

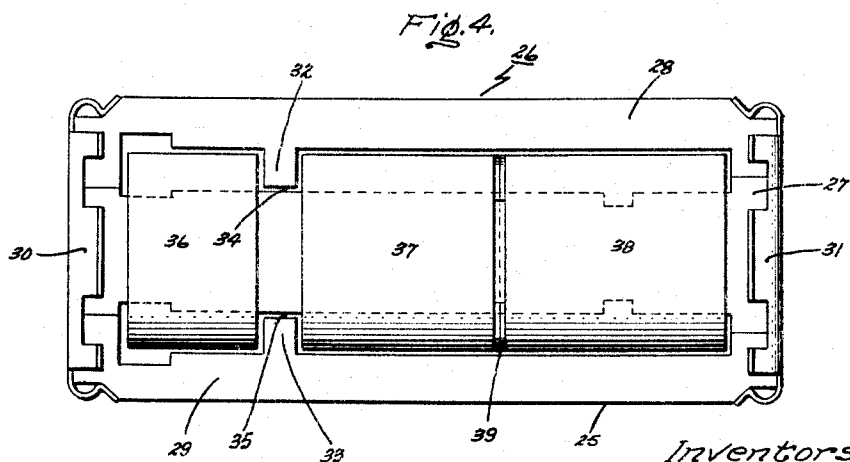
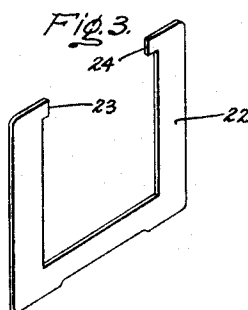
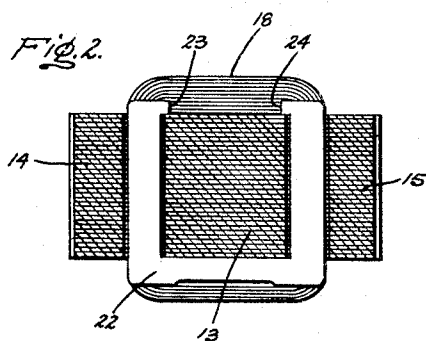
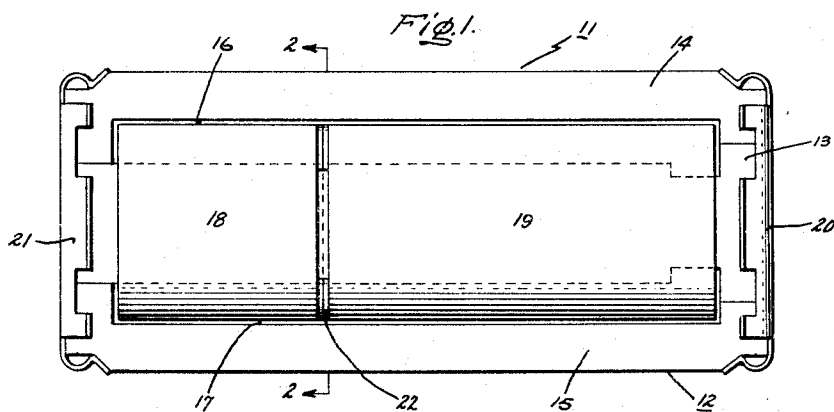
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R. E. HUME ET AL
BALLAST APPARATUS

3,010,050

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3 Sheets-Sheet 1



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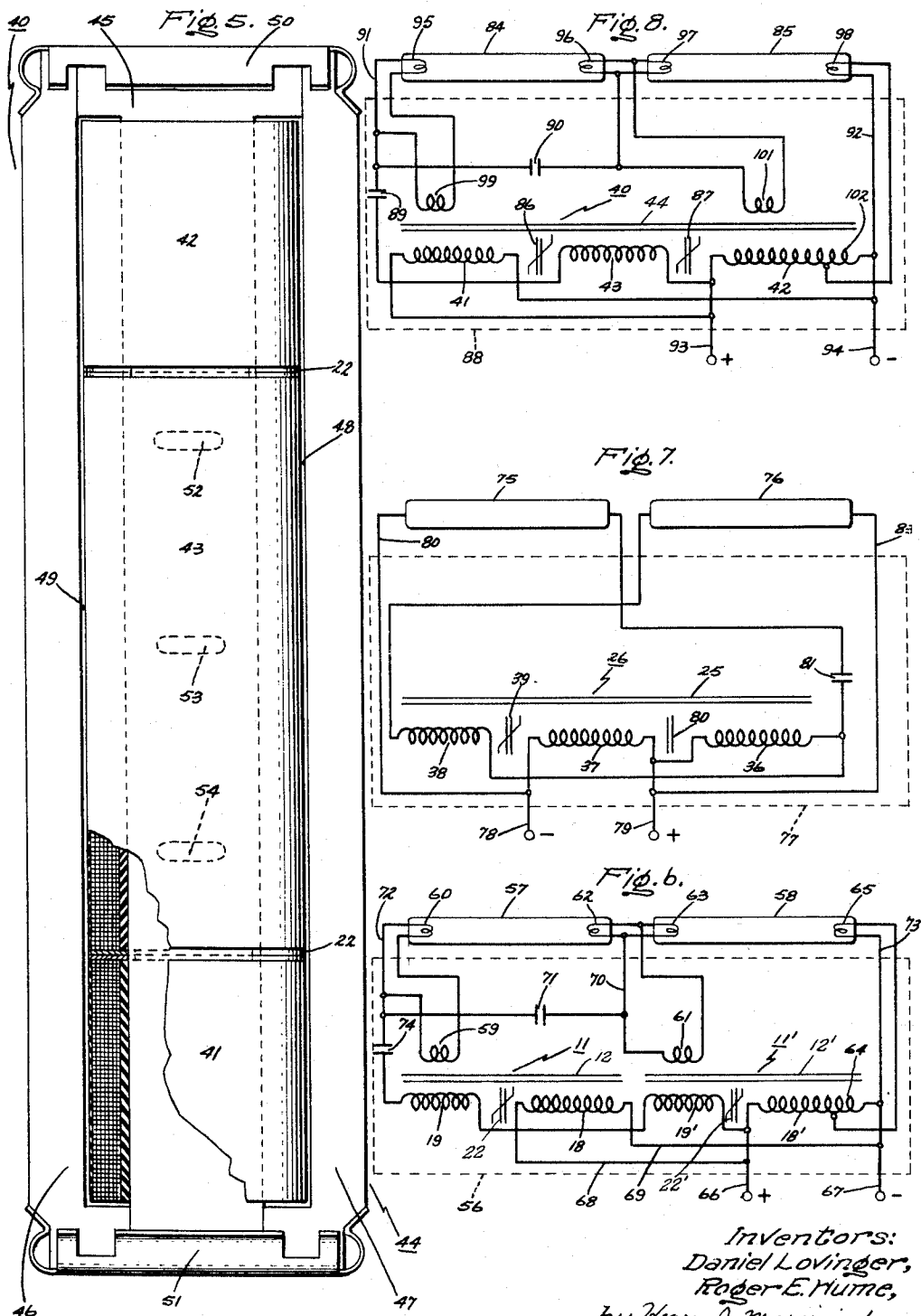
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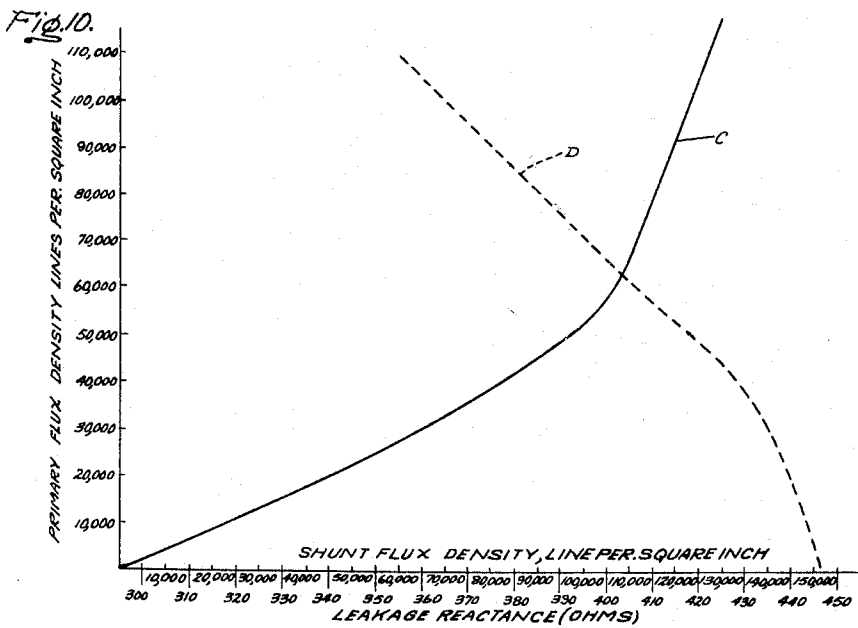
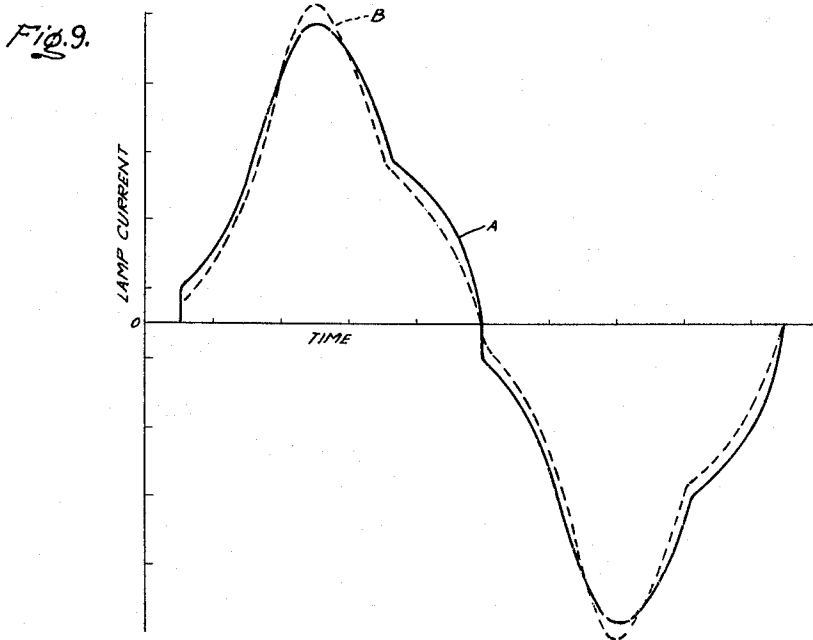
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BALLAST APPARATUS

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3,010,050

BALLAST APPARATUS

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18 Claims. (Cl. 315-138)

This invention relates to ballast apparatus and more particularly to ballast apparatus including a high reactance ballast transformer having a lead secondary winding coupled with a primary winding.

When arc discharge devices, such as fluorescent lamps are operated on alternating current, a high reactance transformer is used to provide a high open circuit voltage for starting the lamps, a relatively lower voltage for operating the lamps, an impedance required to limit the current flow because of the negative resistance characteristic of the lamp. Thus, the functions of voltage modification and current limitation are combined in a high reactance ballast transformer. Ordinarily, in a high reactance ballast transformer, the primary and secondary windings are loosely coupled so that when the transformer is carrying the load current there is a substantial amount of leakage flux, and the voltages induced in the windings tend to cause the transformer to have a relatively high leakage reactance.

The effect of leakage reactance is to reduce the coupling between the primary and secondary over the coupling that would normally be obtained if the primary and secondary windings were tightly coupled. Conventional means used for supplying a path or shunt for the leakage flux are to provide a space in the coil receiving window between the primary and the secondary windings for the flow of leakage flux or to provide a metallic shunt and air gap between the primary and secondary windings, or a distributed path along the length of the secondary coil. Since the magnetic cores generally used in ballast transformer constructions are of the shell-type having an elongated central winding leg on which the primary and secondary windings are arranged and a pair of outer yoke legs surrounding the primary and secondary winding to a return path for the magnetic flux, it has been the common practice to provide leg portions on either the center winding leg or the outer yoke legs to form magnetic shunts between the winding, with the legs being so formed that an air gap is provided in the shunts. In some prior art constructions bundled shunts have been interposed between a primary winding to provide a path for the leakage flux for a lag secondary winding. Such a prior art construction employing transverse bundled shunts and a series air gap is described in U.S. Patent No. 2,568,553—Mauwer. Since the permeability of iron or other magnetic metals used in transformer cores is much better than that of air, it is possible with a metallic shunt to provide the same leakage reactance with a shorter core length as compared with an air path between the primary and secondary windings or a distributed leakage along the secondary coil.

In the past it was considered undesirable to permit the flux density in a metallic shunt to exceed the point at which it would saturate. When a shunt saturates, a lower inductance or leakage reactance results in the circuit. Therefore, an air gap is ordinarily used to control the flux density in the metallic shunt under high current conditions and to prevent the shunt from reaching a point of saturation. In other words, since the iron might introduce a nonlinear effect in the magnetic circuit which might cause the shunt to operate in its saturation region, heretofore, this possible effect was avoided by the use of the air gap in the shunt. The high reluctance provided by the air gap rendered the reluctance of the leakage path

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substantially linear since the air gap contributed most of the reluctance.

The present invention is particularly concerned with a high reactance ballast transformer which includes a lead secondary winding coupled on a magnetic core with a primary winding. A lead secondary, as the term is used herein, is a secondary winding of a ballast transformer which supplies a current to a leading power factor load. In other words, it is a secondary in which a leading current flows during operation due to the predominantly capacitive reactance of the secondary circuit of the ballast apparatus. In such a circuit the lamp is supplied with the leading current flowing in the secondary of the high reactance transformer. Since the lead secondary winding carries a leading current, the flux produced by it in the central winding leg is more or less in phase with the exciting flux produced by the primary winding. The flux which flows through the shunt or leakage path interposed between the lead secondary winding and the primary winding is equal to the vector difference of the primary flux and the total flux under the secondary, and generally is relatively small in magnitude. However, the flux produced by a lag secondary is substantially in phase opposition to the exciting flux induced in the central winding leg by the primary winding. Consequently, the flux which flows in the shunt between a lagging secondary and a primary is the vector sum of the fluxes produced by the windings. Thus, the magnitude of the flux in a shunt between a lag secondary winding and the primary winding is relatively greater. In order to prevent the flux density in metallic shunts from reaching saturation under operating conditions it will be seen that the cross sectional area of shunts used between lag secondary windings and primary windings are necessarily greater than those used between lead secondary windings and primary windings in comparable magnetic circuits.

In the past constructions of high reactance transformers utilizing metallic shunts, the leakage reactance does not change to any appreciable degree between open circuit and normal operating conditions. In other words, the leakage reactance of conventional high leakage reactance transformers has been essentially linear, any nonlinearity which might be introduced because of the high permeability of the iron having been effectively suppressed by air gaps.

Several difficult problems have been encountered in providing suitable ballast apparatus for series lead circuits of desired small size and expense without a sacrifice in lighting efficiency or ballast performance. For example, conventional constructions of high reactance ballast transformers were found to produce the condition of instability in fluorescent lamps and especially with respect to low temperature operation of lamps in series lead circuits. This instability resulted in a low frequency oscillation or variation in the visible light output of the lamps which produced an objectionable flickering. Conventional expedience for increasing the leakage reactance in the ballasting secondary winding have not produced satisfactory results. In some applications insufficient space was available to increase the leakage reactance by adding turns or by providing additional spacing between the primary and secondary windings. Attempts to reapportion the magnetizing and leakage reactance of the secondary winding failed because the instability was still present.

Accordingly, an object of the invention is to provide an improved high reactance ballast transformer and ballast apparatus for starting and ballasting a gaseous discharge lamp, such as a fluorescent lamp, having stable and improved operating characteristics.

Another object of the invention is to provide an improved high reactance transformer and ballast apparatus

wherein the leakage reactance is effectively utilized to improve the waveform of the lamp current.

It is still another object of the invention to provide an improved ballast apparatus for series lead circuits operating a pair of fluorescent lamps.

A more specific object of the invention is to provide an improved ballast apparatus that will provide a leakage reactance at an early portion of each half cycle of the alternating current supplied to the lamp, which is decreased during a later portion of each half cycle.

It is still a further object of the present invention to provide a high reactance ballast transformer of improved versatility that will permit a ballast apparatus of smaller size to be constructed without a sacrifice in lighting efficiency or ballast performance.

In accordance with the invention, a ballast apparatus is provided for starting and operating one or more lamps in a series lead circuit in which a nonlinear shunt is utilized between the lead secondary winding and primary of a high leakage reactance transformer to introduce an increased leakage reactance during the early portion of each half cycle of the secondary current and a decreased leakage reactance during a later portion of each half cycle. Preferably, the ballast apparatus, in accordance with the invention may be used for operating a pair of fluorescent lamps in a series lead circuit arrangement.

In another aspect of the invention, a high reactance ballast transformer is provided having a magnetic core with a central elongated winding leg, on which the primary winding and at least one lead secondary winding are located in an end to end relationship. A pair of outer yoke legs are disposed on both sides of the central elongated winding leg to provide a closed path for the magnetic flux and to form a coil receiving window for the transformer windings. In the coil window space between the primary winding and the lead secondary winding we have inserted a nonlinear shunt having a sufficiently restricted cross-sectional area so as to cause flux saturation in the shunt during each half cycle of the secondary current. The term "nonlinear shunt" is used herein to denote a shunt (1) that is interposed between a primary winding and a secondary winding in a magnetic circuit, (2) that saturates and desaturates during each half cycle of the secondary current, and (3) that provides a leakage reactance which substantially varies during each half cycle of the secondary current.

Although in the illustrated embodiments of our invention we have employed transverse shunt lamination inserts between the primary and the lead secondary windings, it will be apparent that relatively thin projections extending laterally and formed integrally with the central winding leg or the outer yoke legs can be used to provide a nonlinear shunt in accordance with the broader aspects of the invention.

The subject matter which we regard as our invention is set forth in the appended claims. The invention itself, however, together with further objects and advantages thereof may be better understood by referring to the following description taken in connection with the accompanying drawings in which:

FIG. 1 is a plan view of a high reactance ballast transformer in which the invention is embodied;

FIG. 2 is a sectional view along the plane 2-2 of the high reactance transformer of FIG. 1;

FIG. 3 is a perspective view of a shunt lamination used in the illustrated embodiments of the invention;

FIG. 4 is a plan view of another high reactance transformer embodying the invention;

FIG. 5 is a plan view of a high reactance transformer illustrating an embodiment of the invention with a portion of the winding cut away;

FIG. 6 is a schematic circuit diagram of a ballast apparatus utilizing the high reactance transformer of FIG. 1;

FIG. 7 is a schematic circuit diagram of a ballast apparatus utilizing the high reactance transformer of FIG. 4;

FIG. 8 is a schematic circuit diagram of a ballast apparatus utilizing the high reactance transformer of FIG. 5;

FIG. 9 illustrates the two curves showing the waveform of the lamp current flowing in a series lead ballast circuit, curve A representing the waveform of the lamp supplied by a ballast apparatus employing nonlinear shunts in accordance with the invention and curve B representing the waveform of the lamp current supplied by a conventional ballast in which a substantially constant leakage reactance was provided; and

FIG. 10 presents two curves, curve C representing the primary flux density in lines per square inch plotted against the shunt flux density in lines per square inch and curve D representing the primary flux density in lines per square inch plotted against leakage reactance in ohms.

Referring to FIG. 1, there is shown a high reactance transformer generally identified by the numeral 11. The transformer 11 is formed of a magnetic core 12 including a central winding leg 13 and the outer yoke legs 14, 15 arranged respectively on opposite sides of the center leg member 13. The magnetic core 12 is comprised of stacks of a plurality of relatively thin laminations of electrical steel, there being three lamination pieces per lamination layer. Mounted on the elongated central winding leg 13 within a coil receiving windows 16, 17 defined by the yoke legs 14, 15 are the primary winding 18 and the lead secondary winding 19. The cathode heating windings are shown schematically in FIG. 6, one being included in the primary winding 18 and two being coupled in a secondary transformer relationship therewith.

The laminations of the central winding leg 13 and outer yoke legs may be held together by any suitable means, such as the spring clamps 20, 21 which are shown disposed at the opposite ends of the magnetic core 12. It will be seen that the clamps 20, 21 also hold the outer yoke legs 14, 15 in an abutting relationship with the central winding leg 13. In the coil receiving windows 16, 17, two transverse shunt laminations 22 spaced from the outer yoke legs 14, 15 are interposed between the primary winding 18 and secondary winding 19. Although as shown in the sectional view of FIG. 2 and in the perspective view of FIG. 3, the lamination 22 has a C-shaped configuration, this particular configuration was used since it facilitates assembly, the inwardly extending projections 23, 24 preventing the shunt laminations 22 from falling out during the manufacturing operation.

Referring now to FIG. 2, it will be seen that the transverse shunt laminations 22 are disposed vertically in the coil receiving window and spaced from the outer yoke legs 14, 15 and the central winding leg 13. The shunt laminations 22 are retained on the central winding leg 13 by the inwardly extending projections 23, 24. Although we have shown and described shunt laminations in the illustrative embodiment of our invention, it will be readily apparent to those skilled in the art that the nonlinear shunt in accordance with the invention may be integrally formed on the outer yoke legs 14, 15 on the central winding leg 13 or on both the yoke legs 14, 15 and the central winding leg 13, each providing a portion thereof. The lamination 22 was fabricated of electrical, i.e., magnetic, strip sheet steel for reasons of convenience and economy. However, it will be appreciated that magnetic alloys can be used to provide the variable leakage reactance in accordance with this invention.

As shown in FIG. 4, a magnetic core 25 of the high reactance ballast transformer 26 comprises an elongated central winding leg 27 and a pair of yoke legs 28, 29. The spring clamps 30, 31 hold the outer yoke legs 28, 29 in an abutting relationship with the central winding member 27. It will be noted that the yoke legs 28, 29 are provided with integrally formed metallic shunts 32, 33, which are spaced from the central winding leg 27 to provide air gaps 34, 35. As viewed in FIG. 4, a lag secondary winding 36 is disposed to the left of the metallic shunts 32, 33 and a primary winding 37 is disposed

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to the right of the shunts 32, 33. A lead secondary winding 38 is mounted on the central winding leg 27 to the right of the primary winding 37. The air gaps 34, 35 between the shunt and the central winding leg 37 provide a high reluctance which renders the magnetic characteristic of the shunting circuit substantially linear since most of the reluctance of the circuit is in the air gaps 34, 35. Interposed between the lead secondary winding 38 and the primary winding 37 are a pair of nonlinear shunt laminations 39 being spaced from the outer yoke legs 28, 29. In accordance with the invention, the operation of this ballast transformer 26 will be more fully described in connection with the description of its associated ballast apparatus illustrated in FIG. 7.

In FIG. 5 another form of our invention is shown embodied in a high reactance transformer 40 of the shell-type in which two primary windings 41, 42 are disposed at opposite ends of a lead secondary winding 43. Like the ballast transformers 11, 26, shown in FIGS. 1 and 4, the transformer of FIG. 5 is of the shell-type having a magnetic core 44 with an elongated central winding leg 45 and a pair of outer yoke legs 46, 47 disposed in an abutting relationship on opposite sides of the central winding leg 45 to form coil receiving windows 48, 49. Spring clamps 50, 51 hold the outer yoke legs in an abutting relationship with the central winding leg 45.

The high reactance of the transformer 40 is provided by the distributed leakage of magnetic flux between the elongated central winding leg 45 and the yoke legs 46, 47 and the nonlinear shunts of the invention. In accordance with the invention, two laminations 22 of the type shown in FIG. 3 are included at each end of the lead secondary winding 43 to serve as a nonlinear shunt between the primary windings 41, 42 and the lead secondary winding 43. It will be seen that the shunt laminations 22 of this invention do not add appreciably to the length of the magnetic core 44 and are spaced from the outer yoke legs 46, 47.

Three spaced transverse slots 52, 53, 54 are formed in the central winding leg 45 and form bridged gaps serving the purpose of preventing saturation of the secondary winding magnetic circuit in order to keep core losses at a minimum and to prevent distortion of the lamp current waveform. Thus, the advantages derived by using bridged gaps as shown in FIG. 5 and also in the embodiments of FIGS. 1 and 4 can be realized in conjunction with the advantages of this invention.

The specific circuit connections of the high reactance ballast transformers 11, 26, 40 of FIGS. 1, 4 and 5 will now be considered in connection with the schematic circuit diagrams of FIGS. 6, 7 and 8 in which the transformers are schematically illustrated. In the circuit diagrams it will be noted that the nonlinear shunts of this invention are identified symbolically in the circuit using two parallel lines crossed by a slant line.

Referring now to FIG. 6, the ballast apparatus is enclosed in a dashed rectangle 56 and includes two of the high reactance transformers 11, 11', shown in FIG. 1. The ballast apparatus is intended for starting and operating two serially connected 96 PG17 type power groove lamps. The power groove lamps are hot cathode lamps which have an unusually high wattage rating for a given starting voltage rating. The correspondence between the high reactance ballast transformer shown in FIG. 1 and the transformers shown schematically in FIG. 6 is indicated by using like numerals to identify the corresponding parts. The high reactance ballast transformers 11, 11' include primary windings, 18, 18', secondary windings 19, 19', magnetic cores 12, 12' and nonlinear shunts comprising the laminations 22, 22'. A heating winding 59 is connected to filament 60 of lamp 57, and heating winding 61 is connected to filaments 62, 63 of lamps 57, 58. Heating winding 64 which is connected to filament 65 may be an extension, as shown, of the primary winding 18'.

Two external input leads 66, 67 are provided for con-

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nection to a source of alternating voltage (not shown), for example, 115 volts at a frequency of 60 cycles and are connected across primary winding 18'. Primary winding 18 is also connected to the external input leads 66, 67 by conductors 68, 69. It will be noted that the two secondaries 19, 19' are connected in series circuit relationship, the secondary winding 19' being in auto-transformer relationship with the primary winding 18'. A starting capacitor 71 is connected between the high voltage lead or output lead 72 and an intermediate voltage lead 70 which is also connected to the heating winding 61. A second output lead 73 joins one end of the primary winding 18 with filament 65 of lamp 58. Connected in series circuit relationship with the secondary winding 19 is a capacitor 74 selected to have sufficient capacity to deliver to the two lamps 57, 58 the combined output of the currents developed by the two transformers 11, 11' and to provide a net capacitive reactance in the secondary circuit.

When the input leads 66, 67 are connected to a suitable source of alternating current (not shown), the total open circuit voltage, which is the sum of the input voltage across the primary windings 18, 18' and the individual voltages of the secondary windings 19, 19' is impressed across the serially connected lamps 57, 58. Due to the connection of the starting capacitor 71 across the lamp 57, substantially all of the output voltage appears in the first instance across the lamp 58. Also, at the same time the filaments 60, 65 are being quickly heated to electron emitting temperatures and soon thereafter, lamp 58 is ignited. The discharge current in the lamp then flows through the starting capacitor 71 thereby producing a relatively high voltage drop in the capacitor, which voltage drop is impressed across lamp 57 and causes lamp 57 to form an arc discharge between its heated filaments 60, 62. After the lamp 57 has fired, the starting capacitor 71 is effectively short circuited by the lamp 57.

In prior constructions of the high reactance ballast transformers, difficulties were encountered in the lamp stability as attempts were made to reduce the length of the magnetic core in order to meet design requirements. In prior designs of the high reactance transformer used in the ballast apparatus shown in FIG. 6, a space between the primary and the secondary was provided. We found that the length of the magnetic core could be effectively reduced and in addition a very significant improvement in the operating characteristics of the ballast circuit could be obtained by using the nonlinear shunts of this invention.

An important advantage derived from the use of nonlinear shunts between the primary and lead secondary windings in a series lead ballast circuit of the type shown in FIG. 6 lies in the improvement of lamp current waveform. We discovered that the lamp current waveform is improved if the leakage reactance resulting from the leakage flux in the magnetic circuit were high during an early portion of each half cycle during which the lamp reignites. A further improvement in lamp current waveform can be obtained if the leakage reactance is at a minimum during a later portion of the half cycle of each half cycle of the lamp current.

Referring now to FIG. 9, the current waveform defined by the solid line, curve A, represents the waveform obtained on an oscilloscope for the lamp current in the circuit of FIG. 6, in which the high reactance ballast transformers 11, 11' employed nonlinear shunts 22, 22' in accordance with the invention. The current waveform defined by the dashed lines, curve B, represents the lamp current in the same ballast circuit in which an air space forming a linear shunt was provided between the primary windings, 18, 18' and the lead secondaries 19, 19'.

It was found that the low current values occurring during the initial period of each half cycle were primarily responsible for lamp instability and that this low current flow condition at each half cycle was aggravated as the

temperature of the lamp decreased. Thus, as an example, lamps operated in the vicinity of an air conditioning outlet would flicker as a result of the low current flow condition. We discovered that a nonlinear shunt employed in accordance with the invention provided a higher value of leakage reactance at the start of each lamp current half cycle and thereby a higher current at that time. This is evidenced by the substantially increased values of the current flowing during the initial period of the cycle as shown by curve A of FIG. 9. It was found that this ballast transformer, using the nonlinear shunts in accordance with the invention did not experience instability when used for air conditioning applications.

Another advantage resulting from the use of nonlinear shunts in accordance with the invention is further evident from the current waveform during the later part of each half cycle. The low leakage reactance provided by the nonlinear shunt during the later part of each half cycle when the shunt has become saturated allows an increased current to flow, particularly the third harmonic component. In other words, the nonlinear shunt of the invention introduces a variable leakage reactance in ballast circuits. A high leakage reactance is provided early in each lamp current half cycle, and a lesser amount of leakage reactance is provided at a critical time in the later portion of each half cycle when the third harmonic current can be utilized to improve the operating performance of the ballast transformer.

The advantages of the invention may also be obtained in a series lead ballast circuit of the type shown in FIG. 7 in which the high reactance transformer 26 of FIG. 4 is employed in the circuit to operate a pair of fluorescent lamps 75, 76 in which the filament leads (not shown) are short circuited inside the lamp base and which are known generally in the trade as instant start lamps. The ballast apparatus as shown schematically in FIG. 7 is enclosed in a dashed rectangle 77, which represents the ballast apparatus case. The correspondence between the high reactance ballast transformer of FIG. 4 and the schematic diagram shown in FIG. 7 is indicated by using like reference numerals to identify like parts. A primary winding 37 is connected across a pair of input leads 78, 79 which are adapted for connection to an alternating current source (not shown). A first secondary winding 36 and a second secondary winding 38 are mounted on a magnetic core 25. In accordance with the invention, a nonlinear shunt 39 is interposed between the primary winding 37 and the second secondary winding 38. Between the first secondary winding 36 and the primary winding 37, a metallic linear shunt 80 is interposed. The linear shunt 80 symbolically represents the shunt projections 32, 33 and the series air gaps 34, 35 which are shown in FIG. 4. The inductive reactance of the first secondary winding 36 is relatively greater as compared with the capacitive reactance of capacitor 81 so that the current in the secondary will lag, and therefore the first secondary 36 is a lag secondary winding. Since the second secondary 38 supplies a leading current during normal operation of the ballast apparatus, the nonlinear shunt 39 is inserted between the primary winding 37 and the secondary winding 38.

From the circuit connections of the ballast apparatus of FIG. 7 it will be readily seen that lamp 75 is connected across the primary winding 37 and the first or starting secondary winding 36 while lamp 76 is connected across the first secondary winding 36 and the second or ballasting secondary winding 38. When an alternating voltage is applied across the input leads 78, 79, the applied voltage combined with the voltage across the first secondary winding 36 appears across lamp 75 and a lagging current flows in the circuit of lamp 75. As is well-known in the art, the lagging current causes a shift of the phase of the voltage in the first secondary winding 36 so that it becomes generally additive with the voltage in the second or ballasting secondary 38. This combined voltage

appears across lamp 76 and is sufficient to ignite it. When both lamps have ignited, the ballast circuit operates as a series lead circuit, including the primary winding 37 and the ballasting winding 38. The starting windings 36 is of relatively high impedance and is more or less excluded from the operating circuit, drawing only a very small current. During normal operation the path of current flow is from input lead 79 through lead 83, the lamp 76, the secondary winding 38, the capacitor 81, lamp 75 and lead 80 to input lead 78.

It was found that the nonlinear shunts significantly improved lamp stability and the performance characteristics of the ballast apparatus shown in FIG. 7. Thus, the advantages of the invention can be realized where lead and lag secondary windings are disposed in an end to end relationship with a primary winding in a series lead ballast circuit.

Referring now to FIG. 8, a ballast apparatus employing the high reactance transformer 40 of FIG. 5 is illustrated for operating a pair of hot cathode lamps 84, 85. As shown in FIG. 8, the primary windings 41, 42 are arranged on a magnetic core 44, the primary winding 41 being located at one end of the secondary winding 43 and the other primary winding 42 being located at the other end of the secondary winding 43. The two primary windings 41, 42 and the secondary winding 43 are shown disposed on the magnetic core 44. The nonlinear shunts 86, 87, in accordance with the invention, are placed on opposite sides of the secondary winding 43 so they are interposed between the secondary winding 43 and the primary windings 41, 42. The nonlinear shunts 86, 87 are comprised of a pair of the laminations shown in FIG. 3. Except for the single ballast transformer 40 being used with split primary winding arrangement, the ballast circuit of FIG. 8 is generally similar with the circuit shown in FIG. 6.

The correspondence between the high reactance transformer shown in FIG. 5 and the ballast apparatus of FIG. 8 is indicated by the use of like reference numerals to identify like parts. As shown in FIG. 8, the ballast apparatus is enclosed by the dashed rectangle 88, which schematically represents the ballast case. It will be noted that the secondary winding 43 is in auto-transformer relationship with the primary winding 42. A capacitor 89 is connected in series with the secondary winding 43 and with lamps 84, 85. Another capacitor 90 is provided as an aid in starting and is connected in parallel with the lamp 84. A first output lead 91 and a second output lead 92 are connected across the serially connected lamps 84, 85. Two input leads 93, 94 are provided for connection with an alternating current source (not shown). Current for heating the filaments 95, 96, 97, 98 are provided by the heating windings 99, 101, 102.

When an alternating voltage is applied to the input terminals 93, 94, a stepped up voltage comprising the voltage of secondary 43 added to the input voltage appears across the output leads of ballast transformer 40. Due to the starting capacitor 90, this voltage is first applied across lamp 85 to start it. Once lamp 85 starts, most of the voltage then appears across lamp 84 to start it. Once both lamps are started, the ballast apparatus of FIG. 8 operates as a series lead circuit in the same manner as the circuit shown in FIG. 6.

By splitting the primary winding into two primary windings 41, 42, it has been found possible to derive the benefit of a reduced primary winding temperature during normal operation of the lamps and yet maintain the stability, the improved performance characteristics, and other advantages which are realized by constructing a ballast transformer with nonlinear shunts of this invention.

As a specific illustrative example of the invention, the ballast apparatus of FIG. 6 was constructed for starting and operating two 96 PG17 power groove lamps. The apparatus utilized two of the high reactance transformers

11 shown in FIG. 1 and was housed in a ballast case having the following outer dimensions; $19\frac{3}{4}$ inches long, $3\frac{1}{4}$ inches wide and $2\frac{5}{8}$ inches high. Each high reactance transformer 11 was $6\frac{1}{2}$ inches long, $2\frac{7}{32}$ inches wide and $2\frac{3}{8}$ inches high. The outer yoke legs 14, 15 of the magnetic core 12 were formed by laminations .025 inch thick and were stacked to a height of $1\frac{3}{8}$ inches. The center winding leg 13 consisted of a stack of laminations stacked to a height of $1\frac{1}{8}$ inches. Two C-shaped laminations 22 of the type shown in FIG. 3 having a thickness of .025 inch were inserted between the primary winding 18 and the secondary winding 19. The primary winding had 370 turns of number 20 copper wire and the secondary winding had 807 turns of number 20 copper wire. The heating windings 59, 61, 64 had 12, 13, 13 turns respectively. The capacitive reactor had a capacitance of 6.7 microfarads. The starting capacitor had a capacitance of .075 microfarad. The transformer developed an open circuit voltage of 478 volts (root mean square) across both lamps. The power factor with both lamps operating was found to be approximately 98.9.

In order to demonstrate the advantages derived by the ballast apparatus of the invention, the ballast apparatus described in the illustrative example was compared with an identical ballast in which an air space was provided between the lead secondary winding and primary winding in accordance with the conventional practice. The performance characteristics of the two ballasts are summarized in Table I.

Table I

	Ballast with non-linear metallic shunts	Ballast without nonlinear metallic shunts
Lamp current.....	amperes... 1.86	1.46
Lamp power factor.....	percent... 77.3	73.1
Input power.....	watts... 456	471
Input current.....	amperes... 3.91	4.11
Light output.....	percent... 91.4	92.0
Power capacitor.....	microfarads... 6.7	6.7
Primary current of first transformer.....	amperes... 1.52	1.61
Primary current of second transformer.....	amperes... 1.50	1.58

From the data presented in Table I, it will be noted that for substantially the same light output of 91.4 and 92 percent, the ballast with the nonlinear shunts require less power to operate the power groove lamps. The lower values of primary current and lamp current, in addition to the improved lamp power factor, make it possible to obtain an appreciable reduction in size and cost for given performance characteristics as compared with a comparable ballast in which the nonlinear shunts of the invention are not utilized.

To determine the degree of saturation and thereby the nonlinearity of the nonlinear shunts, search coils were wound around the shunt laminations in the ballast transformer of the illustrated example. During this test, the secondary winding was shorted through a low impedance ammeter in order to reduce the flux in the secondary winding to substantially zero. Voltage readings were recorded for various values of the primary flux density and the flux density in the shunt was computed. Curve C of FIG. 10 represents a plot of primary flux density in lines of per square inch against shunt flux density in lines of per square inch. From curve C it will be seen that the metallic shunt contained a major part of the primary flux until it started to saturate at a shunt density of approximately 90,000 lines per square inch. Curve D, the dashed lined curve, represents a plot of primary flux density in lines per square inch against leakage reactance as calculated from measurements of the short circuit secondary current. The maximum flux density with the lamps operating was found to be 110,000 lines per square inch. This value corresponds with a leakage reactance of 400 ohms. The leakage reactance was approximately

450 ohms at the point in each half cycle when the flux density was at a minimum. Therefore, it will be seen that the leakage reactance provided by the shunt varies from 450 ohms to 400 ohms during each half cycle.

When the nonlinear metallic shunts were removed from the ballast transformer, the leakage reactance was found to be substantially constant at approximately 299 ohms. It will be readily apparent to those skilled in the art that the nonlinear shunts provide the ballast circuit designer with a versatile tool for improving a ballast apparatus.

It will be appreciated that although the illustrative embodiments of the invention involve ballast apparatus for starting and operating two arc discharge lamps, it will be apparent that the invention can be readily embodied in a ballast apparatus for starting and operating a single lamp. While this invention has been explained by describing particular embodiments thereof, it will be understood that modifications may be made without departing from the scope of the invention as defined in the appended claims.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. An alternating current source, a ballast apparatus for starting and operating at least one arc discharge lamp therefrom comprising a magnetic core having an elongated central winding leg and a yoke defining at least one coil receiving window with said central winding leg, at least one primary winding and at least one lead secondary winding disposed in an end to end relationship on said central winding leg within said coil receiving windows, a pair of input leads connected with the alternating current source, said primary winding being connected across said input leads, a first and second output lead connected in circuit with said secondary winding, a capacitor connected in circuit with said secondary winding and one of said output leads, said output leads being provided for connection across said lamp, and at least one nonlinear shunt disposed between said primary winding and said lead secondary winding and having at least one end spaced from said magnetic core.

2. The ballast apparatus of claim 1 wherein said nonlinear shunt is comprised of at least one relatively thin transverse lamination of magnetic material vertically disposed between said primary winding and said lead secondary winding.

3. An alternating current source, a ballast apparatus for starting and operating at least one arc discharge lamp therefrom comprising a magnetic core having a central winding leg and a yoke defining coil receiving windows with said central winding leg, at least one primary winding, a pair of input leads connected across the alternating current source, said primary winding being connected across said input leads, a lag secondary winding mounted on said central winding leg, a linear shunt disposed between said primary winding and said lag secondary winding, said metallic shunt separating said coil receiving windows into a first and second section, a lead secondary winding mounted on said central winding leg and disposed in said second section of said coil receiving windows, a first and second output lead connected in circuit with said lead secondary winding, a capacitor, said capacitor being in series circuit relationship with said lead secondary winding and said first output lead, said first and second output leads being provided for connection across said lamp, said primary winding being arranged on said central winding leg adjacent to said shunt and in an end to end relationship with said lead secondary, a nonlinear transverse shunt interposed between said primary winding and said lead secondary winding, said nonlinear shunt providing a substantially variable leakage reactance and said linear shunt providing a substantially constant leakage reactance.

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4. The ballast apparatus set forth in claim 3 wherein said nonlinear shunt is comprised of at least one relatively thin lamination of magnetic material inserted between said lead secondary winding and said primary winding.

5. An alternating current source, a ballast apparatus for starting and operating a pair of arc discharge lamps therefrom comprising a magnetic core having a central winding leg and a yoke defining coil receiving windows with said central winding leg, a first primary winding, a second primary winding, a pair of input leads connected across the alternating current source, said primary windings being connected across said input leads, a secondary winding mounted on said central winding leg within said coil receiving windows, said first primary winding being disposed in an end to end relationship with one end of said secondary winding and said second primary winding being disposed on said central winding leg in an end to end relationship at the other end of said secondary winding, a first output lead connected in circuit with said secondary winding, a second output lead connected in circuit with one of said primary windings, said output leads being provided for connection across said lamps, a capacitor connected in series circuit relationship with said secondary winding and one of said output leads, said secondary winding being connected in autotransformer relationship with one of said primary windings, a first nonlinear shunt interposed between said first primary winding and said secondary winding and having at least one end spaced from said magnetic core, and a second nonlinear shunt interposed between said second primary winding and said secondary winding, both of said nonlinear shunts providing a variable leakage reactance during operation of said transformer.

6. The ballast apparatus of claim 5 wherein said nonlinear shunt is comprised of at least one relatively thin lamination of magnetic material.

7. An alternating current source, a ballast apparatus for starting and operating at least one arc discharge lamp therefrom comprising a magnetic core having a central winding leg and a yoke defining coil receiving windows with said central winding leg, a first primary winding, a second primary winding, a pair of input leads connected across the alternating current source, said primary windings being connected across said input leads, a secondary winding mounted on said central winding leg within said coil receiving windows, a first output lead connected in circuit with said secondary winding, a second output lead connected in circuit with one of said primary windings, said output leads being provided for connection across said lamp, a capacitor connected in series with said secondary winding and one of said output leads, said secondary winding being connected in autotransformer relationship with one of said primary windings, said first primary winding being disposed in an end to end relationship with one end of said secondary winding and said second primary winding being disposed on said central winding leg in an end to end relationship at the other end of said secondary winding, a nonlinear transverse shunt interposed between one of said primary windings and said secondary winding, said nonlinear shunt providing a variable leakage reactance during operation of said transformer and having at least one end spaced from said magnetic core.

8. An alternating current source, a ballast apparatus for starting and operating a pair of arc discharge lamps therefrom comprising a magnetic core having an elongated central winding leg and a pair of yoke legs defining coil receiving windows with said central core leg and integrally formed shunt projections on at least one of said legs, said shunt projections separating said coil receiving windows into first and second sections and having an air gap in the magnetic circuit of said projections, a lag secondary winding disposed on said central winding leg within said first

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section, a primary winding disposed on said central winding leg adjacent to said projections within said second section, a pair of input leads connected across the alternating current source, said primary winding being connected across said input leads, a lead secondary winding disposed on said central winding leg within said second section in an end to end relationship with said primary winding, a pair of output leads for connection across the lamps, a capacitor, said capacitor being connected in series circuit relationship with said lead secondary winding, said output leads being connected in circuit with said secondary winding, and a nonlinear shunt interposed between said lead secondary winding and said primary winding and spaced from said central winding leg, said shunt projections and air gap providing a substantially linear leakage reactance and said nonlinear shunt providing a variable leakage reactance.

9. The ballast apparatus of claim 8 wherein said nonlinear shunt is comprised of at least one relatively thin lamination of magnetic material.

10. An alternating current source, a ballast apparatus for starting and operating arc discharge lamps comprising a first primary winding, a first secondary winding, a first magnetic core, said first primary winding and said first secondary winding being magnetically coupled on said first magnetic core, a first nonlinear shunt interposed between said first primary and secondary windings and spaced from said first magnetic core to define an air gap therebetween, a second magnetic core, a second primary and a second secondary winding coupled therewith on said second magnetic core, a second nonlinear shunt interposed between said second primary winding and said second secondary winding and spaced from said second magnetic core to define an air gap therebetween, a pair of input leads connected across said alternating current source, said first and second primary windings being connected across said input leads, a first output lead connected in circuit with one end of said first secondary winding, said secondary windings being serially connected, a second output lead connected in circuit with one of said primary windings, said output leads being provided for connection across said lamps, a capacitor connected in series circuit relationship with at least one of said secondary windings and with one of said output leads, said nonlinear shunts providing a leakage reactance at an early portion of each half cycle of the alternating current supplied at said output leads, said leakage reactance being decreased during a later portion of said half cycle.

11. An alternating current source, a ballast apparatus for starting and operating a pair of serially connected arc discharge lamps therefrom comprising a first primary winding and a first secondary winding coupled therewith, a first magnetic core, said first primary winding and first secondary winding being mounted on said first magnetic core, a first nonlinear shunt interposed between said first primary winding and said first secondary winding and spaced from said first magnetic core to define an air gap therebetween, a second magnetic core, a second primary winding and a second secondary winding coupled therewith on said second magnetic core, a second nonlinear shunt interposed between said second primary winding and said second secondary winding and spaced from said second magnetic core to define an air gap therebetween, a pair of input leads connected with the source of alternating current, said first and second primary windings being connected across said input leads, a first output lead being connected in circuit with an end of one of said secondary windings, said secondary windings being serially connected, a second output lead being connected in circuit with one of said primary windings, said output leads being provided for connection across said serially connected lamps, a capacitive reactance connected in series with one of said secondary windings to provide a net capacitive reactance in the secondary circuit, a starting capacitor connected in circuit with one of said output leads for connection

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tion across one of said lamps, said nonlinear shunts providing a leakage reactance at an early portion of each half cycle of the alternating current supplied at said output leads, said leakage reactance being decreased during a later portion of said half cycle.

12. The ballast apparatus set forth in claim 11 in which said first secondary winding is connected in auto-transformer relationship with said first primary winding and in series circuit relationship with said second secondary winding.

13. An alternating current source, a ballast apparatus for starting and operating a pair of arc discharge lamps therefrom comprising a pair of serially connected arc discharge lamps, a magnetic core, a primary winding, a first secondary winding, a second secondary winding, said first and second secondary windings being magnetically coupled with said primary winding on said magnetic core, a pair of input leads connected with an alternating current supply, said primary winding being connected across said input leads, a starting circuit including one of said lamps and at least said first secondary winding for applying igniting voltage to said lamp, and an operating circuit including said serially connected lamps, said primary winding and said second secondary winding for applying an operating voltage to both of said lamps, a linear shunt having an air gap and interposed between one end of said primary winding and said first secondary winding, a nonlinear shunt interposed between the other end of said primary winding and said second secondary winding and spaced from said magnetic core to define an air gap therebetween, a capacitor connected in both said starting circuit and said operating circuit, said first secondary winding having sufficient inductive reactance to prevent substantial current flow through the winding during the normal operation of said lamps, said lamps being operated by the voltage across the primary and said second secondary winding and said nonlinear shunt providing a leakage reactance at an early portion of each half cycle of the alternating current supplied to said lamps, said leakage reactance being decreased during the later portion of said half cycle.

14. The ballast apparatus as set forth in claim 13 in which said first secondary winding is in autotransformer relationship with said primary winding and said second secondary winding connected in series circuit relationship with said first secondary.

15. An alternating current source, a ballast apparatus for operating and starting arc discharge lamps therefrom comprising at least one magnetic core, at least one primary winding and at least one lead secondary winding magnetically coupled on said magnetic core, a transverse nonlinear shunt interposed between said primary and said secondary windings and spaced from said magnetic core to define an air gap therebetween, a pair of input leads connected with the alternating current source, said primary winding being connected across said input leads, a pair of output leads for applying the voltage of at least one of said lead secondaries across said lamps, one of said output leads being connected in circuit with one of said input leads and the other of said output leads

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being connected in circuit with one end of said secondary winding, a capacitive reactor connected in series circuit relationship with said secondary winding and one of said output leads, said nonlinear shunt providing a leakage reactance at an early portion of each half cycle of the alternating current at said output leads, said leakage reactance being decreased during a later portion of said half cycle.

16. The ballast apparatus as set forth in claim 15 in which said secondary winding is connected in autotransformer relationship with said primary winding.

17. An alternating current source, a ballast apparatus for operating at least a pair of serially connected arc discharge lamps therefrom comprising at least a pair of serially connected arc discharge lamps, a magnetic core, a first primary winding, a second primary winding and a lead secondary winding, said windings being magnetically coupled on said magnetic core, said first primary winding being disposed at one end of said lead secondary winding and said second primary winding being disposed on the other end of said secondary winding on said magnetic core, a first nonlinear shunt being interposed between said lead secondary winding and said first primary winding and spaced from said magnetic core to define an air gap therebetween, a second nonlinear shunt being interposed between said lead secondary winding and said second primary winding and spaced from said magnetic core to define an air gap therebetween, a pair of input leads connected with the alternating current source, said first and second primary windings being connected across said input leads, a pair of output leads for applying the voltage of at least said lead secondary winding across said serially connected lamps, at least one starting capacitor connected in circuit with one of said output leads for starting at least one of said lamps, a capacitive reactor connected in series circuit relationship with said secondary winding and one of said output leads, said reactance being sufficient to render the net reactance of said secondary circuit capacitive and said nonlinear shunts providing a leakage reactance at an early portion of each half cycle of the alternating current supplied at said output leads, said leakage reactance being decreased during a later portion of said half cycle.

18. The ballast apparatus as set forth in claim 17 wherein said lead secondary winding is connected in autotransformer relationship with said first primary winding across said output leads.

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