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(54) TRANSIENT DETECTION OF END OF LAMP LIFE CONDITION APPARATUS AND METHOD

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H05B 37/02 (2006.01)

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See application file for complete search history.

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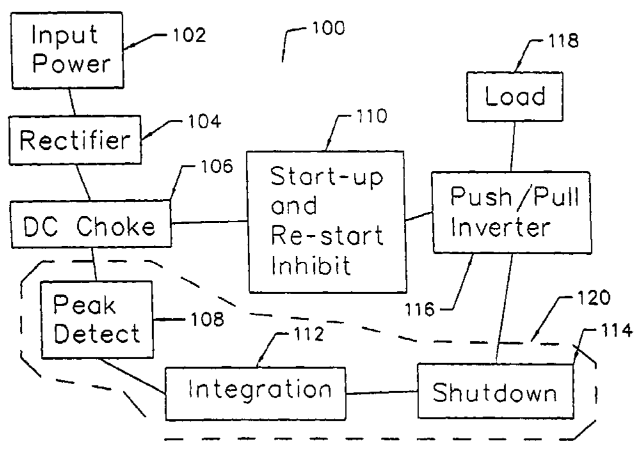
(57) **ABSTRACT**

A sensor system adapted to detect unwanted transients in the primary side of a luminous lamp load driving circuit and effect a change in operation of the driving circuit. A detection circuit is adapted to detect a transient, determine if it is an appropriate end-of-life lamp condition requiring action, and signal an inverter control circuit to provide for an adjustment or shut down of the load driving circuitry. The detection circuit is adapted to detect the transients across the direct current choke as repetitive transients occurring over a period of time. The inverter control circuit includes a negative voltage generator adapted to inhibit power flow into a transistor base inside the inverter. A modified start circuit is also provided with a restart inhibit circuit adapted to prevent the inverter from resuming normal operation after a shutdown condition has been detected.

16 Claims, 2 Drawing Sheets



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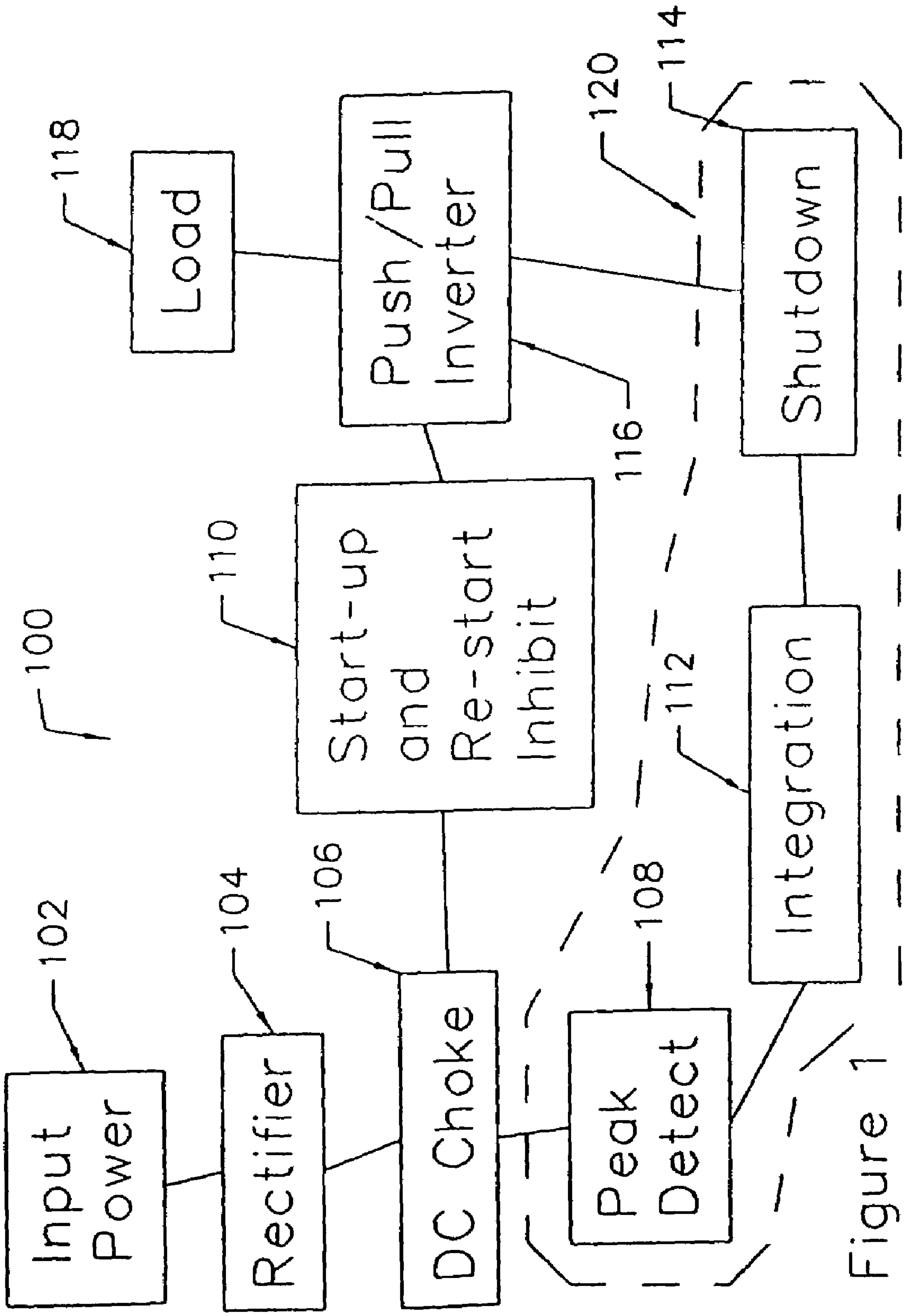
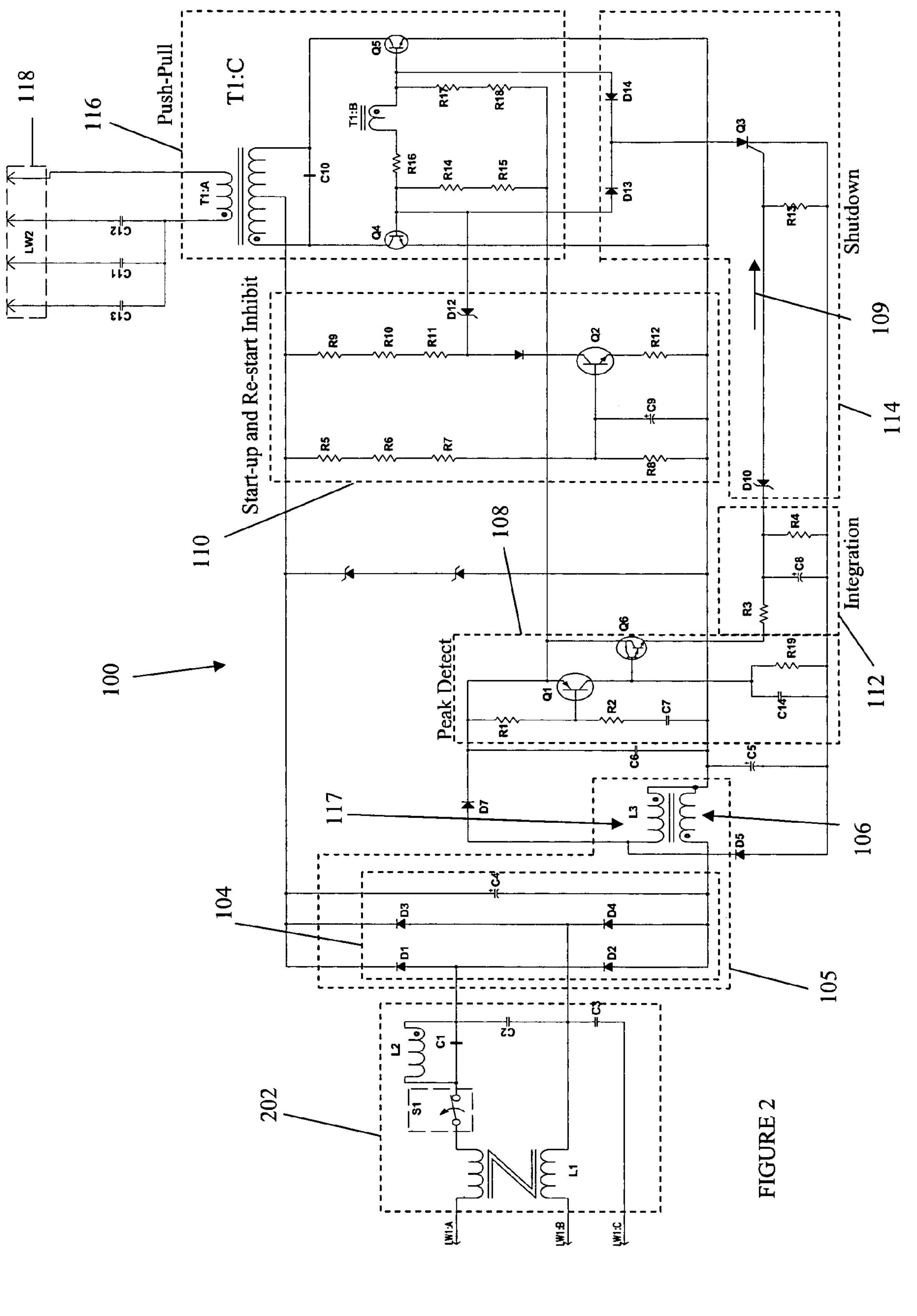

100
Input Power
102
Rectifier
104
DC Choke
106
Peak Detect
108
Start-up and Re-start Inhibit
110
Integration
112
Shutdown
114
Push/Pull Inverter
116
Load
118
120

Figure 1


Push-Pull
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Start-up and Re-start Inhibit
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Integration
Shutdown
100
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202

FIGURE 2

TRANSIENT DETECTION OF END OF LAMP LIFE CONDITION APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

The present invention is directed to a system for sensing a signal in the primary side of a luminous lamp load driving circuit to detect an end-of-life lamp condition and provide for an adjustment or shut down of the load driving circuitry. More particularly, the present invention is designed to detect the transients across the direct current choke associated with an end of lamp life condition in order to provide a shut down signal for the load driving circuitry.

Ballasts using direct current chokes are known in the art. For example, U.S. Pat. No. 5,877,592 entitled Programmed-start parallel-resonant electronic ballast discloses a ballast having a direct current choke. In addition, patents describing protection circuits capable of detecting end-of-lamp-life conditions in lamps are known in the art. Examples of these circuits are described in U.S. Pat. No. 6,127,786 entitled Ballast having a lamp end of life circuit, U.S. Pat. No. 5,808,422 entitled Lamp ballast with lamp rectification detection circuitry, U.S. Pat. No. 5,777,439 entitled Detection and protection circuit for fluorescent lamps operating at failure mode, U.S. Pat. No. 5,635,799 entitled Lamp Protection Circuit For Electronic Ballasts, U.S. Pat. No. 5,606,224 entitled Protection circuit for fluorescent lamps operating at failure mode, U.S. Pat. No. 5,574,335 entitled Ballast containing protection circuit for detecting rectification of arc discharge lamp, U.S. Pat. No. 5,475,284 entitled Ballast containing circuit for measuring increase in DC voltage component, U.S. Pat. No. 5,142,202 entitled Starting and operating circuit for arc discharge lamp, U.S. Pat. No. 5,138,235 entitled Starting and operating circuit for arc discharge lamp, U.S. Pat. No. 5,111,114 entitled Fluorescent lamp light ballast system, U.S. Pat. No. 5,023,516 entitled Discharge lamp operation apparatus, and U.S. Pat. No. 4,429,356 entitled Transistor Inverter Device. Each of these patents is hereby incorporated by reference.

These patent teach different sensors in an electronic ballast, but fail to teach the use of a sensing circuit coupled to the dc choke for detecting the end of life condition. What is needed, then, is a Transient Detection of End of Lamp Life Condition Apparatus and Method.

SUMMARY OF THE INVENTION

The present invention describes an end-of-life sensor device or apparatus for an electronic ballast having a direct current power supply including a direct current choke. The direct current power supply is coupled to an inverter adapted to power a luminous lamp. The device includes an end-of-life sensor operable to detect changes in the voltage across the direct current choke. Once the appropriate level of voltage changes are detected for an end-of-lamp life condition, the sensor generates an end-of-life signal that is communicated to an inverter control circuit. This inverter control circuit will then change the operation of the inverter when the end-of-life signal is received to reduce the stress on the ballast. In the preferred embodiment, the inverter control circuit will shut down the ballast and stop operation of the inverter.

In one embodiment of the present invention where the ballast is shut down by the inverter control circuit, the start circuit connected to a restart inhibit circuit to inhibit the

inverter from restarting and restoring power to the lamp load until the entire unit is de-energized.

A method for controlling a ballast is also taught by the present invention. The method is utilized in a ballast including a direct current choke and an inverter adapted to power a luminous load. The method includes detecting an end-of-life load condition on the direct current choke, and reducing the power provided by the inverter to protect the ballast components.

One advantage and object of the present invention is a prolonged life of the ballast. Yet a further advantage and object is provided in reducing the potential problems associated with an end-of-life failure in a luminous load.

Another advantage of the present invention is the elimination of the need for isolation on the sensing circuit. Sensing circuits connected directly to the lamps in ballasts using transformer isolation must also be isolated in order to ensure that the sensing circuit is properly isolated. The present invention eliminates this requirement by connecting the sensing circuit to the dc choke rather than directly to the lamps. More specifically, the sensing circuit includes an auxiliary winding coupled to the dc choke that allows sensing to be performed on the primary side of the ballast inverter.

Connecting the sensing circuit to the dc choke also eliminates the need for multiple sensing circuits. In ballasts powering multiple lamps in parallel, it is necessary to have sensing circuits coupled to each of the lamps in order to sense lamp failures. This increases the overall costs of these ballasts. By connecting the sensing circuit directly to the dc choke, only one sensing circuit is required, which reduces costs, and that circuit can sense failures in any of the lamps.

The sensing circuit of the present invention also eliminates the need for sensing filament conductivity, which is necessary in some prior art ballasts, and, as a result, can be used for instant-start lamps where there is only one wire from the ballast for each filament.

Other objects and further scope of the applicability of the present invention will become apparent from the detailed description to follow, taken in conjunction with the accompanying drawing wherein like parts are designated by like reference numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic overview of the ballast design of the present invention including the end-of life lamp sensor.

FIG. **2** is an electrical schematic of the preferred circuit embodying the end-of-life sensor in a ballast.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Unlike most ballasts with End-of-Life shutdown circuits that sense an asymmetry or overvoltage at the lamp, this circuit senses a change in the current in the direct current (DC) choke. Load transients, i.e., repetitive fluctuations in the lamp voltage, whether caused by lamp replacement, power on, or an end-of-life lamp, cause a change in the current level into the inverter. During the transition from one current level to another, the voltage on the DC choke primary winding changes. This circuit is designed to sense these voltage changes and shut down the ballast when the voltage changes are caused by fluctuations in an end-of-life lamp. Voltages caused by transients due to lamp replacement and power on will not cause the ballast to shutdown. In other words, the circuit is designed to sense the sustained fluctuations in lamp voltage that occur in end-of-life lamps, yet not shutdown the ballast during temporary transients caused by lamp replacement and power on.

FIG. **1** of the drawings provides a schematic overview of an end-of-life sensing electronic ballast **100** of the present invention including an end-of-life sensor apparatus **120**. Input power **102** is provided from a domestic or foreign alternating current (AC) source for providing power to a direct current power supply **105** including rectifying unit **104** coupled to a direct current (DC) choke **106**. Power from the DC choke **106** is used by the start-up and re-start inhibit circuit **110** to start and power the inverter **116**. The inverter **116** then powers the luminous lamp load **118**. The repetitive pulse monitoring circuit **120**, also known as the sensor apparatus **120**, of the present invention utilizes an end-of-life sensor **108**, also known as a peak detection circuit **108**, coupled to the DC choke **106** to detect end-of-life conditions in the load **118** and generate and end-of-life signal **109** (see FIG. **2**). Signal **109** is only in FIG. **2** for my set of figures. When an end-of-life condition is detected, the peak detection circuit **108** generates an intermediate signal that is coupled to a repetitive pulse monitor **112**, also known as the integration circuit **112**, to ensure that this is an actual end-of-life condition and filter out inaccurate detections. When an accurate detection is made, the repetitive pulse monitor **112** activates the inverter control circuit **114**, also known as the shutdown circuit **114** in the preferred embodiment, to stop or reduce the output of the inverter **116**. The skill in the art has several methods for controlling the inverter **116** for a failure or end-of-life condition. Any of these known methods and their associated devices may be used in the present invention, although the present invention preferably operates by shutting down the inverter **116** and then using the start-up and re-start inhibit circuit **110** to prohibit the inverter **116** from starting again until the ballast **100** has been de-energized.

FIG. **2** of the drawings shows the circuitry of the preferred circuit embodying the end-of-life sensor in a ballast. Line voltage from the utility company is provided at LW**1**:A, LW**1**:B, and LW**1**:C. Line voltage is passed through an input filter **202** including an initial inductor L**1**, switch S**1**, and inductor-capacitor arrangement L**2**, C**1**, C**2**, C**3** to provide an input voltage at the rectifier **104**. The rectifier utilizes diodes D**1**, D**2**, D**3**, and D**4** to provide a rectified voltage which is smoothed by smoothing capacitor C**4**. The voltage across smoothing capacitor C**4** is provided by a first connection directly to both the start-up and re-start inhibit circuit **110** and the inverter **116**, and a second connection through the direct current choke **106** to both the start-up and re-start inhibit circuit **110** and the inverter **116**. The direct current choke is shown as choke inductor L**3**.

The startup and re-start inhibit circuit **110** includes a voltage divider powering time delay capacitor C**9** across the base of inhibiting transistor Q**2**. During the initial charging for time delay capacitor Q**9**, the incoming power from the rectifier will travel through resistor series R**9**, R**10**, R**11** as a start circuit to provide power at Zener diode D**12**. The initial voltage at the cathode of D**12** rises to an operating voltage in excess of 18V, causing D**12** to conduct in the reverse direction, and allowing approximately 1 mA to flow into the base of power transistor Q**4**. This biases power transistor Q**4** ON and starts the push-pull inverter.

Restarting of the inverter **116** is then prohibited by operation of the restart inhibit circuit including the delay capacitor C**9** and the inhibiting transistor Q**2**. Once capacitor C**9** has been charged, inhibiting transistor Q**2** will begin to operate as part of the voltage discharge circuit to pull the cathode of Zener diode D**12** low to remove the operating voltage and the possibility of conduction by Zener diode D**12** which will prohibit a restart of the inverter circuitry **116**. (Note that "input line" is not defined.) The voltage divider comprised of R**5**, R**6**, R**7**, and R**8** is used to bias inhibiting transistor Q**2** on. However, the operation of this voltage divider is affected by a delay circuit including parallel-connected time delay capacitor C**9**. The voltage divider controls the charge rate on capacitor C**9**. Capacitor C**9** is used to delay inhibiting transistor Q**2** from turning on until after the initial start up of the inverter. This provides a delay in the operation of the inhibiting transistor Q**2** to allow the initial startup of the inverter **116** and delay the inhibit circuit operation until after the initial start up has been completed. When the shutdown circuit **114** has activated and stopped operation of the inverter, the restart inhibit circuit **110** prevents the inverter **116** from restarting as long as the ballast **100** is energized. As may be understood by this circuit design, bulk electrolytic smoothing capacitor C**4** must discharge to allow inhibiting transistor Q**2** to shut off.

The voltage across smoothing capacitor C**4** is also connected to the inverter **116**. A conventional current fed, parallel resonant push pull inverter is made using capacitors C**10-13**, bipolar power transistors Q**4** and Q**5**, transformer T**1**, and resistors R**14-18**. Power from smoothing capacitor C**4** is coupled by a connection to transformer T**1** at the mid-point of transformer winding T**1**:C. Power supplied to the mid-point of transformer winding T**1**:C is then transformed across the core of the transformer T**1** to the secondary winding T**1**:A. The output of the secondary winding T**1**:A is connected through capacitors C**11**, C**12**, and C**13** to provide the output at LW**2** for powering the luminous lamp load **118**.

Returning to the transformer T**1**, capacitor C**10** is connected across the primary side winding T**1**:C of transformer T**1**. The end points of the primary winding T**1**:C of transformer T**1** and parallel connected capacitor C**10** are connected to the collectors of power transistors Q**4** and Q**5** respectively. The bases of power transistors Q**4** and Q**5** are driven by transformer drive winding T**1**:B. The first end of transformer drive winding T**1**:B is connected through resistor R**16** into the base of power transistor Q**4**. The second end of transformer drive winding T**1**:B is directly connected to the base of power transistor Q**5**. This provides a push-pull configuration inverter as is known in the art. The present invention is designed to be utilized with either push pull or half-bridge types of load driving circuitry. The inverter is also connected to the peak detection circuit **108** and the shutdown circuit **114**. The base of power transistor Q**4** is connected through resistors R**14** and R**15** and the base of power transistor Q**5** is connected through R**16** and R**17** to the peak detection circuit **108**. The bases of power transistors Q**4** and Q**5** are also directly connected to the shutdown circuitry **114**.

The peak detection circuit **108** is connected to the direct current choke **106**, the inverter **116**, and the integration circuit **112**. Transients are developed across the direct current choke inductor L**3** through the connection with the power transistors Q**4** and Q**5** of the inverter **116**. The emitters of power transistors Q**4** and Q**5** are connected through choke inductor L**3** to the output of the rectifier **104** utilizing diodes D**1**, D**2**, D**3**, and D**4**. This provides a direct coupling of the choke **106** to the inverter **116** such that the transient voltages occurring during operation of the inverter **116** are transferred to the choke **106**.

A negative voltage with respect to emitters of Q**4** and Q**5** is developed through the connection of the diode D**5** and capacitor C**5** across the auxiliary winding **117** of the choke inductor L**3**. This negative voltage is utilized in the peak detection circuit **108**, the integration circuit **112** and the shutdown circuitry **114**.

The peak detection circuit uses a positive rectified value established across the output of the winding of the choke **106** through the utilization of diode D**7** which will charge choke capacitor C**6** with a choke voltage. Choke capacitor C**6** has two functions in the ballast **100**. The first is to store energy for the DC bias for the power bipolar transistors Q**4** and Q**5** in the inverter. The second function is to provide a peak detection voltage that is proportional to the peak voltages across the DC choke.

Once the ballast **100** and lamps **118** have started and stabilized, the voltage on choke capacitor C**6** reaches a stable average value with some ripple due to the current provided to the bases of the power bipolar transistors Q**4** and Q**5**. Change monitoring capacitor C**7** is arranged to act as a change monitoring component with detection resistors R**1** and R**2** to detect changes in the voltage on choke capacitor C**6**. The voltage on change monitoring capacitor C**7** lags changes in the voltage across choke capacitor C**6** due to resistors R**1** and R**2**. Following a load transient, the voltage on the auxiliary winding **117** of choke inductor L**3** rings high, and charges choke capacitor C**6** and change monitoring capacitor C**7** to a higher voltage. When end-of life transients occur, the charging rate differential between the two capacitors C**6** and C**7** produces a voltage differential between the base and emitter of detection transistor Q**1**, also known as peak pulse generator Q**1** and peak detection switch Q**1**. Thus, when the ringing voltage exceeds the steady-state voltage by at least one volt, the voltage across detection resistor R**1** is sufficient to turn PNP detection transistor Q**1** ON.

Once detection transistor Q**1** has been turned on, pulse-stretching capacitor C**14** is rapidly charged during the duration of the ringing voltage across choke capacitor C**6**. After the ringing has subsided, the voltage across capacitor C**14** decays through resistor R**14**. Thus short ringing pulses across choke capacitor C**6** result in longer pulses appearing across pulse-stretching capacitor C**14**. Darlington transistor Q**6** functions as a voltage follower with a high input impedance and a low output impedance so that the voltage at the emitter of Q**16** tracks the voltage across pulse-stretching capacitor C**14** without significantly disturbing that voltage. Each time a pulsed voltage is developed across capacitor C**14**, integrating capacitor C**8** is charged through charge rate control resistor R**3**. This pulse occurs during each transient on the choke **106** that is of sufficient magnitude. Thus, the peak detection circuit **108** generates pulses when the peak values of the ac voltage waveform across the dc choke **106** rapidly increase beyond the steady-state voltage across the dc choke **106**.

The integration circuit **112** accumulates the pulses passing through Darlington transistor Q**6**, and provides a controlled charge rate and discharge rate to monitor the frequency at which the transients occur. Integrating charge storage capacitor C**8**, charge rate control resistors R**3** and discharge rate control resistor R**4** are used to integrate the pulses of current from Darlington transistor Q**6** into a voltage that increases with repeated transients. Integrating charge storage capacitor C**8** is sized to prevent false triggering of the shutdown circuit **114** when the ballast **100** is originally energized, and during short duration load transients, such as lamp removal and replacement. This is accomplished by making the charge rate higher than the discharge rate for integrating charge storage capacitor C**8**. The discharge time constant of integrating charge storage capacitor C**8** and R**4** will be determined by C**8** and R**4**, however, integrating charge storage capacitor C**8** will charge much faster through R**3**. If the voltage developing across integrating charge storage capacitor C**8** is from a singular transient and is not associated with the repetitive transients of an end of lamp life condition, then the voltage developed across C**8** will be insufficient for the shutdown circuit and this charge will be allowed to discharge through resistor R**4** as an unwanted charge. If a repetitive transient occurs, then integrating charge storage capacitor C**8** will charge at a faster rate than the discharge rate, and a sufficient voltage will be developed to operate the shutdown circuit **114**. The voltage across integrating charge storage capacitor C**8** is utilized by the shutdown circuitry to stop the operation of the inverter.

The shutdown circuit **114** is connected to the integration circuit **112**, and the inverter **116**. During normal operation, a negative voltage of approximately **15** volts with respect to the emitters of power transistors Q**4** and Q**5** is generated across capacitor C**5** by the configuration of choke inductor L**3**, diode D**5** and capacitor C**5** to be a reverse polarity voltage from the normal operating voltage on smoothing capacitor C**4**. When an end-of-life condition is detected, the voltage on integrating charge storage capacitor C**8** activates the control switch by reaching the Zener voltage of diode D**10**, also known as an end-of life signal monitor D**10**. Zener diode D**10** then conducts and allows current to flow from integrating charge storage capacitor C**8** to the gate of thyristor Q**3**, also known as a reverse voltage flow control Q**3**. Thyristor Q**3** is a silicon controlled rectifier (SCR) that is controlled by the bias provided across Zener diode D**10** and resistor R**13**. The base of power transistor Q**4** is connected into the shutdown circuitry by diode D**13** to be connected to thyristor Q**3**. The base of power transistor Q**5** is similarly connected through diode D**14** to be connected to the thyristor Q**3**. When the Zener diode D**10** conducts, this current gates Q**3** ON, which presents a negative voltage to the bases of inverter power transistors Q**4** and Q**5**, and stops the oscillations of the inverter. By using this configuration, the shutdown circuit **114** can pull the bases of power transistors Q**4** and Q**5** low in order to shut down the operation of the inverter **116** and remove power from the lamp load **118**. Once the operation of the inverter **116** has been stopped, the inverter **116** will be inhibited from re-igniting by the startup and re-start inhibit circuit **110**.

In this manner, an apparatus for detecting end of lamp life conditions on the primary side of the inverter transformer has been established by utilizing transients occurring across a DC choke.

A simplified method of operation of an inverter may be understood with reference to the circuit of FIG. **2**, where an end of lamp life condition causes a transient DC current through the DC choke **106**. This current is rectified to create a DC voltage on choke capacitor C**6**. Change monitoring capacitor C**7** is connected to C**6** to detect this transient such that the transient voltage may turn on Q**1**. After turning on Q**1**, the circuit will charge up capacitor **14** through R**19** in order to turn on Darlington transistor Q**6**. Repetitive power flow through Darlington transistor Q**6** is utilized through R**3** to charge integrating charge storage capacitor C**8**. The voltage across integrating charge storage capacitor C**8** decays between pulses so that several repetitive pulses sufficiently close together are required to generate an increased voltage across capacitor C**8**. This allows a transient detection charge to build up for repetitive transients. A negative voltage with respect to the emitters of power transistors Q**4** and Q**5** is also provided across capacitor C**5**.

Once the transient detection charge has been built up on integrating charge storage capacitor C**8**, this will overcome the reverse voltage associated with Zener diode D **10** to turn on SCR Q**3** to pull both bases of the inverter power transistors Q**4** and Q**5** negative and shut off the inverter **116**. Finally, the inverter **116** will be inhibited from restarting by the start and restart inhibit circuit **110**.

Although the present invention has been described using analog circuit elements, the applicant contemplates that the present invention might be implemented digitally as well. For example, the embodiment of the integration circuit **112** shown in FIG. **2** is implemented using a capacitor and a pair of resistors. In alternative embodiments, this circuit may be implemented using a digital pulse counting circuit well known in the art. Furthermore, the present invention may be used with a variety of different push-pull or half-bridge current-fed parallel resonant circuits having dc chokes.

Thus, although there have been described particular embodiments of the present invention of a new and useful Transient Detection of End of Lamp Life Condition Apparatus and Method, it is not intended that such references be construed as limitations upon the scope of this invention except as set forth in the following claims.

What is claimed is:

1. An end-of-life sensor apparatus for an electronic ballast having a direct current power supply including a direct current choke, the direct current power supply coupled to an inverter adapted to power a luminous lamp, the sensor comprising:

an end-of-life sensor directly connected to the direct current choke, and adapted to detect an end-of-life lamp condition and generate an end-of-life signal, the end-of-life sensor including a peak detection circuit and a repetitive pulse monitoring circuit, the peak detection circuit coupled to the direct current choke and adapted to detect changes in the voltage level across the direct current choke and generate peak pulses, the repetitive pulse monitoring circuit adapted to receive the peak pulses, detect an end-of-life lamp condition, and generate the end-of-life signal; and

an inverter control circuit electrically adapted to receive the end-of life signal and coupled to the inverter, the inverter control circuit adapted to change the operation of the inverter when the end-of-life signal is received.

2. The apparatus of claim **1**, further comprising:

a restart inhibit circuit coupled to the inverter.

3. The apparatus of claim **2**, further comprising:

a start circuit coupled to the inverter, wherein the restart inhibit circuit is adapted to selectively inhibit operation of the start circuit.

4. The apparatus of claim **3**,

the start circuit including a voltage operated switch activated by an operating voltage; and

the restart inhibit circuit including a voltage discharge circuit adapted to remove the operating voltage from the voltage operated switch.

5. The apparatus of claim **4**, the restart inhibit circuit further comprising:

a delay circuit adapted to delay operation of the restart inhibit circuit during an initial startup of the ballast.

6. The apparatus of claim **1**, the peak detection circuit comprising:

a change monitoring component adapted to detect a change from the normal state operating condition of the direct current choke; and

a peak pulse generator coupled to the change monitoring component, the peak pulse generator adapted to generate the peak pulses when the change component detects the change from the normal state operating condition.

7. The apparatus of claim **6**, further comprising:

a choke capacitor coupled to the direct current choke through a rectifier to establish a peak-detection voltage;

the change monitoring component including a change capacitor connected in parallel with the choke capacitor through a resistance such that a change voltage across the change capacitor lags the peak-detection voltage across the choke capacitor.

8. The apparatus of claim **7**, further comprising:

a peak detection switch electrically connected to the change capacitor, the peak detection switch adapted to pulse power flow to form the peak pulses for the repetitive pulse monitoring circuit when the difference between the voltages across the change and choke capacitors exceeds an established voltage threshold.

9. The apparatus of claim **1**, the repetitive pulse monitoring circuit comprising:

a charge storage element adapted to accumulate the pulses from the peak detection circuit to generate the end-of-life signal.

10. The apparatus of claim **9**, further comprising:

a charge rate control element coupled to the charge storage element establishing a charge rate; and

a discharge rate control element coupled to the charge storage element establishing a discharge rate, wherein the charge rate during the peak pulses is faster than the discharge rate.

11. The apparatus of claim **1**, the inverter control circuit comprising: a shutdown circuit coupled to the inverter and adapted to stop operation of the inverter.

12. The apparatus of claim **11**, the inverter including a forward operating voltage during operation of the inverter, the shutdown circuit comprising:

a reverse voltage generator adapted to generate a reverse polarity voltage; and

a control switch adapted to receive the end-of life signal, the control switch adapted to selectively apply the reverse polarity voltage to the inverter to override the forward operating voltage when the end-of-life signal is received.

13. The apparatus of claim **12**, the reverse voltage generator comprising:

a diode series connected to a capacitor, the diode and capacitor connected in parallel with a direct current choke winding.

14. The apparatus of claim **12**, the control switch comprising:

an end-of-life signal monitor adapted to detect the end-of-life signal; and

a reverse voltage flow control coupled to the end-of-life signal monitor, the reverse voltage flow control adapted to block the reverse polarity voltage until the end-of life signal monitor detects the end-of-life signal.

15. The apparatus of claim **14**, the end-of-life signal monitor comprising:

a Zener diode.

16. The apparatus of claim **14**, the reverse voltage flow control comprising:

a thyristor.

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