventional manner. Assuming further that, as a result of a previous cycle of operation, a remanent flux in the common drive leg 111 is in a downward direction as viewed in the drawing, then the positive current now flowing in the connected drive winding 119 begins to induce a switching flux in the common drive leg 111. The diode 127 connected across the latter winding maintains a constant voltage thereacross and the switching flux in the direction indicated in Fig. 3 by the arrow f_1 begins to close through the first of the switching legs 112₁. As the positive drive voltage of a constant amplitude, represented in Fig. 3 by the idealized wave form 155, continues, the switching legs 112₁ through 112₂ are successively flux reversed in the fashion described in connection with the embodiment of Fig. 1. As the flux in the switching legs 112 is thus successively reversed, output signals are induced responsive thereto in the coupled output windings 123. Since the latter windings are serially connected in alternating senses to produce a sequence of alternating signals on the output terminal 125, the frequency of the latter signals is fixed by the number of flux switching legs 112 and the amplitude of the drive current 155. The latter amplitude is adjusted such that it is sufficient in every case to completely saturate each of the switching legs 112₁ through 112₅. The output signals produced during the first half are shown in Fig. 3 as the wave forms 156 between the times t_1 and t_2 .

When the flux reversal is caused in the switching leg 112₅, output signals are also induced in the control windings 121 and 122 coupled thereto. The latter windings are coupled in opposing senses and the oppositely poled signals induced as a result are applied via the conductors 144 and 149 to the bases 135 and 138 of the transistors 133 and 134, respectively. As determined by the senses of the windings, a positive control signal is induced in the winding 121 and applied via the conductor 149 to the base 135 across the isolating capacitor 141. Similarly, a negative signal induced at this time in the output winding 122 is applied via the conductor 144 to the base 138 across the isolating capacitor 142. As a result, the transistor 133 is cut off and the transistor 134 begins to conduct. This transfer of conducting states occurs at the time t_2 indicated in Fig. 3 and the conduction of transistor 134 aids in the interruption of the transistor 133. The second half of the cycle of operation being described is thus initiated. When the transistor 134 conducts, the positive voltage, represented as the idealized wave form 157 in Fig. 3, is applied to the drive winding 120. The winding 120 is wound on the drive leg 111 in a sense opposite to that of the drive winding 119 and consequently a switching flux in the opposite direction is induced in the common drive leg 111. The successive flux closures through the switching legs 112₁ through 112₅ in the opposite direction again produce a sequence of alternating output signals in the output windings 123. The latter signals again appear on the output terminal 125 and are represented in Fig. 3 by the idealized wave forms 158. When the last switching leg 112₅ is completely flux reversed a positive signal is now generated in the output winding 122 and a negative output signal is generated in the output winding 121. The latter signals are transmitted via the conductors 144 and 149 to again control the transfer of the conducting state from the transistor 134 to the transistor 133.

Interruption of the drive voltages 155 and 157 is thus

accomplished as a result of the flux reversals in the last switching leg 112₅ at the end of each half cycle of operation of the circuit of Fig. 3. These interruptions may be understood as occurring at the times t_2 and t_3 indicated in Fig. 3 at the end of each sequence of output signals 156 and 158 generated during each half cycle of operation. In the embodiment of Fig. 3 the volt-second area of each input voltage 155 and 157 is thus adjusted to control the output frequency with the amplitude of the voltages 155 and 157 being constant. In order to maintain continuity between the two sequences of output signals 156 and 158 and thereby achieve an unbroken generation of output signals, the legs 112₁ are determined as an odd number. Although in the specific circuit of Fig. 3 five switching legs 112 are shown, it is clear that any number of such legs may be provided in the element 100 within the limits which may be established by considerations such as the particular magnetic materials employed, available power sources, and the like. The guard leg 114 again provides a closure path for any surplus of flux induced after the flux closures in the individual switching legs 112.

The illustrative circuit shown in Fig. 3 lends itself to various modifications therein each of which falls within the scope of this invention. Thus, separate outputs may be taken from each of the switching legs 112 by providing individual windings thereon. A sequence of individual clock pulses, for example, may in this manner be advantageously generated. Another adaptation of the circuit of Fig. 3 is shown in Fig. 4. The circuit of Fig. 3 is similar in every respect to the circuit described in detail above and shown in Fig. 3 with the exception of the drive voltage control circuit. Thus, instead of a pair of diodes 127 and 128 for providing a constant voltage, signal generators 127' and 128' are connected across the drive windings 119 and 120, respectively. The latter generator may comprise any well known circuits for providing controllable output signals and are in turn controlled by a variable control means 129'. The latter means may comprise, for example, a microphone by means of which the output frequency of the circuit is advantageously voice modulated. The remaining elements of the circuit of Fig. 4 are identical to those described in Fig. 3 and are accordingly designated with the same reference characters.

In considering the specific operation of the circuit of Fig. 4, it will be recalled that in connection with the frequency generator of Fig. 3, the amplitude of the drive voltages applied to the drive windings 119 and 120 was held constant. As a result, the rate at which the switching legs 112₁ through 112₅ were successively flux saturated was constant. As the last leg 112₅ was saturated by the induced switching flux, the successive flux reversals were re-initiated in the switching legs in the opposite direction to complete a full cycle of operation. The output frequency as a result is thus held a constant multiple of the frequency of the drive voltage applied to the drive windings 119 and 120. In the arrangement of Fig. 4, as the amplitude of the drive voltage is also varied in accordance with the control of the voltage control means 129', the output frequency is correspondingly varied. The latter variation in frequency thus follows substantially the variations in amplitude of the signal supplied by the control means 129'.

The foregoing circuits are to be understood as comprising only illustrative embodiments of the present invention. Accordingly, various and numerous other arrangements may also be devised by one skilled in the art without departing from the spirit and scope of this invention.

What is claimed is:

1. An electrical circuit comprising a multi-apertured magnetic element of a material having substantially rectangular hysteresis characteristics, said element presenting a sequence of flux legs therein and a common drive leg,

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means for successively causing flux reversals in one and the opposite direction in said flux legs comprising drive winding means coupled to said common drive leg and input drive means for applying a first and a second input signal to said drive winding means, a first and a second control winding coupled to a last of said sequence of flux legs energized responsive to flux reversals in said last-mentioned flux leg in said one and said opposite direction, respectively, for generating a first and a second control signal, control circuit means energized responsive to said first and said second control signal for controlling said input drive means to adjust the volt-second area of said first and said second input signal, respectively, and output windings coupled to particular ones of said sequence of flux legs.

2. An electrical circuit comprising a multi-apertured magnetic element of a material having substantially rectangular hysteresis characteristics, said element presenting a sequence of flux legs therein and a common drive leg, said flux legs defining a plurality of flux paths being completed through said common drive leg, means for successively inducing a switching flux in one and the opposite direction in said flux paths comprising a first and a second drive winding coupled to said drive winding in opposing senses and input drive means for alternately applying a first and a second input drive signal to said first and said second drive windings, a first and a second control winding coupled to a last of said sequence of flux legs energized responsive to said switching flux in said last-mentioned leg for generating a first and a second control signal respectively, control circuit means energized responsive to said first and said second control signals for controlling said input drive means to adjust the magnitude of said first and said second drive signals, and output windings coupled to particular ones of said sequence of flux legs.

3. An electrical circuit as claimed in claim 2 in which said flux legs are of progressively increasing length.

4. An electrical circuit as claimed in claim 2 also comprising a flux guard leg in said magnetic element following said sequence of flux legs.

5. A frequency control circuit comprising a multi-apertured flux limited magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg, a sequence of flux switching legs, and an error control leg, a first and a second drive winding coupled to said drive leg in opposing senses, input means for alternately applying a constant frequency drive signal to said first and second drive windings, a first and a second control winding coupled to said error control leg energized responsive to flux reversals in said last-mentioned leg for generating a first and a second error control signal, a first and a second control circuit means energized responsive to said first and said second error control signal, respectively, for controlling said input means to adjust the amplitude of said constant frequency drive signal, and output windings coupled to said sequence of flux switching legs.

6. A frequency control circuit as claimed in claim 5 also comprising output circuit means for serially connecting said output windings in alternating senses.

7. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg, a sequence of flux switching legs, and an error control leg, said flux legs and said control leg being flux limited to substantially the same flux magnitude, a drive winding coupled to said drive leg, first input means for applying a first constant frequency signal to said drive winding to cause successive flux reversals in one direction in said sequence of flux switching legs, a first control winding coupled to said error control leg energized responsive to flux reversals in said last-mentioned leg for generating a first error control signal, a first control circuit means energized responsive to said first error control

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signal for controlling said input means to adjust the amplitude of said first constant frequency drive signal, and output circuit means including an output winding coupled to each of said flux switching legs in alternating senses.

8. A frequency control circuit as claimed in claim 7 also comprising a second drive winding coupled to said drive leg, second input means for applying a second constant frequency signal to said second drive winding to cause successive flux reversals in the other direction in said sequence of flux switching legs, a second control winding coupled to said error control leg energized responsive to flux reversals in said last-mentioned leg for generating a second error control signal, and a second control circuit means energized responsive to said second error control signal for controlling said second input means to adjust the amplitude of said second constant frequency drive signal.

9. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg, and a sequence of flux switching legs, means for successively causing flux reversals in said sequence of flux switching legs at a predetermined rate comprising a first and a second drive winding coupled to said drive leg in opposing senses and input circuit means for alternately applying an input signal of constant frequency to said first and second drive windings, means for adjusting the flux reversals of the last switching leg of said sequence to the frequency of said input signal comprising an error control leg in said magnetic element having flux reversed therein at a time other than the flux reversal in said last switching leg, a first and a second control winding coupled to said error control leg, each of said last-mentioned windings being energized responsive to flux reversals in a particular direction for generating respectively an error control signal, and a first and a second control circuit means energized responsive, respectively, to said first and said second error control signals for controlling said input circuit means to adjust the amplitude of said input signal; and output circuit means including an output winding coupled to each of said flux switching legs.

10. A frequency control circuit as claimed in claim 9 in which said error control leg follows said last switching leg in said magnetic element with respect to said common drive leg.

11. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg and a sequence of flux switching legs therein, means for successively causing flux reversals in said sequence of switching legs at a predetermined rate comprising a first and a second drive winding coupled to said drive leg in opposing senses and input circuit means for alternately applying an input signal of constant amplitude to said first and said second drive windings, means for adjusting the flux reversals of the last switching leg of said sequence to the frequency of said input signal comprising a first and a second control winding coupled to said last switching leg, each of said control windings being energized responsive to flux reversals in a particular direction for generating, respectively, a pair of control signals, and a first and second control circuit means energized responsive to said control signals for controlling said input circuit means to adjust the frequency of said input signal; and output circuit means including an output winding coupled to each of said flux switching legs.

12. A frequency control circuit as claimed in claim 11 in which said input circuit means comprises a two state alternately conducting flip-flop circuit and said first and said second control circuit means comprises means for applying said control signals to alternately cut off said stages of said flip-flop circuit.

13. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectan-

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gular hysteresis characteristics, said element presenting a common drive leg and a sequence of flux switching legs therein, a first and a second drive winding coupled to said drive leg in opposing senses, input means for alternately applying a constant amplitude drive signal to said first and said second drive windings, a first and a second control winding coupled to the last of said sequence of switching legs energized responsive to flux reversals in said last-mentioned leg for generating a first and a second control signal, a first and a second control circuit means energized responsive to said first and said second control signal, respectively, for controlling said input means to adjust the frequency of said constant amplitude drive signal, and output circuit means including an output winding coupled to each of said flux switching legs.

14. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg and a sequence of flux switching legs, said flux switching legs being flux limited to substantially the same flux magnitude, a first drive winding coupled to said drive leg, first input means for applying a first constant amplitude signal to said drive winding to cause successive flux reversals in one direction in said sequence of flux switching legs, a first control winding coupled to the last of said sequence of flux switching legs energized responsive to flux reversals in said last-mentioned leg for generating a first control signal, a first control circuit means energized responsive to said first control signal for controlling said input means to adjust the frequency of said first constant amplitude drive signal, and output circuit means including an output winding coupled to each of said flux switching legs in alternating senses.

15. A frequency control circuit as claimed in claim 14 also comprising a second drive winding coupled to said drive leg, second input means for applying a second constant amplitude signal to said second drive winding to cause successive flux reversals in the other direction in

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said sequence of flux switching legs, a second control winding coupled to said last of said sequence of flux switching legs energized responsive to flux reversals in said last-mentioned leg for generating a second control signal, and a second control circuit means energized responsive to said second control signal for controlling said second input means to adjust the frequency of said second constant amplitude drive signal.

16. A frequency control circuit comprising a multi-apertured magnetic element having substantially rectangular hysteresis characteristics, said element presenting a common drive leg, a sequence of flux switching legs, and a flux guard leg, a first and a second drive winding coupled to said drive leg, an alternately conducting two stage flip-flop circuit, an output of one of said stages being connected to said first drive winding and an output of the other of said stages being connected to said second drive winding, a first voltage control means connected across said first drive winding, a second voltage control means connected across said second drive winding, a first and a second control winding connected to the last of said sequence of flux switching legs, a first and a second control circuit means including, respectively, said first and said second control windings for controlling, respectively, said stages of said flip-flop circuit, and an output circuit means including an output winding coupled to each of said flux switching legs in alternating senses.

17. A frequency control circuit as claimed in claim 16 in which said first and said second voltage control means each comprises a variable signal generator and also comprising means for simultaneously controlling said signal generator in accordance with voice currents.

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