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[54] **CLOSED-LOOP FERRORESONANT VOLTAGE REGULATOR WHICH SIMULATES CORE SATURATION**
7 Claims, 1 Drawing Fig.

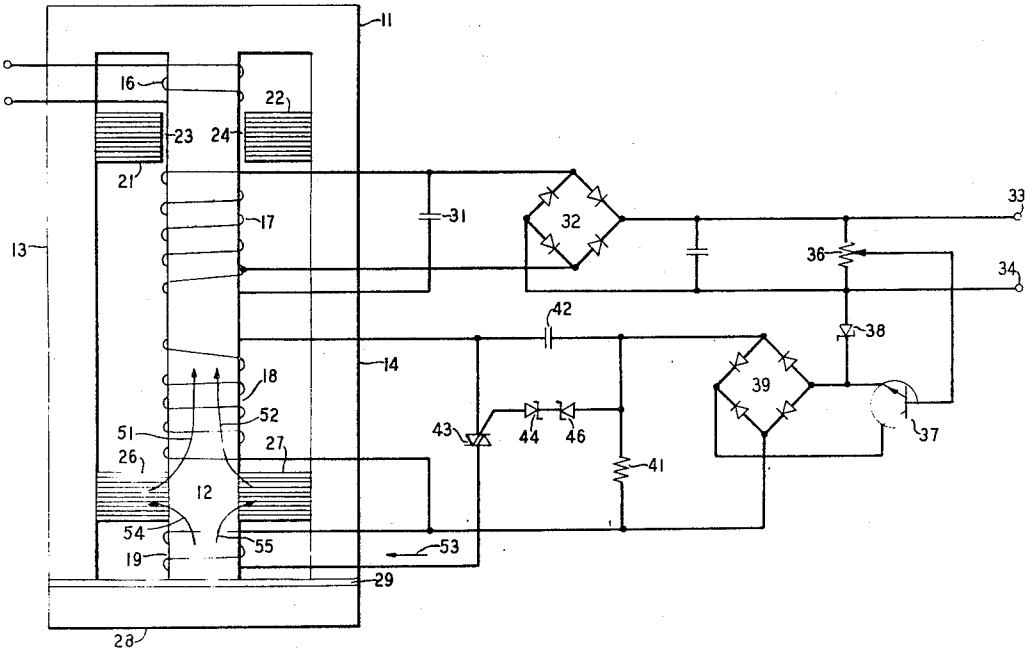
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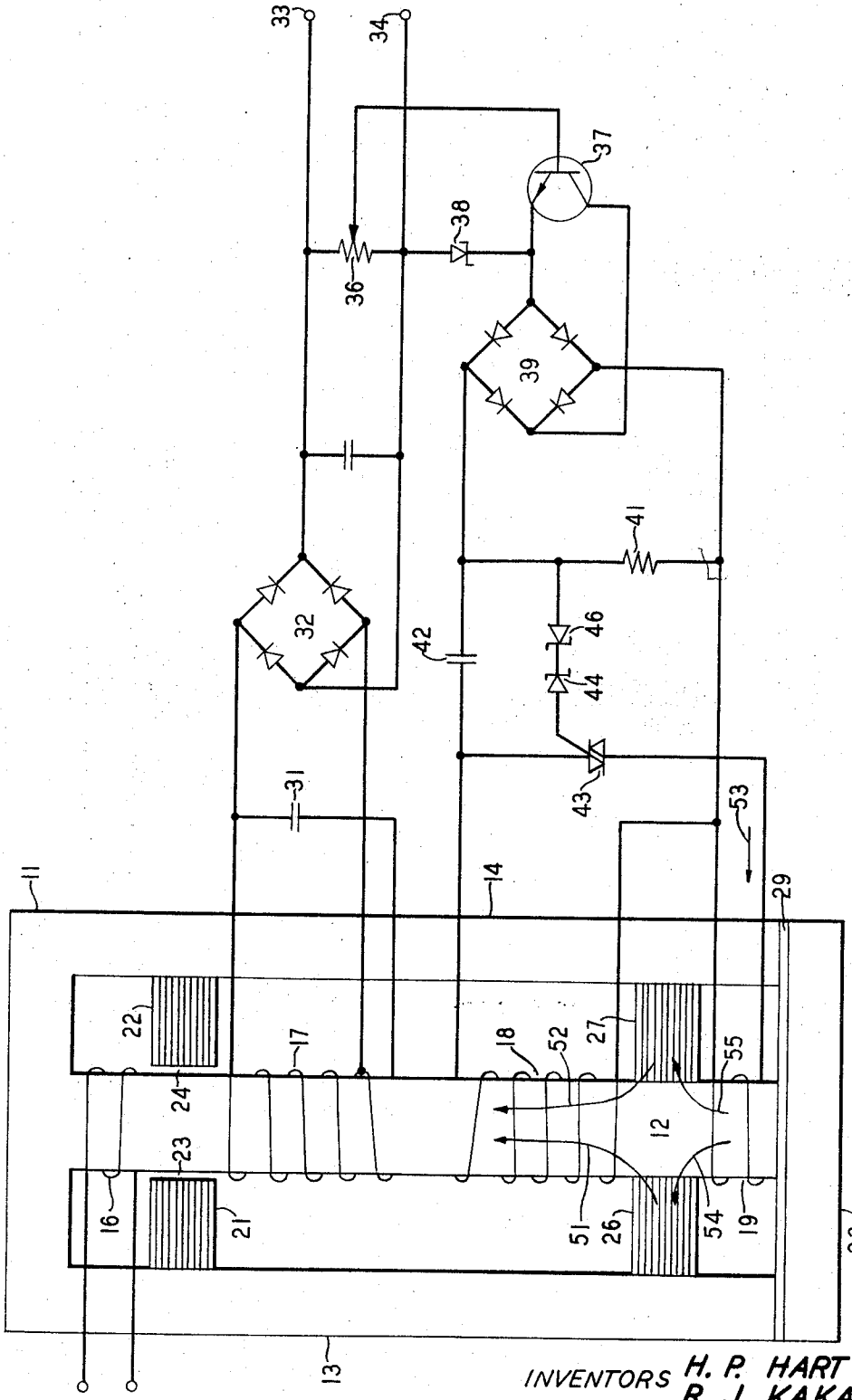
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ABSTRACT: In a ferroresonant voltage regulator of the type in which transformer core saturation is simulated by the switching of a separate inductor effectively across the ferrocapacitor in response to the volt-time integral of output voltage, the separate inductor is incorporated into the main transformer as an "inductance" winding on the output or center leg of three core legs. Unwanted magnetic coupling between the inductance winding and the output winding is substantially eliminated by a magnetic shunt between the windings, and the inductance winding is wound in a direction to minimize the flux in the shunt. The inductance is optimized by the choice of thickness of a nonmagnetic spacer between the transformer core endpiece and the legs.





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CLOSED-LOOP FERRORESONANT VOLTAGE REGULATOR WHICH SIMULATES CORE SATURATION

BACKGROUND OF THE INVENTION

This invention relates to ferroresonant voltage regulating circuits and particularly to those with adjustable output voltage or closed feedback loops.

Ferroresonant voltage regulators are well known and often used because of their several advantages. They are simple and reliable, often consisting of only a transformer and a capacitor. They provide good output voltage regulation with changes in line voltage, input noise suppression, inherent output short circuit protection, good input power factor and a relatively square output waveform that is particularly well suited for rectifying and filtering. Ferroresonant regulators operate on the principle that a saturable transformer core requires a fixed amount of magnetic flux to saturate. Since the voltage induced in a coil is proportional to the time rate of change of flux linking the coil, in the absence of initial bias flux the amount of flux linking the coil at any time is proportional to the integral of the product of coil voltage and time. Upon saturation, no further flux change can occur, and hence induced voltage drops to zero. The volt-time integral of the inducted voltage waveform of a coil wound on a saturating core is therefore a constant. In a ferroresonant transformer circuit, the output winding is wound on a saturating core that saturates every half cycle, and a ferrocapacitor shunts the output winding. Upon core saturation, the output winding presents a low impedance discharge path for the ferrocapacitor to terminate the half cycle of output voltage. As the capacitor discharge decays, the transformer core drops out of saturation, and the output winding represents an inductance which resonates with the ferrocapacitor. The capacitor therefore quickly discharges and recharges in the opposite direction to start a new half cycle of output voltage. The volt-time integral of each half cycle of induced output voltage waveform is therefore a constant, and with a constant input frequency the output voltage is regulated with varying input voltage.

Recently, the ferroresonant regulator has been improved by provision for variation in the volt-time integral of induced output voltage to compensate for changes in load or changes in frequency. According to one such improvement, the transformer core is never allowed to saturate. Instead, an electronic switch connects a relatively small inductor across the ferrocapacitor to provide the low impedance discharge path and resonating inductance formerly supplied by the winding on the saturating core. The switch timing and hence the simulated core saturation can be varied by a feedback loop. This improvement has, however, heretofore required the expense and space of a separate inductor that must for proper operation be held to closer than normal tolerances.

The object of this invention is to provide a new and improved construction of a closed loop ferroresonant regulator that takes less space, costs less to build and is easily adjustable for maximum efficiency.

SUMMARY OF THE INVENTION

In a ferroresonant regulator of the type in which the voltage regulating function normally performed through magnetic switching by a saturating core is performed through electric current switching by an integrating circuit, a switch and a separate inductor, the separate inductor is incorporated into the main transformer as a "inductance" winding on the output or a center leg of three core legs. Unwanted magnetic coupling between the output winding and the inductance winding is substantially eliminated by a magnetic shunt between the two windings, and the inductance of the inductance winding is adjusted for optimum performance by the substitution of nonmagnetic spacers of various thickness between the transformer core end piece and the legs. With this space saving novel structure, the need for interleaving transformer core laminations is eliminated, and the magnetic flux in the shunt generated by the current in the inductance winding can be made to oppose that generated by the input winding to reduce the size and weight of the shunt. Closed-loop regulation may be added by a feedback network responsive to the load voltage for varying the integrating constant of the integrating circuit. Savings in cost, space and weight are therefore realized without the specific of regulation or load carrying capacity.

BRIEF DESCRIPTION OF THE DRAWING

The drawing is a combined schematic and pictorial diagram of a useful embodiment of the invention.

DETAILED DESCRIPTION

In the circuit of the drawing, a transformer core **11** has three legs, a main center leg **12** and two outer legs **13** and **14**, respectively. Wound on the main center leg are: an input winding **16**, an output winding **17**, an auxiliary winding **18** and an "inductance" winding **19**. The inductance winding has been so named because, as will be seen later, although it is a winding on transformer core **11**, it functions as a separate inductance. A pair of magnetic shunts **21** and **22** each of which comprises a stack of core laminations, are disposed between input winding **16** and output winding **17**, and extend from outer legs **13** and **14**, respectively, almost to center leg **12**. Air gaps **23** and **24** separate shunts **21** and **22**, respectively, from center leg **12**. The shunts provide a path for leakage flux to reduce the coupling between input and output windings and the air gap reduces the permeability of the leakage flux path to limit the decoupling defect. A second pair of magnetic shunts **26** and **27** are disposed between auxiliary winding **18** and inductance winding **19** and extend from outer legs **13** and **14**, respectively, to center leg **12** without an air gap. These shunts serve to provide almost complete decoupling between windings **17** and **18** and inductance winding **19**. A magnetic core endpiece **28** is separated from legs **13**, **12** and **14** by a nonmagnetic spacer **29**. A ferrocapacitor **31** is connected across output winding **17** and the AC terminals of a full wave bridge rectifier **32** are connected across a portion of output winding **17**. The DC terminals of bridge rectifier **32** are connected to DC output terminals **33** and **34**. A feedback loop is connected as follows: an output sensing potentiometer **36** is connected across output terminals **33** and **34**. The potentiometer slider is connected to the base of an error detector transistor **37**. The emitter of transistor **37** is connected through a zener diode **38** to the negative output terminal **34**. The emitter-collector path of error detector transistor **37** is shunted by the DC output terminals of a full wave bridge rectifier **39**. The AC or input terminals of bridge rectifier **39** are in turn shunted by an integrating resistor **41**. The series combination of integrating resistor **41** and integrating capacitor **42** are connected across auxiliary winding **18**. Also connected across auxiliary winding **18** is the series combination of inductance winding **19** and an AC semiconductor switch **43**, generally known as a triac.

Triac **43** is a three-terminal bilateral triode switch which is capable of passing current in either direction in response to the application of a relatively low current, low voltage pulse between its gate and cathode terminals. Such a switch is described in detail at pages 142 through 148, 245, and 279 of the text Semiconductor Controlled Rectifiers: Principles and Applications of P-N-P-N Devices by F. E. Gentry et al., Copyright 1964. Obviously, the invention is not limited to the use of this device, however, as any equivalent switching device or combination of switching devices could be substituted therefor in the manner well known in the art. Finally, the control electrode of triac **43** is connected through a back-to-back pair of zener diodes **44** and **46**, respectively, to the junction between integrating capacitor **42** and integrating resistor **41**.

The circuit operates in the manner of a nonsaturating switching type ferroresonant regulator. An AC voltage fed into primary winding **16** produces a corresponding AC voltage across secondary winding **17**. The output from a portion of the

winding 17 is rectified by a bridge rectifier 32 to supply DC to terminals 33 and 34. Of course, if AC output is desired, it may be taken directly from winding 17 or a portion thereof. In a saturating type ferroresonant circuit, the saturating core saturates each half cycle after a fixed volt-time integral of output voltage. When the core saturates, the ferrocapaciter 31 discharges and recharges in opposite polarity through the secondary winding 17 to terminate the output half cycle.

In the nonsaturating switching type ferroresonant regulator, however, core 11 does not saturate. The function of the saturating core is supplied by an inductance and a switch. According to the principles of this invention, the function is supplied by inductance winding 19, triac 43, integrating resistor 41 and integrating capacitor 42. Since winding 18 is closely coupled to winding 17, the voltage across both windings is substantially proportional. The combination of resistor 41 and capacitor 42 integrates the voltage waveform across winding 18 so that the voltage across capacitor 42 is proportional to the volt-time integral of the voltage across ferrocapacitor 31. Since Zener diodes 44 and 46 are connected back-to-back, one is back biased and the other forward biased for each polarity of voltage across the integrating capacitor 42. Each half cycle, therefore when capacitor 42 voltage exceeds the breakdown voltage of the Zener diode that is currently back biased, triac 43 fires to connect inductance winding 19 directly across winding 18. Because of the close coupling between windings 17 and 18, this is equivalent to a connection across output winding 17. Ferrocapacitor 31 consequently discharges through the relatively low impedance of inductance winding 19 and triac 43, and because of the inductance of winding 19 it inherently recharges in the opposite polarity. The reverse breakdown voltage of Zener diodes 44 and 46 together with the values of integrating resistor 41 and integrating capacitor 42 therefore determine the magnitude of volt-time integral at which each half cycle of output voltage is terminated. For symmetry of output waveform and maximum efficiency, Zener diodes 44 and 46 would preferably be identical.

By the incorporation into the transformer of the inductance needed to simulate saturation according to the principles of the invention, significant cost, space and weight savings can be realized. Physically and electrically separate inductors used in electrically switched ferroresonant regulators according to previous teachings, had to include complete magnetic cores. With this integral structure, however, magnetic shunts 26 and 27 do double duty as part of the magnetic circuits of both the transformer and the inductor to eliminate a considerable amount of core material and thereby appreciably reduce the space, weight and cost of the regulator. The relative winding directions of windings 18 and 19 affect the total flux in shunts 26 and 27 and therefore the required shunt cross section area. As will be shown, the smallest cross section can be utilized to effect the greatest savings when the relative winding directions are as illustrated in the drawing. Consider an increasing magnetic flux in center leg 12 in the direction of arrows 51 and 52. This flux is, of course, generated by current in input winding 16 and produces a positive voltage at the top of winding 18 and a negative voltage at the bottom, where it joins winding 19. When triac 43 fires current flows through winding 19 in the direction of arrow 53. This current in turn produces magnetic flux in shunts 26 and 27 in the direction of arrows 54 and 55, respectively. With the auxiliary and inductance windings wound in the direction shown, therefore, the flux from the two sources, input current and inductance winding current, oppose one another in the shunts. As a result, the net flux in shunts 26 and 27 is considerably reduced. Thus, although it is important to have all core parts large enough to avoid saturation that would limit output voltage and spoil regulation, shunts 26 and 27 can be smaller in cross section than legs 13 and 14.

Further cost savings can be realized by the use of this novel structure because of manufacturing methods. In the usual construction of transformers including those used for switching type regulators, three-legged cores are made up of layers, each consisting of an E-shaped lamination and an I-shaped lamination abutting it to close the magnetic circuit. To prevent possible air gaps which greatly increase the current required for a given magnetic flux, the joint between the two laminations is reversed in adjacent layers. Such interleaving of laminations is a costly production process. When a single transformer core is used according to this invention, there is no core saturation and the inductance of winding 19 is relatively low. As a result, no interleaving is required. The core can be made up of a stack of E-shaped laminations; the shunts may be inserted as individual lamination stacks and the core end piece 28 may be attached as a separate stack.

For optimum performance, the inductance of winding 19 is fairly critical. It must be low enough to provide fast switching and almost square output waveform, yet high enough to allow triac 43, which is a relatively slow switching device, to operate properly. Normal inductor tolerance is too wide for such an application. However, with the construction of the present invention, a nonmagnetic spacer 29 can be quickly and easily inserted between core endpiece 28 and the core legs. Since thickness of the spacer affects the value of inductance, the present regulator may easily be peaked for optimum performance by the single substitution of spacers of different thickness. The feedback circuit operates to close the regulator loop by varying the effective integrating resistance as a function of output voltage. The AC voltage appearing across resistor 41 is rectified by bridge 39 and appears across the collector-emitter path of transistor 37. Zener diode 38 holds the emitter to a constant reference voltage with respect to output terminal 34. Changes in output voltage appearing between terminals 33 and 34 appear also in proportion, according to the setting of the tap of potentiometer 36, on the base of transistor 37 to vary the transistor's bias. As this bias is thus varied because of a change in output terminal voltage, the conductivity of the collector-emitter path which effectively shunts resistor 41 is varied and therefore the integrating resistance. For a greater range of integrating resistance and more gain in the feedback loop, resistor 41 may be eliminated entirely. Transistor 37 then would become the integrating resistor. As the output voltage tends to rise because of, for example, a sudden decrease in load, transistor 37 becomes more conductive to lower the effective integrating resistance. This causes capacitor 42 to charge more quickly and limits the half cycle of output to a lower volt-second integral, thereby lowering output voltage. Regulation against changes in load and frequency is thus achieved.

In summary, thus, according to this invention, a high degree of voltage regulation may be obtained with a simple circuit using only one transformer core. That core is considerably lighter in weight and more compact than the previously required two cores. In addition, the single core is appreciably less expensive to assemble, and is readily adjustable for optimum performance. In short, this invention provides advantages in cost, space, weight and performance.

We claim:

1. Voltage regulating apparatus comprising a transformer core having three legs and two magnetic end sections, each end section bridging a corresponding end of said three legs to form a closed magnetic structure, an input winding, an output winding, an inductance winding, each of said input, output and inductance windings being wound on the center leg of said three legs, a first magnetic shunt means disposed between the outer two legs of said three legs and the portion of said center leg between said input and said output windings to reduce the mutual magnetic coupling between said input and said output windings, second magnetic shunt means disposed between said outer two legs and the portion of said center leg between said output winding and said inductance winding to substantially eliminate the mutual magnetic coupling between said output winding and said inductance winding, a ferrocapacitor coupled to said output winding, an AC voltage source connected to said input winding, a load coupled to said output winding, an integrating circuit including an integrating capaci-

tor coupled to said output winding for developing a voltage proportional to the volt-time integral of the voltage across said ferrocapacitor, and switching means connected to said integrating capacitor and said inductance winding to intermittently couple said inductance winding to said output winding in response to the voltage across said integrating capacitor and thereby reverse the charge on said ferrocapacitor.

2. Voltage regulating apparatus as in claim 1 including nonmagnetic spacing means disposed between the one of said core endpieces nearest said inductance winding and said three core legs whereby the inductance of said inductance winding may be adjusted.

3. Voltage regulating apparatus as in claim 1 including an auxiliary winding wound on said center transformer core leg closely coupled to said output winding, wherein said load is connected across at least a portion of said output winding, said integrating circuit is connected across said auxiliary winding, and said switching means operates to connect said inductance winding across said auxiliary winding.

4. Voltage regulating apparatus as in claim 1 wherein said switching means comprises an AC semiconductor switch having a conducting path connected in series with said inductor and a gating path connected across said integrating capacitor.

5. Voltage regulating apparatus as in claim 1 including feedback means responsive to the voltage across said load and connected to said integrating circuit and across said load to vary the charging rate of said integrating capacitor.

6. Voltage regulating apparatus as in claim 5 wherein said integrating circuit includes an integrating resistor, and said feedback means comprises an error detector connected across said load for producing an error voltage proportional to the difference between the voltage across said load and a reference voltage, a full wave bridge rectifier having a pair of AC terminals connected across said integrating resistor and a pair of DC terminals, and unidirectional conductive means responsive to said error voltage connected across said DC terminals.

7. Voltage regulating apparatus as in claim 3 wherein said inductance winding, said switching means, and said auxiliary winding are interconnected in such polarities that the flux in said second magnetic shunt means generated by the current in said inductance winding opposes the flux in said second shunt means generated by the current in said input winding whereby the required size of said second shunt means is reduced.