United States Patent

[11] **3,579,088**

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[45] Patented **May 18, 1971**

[54] **FERRORESONANT TRANSFORMER WITH CONTROLLABLE FLUX**
17 Claims, 16 Drawing Figs.

[52] **U.S. Cl.** **323/6,**
323/50, 323/56, 323/60, 323/81
[51] **Int. Cl.** **G05f 1/38,**
G05f 7/00
[50] **Field of Search** 323/6, 48,
50, 56, 57—61, 8, 81, 85; 321/57, 68

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Assistant Examiner—Gerald Goldberg
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ABSTRACT: A ferroresonant transformer with means for varying saturation flux capacity for controlling the transformer output. A ferroresonant transformer with at least a portion of the core structure carrying the secondary winding having two separate sections providing parallel magnetic paths for the secondary and resonant flux, with a control winding on one of the sections and a switching circuit for opening and closing the control winding. A low frequency version utilizing E and I laminations with the control winding on one of the outer legs of the E. Another low frequency version utilizing E and I laminations with the control winding encircling a portion of the secondary magnetic circuit. A high frequency version utilizing a plurality of toroid cores with the control winding on one of the cores.

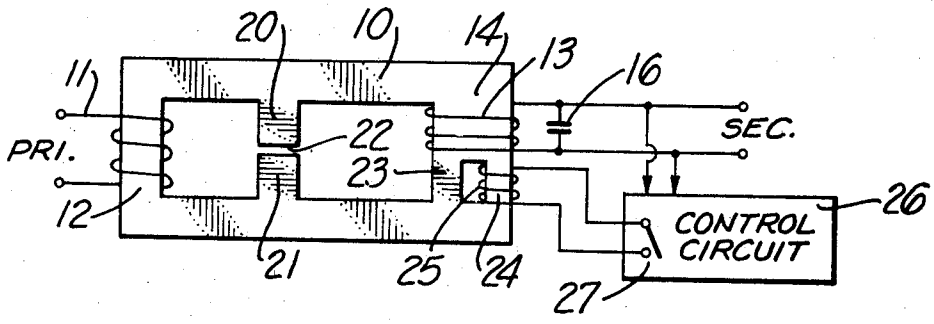


FIG. 1.

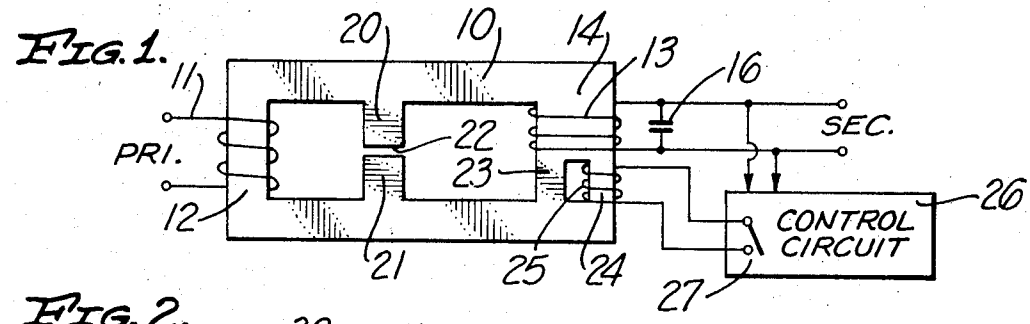


FIG. 2.

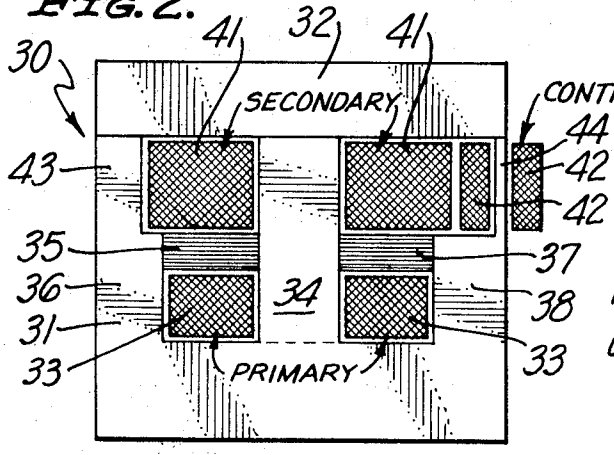
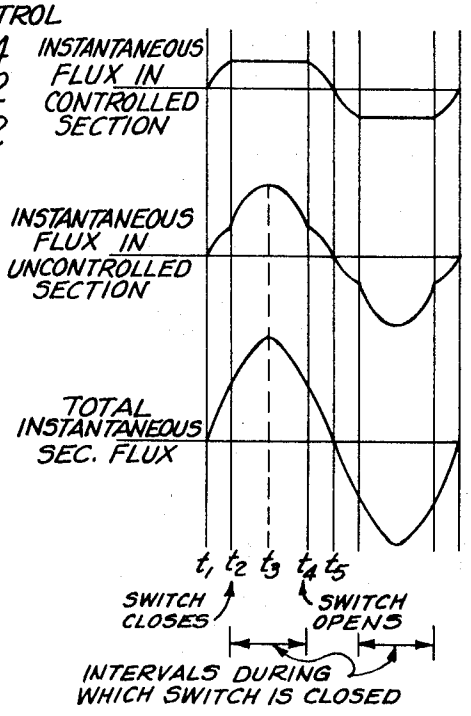


FIG. 3.



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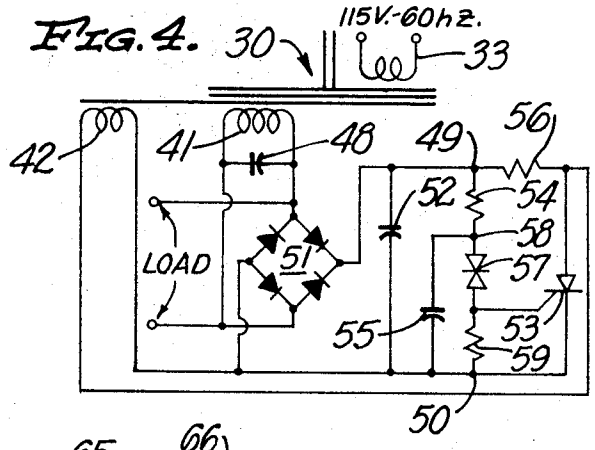
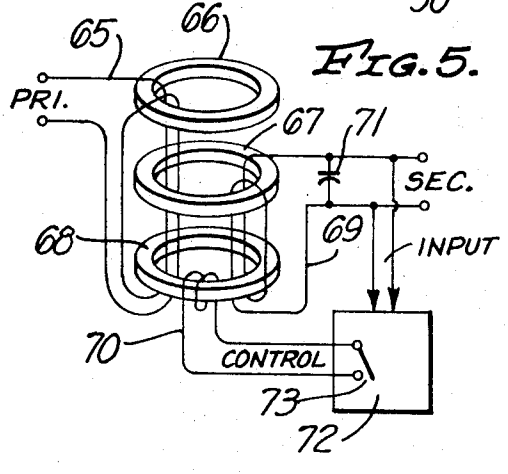


FIG. 5.



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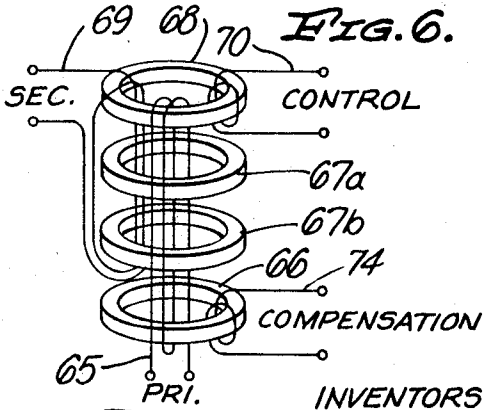

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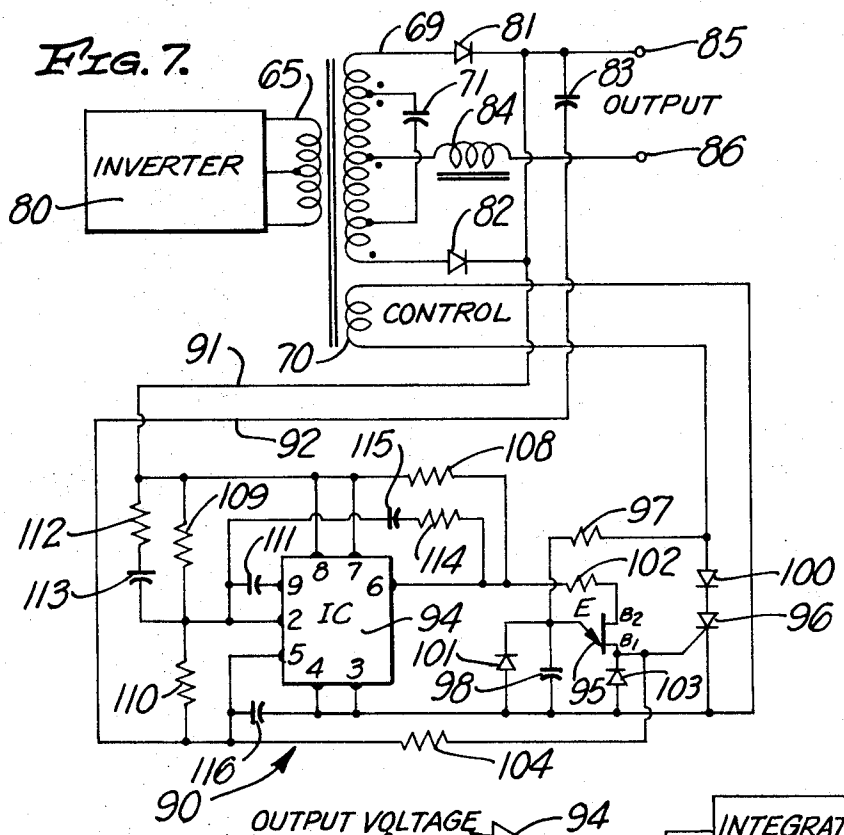
FIG. 7.



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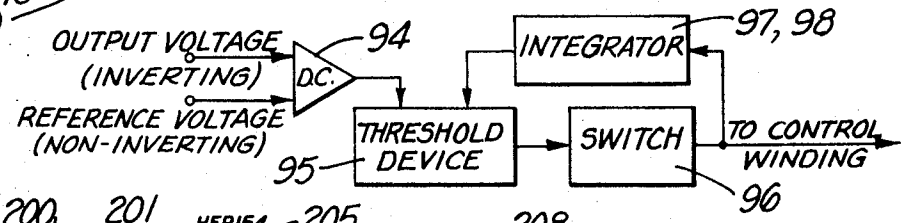

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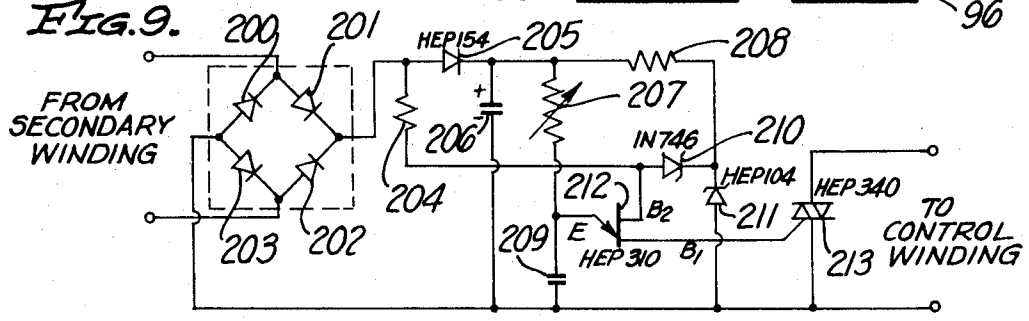

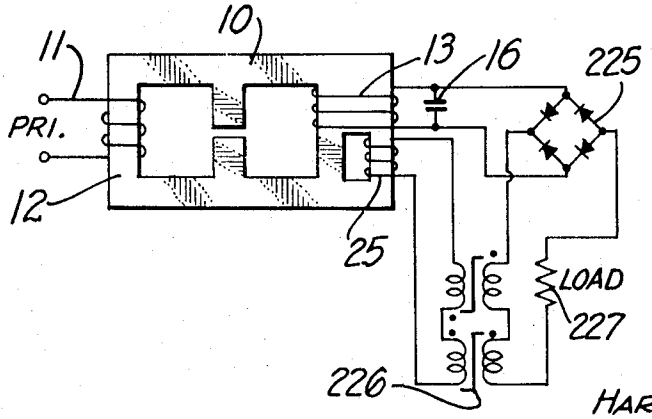

FIG. 10.

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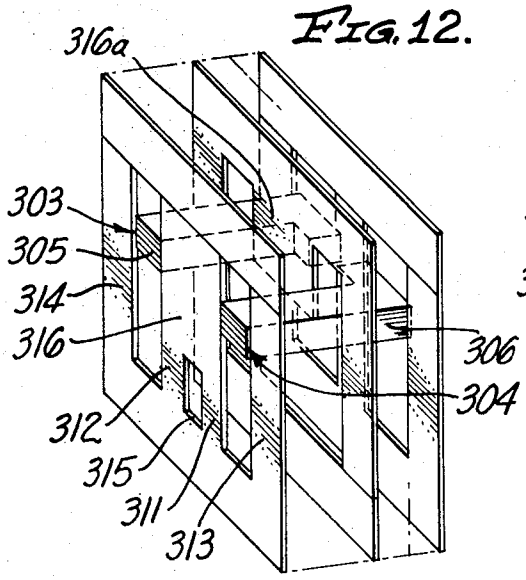
FIG. 12.



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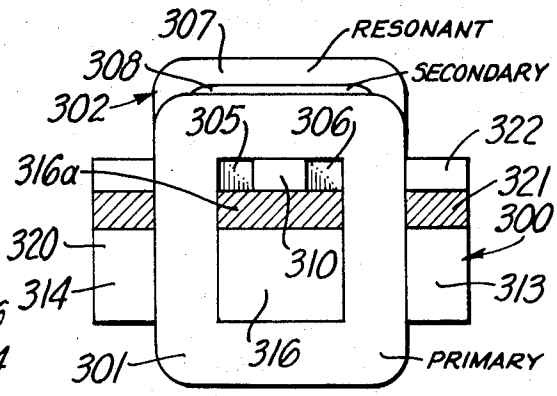

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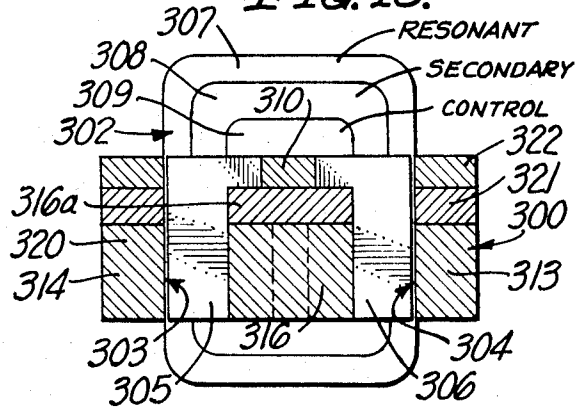

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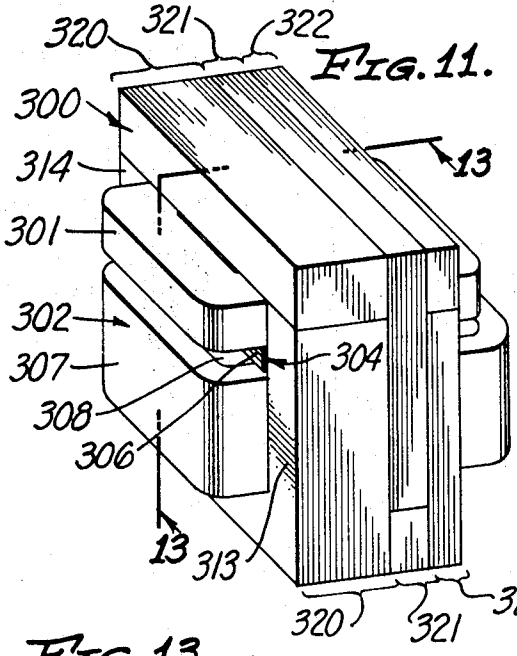

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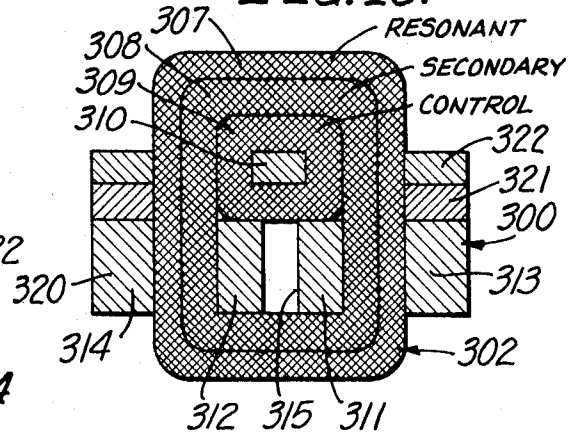

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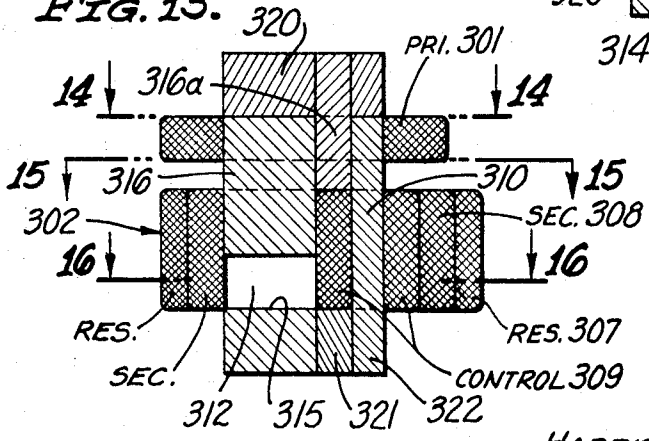

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FERRORESONANT TRANSFORMER WITH CONTROLLABLE FLUX

This invention relates to ferroresonant transformers and in particular, to a new and improved ferroresonant transformer incorporating means for varying the saturation flux capacity in the core structure for controlling the transformer output. Ferroresonant transformers are widely used today for a variety of regulating and control purposes and the basic design is shown in the U.S. Pat. to Sola, No. 2,143,745. A conventional ferroresonant transformer utilizing toroid cores is shown in the U.S. Pat. to Sola, No. 2,753,513. Various modifications and improvements are shown in other patents to the same patentee. It is an object of the present invention to provide a new and improved ferroresonant transformer construction which may be utilized with any of the presently known ferroresonant transformers and which provides for saturation flux capacity variation and transformer output control.

The conventional ferroresonant transformer has a magnetic core structure with a primary winding, a secondary winding and a resonant winding thereon. A capacitance is connected across the resonant winding. The resonant winding may be a separate winding or may actually be the secondary winding, with the capacitance connected across the secondary winding. A leakage flux path is provided in the core structure. In a transformer utilizing E and I laminations for the core structure, a quantity of core material is installed between the primary and secondary windings to provide a magnetic shunt for the leakage flux path. In transformers utilizing a toroid for the core structure, at least two toroids are utilized with the primary winding linking all of the toroids and with the secondary winding not linking all of the toroids. The ferroresonant type of operation may also be achieved with a core structure having two or more separate core units, and several such devices utilizing a saturating transformer, without a shunt, and a series choke are shown in the U.S. Pats. to Schmutz et al., No. 2,179,353, John et al., No. 2,505,620, Buie No. 2,764,725, and Kohn No. 2,967,271. The theory of operation and the details of construction of these conventional regulating devices may be obtained from various prior art publications, including the aforementioned patents. The term "ferroresonant transformer" as used herein is intended to include all such regulating devices.

In all ferroresonant transformers, the saturation flux capacity of the secondary magnetic circuit is predominant in determining the output voltage for a given number of secondary turns and a given frequency.

Because of external drops such as rectifiers and wiring resistance and because of other parameter changes such as frequency and saturation drifts with temperature, means for controlling the saturation flux capacity and hence the output voltage is desirable. Attempts have been made to achieve such control in the past by using windings with DC bias which affect the effective saturation flux density of the core material. These techniques require a sizeable mmf. in order to achieve control and the cost and complexity of the required driving circuits offset the advantages of using a ferroresonant approach.

The present invention provides for changing the saturation flux capacity of the secondary magnetic circuit in a ferroresonant transformer by isolating a portion of the secondary core material and controlling the flux in this section. In the present invention the secondary magnetic cross-sectional area is divided into two sections, which may be referred to as an uncontrolled section and a controlled section. Means are provided in the controlled section to limit the maximum value of the instantaneous flux passing through this section. Said means comprises a control winding encircling the controlled section and a switch element for shorting or opening said winding. By varying the time in the cycle at which the switch is operated, the maximum instantaneous flux in the controlled section can be varied from zero to a maximum value equal to the saturation flux capacity of the controlled section. As used herein, the term saturation flux capacity means the sum of (1) the product of saturation flux density of the magnetic material multiplied by the cross-sectional area of the core at the uncontrolled section and (2) one-half the total change of flux in the core at the controlled section.

Accordingly, it is an object of the invention to provide a new and improved ferroresonant transformer with a core construction incorporating two separate sections in the secondary path, with a control winding on one of the sections, and switch means for opening and closing a circuit across the control winding. A further object is to provide transformers incorporating the invention for operation at low frequencies and for operation at high frequencies. An additional object is to provide such a transformer which may incorporate the various features of conventional ferroresonant transformers and which may be constructed utilizing present day manufacturing techniques, including E and I laminations and toroidal cores.

Other objects, advantages, features and results will more fully appear in the course of the following description. The drawings merely show and the description merely describes the preferred embodiments of the present invention which are given by way of illustration or example. Various configurations for the magnetic core structure may be utilized including simple rectangular cores, E and I lamination cores, toroids, C-cores, and separate choke and transformer elements, and several specific forms are illustrated. The switch means for shorting and opening the control winding typically may include a switch element and a control circuit for actuating the switch element. Various devices may be used as the switch element, including a simple mechanical switch or relay, a transistor, an SCR, a Triac, a thyratron, an ignitron, a gas triode, a magnetic amplifier, and a saturable reactor. Various circuitry arrangements may be used as the control circuit, including a synchronized oscillator, a phase shifter, a magnetic amplifier, and a saturable reactor. Several specific examples of the switch means are set out herein. The switching operation may be performed every cycle or every half-cycle, and circuits for both modes are illustrated.

In the drawings:

FIG. 1 is a diagram of a ferroresonant transformer incorporating an embodiment of the present invention;

FIG. 2 is a view of an alternative form of construction of a ferroresonant transformer of the present invention suitable for use at power frequencies;

FIG. 3 is a diagram indicating typical flux waveforms in the controlled and uncontrolled sections and the total secondary flux waveform;

FIG. 4 is a schematic diagram of a circuit providing a synchronized oscillator with half-wave control for use with the transformers of FIG. 2 and FIG. 11;

FIG. 5 is a view of an alternative form of construction of a ferroresonant transformer incorporating another embodiment of the present invention;

FIG. 6 is a view of another alternative form of construction of a ferroresonant transformer incorporating a preferred embodiment of the present invention for use at higher frequencies;

FIG. 7 is a schematic diagram of a circuit providing a phase shifter control for use with the transformer of FIG. 6;

FIG. 8 is a block diagram illustrating the circuit of FIG. 7;

FIG. 9 is a schematic diagram of an alternate circuit providing a synchronized oscillator with full-wave control for use with transformers described herein;

FIG. 10 is a diagram of a ferroresonant transformer of this invention used in conjunction with a saturable reactor to obtain DC load compensation;

FIG. 11 is an isometric view of a form of construction of a ferroresonant transformer incorporating a preferred embodiment of the present invention suitable for use at power frequencies and for frequencies up through the audio range;

FIG. 12 is a skeletonized view of the core of the transformer of FIG. 11, indicating the placement of the various laminations;

FIG. 13 is a sectional view taken along the line 13–13 of FIG. 11; and

FIGS. 14, 15 and 16 are sectional views taken along the lines 14–14, 15–15, and 16–16, respectively, of FIG. 13.

The transformer of FIG. 1 includes a magnetic core 10 which may be constructed in the usual manner of interleaved or butt stacked laminations. The various conventional transformer manufacturing processes may be utilized. Typical core constructions for use with E and I laminations are illustrated in FIGS. 2 and 11—16. Core constructions for use with toroids are illustrated in FIGS. 5 and 6 and will be described later. Referring to FIG. 1, an input or primary winding 11 is provided on a leg portion 12 of the core 10. An output or secondary winding 13 is provided on another leg portion 14. In the embodiment illustrated, the secondary winding also serves as the resonant winding, and a capacitor 16 is connected across the secondary winding 13. In an alternative arrangement, a separate resonant winding could be provided on the leg portion 14, with the capacitor 16 connected thereacross.

A leakage flux path is provided in the core 10 between the primary winding 11 and the secondary winding 13, and comprises a magnetic shunt of core sections 20, 21 with a nonmagnetic gap 22, usually an air gap, therebetween. The elements described thus far are found in the conventional ferroresonant transformers such as described in the aforementioned Sola patents and reference may be made to the prior art for a study of the theory of ferroresonance. A power source is connected to the primary winding and a load is connected to the secondary winding, and the transformer functions to maintain the output voltage of the secondary winding constant within predetermined limits for variations in load and variations in voltage of the power source.

In the core of the invention, as illustrated in FIG. 1, the secondary leg portion 14 is divided into two sections 23, 24, which may be identified as the uncontrolled section 23 and the controlled section 24. The uncontrolled section is designed to saturate. A control winding 25 is provided on the section 24. A control circuit 26 operates a switch 27 connected across the control winding 25. The control circuit serves to open and close the switch at a particular phase angle of the output waveform. This phase angle is a prescribed function of a controlling signal. If a closed loop regulating device is desired, the controlling signal is derived from the output voltage. While a variety of devices may be utilized as the switch, contemporary solid state devices are presently preferred, such as a silicon-controlled rectifier, and two examples of control circuits and switches are described herein below.

When the switch 27 is open, the control winding 25 is open circuited and the secondary and resonant flux varies in both the uncontrolled section 23 and the controlled section 24. With the switch 27 closed, the control winding 25 is short circuited and further variation of flux in the controlled section is prevented. Since the flux in the controlled section is maintained constant by the action of switch 27, the total saturation flux capacity is reduced as compared to the total saturation flux capacity when the switch is closed for a minimum duration; the time required for the capacitor ring-over cycle.

In order for the device to operate in the ferroresonant mode the uncontrolled section must saturate. During periods when the mmf. across the controlled section exceeds the mmf. required to maintain the desired flux in this section the switch must be shorted or closed. The maximum switch closure time is a half-cycle and this condition corresponds to the the minimum total secondary saturation flux capacity. Since increasing the switch closure time causes a reduction in total secondary saturation flux capacity, a corresponding reduction in the output voltage is obtained. Therefore by opening or closing the circuit across the control winding, the saturation flux capacity and hence the output voltage may be changed.

Prior to closing the switch and shorting the control winding the flux variation in the controlled section follows the instantaneous secondary voltage. The magnitude of the flux rate of change in the controlled section is determined by the instantaneous secondary voltage and the ratio of the reluctances of the two sections. After the switch in the control winding closes, and thereby shorts the control winding, the flux in the controlled section remains constant because any further changes in flux are prevented by the induced mmf. in the short-circuited control winding.

As a consequence of shorting the control winding and forcing the flux in the controlled section to remain constant, the rate of change of flux in the uncontrolled section must then increase to a level sufficient to maintain the voltage that existed in the secondary winding at the time of switch closure.

The secondary voltage prior to and after switch closure at time t_2, (FIG. 3), must be identical because the resonant capacitor across the secondary magnetic circuit prevents any instantaneous change of voltage. The instantaneous variation of fluxes in the two sections and the control action of the switch and control winding is indicated in FIG. 3. In the drawing, t_1 and t_5 are the times when the flux waveforms pass through zero, t_2 is the time when the switch is closed, and t_4 is the time when the switch is opened.

After the switch closes, the flux in the uncontrolled section continues to increase until the magnetic material in the uncontrolled section saturates. When this occurs, at time t_3, the secondary resonant winding reflects a low impedance to the resonant capacitor and initiates a ring-over cycle that inverts the voltage on the secondary and resonant circuits. As a result of the inversion of the secondary voltage by the capacitor ring-over cycle the rate of change of fluxes reverses and the flux in the uncontrolled section begins to decrease. At time t_4, when the flux in the uncontrolled section decreases to a value approximately equal to the magnitude of flux that existed at the time of switch closure, t_2, the switch is opened. With the switch open the flux in both sections can now change. The total rate of change of flux in both sections is again determined by the instantaneous value of the secondary voltage, and the flux division between the two sections is again given by the ratio of the reluctances. After switch opening the magnitude of the rate of change of flux in the uncontrolled section decreases since the rate of change of total flux before and after switch opening must be identical.

The process then repeats itself in the following half-cycle with the polarity of fluxes and voltages being reversed.

The peak value of the total flux is equal to the peak value of the flux in the controlled section plus the peak value of flux in the uncontrolled section.

By varying the time of switch closure the peak flux in the controlled section is varied, since the flux in this section increases up the time the switch is closed. If the switch is closed at the time of flux zero crossing the peak flux in the controlled section will be approximately zero. If the switch is closed at the time the secondary flux waveform has a maximum, the peak flux in the controlled section will be a maximum and will be equal to the saturation flux capacity of the controlled section.

The peak value of the flux in the uncontrolled section is not affected by varying the switch closing point since the uncontrolled section is driven into saturation each half-cycle.

As a consequence, the peak value of the total secondary flux will vary as the peak value of the controlled flux.

Since the average secondary output voltage is directly proportional to the peak value of the total flux, the magnitude of the average secondary output voltage can be varied by varying the length of the interval when the switch is closed.

Since the device of this invention is operating in the ferroresonant mode and hence the secondary voltage does not ring over until the uncontrolled section saturates, the shorting or opening of the control winding does not introduce a discontinuity in the output voltage waveform. The only effect of shorting the control winding is to cause a change in the amplitude of the waveform over the entire half-cycle.

For operation of the transformer as a voltage regulator, a smooth control between the two conditions is desirable. This may be achieved by shorting the control winding for a certain portion of each cycle or each half-cycle of the primary supply frequency. By varying the duty cycle between open circuit and closed circuit conditions, the output may be smoothly ad-

justed from minimum to maximum voltage. Suitable circuits for effecting this control are illustrated in FIGS. 4 and 7 and 9. FIGS. 4 and 7 are half-wave control circuits and operate once per cycle. FIG. 9 is a full wave control that closes the switch each half-cycle.

The ferroresonant transformer of the invention circulates sizeable mmf. in the control winding. One advantage of the transformer of the present invention is that this mmf. is generated by the transformer in the form of induced current and the control circuit must merely contain a switch capable of carrying this current. No separate power supply is required to supply the mmf. in the control winding.

When the controllable ferroresonant transformer of the invention is used as a closed loop regulator, a method for determining when in the cycle to close the control winding is desired. Most existing phase control methods are troubled with the fact that the instantaneous phase angle of the ferroresonant transformer varies with load changes and varies during dynamic voltage variations in the output. Such phase variations can cause severe instabilities in a phase controlled loop.

A more satisfactory mode of control is the type embodied in the circuit of FIG. 7. In this circuit the control winding voltage is integrated with respect to time and the switch across the control winding is closed when this integrated value reaches the required level. This level is determined by comparing a signal proportional to the output voltage with a reference voltage and amplifying the error signal. By varying the proportionality relationship between the output voltage and the reference voltage, the output voltage amplitude can be adjusted, as by resistors **109** and **110**. The integrator may be reset at the time the short circuit is applied to the control winding so that the integrator will be ready for the next half-cycle.

In some applications, it is only necessary to short the control winding once every cycle instead of every half-cycle because the magnetic core will automatically saturate at the desired time during the other half-cycle. This occurs when a core with square loop material is used in the controlled section of the transformer. Under these conditions, the integrator of the control circuit may be reset at any time between the application of the short circuit and the beginning of the next cycle. A variety of integrators may be utilized, such as a resistor and capacitor circuit, a Miller integrator, an operational amplifier connected as an integrator, a magnetic amplifier, and the like.

Turning now to the embodiment of FIGS. 2 and 4, a core **30** is formed of butt stacked E and I laminations **31**, **32**, respectively. A primary winding **33** is positioned about the center leg **34** of the stack of E laminations. A shunt **35** is positioned between the center leg **34** and the outer leg **36** and a similar shunt **37** is positioned between the center leg **34** and the outer leg **38**. These shunts may be conventional in construction and typically each comprises a stack of laminations.

A secondary winding **41** is positioned about the center leg **34** and a control winding **42** is positioned about portion **44** of the outer leg **38** so that the portion **44** functions as the controlled section of the core and the portion **43** of the outer leg **36** functions as the uncontrolled or saturating section of the core. In the embodiment illustrated, the leg **36** is reduced in cross-sectional area at **43** for the purpose of assuring saturation in this section and the leg **38** is reduced in cross-sectional area at **44** for the purpose of minimizing the induced voltage in the control winding.

In the diagram of FIG. 4, the resonant capacitor **48** is connected across the secondary winding **41**. The AC output voltage on the secondary **41** is converted to a DC control signal voltage at points **49**, **50** by a full-wave rectifier **51** and a filter capacitor **52**. A silicon-control rectifier **53** is connected across the control winding **42** and functions as the switch for opening and closing the circuit across the control winding. An integrator comprising a resistor **54** and a capacitor **55** is connected across the points **49**, **50**. A resistor **56** is connected between the point **49** and the control winding for the purpose of supplying holding current to SCR **53**. A trigger diode **57** is connected between the junction point **58** of the integrator and the control element of the silicon-control rectifier **53**. A resistor **59** is connector from the silicon-control rectifier control element to the point **50** to provide a load to ground for the trigger diode. The trigger diode **57** passes substantially zero current until voltage thereacross builds up to a given level, after which the diode conducts with a relatively low impedance. A typical diode would be an MPT **28**.

In operation, the control rectifier **53** and the diode **57** are initially not conducting. As the output voltage of the transformer builds up, the capacitor **55** is charged through the resistor **54**. When the voltage level at point **58** reaches a predetermined value, the diode **57** conducts, discharging the capacitor **55** into the control rectifier **53** and turning the control rectifier on. The control rectifier remains conducting until the end of the half-cycle when it automatically turns off. The operation is repeated for every alternate half-cycle.

The resistor **54**, the capacitor **55** and the diode **57** function as a relaxation oscillator which normally runs in synchronism with the line frequency under equilibrium conditions. If the output voltage of the transformer increases, the DC voltage at points **49**, **50** increases and the frequency of the relaxation oscillator increases, resulting in an earlier shorting of the control winding **42** and a reduction in the output of the transformer which in turn causes the oscillator to return to synchronism. Similarly, a reduction in the transformer output causes a reduction in frequency of the oscillator and a later closing of the switch **53** with a subsequent increase in transformer output voltage.

A preferred embodiment of this invention is illustrated in FIGS. 11—16, and may be used with the control circuit of FIG. 9. FIG. 11 is an overall view of the complete transformer assembly which includes a magnetic core **300**, a primary coil **301**, a secondary coil assembly **302**, shunts **305** and **306** and gaps **303** and **304** (FIG. 15). The secondary coil assembly includes a resonant winding **307**, a secondary winding **308** and control winding **309** (FIGS. 13 and 16). The secondary magnetic circuit includes a controlled section **310**, and uncontrolled sections made up of **311** and **312** (FIG. 16). To assure saturation in the uncontrolled section **311** and **312**, a window **315** is cut in the tongue of the uncontrolled section (FIGS. 12, 13 and 16). This window **315** reduces the cross-sectional area of the uncontrolled secondary magnetic circuit relative to the cross-sectional area of the outer legs **314** and **313** and the total primary core cross-sectional area of core tongues **316** and **316*a*** and **310**.

The control winding **309** encircles the controlled section **310**. The resonant winding **307** and the secondary winding **308** encircle both the controlled core section **310** and the uncontrolled core section **311** and **312**. The control winding **309** is encircled by secondary coil **308** and the resonant coil **307** encircles both the secondary winding **308** and the control winding **309** (FIG. 16).

FIG. 15 is a view through the magnetic shunt structure. Shunts **305** and **306** appear in plan view and have an L-shape to provide magnetic flux shunting of the primary flux existing in the primary magnetic circuit **316** and **316*a*** and the controlled section core tongue **310**. The primary coil **301** encircles both core tongues **310** and **316**, **316*a***. If the cross-sectional area of tongue **310** is small relative to the cross-sectional area **316**, **316*a***, then the shunts **306** and **305** may be straight sections that only extend the length of the primary core tongue **316**, **316*a***.

FIG. 14 is a view showing the primary coil structure. The primary coil **301** encircles both the controlled section core tongue **310** and the primary core tongue **316**, **316*a***.

The core **300** of the transformer structure is assembled from modified standard E and I laminations. The laminations in stack **320** are only encircled by the resonant winding **307** and secondary **308** winding and consist of standard E's and I's with a window **315** cut at the back of the E. In the stack **321**, space for the control winding **309** is obtained by cutting off a portion

of the tongue of a standard E lamination. The stack **322** is made from the same standard E and I laminations with the center leg **310** of the E reduced in width to receive the control winding **309**.

A particularly simple form of full-wave control for the transformer of FIGS. **11—16** is shown in FIG. **9**. The circuit of FIG. **9** utilizes a Triac for the switch element. Since the Triac operates each half-cycle, the nominal frequency of the relaxation oscillator must be twice the transformer operating frequency.

Diodes **200, 201, 202,** and **203** form a rectifier bridge which rectifies the output of the transformer. This rectified AC is applied to resistor **204** and the anode of rectifier **205**. The cathode of rectifier **205** is connected to capacitor **206**. This capacitor filters the rectified signal to DC. This DC in turn supplies current through resistor **208** to the Zener diode **211** which results in a constant potential appearing on the cathode of the Zener **211**. The DC appearing on capacitor **206** also causes resistor **207** to supply current to capacitor **209** which charges until the firing point of the unijunction **212** is reached. At this point, the unijunction switches to a conducting state which causes the charge on capacitor **209** to be delivered to the control electrode of the Triac **213** which in turn causes the Triac to conduct, shorting the control winding.

The function of resistor **204** and Zener **210** is to supply a synchronizing pulse to the B2 electrode of unijunction **212**. This is accomplished as follows. The rectified voltage out of the bridge is not filtered because rectifier **205** isolates this point from the filter capacitor **206**. As a result, when the AC voltage into the bridge crosses through zero, the voltage out of the bridge drops to zero which stops the current flow in resistor **204**. At this time, the voltage on the B2 electrode of the unijunction **212** is given by the Zener voltage of Zener **211** minus the Zener voltage of Zener **210**. During the remainder of the half-cycle, when the voltage is high, current flows in resistor **204** which causes the Zener **204** to become forward biased. The voltage on the B2 electrode of unijunction **212** is then given by the Zener voltage of Zener **211** plus the forward voltage of Zener **210**. This latter voltage appears during most of the half-cycle but during the zero-crossing period of the AC, the voltage momentarily drops to the former level resulting in a negative pulse on the B2 electrode of unijunction **212**.

Since the firing point of the E electrode of unijunction **212** is a fixed percentage of the voltage on the B2 electrode, reducing the B2 electrode potential reduces the firing point of the E electrode. This will cause the unijunction to fire at this time if capacitor **209** is charged to a potential near the firing level when the voltage on the B2 electrode is at its high level.

In operation, resistor **207** is adjusted such that capacitor **209** will charge to the firing level of the E electrode of unijunction **212** in one-half cycle of the AC period when the DC voltage on capacitor **206** is at the desired potential. If the voltage is too high, the capacitor **209** charges faster, causing the firing angle of unijunction **212** and Triac **213** to advance which in turn reduces the voltage on capacitor **206** until equilibrium is established with the voltage on capacitor **206** at the proper potential for capacitor **209** to charge to the firing level in one-half cycle. Likewise, if the voltage on capacitor **206** is too low, the charging time of capacitor **209** lengthens which retards the firing angle until equilibrium is again established as before.

In the event the transformer is unable to supply the desired voltage, the firing angle is delayed until the following zero crossing of the AC waveform is reached. At this point the previously mentioned synchronizing pulse causes the unijunction to fire which prevents any further delay in the firing angle and the resultant loss of synchronization. A ferroresonant transformer constructed as illustrated in FIGS. **11—16** and operated with the circuit of FIG. **9** at 60 Hz. as a voltage regulator provided substantially constant output voltage (i.e., ±0.3-volts variation at 166.6-volts output) over the range of no load to full load for input voltage variations in the range of 100 to 135 volts.

FIGS. **5** and **6** illustrate alternative constructions for the transformer of the invention particularly suitable for operation at higher frequencies, such as 20 kHz., and utilizing a plurality of toroids for the magnetic core structure. In FIG. **5**, a primary winding **65** is linked through toroids **66, 67** and **68**. A secondary winding **69** is linked through the toroids **67** and **68**. A control winding **70** is linked through the toroid **68**. The resonant capacitor **71** is connected across the secondary winding, and the control circuit **72** provides for closing the switch **73** across the control winding. The cores **67, 68**, comprise the secondary portion of the core structure, with the core **67** corresponding to the uncontrolled section **23** of FIG. **1** and with the core **68** corresponding to the controlled section **24** of FIG. **1**. The operation of the transformer will be the same as described in conjunction with the transformer of FIG. **1** and the transformer of FIGS. **2—4**.

FIG. **6** illustrates an alternative form for the transformer of FIG. **5**. The toroid **67** is replaced by two toroids **67*a***, **67*b*** to provide the desired amount of magnetic material. A compensation winding **74** may be provided on one of the toroids, here the toroid **66**. The compensation winding is used in the same manner as in the conventional ferroresonant transformer as described in some of the aforementioned patents. The toroids of FIGS. **5** and **6** may be formed as unitary molded elements, or pairs of C-cores, or wound ribbons, or in other forms as desired.

FIG. **7** illustrates the use of a ferroresonant transformer as shown in FIGS. **5** and **6**, as the output transformer in a transistor inverter circuit. A typical inverter utilizes a pair of transistors connected in series opposition across a primary winding of an output transformer, with the AC output appearing at a secondary or load winding of the transformer. The DC power source is connected to the junction point of the transistors and to a center tap of the primary winding, and a drive circuit provides a drive current to the transistors for turning the transistors off and on. The drive circuit may be energized from a winding on the transformer providing a self oscillating inverter or the drive circuit may be energized from an external source. The two transistors operate as switches with first one and then the other being closed to connect the DC source current through the transformer primary winding alternating in the positive and negative directions to provide the AC voltage on the transformer. This basic inverter circuit is well known and several variations thereof are shown in U.S. Letters Pat. Nos. 2,990, 519; 3,256,495; 3,317,856; and 3,405,342.

The output of an inverter **80** is connected to the primary winding **65**. The secondary winding **69** is connected to a full-wave rectifier comprising diodes **81, 82** and a filter comprising a capacitor **83** and an inductance **84**, to provide a DC output at the terminals **85, 86**. The resonant capacitor **71** is connected across a portion of the secondary winding **69**.

The DC output voltage is connected to a control circuit **90** via lines **91, 92**. The control circuit **90** includes an integrated circuit component **94** which provides a reference voltage and a DC amplifier, a threshold or trigger device in the form of an unijunction transistor **95**, a switch in the form of a silicon-controlled rectifier **96**, and an integrator comprising a resistor **97** and a capacitor **98**.

The function of the control circuit is to vary the area under the voltage vs. time waveform of the control winding **70**. The reset period occurs in the following half-cycle and will exhibit the same area as the controlled area because a magnetic device will not support a DC unbalance. As a result, it is only necessary to control during one-half cycle out of every cycle. Since the prime objective is to control the area, a means of controlling the firing angle as a direct function of area is used in this control circuit. The basic operation of the circuit is shown in the block diagram of FIG. **8**.

The voltage on the control winding **70** is integrated with time by the integrator **97, 98**. Since the value of the integral is proportional to the area to be controlled, it is only necessary to close the switch **96** when the integral reaches a predeter-

mined level. This triggering function is accomplished by the threshold device **95** which supplies a trigger or drive signal to the switch **96** when the integral exceeds the preset threshold value. In order to obtain control however, it is necessary to vary the area and hence the threshold value. The threshold device has another input which controls the threshold level in proportion to the voltage applied to that input. To provide a control loop, the voltage applied to the other input of the threshold device is derived by comparing the output voltage of the transformer at terminals **85, 86** with a reference voltage and amplifying the resulting error signal with a DC amplifier **94**.

One circuit arrangement suitable for use as the control circuit **90** is illustrated in FIG. **7**. A diode **100** is connected in series with the rectifier switch **96** to enhance the reverse blocking of the switch. Diode **101** is connected across the capacitor **94** of the integrator to limit the swing during the reset period of the control winding to essentially zero so that the integrator will start at zero for the next control interval.

When the voltage on the electrode E of the unijunction transistor **95** reaches a certain percentage of the voltage on the electrode **B2**, usually 60 to 80 percent, the device switches from essentially an open circuit between the electrodes E and **B1** to a very low impedance. This action causes the charge on capacitor **98** to be delivered to the gate or control electrode of the rectifier **96**, firing the rectifier into conduction. The impedance between electrode **B2** and electrode **B1** is substantially reduced during this period and a resistor **102** is included as a current limiting resistor.

The integrated circuit **94** contains a voltage regulator which supplies a fixed reference voltage and contains a DC amplifier. A typical integrated circuit may be a Fairchild μ A723C. Terminals **7** and **8** are the positive input terminals, terminal **5** is the negative terminal, terminal **4** is the reference voltage output and is connected to terminal **3** which is the noninverting or reference input for the DC amplifier. Terminal **4** is used as the return point for diode **101**, capacitor **98**, diode **103**, and rectifier **96**, enabling a reverse bias to be developed on the gate of rectifier **96** and the leakage current of transistor **95** to be bled off by resistor **104**. Diode **103** serves to limit the reverse bias on the rectifier **96**.

Terminal **6** of the integrated circuit **94** is the DC amplifier output and provides the varying control signal voltage for the electrode **B2** of the threshold device **95**. Resistor **108** functions to prevent the voltage on electrode **B2** from becoming so low that the charge from the capacitor **98** is insufficient to fire the rectifier **96**. Terminal **2** of the integrated circuit **94** is the inverting input to the DC amplifier and resistors **109, 110** form a voltage divider which divides the output voltage down to an appropriate level for the amplifier. Terminal **9** is a terminal provided for frequency compensation of the DC amplifier to prevent high frequency instability. Capacitor **111** provides this compensation. Additional frequency compensation is provided by resistor **112**, capacitor **113**, resistor **114**, and capacitor **115**. Capacitor **116** serves to prevent noise from disturbing the reference voltage on terminal **4**.

A ferroresonant transformer connected as illustrated in FIGS. **6—8** operated at 20 kHz. as a voltage regulator provided substantially constant output voltage (i.e., 0.06-volts variation at 30.03-volts output) at no load and at full load for input voltage variations in the range of 20 to 36 volts for a 28-volt rated input.

Thus, it is seen that the objects of the invention are achieved in providing very close control of a ferroresonant transformer utilizing flux switching and without requiring separate power supplies.

The control winding can be used in other ways. By way of example, a mechanical switch may be used to change the output voltage or the operating frequency for a fixed output voltage. By connecting a suitable frequency sensitive impedance, such as a series resonant circuit, across the control winding, frequency compensation can be obtained. The ferroresonant transformer of the invention can be used with any device having an impedance that is dependent on load, line, frequency or other desired parameter, in conjunction with the control winding to obtain close loop control or open loop compensation.

FIG. **10** illustrates the utilization of the transformer of this invention in combination with a saturable reactor to obtain DC load compensation.

The circuit of FIG. **10** utilizes the transformer of FIG. **1** and corresponding elements are identified by the same reference numerals. A full-wave rectifier **225** is connected across the secondary and resonant winding **13**. The rectified output from the rectifier **224** is connected through one winding of a saturable reactor **226** to the load **227**. The other winding of the saturable reactor **226** is connected across the winding **25**.

The saturable reactor **226** offers a low impedance to the control winding **25** when it is saturated and a high impedance during unsaturated periods. Essentially, the reactor functions as a switch. To obtain load compensation, the reactor windings are interconnected in a manner that will cause the conduction period of the saturable reactor to be a maximum at no load and a minimum at full load. With this configuration of elements it is possible to obtain a variety of load compensation characteristics.

We claim:

1. A ferroresonant transformer including a magnetic core structure, a primary winding and a secondary winding,

wherein the core structure with the secondary winding includes two separate sections providing parallel magnetic paths for the secondary and resonant flux;

a control winding on one of said sections; and

switch means for opening and closing a circuit across said control winding, with no current source connected to said control winding whereby the only current in said control winding is self induced current resulting from flux in said one section.

2. 2. A ferroresonant transformer as defined in claim **1** wherein the core structure includes an opening therethrough, with said two sections forming opposite walls thereof.

3. A ferroresonant transformer as defined in claim **1** wherein said core structure includes stacked E and I laminations, with said two sections comprising the outer legs of the E laminations.

4. A ferroresonant transformer as defined in claim **1** wherein said core structure includes at least two groups of stacked E and I laminations, with said two sections comprising the center legs of two different groups of said stacked laminations.

5. A ferroresonant transformer as defined in claim **1** wherein said core structure is formed of a plurality of toroids, with said two sections comprising separate toroids.

6. A ferroresonant transformer as defined in claim **1** wherein said core structure includes three sets of stacked E and I laminations assembled side by side, with the center set inverted with respect to the outer sets, and with said two sections comprising the center legs of the outer sets, respectively.

7. A ferroresonant transformer including a magnetic core structure, a primary winding and a secondary winding,

wherein the core structure with the secondary winding includes two separate sections providing parallel magnetic paths for the secondary and resonant flux;

a control winding on one of said sections; and

switch means for opening and closing a circuit across said control winding as a function of the secondary voltage, with no current source connected to said control winding whereby the only current in said control winding is self induced current resulting from flux in said one section.

8. A ferroresonant transformer as defined in claim **7** wherein said switch means includes a synchronized oscillator.

9. A ferroresonant transformer as defined in claim **7** wherein said switch means includes a phase shifter.

10. A ferroresonant transformer as defined in claim **7** wherein said switch means includes a saturable reactor.

11. A ferroresonant transformer as defined in claim **7** wherein said switch means provides for switching operation every half-cycle of the supply voltage.

12. A ferroresonant transformer as defined in claim 7 wherein said switch means provides for switching operation every cycle of the supply voltage.

13. A ferroresonant transformer as defined in claim 7 including rectifier means connected across the secondary winding for producing a DC control signal voltage; and

said switch means includes a switch element and a control circuit having said control signal voltage as an input for closing said switch element when said control signal voltage exceeds a predetermined magnitude.

14. A ferroresonant transformer as defined in claim 13 in which said control circuit includes an integrator connected for charging from said control winding, and a trigger unit having the integrator output and said control signal voltage as inputs with said trigger unit actuating said switch element at least once each cycle of the supply voltage connected to the primary winding.

15. A ferroresonant transformer as defined in claim 14 in which said integrator comprises a resistor and capacitor circuit.

16. A ferroresonant transformer as defined in claim 14 in which said integrator comprises an operational amplifier connected as an integrator.

17. A ferroresonant transformer including a magnetic core structure, a primary winding and a secondary winding,

wherein the core structure with the secondary winding includes two separate sections providing parallel magnetic paths for the secondary and resonant flux; and

means for varying the saturation flux capacity in the core structure by switching the secondary and resonant flux between a first condition with flux change occurring in both of said sections and a second condition with substantially all of the flux change occurring in one of said sections,

said means for varying including a control winding on the other of said sections, and means for closing and opening a circuit across said control winding, with no current source connected to said control winding whereby the only current in said control winding is self induced current resulting from flux in said other section.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,579,088 Dated May 18, 1971

Inventor(s) TAYLOR C. FLETCHER

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 10, line 11, "224" should read --225--.

Claim 2, line 1, "2.2." should read --2.--.

Signed and sealed this 4th day of January 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Acting Commissioner of Patents