Dec. 8, 1970 T. C. FLETCHER ET AL 3,546,571

CONSTANT VOLTAGE FERRORESONANT TRANSFORMER UTILIZING UNEQUAL AREA CORE STRUCTURE

Filed June 21, 1968

FIG. 1.

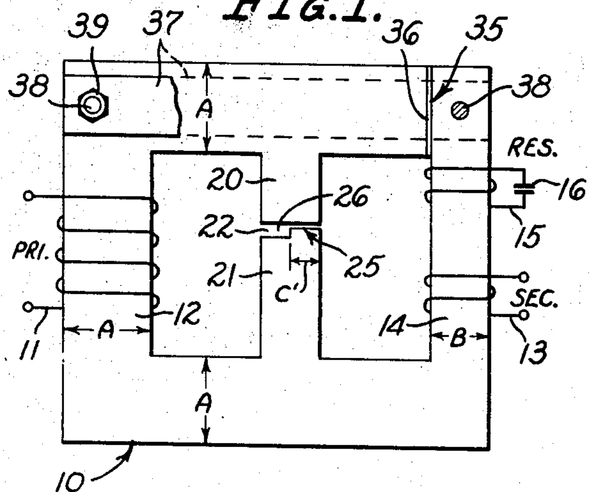


FIG. 2.

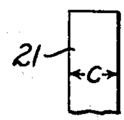


FIG. 3.

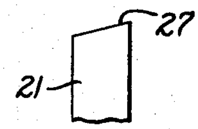


FIG. 4.

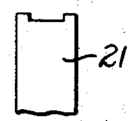


FIG. 5.

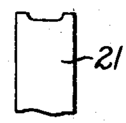


FIG. 6.

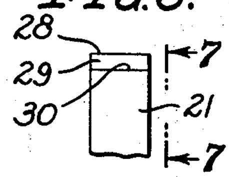


FIG. 7.

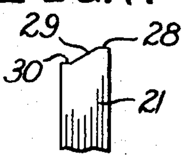


FIG. 8.

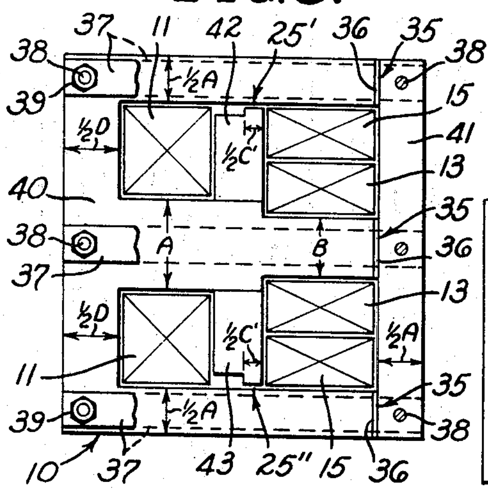


FIG. 9.

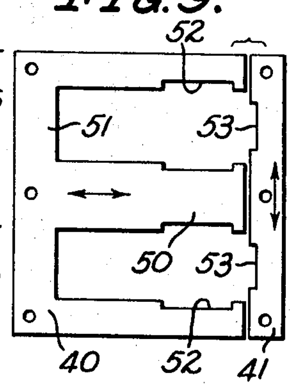


FIG. 10.

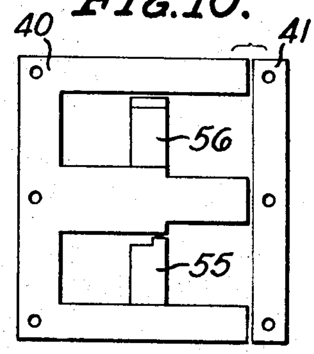


FIG. 11.

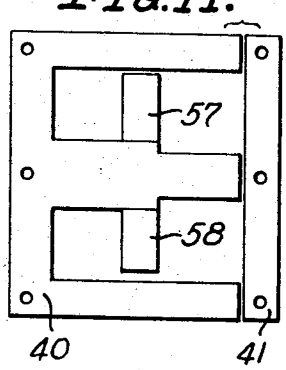


FIG. 12.

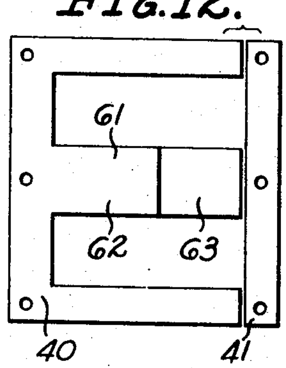
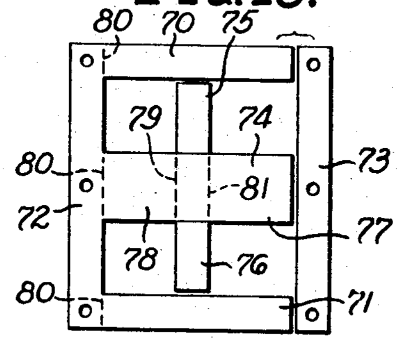


FIG. 13.



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CONSTANT VOLTAGE FERRORESONANT TRANSFORMER UTILIZING UNEQUAL AREA CORE STRUCTURE

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ABSTRACT OF THE DISCLOSURE

A ferroresonant transformer with unequal primary and secondary saturation characteristics for operation with smaller capacitance and smaller resonant winding, a shunt which saturates as the load increases, an adjustable gap for matching core and capacitance, and a grain oriented design with selected core dimensions for controlling location of flux saturation.

This invention relates to new and improved transformers of the type sometimes referred to as ferroresonant transformers, and in particular to new and improved core designs.

The basic ferroresonant transformer is described in United States Letters Patent No. 2,143,745, issued to Joseph G. Sola, Jan. 10, 1939. Various improvements in ferroresonant transformer design are described in subsequent patents, many of which have issued to said Joseph G. Sola. Transformers of this type are widely used today as voltage regulators and the selection of a particular design for use depends primarily upon the performance or regulation achieved and the cost. The cost in turn depends primarily upon the amount of electrical iron in the core, the amount of copper in the windings, and the size of the capacitor. It is an object of the present invention to provide a new and improved ferroresonant transformer design which will permit reduction in the size of the unit and the material required to meet a given set of performance specifications. A further object is to provide a new and improved design which achieves improved stability and improved load regulation and which permits a wider tolerance range for capacitors used with the resonant winding.

It is a particular object of the invention to provide a new and improved design utilizing E and I laminations with grain oriented material and butt stacking and hence reduce manufacturing costs.

The invention contemplates a ferroresonant transformer with the cross-section areas and/or materials of various portions of the core selected so that saturation occurs in specific predetermined locations for specific operating conditions. The invention further contemplates such a transformer with the flux capacity of the primary magnetic circuit greater than the flux capacity of the secondary magnetic circuit. The invention also contemplates selection of shunt gap configuration and an additional gap of controlled width and designs particularly adapted for butt stacked assembly and grain oriented material.

The invention also comprises novel details of construction and novel combinations and arrangements of parts which will more fully appear in the course of the following description. The drawings merely show and the description merely describes preferred embodiments of the present invention which are given by way of illustration or example.

In the drawings:

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

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FIGS. 2–6 show alternate configurations for the shunt portions of the transformer core;

FIG. 7 is a side view of the shunt of FIG. 6;

FIG. 8 is a view of an alternative form of construction of a ferroresonant transformer incorporating a preferred embodiment of the present invention; and

FIGS. 9–13 show alternate configurations for the transformer core of FIG. 8.

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. A particular type of core construction with butt stacked laminations and grain oriented material is shown in FIG. 8 and will be described later. 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**. Another winding **15**, referred to as the resonant winding in a ferroresonant transformer, is also provided on the leg **14**. A capacitor **16** is connected across the resonant winding **15**.

A leakage flux path is provided in the core **10** between the primary winding **11** and the secondary and resonant windings **13**, **15**, 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 transformer such as is described in the aforementioned Sola patent 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, 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. The capacitance of the capacitor **16** is selected to provide the proper output voltage and, in conventional units, the magnitude of the capacitance must be selected within close tolerances in order to achieve desired operation.

In one embodiment of the transformer of the invention, the cross-section area of the portion **12** of the core encircled by the primary winding **11** is made greater than the cross-section area of the portion **14** of the core encircled by the secondary winding **13**, that is to say, the dimension A is made greater than the dimension B. Best results are achieved when the portion **12** is in the order of 20 to 60 percent greater in cross-section area than the portion **14**. The figure selected for a particular unit will depend upon the specifications prescribed for the unit, such as the input voltage range, the input power factor and the short circuit current. This core size variation permits less core material, less copper, and a smaller resonant capacitor than conventional units with the same performance characteristics.

The secondary flux (the flux in the core portion **14**) is divided into two components. One component is that which links the primary magnetic circuit, the other is that which returns through the magnetic shunt. At no load, the mmf. required to drive the flux around the secondary loop is given by the algebraic sum of the excitation requirements of the saturated secondary core and the mmf. drop across the gap in the magnetic shunt. This mmf. must be supported by a current in a winding linking the secondary magnetic circuit, in this case, the resonant winding.

Since the magnetic shunt is common to both primary and secondary magnetic circuits, the mmf. appearing across the shunt gap must also be supported by a current in the primary winding. By reducing the flux returning to the secondary through the shunt, the current demands of both the primary and resonant windings may be reduced.

This flux returning through the shunt may be decreased by increasing the amount of flux that links the primary. In order to prevent saturation of the primary magnetic circuit it is necessary to increase the cross-sectional area of the core in the primary magnetic circuit as the primary flux is increased.

The primary flux may be increased until the flux in the shunt is reduced to zero. At this point, further increase in primary flux causes an increase in shunt flux in the opposite direction as was previously encountered. This new shunt flux causes a further reduction of the required current in the resonant winding because of the algebraic addition of the mmf. drops around the secondary magnetic circuit. However, the current in the primary winding must increase in magnitude as the flux and hence the mmf. across the shunt is increased. As a result, an optimum balance between resonant va. (volt amperes) and primary va. is achieved with primary to secondary area ratios on the order of 1.2 to 1.6, depending on specific design requirements. A transformer designed to these requirements and having good regulation will require a ratio of resonant va. to load va. in the range of about 0.5 to about 1.5. An example of good regulation would be a transformer supplying rectifier loads with capacitor input filters and having regulation of $\pm 2\%$ to $\pm 5\%$ for line and load. If a poorer performance is acceptable in the transformer of the invention for a particular end use, the ratio of resonant va. to load va. may be in the range of about 0.3 to about 0.8. In comparison, in a transformer of the conventional design with comparable performance, the ratio is twice as much.

Primary, resonant, and load va. as discussed in the preceding paragraph, are determined at rated load. Resonant va. is the reactive power circulating in the resonant winding at rated load. The load va. for a particular unit will be set by the rating of the unit. The resonant va. is determined by the secondary mmf. and the secondary volts-per-turn. Since the utilization of a greater primary core cross-section area permits an optimum balance between primary mmf., shunt mmf., and secondary mmf., it is readily seen that the core design of the present invention permits a reduction in capacitor size. Typically, a reduction in the order of one-half. This is a significant improvement since a typical ferroresonant regulator of conventional design operating at 60 Hz. and rated at 500 watts, requires a capacitor of 7 microfarads and 600 volts. The capacitor current circulates in the resonant winding and determines the size of the winding. The reduction in resonant va. of the present design permits a corresponding reduction in the physical size and cost of the resonant winding.

In the embodiment illustrated in FIG. 1, the gap **22** in the shunt portions **20, 21** of the core, is stepped providing a minimum gap portion **25** and a gap portion **26** of greater width. The cross-section area of the shunt portion of the core at the minimum gap **25** is made less than the cross-section area of the portion **14** of the core encircled by the secondary winding **13**. That is to say, the dimension C′ is made less than the dimension B. With this construction, the core material saturates in the region of minimum gap **25** as the load on the transformer increases and serves to reduce the leakage reactance as the load increases, permitting stable operation at light loads and providing good regulation at heavy loads.

In ferroresonant voltage regulators where a large portion of the excitation for saturation of the secondary portion **14** of the core is provided by the primary winding instead of by the capacitor **16** or resonant winding **15**, there is a tendency for the wave form of the output voltage to be unstable and switch to different modes of operation at light loads. These other modes typically appear as an oscillation superimposed on the source frequency output or the generation of a large number of even harmonics in the output. Such oscillations and harmonics may be suppressed by increasing the leakage reactance which isolates the primary winding from the secondary winding by utilizing a shunt with a relatively narrow gap. However, this configuration adversely affects the ability of the transformer to operate satisfactorily at high loads. The shunt design described herein provides a solution for this problem by permitting operation with a minimum gap at light loads and producing saturation and thereby a reduction in leakage reactance with heavier loads. In a typical unit, the minimum gap may be in the order of three thousandths of an inch and the maximum gap may be in the order of forty thousandths of an inch.

A number of alternative configurations for the shunt, which will provide the desired result, are shown in FIGS. 2–7. In the configuration of FIG. 2, the gap has a uniform width with the gap end of the core portion **21** being flat and square, with the dimension C less than the dimension B. In the configuration of FIG. 3, the gap end of the core portion **21** is made flat and tapered, with the minimum gap occurring at the corner **27**. FIGS. 4 and 5 show two other forms of stepped gap designs for the core portion **21**, with FIG. 4 showing a sharp transition from minimum gap to maximum gap and FIG. 5 showing a gradual transition. FIGS. 6 and 7 shows another form with a flat minimum gap portion **28**, a tapered or bevelled portion **29**, and another flat maximum gap portion **30**.

Another nonmagnetic gap **35** may be incorporated in the core in the secondary flux path. The width of this gap is adjustable and typically this may be accomplished by placing one or more shims **36** of nonmagnetic material in the gap and affixing a clamp around the core to force the core portions against the shims. The shims **36** may be made of any suitable nonmagnetic, electrical nonconducting material, such as epoxy glass, mica or paper. A conventional core clamp comprising straps **37** held in place on opposite sides of the core by bolts **38** and nuts **39** passing through holes in the core, may be used to clamp the shims **36** in the gap **35**.

In the manufacture of a ferroresonant transformer, the capacitance of the capacitor **16** must be matched to the particular core and coils in order to obtain the desired output voltage and output voltage regulation. The desired output voltage is ordinarily achieved by placing a very close tolerance on the capacitance, which of course requires a more expensive capacitor. In the transformer of the present application, the nonmagnetic gap **35** provides an effective shunt inductance producing an inductive current which cancels a portion of the capacitive current, thereby changing the effective value of the capacitor. By varying the width of the gap **35**, the effective inductance, and hence the capacitance, may be varied. With this construction, the actual value of capacitance of the capacitor **16** may vary over a wide range. The transformer is assembled in the usual manner with the capacitor connected to the resonant winding. A power source is connected to the primary winding and a load is connected to the secondary winding. The thickness of the shims **36** and the gap **35** is varied until the desired output voltage is achieved, after which the shims are permanently clamped in place.

A preferred form of core and coil arrangement, which incorporates the features of the embodiment of FIG. 1 and some additional features, is illustrated in FIG. 8, where elements corresponding to those of FIG. 1 are identified by the same reference numerals. The core **10** is formed of butt stacked E and I laminations **40, 41**. The windings **11, 13** and **15** are positioned about the center leg of the E laminations and are enclosed by the two outer legs. After the primary winding **11** is placed in position, lamination stacks **42, 43** are placed in position to serve as the shunts, with air gaps **25′** and **25″**. The shunt portions **42, 43** may be held in place by nonmagnetic, electrically nonconducting shims in the air gaps. The windings **13, 15** are placed in position, one or more of the gaps **35** are appropriately shimmed with nonmagnetic material, and the two portions **40, 41** of the core are clamped together.

In the core of the structure of FIG. 8, the cross-section area encircled by the primary winding is made greater than the cross-section area encircled by the secondary winding by making the dimension A greater than the dimension B, typically in the order of 20 to 60 percent greater. The cross-section area of the shunt portion of the core at the minimum gap is made less than the cross-section area of the core encircled by the secondary winding by designing the shunt portions **42, 43** in the same manner as the shunt portion **21** of FIG. 1. The various gap constructions illustrated in FIGS. 1–7 may be utilized in the core of FIG. 8. The width of the gap **35** in the core of FIG. 8 is adjusted in the same manner as the gap **35** in the core of FIG. 1 to match the coil and core to the capacitor which is connected across the resonant winding **15**.

The E and I laminations of the core of FIG. 8 preferably are made of grain oriented electrical iron sheet, with the grain orientation as indicated by the double arrows in FIG. 9. A grain oriented electrical iron has a superior magnetic characteristic with flux along the orientation and a poorer characteristic at 90° to the orientation or "cross-grain." In the transformer of FIG. 8 utilizing the grain oriented material, the cross-section areas in the secondary portion of the core are selected such that the cross-section area in a portion where the flux is parallel to the orientation is made less than the cross-section area in the portions where the flux is perpendicular to the orientation. As illustrated in FIG. 8, in the secondary portion of the core, the dimension B is made less than the dimension A. With this construction, the core first saturates in the portion with the dimension B where the flux is parallel to the grain orientation. Referring to FIG. 9, the saturation occurs in the zone **50** before it occurs in the I lamination adjacent the air gaps between the E and I. With this arrangement, the sharp knee in the magnetization curve of the grain oriented material is retained in the laminations comprising the core, which is not the case when saturation occurs in the cross-grain sections in the I at the air gaps. Rounding of the knee of the saturation curve adversely affects the regulating properties of the magnetic material at low excitations, thereby requiring more excitation which in turn consumes some of the volt-ampere capacity of the transformer. Of course, the difference in cross-section area required to achieve the desired selective saturation will depend upon the magnetic characteristics of the particular material utilized.

In the laminations illustrated in FIG. 9, the reduced area **50** does not extend to the end of the center leg of the E, which is the ideal situation. In the preferred form of FIG. 8, the section B corresponds to the reduced section **50** of FIG. 9 and does extend to the end of the center leg, providing more space for the secondary and resonant windings, with a slight reduction in performance. However, with this construction, the portion B can be used to meet the condition that the cross-section area encircled by the primary winding be greater than the cross-section area encircled by the secondary winding and meet the condition that in the secondary portion of the core, the cross-section area in the cross-grain flux portions be greater than the cross-section area in a parallel flux portion.

Referring again to FIG. 9, it should be noted that initial saturation in a parallel flux location can also be achieved by providing the reduced area in the outer legs of the E, as at **52**, or in the I, as at **53**.

Another feature used with the grain oriented laminations of FIG. 8 is the relation between the dimensions D and A, where D is that portion of the core with flux perpendicular to the grain orientation or cross-grain, and A is that portion of the core with the flux parallel to the grain orientation or with-grain. The cross-section area of the core in the cross-grain portion and the cross-section area of the core in the with-grain portion are selected so that the product of cross-section area and saturation flux density for the two portions are substantially equal. The exact dimension will of course depend upon the cross-grain saturation flux density and the with-grain saturation flux density of the particular material utilized. In the typical transformer incorporating this feature, the dimension D will be about 25 percent greater than the dimension A. With this construction, no one portion of the primary magnetic circuit (except for the shunt) will start to saturate before another part. Thus, the magnetizing current in the primary winding is reduced to a minimum permitting a reduction in the total amount of iron and copper required in the transformer for a particular rating.

The shunts **42, 43** may be manufactured and installed in the same manner as in the conventional ferroresonant transformer. Typically, the two shunts are manufactured separately and are installed after the primary winding has been installed on the E portion of the core. The shunts may be made of laminations or of solid material or may be molded or may be a sandwich construction of different materials. Typically, the shunt is butt joined to the core at one end with a gap at the other. The gap may be at either end or some gap may be provided at each end. The various configurations illustrated in FIGS. 1–7 may be used. Other configurations will readily come to mind. The basic concept in the shunt design is to provide a change in reluctance in the magnetic path in the shunt by saturation only in a portion of the shunt for a particular operating condition. The shunts may be oriented as shown in FIG. 8. Alternatively the shunts can be turned 180° as illustrated in FIG. 10, Item **55**, or turned 90° as illustrated in FIG. 10, Item **56**. The desired saturation characteristic may be obtained by making both shunts with the same cross-section area and of the same material and with the same end configuration, but with one longer than the other, as illustrated in FIG. 11. The shunt **57** with the smaller gap will experience saturation before the shunt **58** with the larger gap. Alternatively, the shunts **57** and **58** may be identical in size and shape, but made of materials having different flux capacities.

An alternative construction for obtaining the reduced core area in the secondary portion of the core is illustrated in FIG. 12. Here the center leg **61** of the E **40** has a uniform width along its entire length, as in the conventional ferroresonant transformer. However, the outer ends of the center leg **61** of a number of the laminations are removed, so that the thickness of the portion **62** on which the primary winding is positioned is greater than the thickness of the portion **63** on which the secondary and resonant windings are positioned. The approach of removing portions of laminations also may be used in other sections of the core for cross-section area control.

The structures described thus far have incorporated selected variations in core cross-section area for causing saturation to occur at predetermined locations and/or under predetermined operating conditions. The discussion of operation shows that it is the saturation characteristic of the core and not the core size per se, that is the key to the superior results obtained with the transformer of the present invention. It should be noted that the saturation characteristics of the present invention can readily be obtained using the core dimensional relation of the conventional ferroresonant transformer, but with various core components formed of materials having different flux capacity. Flux capacity may be defined as the product of the flux density at which the material saturates times the cross-sectional area.

By way of example, see the core of FIG. 13. The legs **70, 71**, back **72**, and I **73** are the same width and are half the width of the leg **74**. The shunts **75, 76** are rectangular and the same size. However, the secondary portion of the center leg **74**, which could be either portion **77** or portion **78**, is made of a material having a lesser flux capacity than the material of the primary portion. The two portions are butt joined, as at the dashed line **81** if **77** is the secondary portion, or at the dashed line **79** if **78** is the secondary portion. One of the shunts is made of a material having a different flux capacity than the material of the other shunt. Alternatively, one or both shunts could be made of a sandwich of two or more materials having different flux capacities. Thus the operating characteristics of the invention are obtained. This form of construction usually will be more expensive than that of FIG. 8. The design approach of FIG. 13 is more likely to be used with molded cores instead of laminations, as in higher frequency applications.

Ferroresonant transformers utilizing the construction described above have been built for use as voltage regulators and require less iron and copper, utilizing smaller capacitors with wider tolerances on capacitance, and are less expensive to manufacture, while meeting the same performance specifications as conventional ferroresonant transformers. While it is preferred to incorporate all of the features described above in each transformer, it should be noted that transformers can be produced utilizing one or more of the features without incorporating all of the features to obtain certain of the advantages and improved results.

Most of the specification discusses cores formed of laminations of magnetic material, but it should be noted that many of the features of the invention are equally applicable to solid cores and molded cores. Molded construction is particularly suitable for forming shunts of the types shown in FIGS. 3, 4, 5, and 8.

In FIG. 8, the secondary and resonant windings are installed after the primary winding because of better space utilization, but this configuration is not essential and the positions can be reversed if desired.

The present specification discloses a ferroresonant transformer whose cross-sectional area in the primary is larger than the cross-sectional area in the secondary and whose resonant va. is near the load va., permitting a substantial reduction in core size, winding size, and capacitor size.

The ferroresonant transformer may include a magnetic shunt or shunts wherein part of the shunt or shunts will saturate as the load increases. This enables one to use a smaller resonant capacitor and resonant winding while maintaining the transformer stability over a wide voltage and load range. The saturating shunt enables the ferroresonant transformer to be designed so that it has a high input leakage reactance at light loads yet will deliver full load when required. For example, the leakage reactance can be made such that at currents well below full output all of the input voltage would have been dropped completely across the input leakage reactance thus causing the complete collapse of the secondary voltage. With the saturating shunt the effective leakage reactance decreases as the load is increased. This is accomplished by saturating a portion of the shunt as the load is increased. This increases the effective magnetic reluctance of the shunt which in turn decreases the input impedance. Thus the effective voltage applied to the secondary voltage can be made to actually increase by applying a load to the secondary. This provides a means for compensating for load variations. The saturating shunt design permits circulation of a relatively small amount of reactive power at light load, thus providing a transformer with improved power factor under light load conditions.

The ferroresonant transformer may use grain oriented material whose primary magnetic cross-sectional area is designed to keep the product of the saturation flux density and the cross-sectional area of the core a constant. For example, using M6 EI laminations in a butt stack configuration, the cross grain material i.e. the back of the E, will have about 25 percent greater cross-section area than will the legs of the E.

The ferroresonant transformer may have in the secondary magnetic circuit one or more sections which saturate while the remainder of the secondary magnetic circuit re-

mains unsaturated. By making the length of the restriction where saturation occurs short, it requires a minimum of mmf. to cause saturation and thus regulation. By making the saturating section of grain oriented material such as M6 and oriented with the flux parallel to the grain, it will saturate extremely sharp thus giving better regulation properties. By using a relatively short restricted section the losses in the core will be less, as the zone with very high flux density will be confined to a small volume. An increase in the length of the portions of the core which saturates increases the mmf. required to cause saturation and the residual inductance after saturation (caused by flux in what is now essentially an air gap, the saturated section) is decreased and the regulation with changes in input voltage is improved.

The secondary of the ferroresonant transformer may have an adjustable air gap which provides means of adjusting the output voltage for variations in core material and/or variations in the resonant capacitor value. One example is a butt stacked EI lamination wherein the gap between the E and the I provides the voltage adjustment. The gap typically is adjusted by inserting nonmagnetic, nonconducting shim material between the E and I.

For clarity of presentation, this disclosure has not discussed the utilization of compensation windings for improving the line, load, or line and load regulation characteristics. These conventional compensation windings do not alter the inherent advantages of the present invention but merely provide a means for obtaining improved regulation with a given design or equivalent regulation with a smaller transformer. As in the prior literature, the compensation winding or windings may be located in the primary magnetic circuit or the leakage flux magnetic circuit or both. The method of interconnection of the winding with the secondary output winding is identical to the methods used in conventional constant voltage transformers.

By way of example, data is provided herein on two transformers designed to meet the same performance specification, one being of conventional design (No. 1) and the other utilizing features of the present invention (No. 2). Both transformers were fabricated from identical EI–175 laminations, with a stack height of 4.125″ for No. 1 and 2.60″ for No. 2. The outer end of the center leg of the E for No. 2 was reduced in width from 1.75″ to 1.306″ for a distance of 1.07″, giving a ratio of primary to secondary core cross-section area of 1.34. The shunts are formed of the same material and the shunts for No. 2 have the configuration of FIG. 4, with a minimum gap at each side of .003″ and a maximum gap of .040″, with the minimum gap .336″ long on each end of the shunt. The gap for No. 1 is .019″ at each side. The center leg of the E for No. 2 was reduced from 1.75″ to 1.40″ over the entire length of the center leg. The rated primary voltage is 107 to 127 volts, and there are two secondaries of 24 volts each, one having a center tap. The winding data is tabulated in Table I. The performance of both units is set out in Table I. No. 2 used .445 the effective capacitance and about 63 percent the iron of No. 1. While the two capacitors have the same capacitance, the applied voltage is reduced by one-third for No. 2. If the capacitor for No. 2 was operated at 600 volts, the capacitance could be reduced to 3.1 μf.

TABLE I

	Transformer No. 1	Transformer No. 2
Lamination stack height	4.125″	2.60″.
Capacitor	7 μf. 600 v	7 μf. 400 v.
Primary winding	78 turns #15	88 turns #15.
#1 Secondary winding	12 turns #13	22 turns #13.
#2 Secondary winding	do	Do.
Resonant winding	308 turns #12	358 turns #20.
Weight-Primary winding	1.0 lb	1.0 lb.
Weight-Secondary and Resonant windings.	2.62 lbs	1.97 lbs.
Weight-Completed transformer	25.06 lbs	16.62 lbs.

TABLE I.—Continued

PERFORMANCE (INCLUDING RECTIFIER AND CAPACITATOR INPUT FILTERS)

	Transformer No. 1	Transformer No. 2
(1) Regulation combined for input voltage variation 107–127 volts and output load from 135 to 437 volts:		
+24 volt output	±3.6%	±2.65%.
+12 volt output	±3.0%	±2.05%.
−12 volt output	±1.6%	±0.75%.
(2) Peak input current under normal operation.	5.4 amps rms	5.8 amps rms.
(3) Short circuit current:		
+24 volt output	30.2 amps	27.8 amps.
+12 volt output	60.8 amps	55.1 amps.

The terms "primary portion," "secondary portion" and "shunt portion" are used in the specification and claims in referring to the magnetic circuits and core. Primary portion is defined as that portion of the core which carrys the primary flux, i.e., the flux that links the primary winding. Secondary portion is defined as that portion of the core which carrys the secondary flux, i.e., the flux that links the secondary and resonant windings. Shunt portion is defined as that portion of the core which carrys the difference between the primary and secondary fluxes.

Although exemplary embodiments of the invention have been disclosed and discussed, it will be understood that other applications of the invention are possible and that the embodiments disclosed may be subjected to various changes, modifications and substitutions without necessarily departing from the spirit of the invention.

We claim:

1. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the flux capacity of that portion of the core encircled by the primary winding is greater than the flux capacity of that portion of the core encircled by the secondary winding and the windings and capacitance are selected such that the ratio of resonant volt amperes to load volt amperes is in the range of about 0.3 to about 1.5; and

the flux capacity of the shunt portion of the core at the minimum gap is less than the flux capacity of that portion of the core encircled by the secondary winding, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads; and

the core includes another nonmagnetic gap in the flux path of the secondary winding, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained; and

the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion; and

with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

2. A transformer as defined in claim 1 wherein the cross-section area of that portion of the core encircled by the primary winding is greater than the cross-section area of that portion of the core encircled by the secondary winding.

3. A transformer as defined in claim 2 wherein the cross-section area of that portion of the core encircled by the primary winding is in the order of 20 to 60 percent greater than the cross-section area of that portion of the core encircled by the secondary winding.

4. A transformer as defined in claim 1 wherein the cross-section of the shunt portion of the core at the minimum gap is less than the cross-section area of that portion of the core encircled by the secondary winding.

5. A transformer as defined in claim 4 wherein the end of the shunt at the gap is stepped to provide one gap portion of minimum width and another gap portion of greater width.

6. A transformer as defined in claim 4 wherein the end of the shunt at the gap includes a bevel to provide a gap with a tapering width.

7. A transformer as defined in claim 1 wherein the end of the shunt at the gap is flat to provide a gap of substantially constant width.

8. A transformer as defined in claim 1 wherein the shunt is formed of at least two materials having different flux capacities.

9. A transformer as defined in claim 2 wherein said core portion with flux parallel to grain orientation and cross-section area less than core portions with flux perpendicular to orientation, is the entire core portion encircled by the secondary winding.

10. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the cross-section area of that portion of the core encircled by the primary winding is greater than the cross-section area of that portion of the core encircled by the secondary winding; and

the core includes another nonmagnetic gap in the flux path of the secondary winding, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained; and

the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

11. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the flux capacity of that portion of the core encircled by the primary winding is greater than the flux capacity of that portion of the core encircled by the secondary and resonant windings and the windings and capacitance are selected such that the ratio of resonant volt amperes to load volt amperes is in the range of about 0.3 to about 1.5.

12. A transformer as defined in claim **11** wherein the cross-section area of that portion of the core encircled by the primary winding is greater than the cross-section area of that portion of the core encircled by the secondary and resonant windings.

13. A transformer as defined in claim **11** wherein the core includes another nonmagnetic gap in the flux path of the secondary and resonant windings, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

14. A transformer as defined in claim **11** wherein the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

15. A transformer as defined in claim **14** wherein said core portion with flux parallel to grain orientation and cross-section area less than core portions with flux perpendicular to orientation, is the entire core portion encircled by the secondary winding.

16. A transformer as defined in claim **14** with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

17. A transformer as defined in claim **11** wherein the flux capacity of the shunt portion of the core at the minimum gap is less than the flux capacity of that portion of the core encircled by the secondary and resonant windings, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads.

18. A transformer as defined in claim **11** wherein the cross-section area of the shunt portion of the core at the minimum gap is less than the cross-section area of that portion of the core encircled by the secondary winding, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads, and

the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

19. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the flux capacity of the shunt portion of the core at the minimum gap is less than the flux capacity of that portion of the core encircled by the secondary and resonant windings, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads.

20. A transformer as defined in claim **19** wherein the cross-section area of the shunt portion of the core at the minimum gap is less than the cross-section area of that portion of the core encircled by the secondary and resonant windings.

21. A transformer as defined in claim **19** wherein the core includes another nonmagnetic gap in the flux path of the secondary and resonant windings, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

22. A transformer as defined in claim **19** wherein the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

23. A transformer as defined in claim **22** wherein the core includes another nonmagnetic gap in the flux path of the secondary winding, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

24. A transformer as defined in claim **22** wherein said core portion with flux parallel to grain orientation and cross-section area less than core portions with flux perpendicular to orientation, is the entire core portion encircled by the secondary winding.

25. A transformer as defined in claim **22** wherein with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

26. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the core includes another nonmagnetic gap in the flux path of the secondary and resonant windings, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

27. A transformer as defined in claim **26** wherein the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

28. A transformer as defined in claim **27** wherein with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

29. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

30. A transformer as defined in claim **29** wherein with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

31. In a ferroresonant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for connection to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the flux capacity of that portion of the core encircled by the primary winding is greater than the flux capacity of that portion of the core encircled by the secondary and resonant windings; and

the flux capacity of the shunt portion of the core at the minimum gap is less than the flux capacity of that portion of the core encircled by the secondary and resonant windings, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads.

32. A transformer as defined in claim **31** wherein the core includes another nonmagnetic gap in the flux path of the secondary and resonant windings, and the transformer includes means for adjusting the width of said other gap, whereby the portion of the core through the resonant winding can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

33. A transformer as defined in claim **31** wherein the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

34. A transformer as defined in claim **33** wherein said core portion with flux parallel to grain orientation and cross-section area less than core portions with flux perpendicular to orientation, is the entire core portion encircled by the secondary winding.

35. A transformer as defined in claim **33** wherein with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

36. In a ferroresant transformer for use as a voltage regulator and the like, and having

a magnetic core with a primary winding for conncetion to a power source, a secondary winding for connection to a load, a resonant winding, and a capacitance connected across the resonant winding, with the core including a shunt with a nonmagnetic gap providing a leakage flux path for shunting fluxes resulting from currents in the primary winding and the secondary and resonant windings, the improvement wherein:

the secondary and resonant windings are on the same flux path of the core and the flux capacity of the primary portion of the core is greater than the flux capacity of at least a portion of the secondary portion of the core and the windings and capacitance are selected such that the ratio of resonant volt amperes to load volt amperes is in the range of about 0.3 to about 1.5.

37. A transformer as defined in claim **36** wherein the cross-section area of the primary portion of the core is greater than the cross-section area of at least a portion of the secondary portion of the core.

38. A transformer as defined in claim **36** wherein the core includes another nonmagnetic gap in the secondary portion, and the transformer includes means for adjusting the width of said other gap, whereby the core can be adjusted so that in conjunction with the particular connected capacitance, the desired output voltage is obtained.

39. A transformer as defined in claim **36** wherein the core is formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

40. A transformer as defined in claim **39** with the cross-section area in the primary portion of the E section of the core where the flux is parallel to the orientation and the cross-section area in the portion of the E section of the core where the flux is perpendicular to the orientation related such that the products of area and saturation flux density for such portions are substantially equal.

41. A transformer as defined in claim **36** wherein the flux capacity of the shunt portion of the core at the minimum gap is less than the flux capacity of the secondary portion of the core, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads.

42. A transformer as defined in claim **36** wherein the cross-section area of the shunt portion of the core at the minimum gap is less than the cross-section area of the secondary portion of the core, whereby saturation occurs in the shunt portion of the core as the load increases thereby reducing the leakage reactance at higher loads, and

the core if formed of butt stacked E and I shaped laminations of grain oriented material, with the cross-section area in a secondary portion of the core where flux is parallel to the orientation being less than the cross-section area in the secondary portions of the core where flux is perpendicular to the orientation, whereby the core first saturates in such lesser area parallel portion.

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